Morphology, Geologic History and Dynamics of Wimble Shoals, Rodanthe, NC

By

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ABSTRACT

Barrier islands around the world protect estuaries and mainland areas, creating important habitat as well as environmentally and economically valuable property. Barrier islands represent 10% of global shorelines and are often prevalent on passive margins. Much of the east coast of the United States is protected by barrier island systems, and like other areas, these coastlines are dynamic, responding to storms and sea-level rise. Research of these areas is needed to aid in understanding habitats, hazards, resource availability and best management approaches.

The Outer Banks of North Carolina is a strip of nearly continuous sediment, broken only by a few inlets and is an archetypal wave-dominated barrier system. In many coastal studies, onshore processes of erosion and accretion have been correlated to the location of nearshore morphological features, such as ridges, shoals, and shore-oblique bars. These nearshore features are commonly used as sediment borrow sources for nearby beach nourishment projects. Wimble Shoals, offshore of Rodanthe, NC, is a major bathymetric feature that consists of five shore-oblique ridges and is adjacent to a perennial erosional hotspot region that has been the subject of a recent nourishment project. Although it is often reported that nearshore bathymetric features

impact onshore dynamics, little is known about the nature and origin of these features, particularly the evolution, morphology, and influence on the adjacent coast.

This study focused on the geology and morphology of Wimble Shoals through a series of descriptive and comparative analyses involving two separate geophysical and sedimentological datasets collected almost a decade apart. The primary objective was to evaluate the morphological character, variations, onshore influence, geologic history and sand resource potential of Wimble Shoals. High-resolution bathymetry, slope, and backscatter was used to delineate the morphology of Wimble Shoals including subaqueous dunes, morphological ridges, and areas of outcropping. Shoreline change rates (SCR) were calculated using five digitized shorelines from separate time steps (1873, 1946, 1988, 1997, and 2009). In the study region, the average long-term SCR was -0.47 m/yr, with approximately half (54%) of the analyzed oceanfront region eroding. In more recent years (1997-2009), the average SCR was higher (-1.82 m/yr) with 84% of the island eroding. Seismic-reflection and multibeam data were used to examine the morphology of Wimble Shoals. Decadal- and century-scale bathymetric analyses showed that Wimble Shoals is migrating southward and has some control over the areas of accretion and erosion observed onshore. Wimble Shoals is interpreted to be highstand and lowstand systems tract sands that overly a gently dipping lowstand (Pleistocene) strata. The sands that compose the shoals are medium to fine-sand that are useful for adjacent nourishment projects. It is estimated that Wimble Shoals could potentially be a nourishment borrow source for over 100 nourishment projects of similar size to recent projects in the area, but multiple environmental, ecological, and cultural factors must to be considered before mining these shoals.

Morphology, Geologic History and Dynamics of Wimble Shoals, Rodanthe, NC

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1. INTRODUCTION

Over 20,000 km of barrier islands systems exist throughout the world's coastlines (Stutz and Pilkey, 2011). These barrier island systems are important environmentally, economically, and ecologically and are vulnerable to the effects of climate change. Barrier island systems are complex systems that vary in morphology and characteristics due to anthropogenic and environmental factors such as wave and tidal energy, storm frequency, sediment supply, and geologic setting (Hayes, 1979; Inman and Dolan, 1989; Riggs et al., 1995). Three types of barrier island systems exist; wave-dominated, tide-dominated and mixed energy systems. A wave-dominated system usually contains elongated and narrow islands with migrating and ephemeral channels, while a tide-dominated barrier system is characterized by short, wide islands with extensive back-barrier marshes (Davis and Hayes, 1984; Moslow and Tye, 1985). An archetypal example of a wave-dominated barrier island system is the Outer Banks of North Carolina. This system is a long (~300 km) and narrow (<2 km) barrier island chain that constrains the second largest estuarine system in the U.S., the Albemarle Pamlico Estuary System (APES). The Outer Banks is a sediment-limited, high-energy, dynamic system and thus its economical, biological and physical management is difficult.

In many coastal environments, storms and sea-level rise are causing severe erosion. Beach nourishment has become the most widely used approach to mitigate against erosion (Valverde et al., 1999; Cleary et al., 2000; Kelley et al., 2004). Beach nourishment requires a sediment source to complete a project, but suitable materials can be difficult to find in some nearshore areas (Cleary et al., 2000; Finkl et al., 2007). The Outer Banks is an example of a system with some island areas that are undergoing erosion and have limited sediment available nearshore for maintenance. Nourishment costs include the transport from the borrow area to that

being nourished, the effort needed to extract quality sand, and the nature of the borrow source (Dobkowski, 1998; Leatherman, 1989). Nearly $200 million has been spent on nourishment projects on the Outer Banks within the last 50 years (Table 1, Program for the Study of Developed Shorelines, 2016). As communities in North Carolina and other areas around the world are faced with diminishing beaches, increased knowledge of nearshore geology and processes is critical to help minimize impact and prepare for future needs.

Table 1. Dare County beach nourishment projects from 1966 to 2017 (planned). (Information from Program for the Study of Developed Shorelines, 2016).

Location	Project Year(s)	Total Volume (m³)	Cost ($)
Duck	2017	1,061,200	14,589,000
Kitty Hawk	2017	1,913,000	18,440,000
Kill Devil Hills	2017	914,800	10,008,000
Nags Head	2011	4,600,000	37,344,398
Pea Island	1990, 1991, 1992, 1993, 1995, 1996, 1997, 1998, 1999, 2000, 2001, 2002, 2003, 2004, 2013	7,747,902	29,611,318
Rodanthe	2014	1,620,000	20,422,535
Buxton	1966, 1971, 1973, 2017	4,412,000	46,390,374
Hatteras	1974, 1977, 1984, 1986, 1988, 1992, 2003	887,801	11,825,429
Total		23,156,703	188,631,054

Nearshore regions of continental shelves are areas where sediments can be stored permanently or temporarily in features such as sorted bedforms, sand ridges and incised valleys (Murray and Thieler, 2004; Finkl et al., 2007; Schwab et al., 2013; Thieler et al., 2014; Schwab et al., 2014; Mazières et al., 2015). Multiple sediment deposits persist on the inner continental shelf of North Carolina including Wimble Shoals, Platt Shoals, Diamond Shoals, and others (Fig. 1). These sediment deposits are variably thick (1-16 meters) and have varying morphologies

(Inman and Dolan, 1989; Boss et al., 2002; Gutierrez et al., 2005; Thieler et al., 2014). Seismic reflection data coupled with bathymetric information and cores have been used to understand inner shelf morphology, dynamics, processes and geologic history providing a greater knowledge of resource availability, marine habitat, and coastal evolution (Cowell et al., 2003; Fagherazzi and Overeem, 2007; Finkl et al., 2007; Thieler et al., 2014; Mazières et al., 2015). Along the Outer Banks, most of the beach compatible sand lies within a "lens" of Holocene material that is variably thick along the nearshore shelf (NC Beach and Inlet Management Plan, 2011). This Holocene material is thickest in shoreface ridges and shoals, specifically, Platt Shoals, Diamond Shoals, and Wimble Shoals (Thieler et al., 2013; 2014) (Fig. 1). Understanding the character and variability of these features is important for evaluating the needed resources for nourishment associated with changes of the shoreline (Cleary et al, 2001; Hayes and Nairn, 2004; Finkl et al, 2007; Hobbs, 2007).
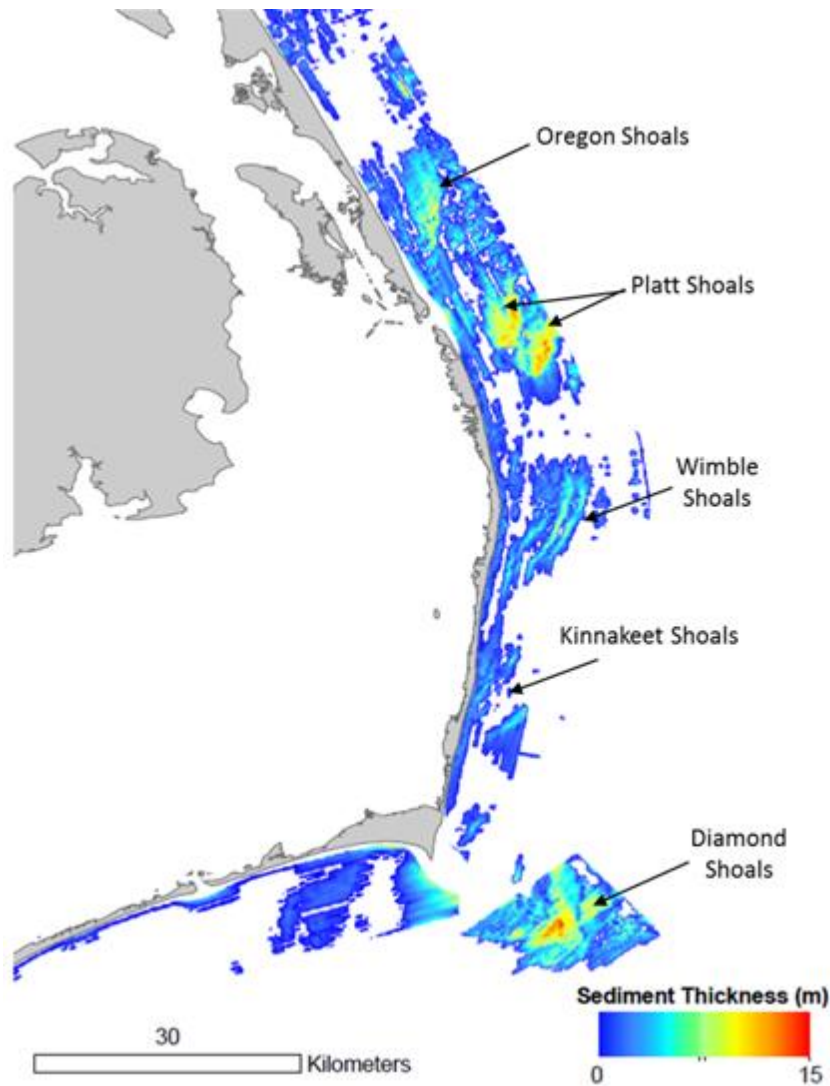
Figure 1. Location and sediment thickness of major nearshore bedforms along the Outer Banks of North Carolina. Warmer colors indicate thicker modern sediment deposits (Modified from Thieler et al., 2014).

The overarching objective of this study is to examine a shoal-ridge complex in North Carolina, Wimble Shoals (Fig. 2), to better understand its sedimentary character, morphology, evolution, and potential impact on the morphology of adjacent beaches. The specific objectives are:

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1) Elucidate the detailed morphology and surface dynamics of Wimble Shoals and use the findings to define its evolution. A better understanding of the morphology and dynamics of Wimble Shoals is important for understanding the sediment transport dynamics as it appears to have some control on the adjacent shoreline morphology.

2) Examine the geological characteristics of Wimble Shoals as it pertains to sand resources for beach nourishment projects, such as the 2015 nourishment of Pea Island National Wildlife Refuge. Informing on how this sand is distributed and potentially migrating will allow managers and scientists to effectively utilize this resource.

3) Evaluate the influence of Wimble Shoals on changes of the adjacent shoreline, potentially through wave refraction. Understanding nearshore bathymetric features and the associated impact on onshore variability will help best manage complex coastal systems.
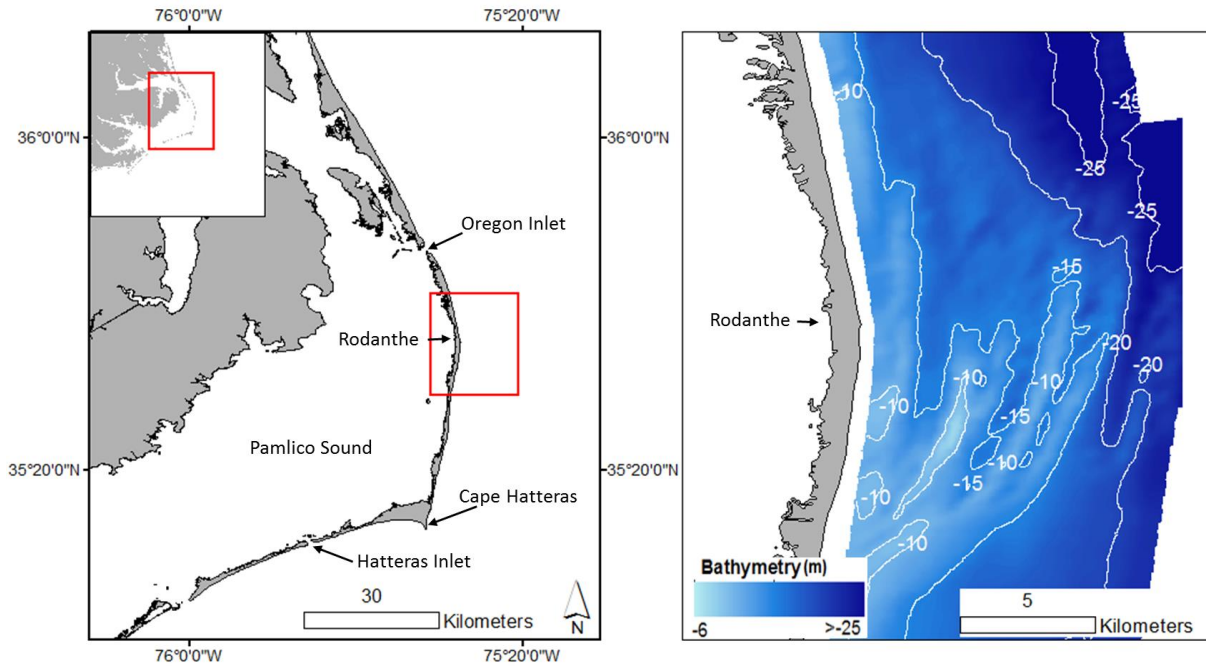
Figure 2. A) Site map of Wimble Shoals located off of Rodanthe, Outer Banks, North Carolina. The location of the study area is shown highlighted in red. The towns of Rodanthe, Waves and Salvo and areas of Hatteras Inlet, Oregon Inlet and Pamlico Sound are also listed for reference. B) Study area with bathymetric map and contours showing the morphology of Wimble Shoals.

BACKGROUND

2.1 Geologic History

The Outer Banks sedimentary system has been created by the reworking of sediment along the shoreline and shelf during the Holocene sea-level rise (Riggs et al., 1995, Riggs and Ames, 2006; Mallinson et al., 2010). During the Last Glacial Maximum, sea-level was much lower (~125 m) and the shoreline was positioned farther east (~100 km) than today (Riggs et al., 1995). Since the shoreline was positioned seaward of today, paleo-rivers and incised valleys cut across the landscape, what is now the shelf and location of the Outer Banks (Riggs et al., 1995; Riggs and Ames, 2006; Mallinson et al., 2005; 2010). As sea-level rose from 18 ka to present, deposits on the paleo-landscape were reworked by storms, longshore transport, and wave energy to form the Outer Banks (Kraft, 1971; Riggs et al., 1995; McNinch, 2004; Culver et al., 2006; Mallinson et al., 2010; Mallinson et al., 2011). The modern shoreface morphology and sediment composition of the Outer Banks is thus related to and still highly influenced by the relict and reworked offshore stratigraphy (Fisher, 1962; Riggs et al., 1995).

2.2 Barrier Island Morphology

Barrier islands around the world protect estuaries and mainland areas, creating important habitat and environmentally and economically valuable property. Barrier islands represent a small percentage, 10%, of global shorelines, but are often prevalent on passive margins such as the east coast of the United States (Stutz and Pilkey, 2001; Riggs and Ames, 2006; Stutz and Pilkey, 2011). Barrier islands are often found along sediment-limited shelves and, because of changing ocean and other conditions, are notoriously dynamic. Their morphology is affected by a multitude of factors including tides, currents, wind transport, wave energy, human infrastructure, sediment supply, sea-level rise and fall, and storms (Hoyt and Henry, 1967;

Leatherman, 1979). Seaward of barrier systems, bathymetric highs can often be found on the inner shelf and are hypothesized to have a primary control over erosion rates and beach morphology (Swift et al., 1971; Riggs et al., 1995; McNinch, 2004; Schupp et al., 2006; Miselis and McNinch, 2006).

2.3 Shoreline Dynamics

Erosion is a significant concern around the world, especially along barrier systems. The Outer Banks have areas of chronically high rates of erosion or deposition, referred to as hotspots. The Outer Banks is subjected to major storms throughout the year with nor'easters impacting the coast generally during the early winter to spring, and hurricanes during the summer and fall (Kochel et al., 1985; Dolan, 1988; Fenster and Dolan, 1993). Although hurricane landfalls are relatively rare along the Outer Banks (28 hurricanes have passed within 60 miles of Rodanthe since 1980; NOAA), many tropical systems, such as Irene in 2011 and Sandy in 2012, have caused significant problems including sound-side flooding and inlet breaches (Mulligan et al., 2014, Klausmann, 2014). Along with storms, northeastern NC is also experiencing a moderate rate of sea-level rise, 0.45 ± 0.07 cm/yr (NC Sea-level Rise Assessment, 2015). As North Carolina has legislation restricting the use of hardened structures on the oceanfront, beach nourishment is a widely used technique to overcome issues with erosion and beach loss. As humans continue to develop these coastal areas, the importance of shoreline management increases.

2.4 Nearshore Bathymetric Influence

Previous work has shown that bathymetric features in the nearshore can impact wave energy by refraction. The refraction of wave energy can lead to spatial variations along the shoreline (Bender and Dean, 2002; McNinch 2004), and it is hypothesized that these variations

can cause shoreline change hotspots along the Outer Banks and other barrier island systems (Kraus and Galgano, 2001). McNinch (2004) showed that areas with chronic erosional hotspots are typically adjacent to offshore shore-oblique ridges or other bathymetric highs, and Schupp et al. (2006) illustrated how such areas are correlated with onshore variability of shoreline change rates. Miselis (2006) reported that decadal-scale shoreline change rates for North Carolina are related to the stratigraphic framework of the nearshore and amount of sediment overlying the geologic basement (usually Pleistocene material). While recent research highlights a relationship between offshore and onshore properties, additional work is needed to understand the connections.

2.4.1 Distribution of Nearshore Sedimentary Features

Studies around the world have defined and discussed shelf sedimentary features, such as ridges, shoals, and shore-oblique bars (collectively referred to as *morphologic ridges*) (Swift et al., 1971; McBride and Moslow, 1991; Dyer and Huntley, 1999; McNinch and Luettich, 2000; Schupp et al., 2006; Thieler et al., 2014; Simarro et al., 2015). Large sorted bedforms occur throughout all coastal sandy environments where water depths are greater than 1 m, currents are greater than 0.4 m/s and sediment is coarser than 0.15 mm (Ashley, 1990; Dyer and Huntley, 1999; Calvette et al., 2001). These features include all types of bedforms created on the seafloor by near-bed currents, or in some cases could be caused by deposition on top of erosional features. While the emphasis of this thesis is on large-scale bedforms, these features have a large range in size from small ripples (i.e., 1-2 cm tall; with wavelengths of tens of centimeters) to large ridges (i.e., 10s of meters tall; with wavelengths of hundreds of meters or more). Bedform size and structure are dependent upon flow velocity, depth of water, and grain size (Fig. 3). Large-scale shoals and morphological ridges are generally over 1000 m long, have side slopes of

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less than 1°, are 1-3 km wide, and have up to 10 m of relief (Swift et al., 1978; Duane et al., 1972; Field, 1980; McBride and Moslow, 1991). According to Swift (1975) and Dyer and Huntley (1999), there are three types of inner shelf sand ridges: open-shelf ridges, estuary-mouth ridges, and headland-associated banks, although this example is from the North Sea which has different tidal regimes than the east coast of the U.S. (Fig. 4). Open-shelf ridges are typically oriented at a small oblique angle to the peak tidal flow direction, can be 80-km long and up to 13-km wide (Dyer and Huntley, 1999). Well-described examples of large-scale sand ridges and shoals are found along the eastern coasts of North and South America, as well as the North Sea. These nearshore features have 25° to 40° angles to the coast (Duane et al., 1972; Swift et al., 1978; McBride and Moslow, 1991; McNinch, 2004; Schupp et al., 2006; Snedden et al., 2011; Denny et al., 2013; Nnafie et al., 2014). An interesting phenomenon regarding the formation and morphology of these large-scale nearshore sand features is that in the southern hemisphere the features typically have a southward opening angle, which is opposite of the northern hemisphere features. This is possibly due to the fact that the southern hemisphere storms would be "southeasters", which would drive northward currents analogous to the nor'easters and southerly driven currents of the North American shelf (Swift et al., 1978).
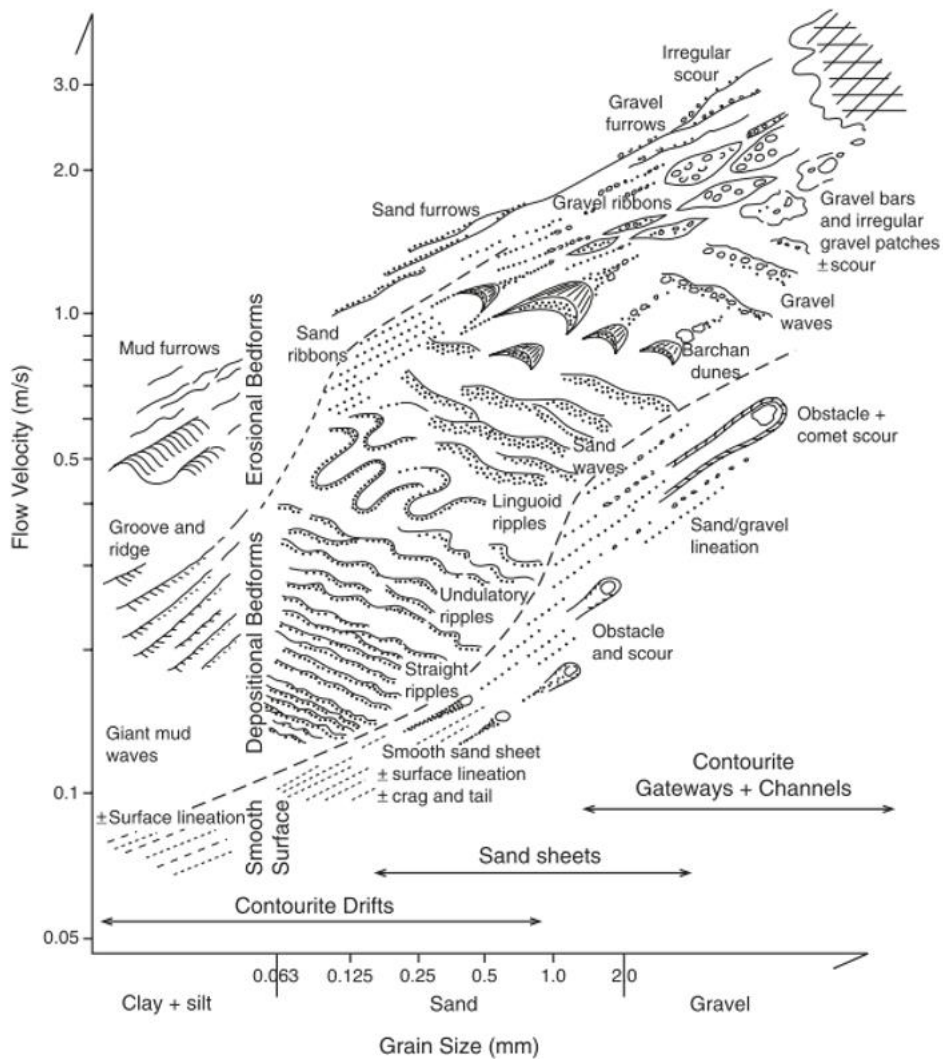
Figure 3. Relationship between bottom current speeds and grain size as it relates to size and structure of bedforms. As flow velocity and grain size increase, bedforms become larger and more complex. (Stow et al, 2009)
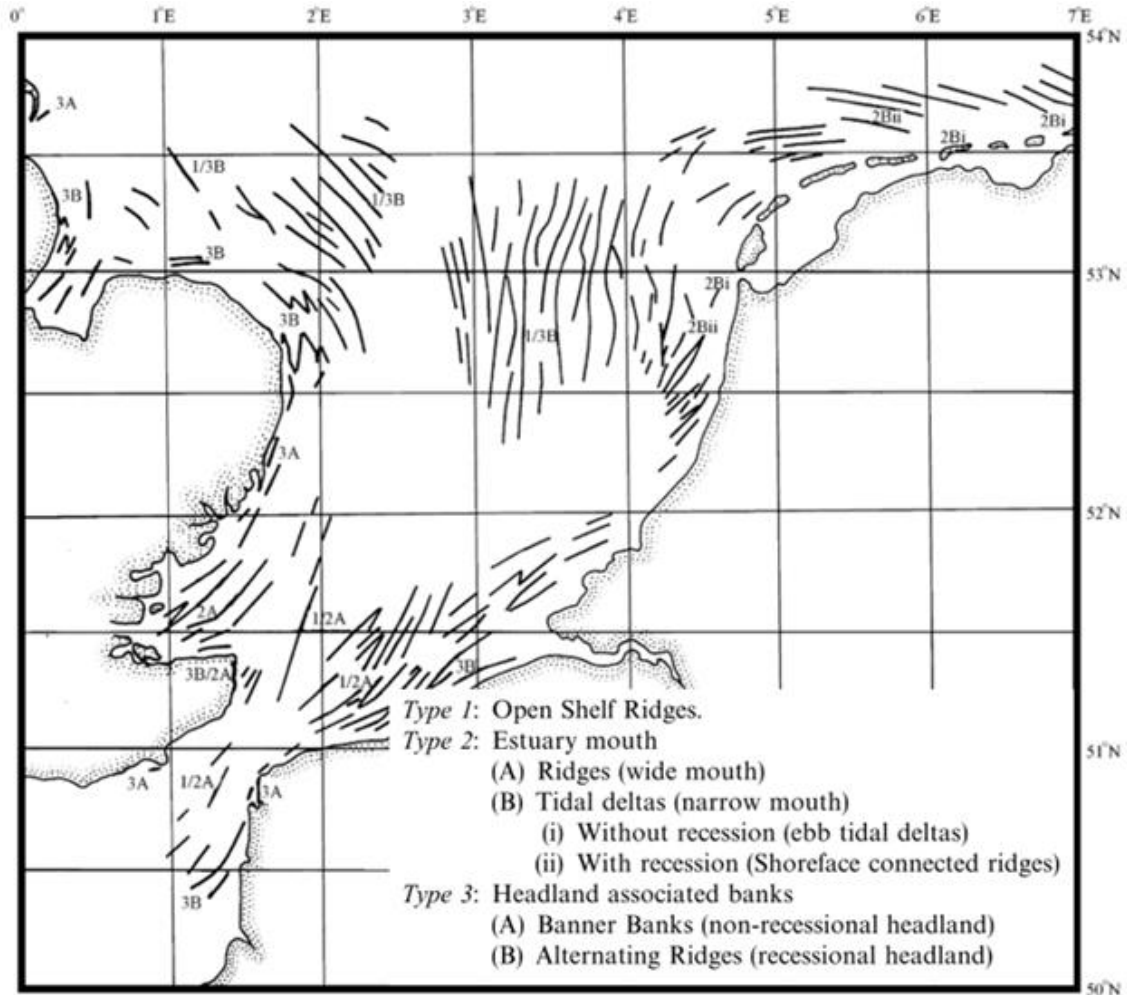
Figure 4. Map of inner shelf ridges in the North Sea with classifications showing types of ridge features. Keep in mind that the North Sea is very different than the Mid-Atlantic shore with respect to tidal influence. (Dyer and Huntley, 1999)

The North Carolina continental shelf are home to several large sedimentary ridge and shoal features including Wimble Shoals, Platt Shoals, Kinnakeet Shoals, Oregon Shoals, and Diamond Shoals. Each of these sedimentary features is unique in its morphology, shape, and size (Fig. 1). In areas of less sediment abundance (e.g. offshore of Wrightsville Beach), the North Carolina seafloor is dominated by sorted bedforms of smaller scales (Gutierrez et al., 2005; Thieler et al., 2014). A study compiled by McBride and Moslow (1991) showed that there are 43 sand ridge and shoal features along the Virginia and North Carolina coast averaging 0.13

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ridge features per kilometer of coastline. These sand ridges have an average orientation of 26° to the coastline, are concentrated in small clusters, migrate south, and are located in areas that correspond to historical inlets (McBride and Moslow, 1991).

2.5 Origin and Morphology of Nearshore Sedimentary Features

McBride and Moslow (1991) proposed that there is a two-step process for the development of most sand ridges along the U.S. Atlantic coast. This process begins with sand being deposited as river deltas or ebb-tidal deltas along the inner continental shelf, for example during lower positions of sea-level during the Quaternary. Transgression of the sea afterward reworked the deposits into potentially more-linear sedimentary features submerged on the shelf, which are now located below wave base and beyond the dynamic shoreface. Multiple studies found that shore-oblique bars tend to be associated with the underlying geologic framework (McNinch, 2004; Browder and McNinch, 2006; Schupp et al., 2006), while sorted bedforms reflect the hydrodynamics and reduced sediment availability (Murray and Thieler, 2004; Thieler et al., 2014).

Research has shown that nearshore ridge and shoal formations are able to withstand storms, increased wave and current strengths, and natural sediment transport processes over many years (McNinch, 2004; Gutierrez et al., 2005; Schupp et al., 2006; Thieler et al., 2014; Goff et al., 2015; Mazieres et al., 2015). Son et al. (2012) concluded that not only do shoreface-connected ridges withstand storms, but also that the storm conditions likely control their development. Although these features can be persistent in their general location and morphology, evidence suggests they migrate laterally (Snedden et al., 1994; Dyer and Huntley, 1999; Schupp et al., 2006; Snedden et al., 2011; Thieler et al., 2014; Schwab et al., 2014; Goff et al., 2015). While studies have concluded that storms contribute to the persistence of sorted

bedforms by expelling fine-grained sediment (Green et al., 2004; Goldstein et al., 2011; Mazieres et al., 2015), others have shown that storms can induce destruction, creation or migration of sorted bedforms (Schwab et al., 2013; Trembanis et al., 2013; Goff et al., 2015). The variability of these bedforms is potentially an important factor in our understanding of the morphology and change onshore as well as being important for sand resources.

3. METHODS

3.1 Data Sources

This study included the use of bathymetric data, side-scan sonar data, chirp sub-bottom data, historic shorelines, historic bathymetry, and previously collected vibracores. A major source of information was provided by a comprehensive, cooperative USGS-funded study of the northeastern North Carolina coast. This early study generated an improved understanding of the geological evolution of coastal North Carolina including the extent of sediment sources. A dataset collected between 1999 and 2002 (USGS Dataset) was made available through Thieler et al. (2013) OFR 2011-1015 and includes over 8,000 kilometers of tracklines consisting of boomer and chirp seismic, sidescan sonar, and single beam bathymetry data. These data are of variable resolution.

Along with the USGS data, a high-resolution dataset from 2013 was obtained from Geodynamics, LLC. with permission from the U.S. Army Corps of Engineers (USACE) and NC Department of Transportation (NCDOT). These data were collected to evaluate sand resource availability near northern Rodanthe and were used to complete a nourishment project along the adjacent shoreline of Pea Island National Wildlife Refuge. These data are herein referred to as the Geodynamics data (Fig. 5). The location where the nourishment was completed is referred to as the "S-Curves" that is a perennial location for high erosion rates and destruction of infrastructure. This nourishment project was completed in 2014 and placed 1.3 million cubic meters of sand across a 2.3-mile stretch of Pea Island National Wildlife Refuge (USACE, 2013).

Interpreted and raw data were obtained from Geodynamics, LLC. The data included ~125 kilometers (78 miles) of tracklines consisting of chirp, multibeam bathymetry, and multibeam backscatter data spanning covering two separate sites (area A to the north and area B to the

south) consisting of a total area of 17.3 km² (Fig. 5). The spacing for the tracklines of both the USGS and Geodynamics data was 300 meters, which provided a large number of tie points (i.e., trackline intersections) between the two studies. The USGS and Geodynamics datasets both provided sediment cover information derived from interpretations of the seismic lines (i.e., sediment thickness isopachs) and were compared quantitatively using ArcGIS.

3.2 Bathymetry and Backscatter Analysis

Bathymetric data have been collected since the early 1800s as a means to provide answers to scientific, commercial and military needs. Early measurements were recorded as soundings by using a lead weight and rope and lowering the weight until it hit the seafloor, at which point the depth was recorded. These measurements provided a rough layout of the seafloor and typically only included large anomalies (Dierssen and Theberge, 2014). With technological advancements and as our understanding of the speed of sound in water evolved, single-beam echosounders became the norm for measuring depth. These systems produce a continuous depth profile of the elevation of the seafloor directly beneath the sensor. Today, bathymetric data are also gathered from multibeam swath systems aboard ships using acoustics to map out a swath of the seafloor (usually 3-4 times wider than water depth), and data are corrected for ship motion and sound speed (Dierssen and Theberge, 2014).
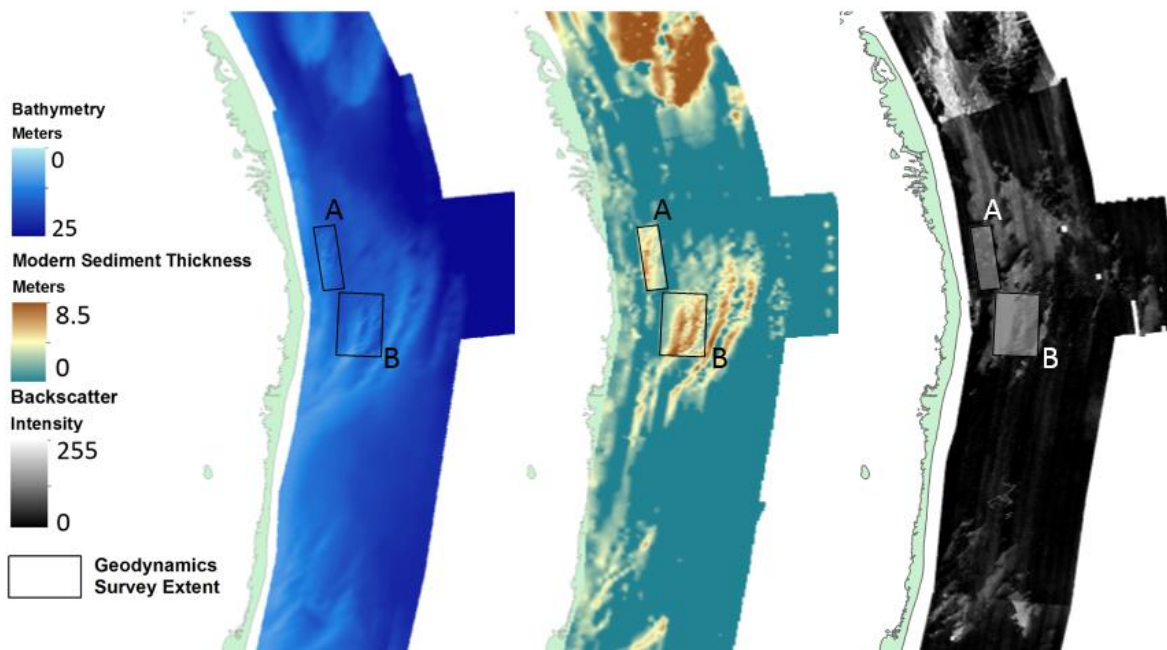
Figure 5. Map of both the USGS and Geodynamics (indicated by A and B inset boxes) surveys of Wimble Shoals. Note the increased resolution of the Geodynamics survey.

Historical bathymetric charts were obtained from NOAA's Office of Coast Survey for 1870 and 1902 and were georeferenced in ArcGIS (https://historicalcharts.noaa.gov/historicals/ search). These images were georeferenced using existing coordinates on the images themselves and matching them with four separate points on ArcGIS to ensure spatial accuracy by using the Georeferencing Tools in ArcGIS 10.2. As previously noted, modern multibeam bathymetry was acquired from surveys in 1999 (USGS) and 2013 (Geodynamics, LLC.).

Data obtained from the USGS covered an inner-shelf area over 2600 km^2 using both single-beam and swath bathymetry techniques. The single-beam data were collected using a Furuno fathometer, while the swath bathymetry data were collected using a SEA, Ltd. SwathPLUS 234-kHz bathymetric sonar. Both soundings from the single-beam and swath

bathymetry surveys were processed using SwathED multibeam processing software. The track

spacing for the collection of bathymetry was 300 meters (with the swath bathymetry resulting in

30-40% coverage). Datasets were interpolated to fill areas of no data and generate a continuous

bathymetric grid. Navigational data were acquired using a Differential Global Positioning

System with a horizontal accuracy of 1-3 meters. Ship motion was recorded using a TSS DMS

2-05 Attitude Sensor, providing corrections for heave, pitch, and roll with a vertical accuracy of

0.2 meters. The USGS dataset is available through USGS Open File Report 2011-1015. Data

from the USGS was used to analyze three large morphological ridge systems along the Outer

Banks; Platt, Wimble and Kinnakeet shoals.

Data obtained from Geodynamics, LLC. included multibeam sonar data over two

separate areas of Wimble Shoals (Fig. 5, insets A and B). These bathymetric data were collected

using two paired Simrad EM3002 multibeam sonars with an Applanix POS MV 320 v4 inertial

navigation system for precise location and motion corrections. Navigation data were acquired

using a high-accuracy Trimble 5700 real time kinematic GPS system that provides centimeter-

scale positioning. Trackline spacing for the Geodynamics survey was 300 meters and resulted in

100% coverage. Bathymetric datasets were compared using ArcGIS's Raster Calculator tool, as

well as the comparison of isobaths taken from georeferenced historical images.

A tool for classifying the grain size, complexity and features of the seafloor is the

acoustic backscatter derived from both multibeam and side-scan sonar systems (Goff et al., 2000;

Collier and Brown, 2005; Ferrini and Flood, 2006; McGonigle and Collier, 2014). Both datasets

(i.e., USGS and Geodynamics) provided backscatter data for the study area, represented as

greyscale GeoTIFFs. Backscatter intensity is a measure of the sound that is scattered back

toward the transmitter and the greyscale values corresponded to the varied strength of the

returned signal (Goff et al., 2000; Ferrini and Flood, 2006). For example, low intensity returns commonly suggest fine sediment on the seabed while a high intensity return is suggestive of rock or coarser-grained material; however quantitative relationships are dependent upon complex environmental factors (Huvenne et al., 2002; Collier and Brown, 2005). Simply, based on the reflection of acoustic energy, these methods help map the depth and character of the seabed.

3.3 Shoreline Change Analysis

Shoreline data was obtained from the NC Division of Coastal Management (NC DCM) for five individual time steps including both historical and modern shorelines to determine long-term and recent change. Shorelines from 1873, 1946, 1988, 1997, and 2009 were analyzed in ArcGIS. The first three shoreline timesteps represent the high water line at the time of survey (compiled by NC DCM and include a multitude of different data sources), while the latter are derived from LiDAR to show the high water line (compiled by NC DCM). Erosion rates were quantified using AMBUR (Analyzing Moving Boundaries using R; Jackson, 2010). A tool within AMBUR allows the user to decide the spacing of transects for shoreline change analysis (150 m for this study). Using 213 transects spaced at 150 m, shoreline change rates (SCRs) were determined in this study to evaluate along-shore variability. Mean change rates for an area take into account all erosional and accretionary transects and are a commonly used statistic to report how a system (or portion of a system) is responding to environmental variables. Overall, shoreline change rates can provide an analysis of how a barrier system is responding over time and can give insight into potential impacts on and need for resources (Jackson et al., 2012). Total error rates were calculated using a combination of both shoreline mapping and tidal cycle errors (associated with different survey events occurring at different times), and followed methods outlined by Genz et al. (2007) and Cowart et al. (2011). The digitization error for

shorelines was pre-determined by the NC DCM and accounted for orthophotography error (~1 m), repeated digitization error, and any short term variations including wave run-up and tides.

Four separate time steps were analyzed for shoreline change rates, including: 1873-1946, 1946-1988, 1988-1997 and 1997-2009. The latter two time steps integrate over a shorter duration (9 years and 12 years, respectively). Although the shorter time steps may provide greater variability of both erosion and accretion, the data provide insight on decadal-scale shoreline change rates over a similar time period as the geophysical measurements.

3.4 Seismic Interpretation

Chirp seismic data were collected by both the USGS study and the Geodynamics study. Both surveys had fairly collocated lines and intersected one another 249 times. Chirp data provided by Geodynamics were sub-contracted out to Coastal Carolina University, who used a Edgetech SB-512i subbottom sonar. Seismic data from USGS were collected with a Teledyne Benthos (Datasonics) SIS-1000 Chirp system. Seismic data from both USGS and Geodynamics LLC were analyzed using Information Handling Services' (IHS) Kingdom Suite (version 8.8) software to manipulate and analyze the seismic lines. Both USGS and Geodynamics LLC used this software to create isopachs of unlithified sediment thickness and a base of sediment map. To alleviate any uncertainty associated with the interpretation of different digitizers, both datasets were re-interpreted using similar methods employed by USGS and Geodynamics. Two reflectors were mapped out: SS1, a shallow reflector and SS2, a deeper reflector. The re-interpreted lines were exported to ArcGIS as point files for a quantitative comparison. Within ArcGIS, 235 intersection points between the USGS and Geodynamics tracklines were analyzed. Each of these intersection points contained data from both the re-interpreted horizons as well as the original isopach thickness measurements. The average sediment thickness at each

intersection of both the re-interpreted horizons and the isopachs were calculated and compared to one another.

3.5 Volumetric Analysis

To better understand the distribution of unlithified sediment, volumetric calculations were conducted. Sand bodies associated with three distinct seafloor features; Kinnakeet Shoals, Wimble Shoals, and Platt Shoals, were assessed. This analysis involved delineating the boundaries of the three shoal complexes in ArcGIS 10.2 and then using the Zonal Statistics tool to determine the mean thickness. The area of each shoal and the calculated mean thickness values were then used to calculate the total volume of sediment.

To place the 2015 nourishment in a sedimentary context, an effort was made to determine the amount of material extracted from Wimble Shoals. Maps from USACE (2013) were georeferenced in ArcGIS using four control points. Then borrow areas were digitized for the various dredge cuts (i.e., USACE labeled 2-4 ft, 4-6 ft and 6-8 ft cuts). Based on sediment thicknesses, volumes were estimated.

3.6 LiDAR

Airborne based LiDAR (Light Detection and Ranging) is a widely used tool for evaluating beach morphology, shoreline evolution, beach and dune volume changes, and nourishment progress (Sallenger et al., 2003; White and Wang, 2003; Pietro et al., 2008; Brock and Purkins, 2009; Mitasova et al., 2009). Over the last two decades, the application of LiDAR to coastal environments has continuously grown (Sallenger et al., 2003, White and Wang, 2003; Brock and Purkis, 2009). For example, raster datasets derived from LiDAR data can be used to measure the per cell change in elevation along a beach which can be related to volumetric change (Mitasova et al., 2009). For this study, multiple LiDAR datasets were acquired from the NOAA

Office for Coastal Management Digital Coast (NOAA Coastal Services Center, 2010) including the 2009, 2011, and 2014 surveys of Pea Island. Data are spatially referenced to North American Datum of 1983 (NAD83) and vertical positions are in North American Vertical Datum of 1988 (NAVD88). The horizontal accuracy is estimated to be ~2m, while the vertical accuracy of these data are; ± 15 cm for 2004, ± 20 cm for 2009 and ± 18 cm for 2014 (NOAA Coastal Services Center, 2010). Calculated difference values of less than 0.2 meters in subsequent analyses are considered to be within the error of the data.

Raster layers were differenced in ArcGIS to evaluate change between years. Differences between two LiDAR datasets provides insight into how the island is losing or gaining volume. Individual cells give insight to the location and variability of onshore erosional hotspots. Mean elevation was calculated using the Zonal Statistics tool in ArcGIS to produce a snapshot of how the island is evolving through the different time steps. Profiles were then cast upon selected areas of the LiDAR data using the Profile tool in ArcGIS to quantitatively evaluate differences between years.

4. RESULTS

4.1 Wimble Shoals Morphology

The morphology of Wimble Shoals was studied both quantitatively and qualitatively to understand its modern character and change. As noted by Thieler et al. (2014), Wimble Shoals is composed of five shore oblique ridges approximately 500 meters wide, 10-13 kilometers long and up to seven meters high although it should be noted that the ridges have a fan-arrangement, attached both to the shore and connected to one another in the south and thinning to the north (Fig. 2) . The five large ridge structures have corresponding properties of very large sorted bedforms (Thieler et al., 2014; Mazieres et al., 2015). Mazieres (2015) describes similar ridges as a first order scale bedform called "morphological ridges". In the study area, the morphological ridges include second-order sedimentary features; subaqueous dunes that form the undulating surface over the larger morphological ridges and have an E-W orientation in the northern portion of Survey Area "B" (Fig. 6) and NE-SW in the southern portion of Survey Area "B' (Figs. 6 and 7). An example interpretation of part of Wimble Shoals is provided in Figure 8. Slopes of the dunes on top of the ridges are higher (10°+) than the slopes defining the ridge edges, and the dunes are around 1 kilometer in length, with wavelengths of 50-100 meters and up to 2 meters of relief (Figs. 6 and 7).

In between the ridges, the seafloor has varied complexity and morphology. Generally, the slopes are modest (0-2°), relief is <2 m, and there are linear structures that are oriented N-NE to S-SW (Figs. 7 and 8). It is interpreted that the linear features are outcrops that formed during an earlier time and under different environmental conditions than the processes responsible for the morphological ridges and dunes. These scarps have relief up to 2 meters and have very little overlying sediment (Figs. 7 and 8).
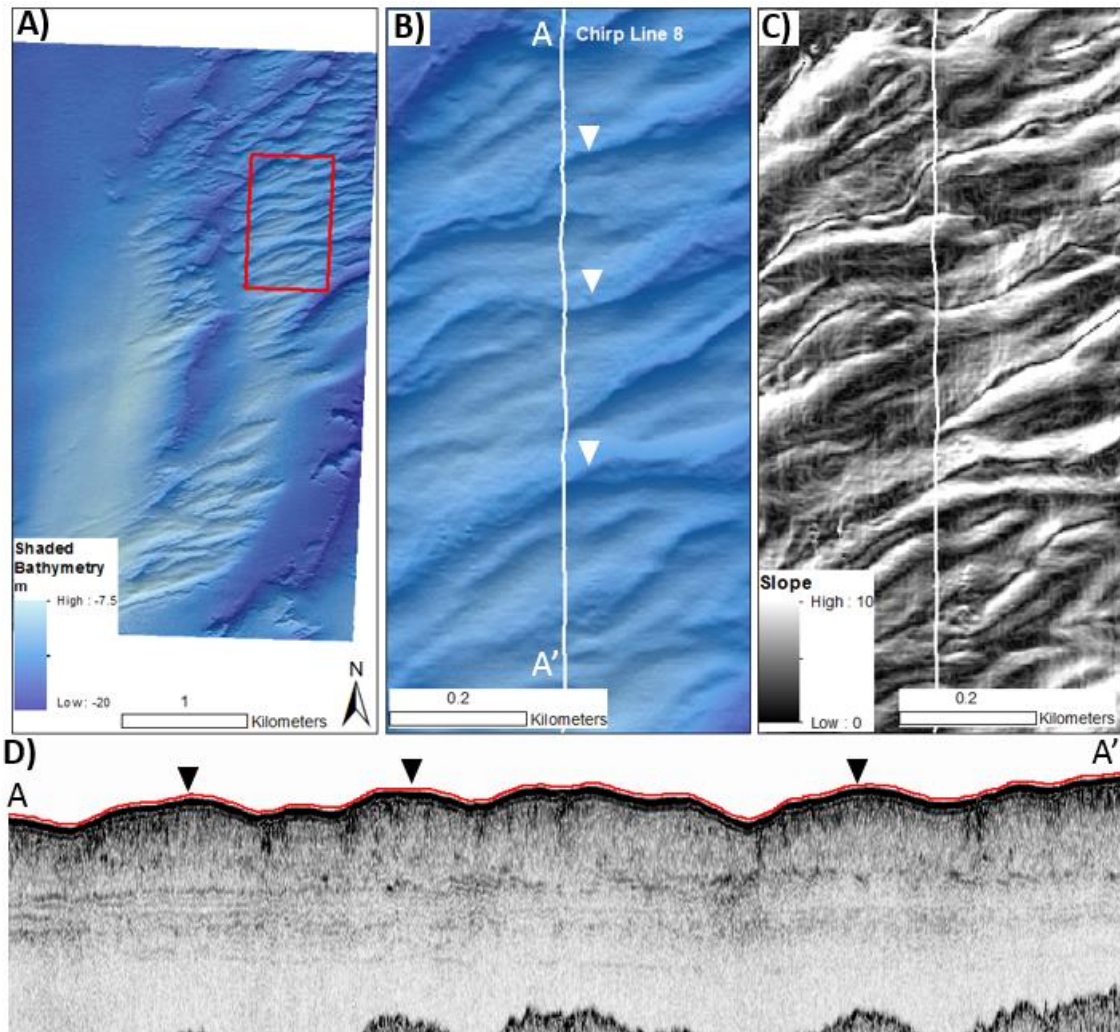
Figure 6. A) Overview map showing shaded bathymetry with area of interest (red box), B) Area of interest showing detailed shaded bathymetry and chirp line 8 and triangles pointing out dune features on top of the ridge, C) Map showing slopes of corresponding features on the seafloor and D) Chirp line 8 with ridges labeled with black triangles.
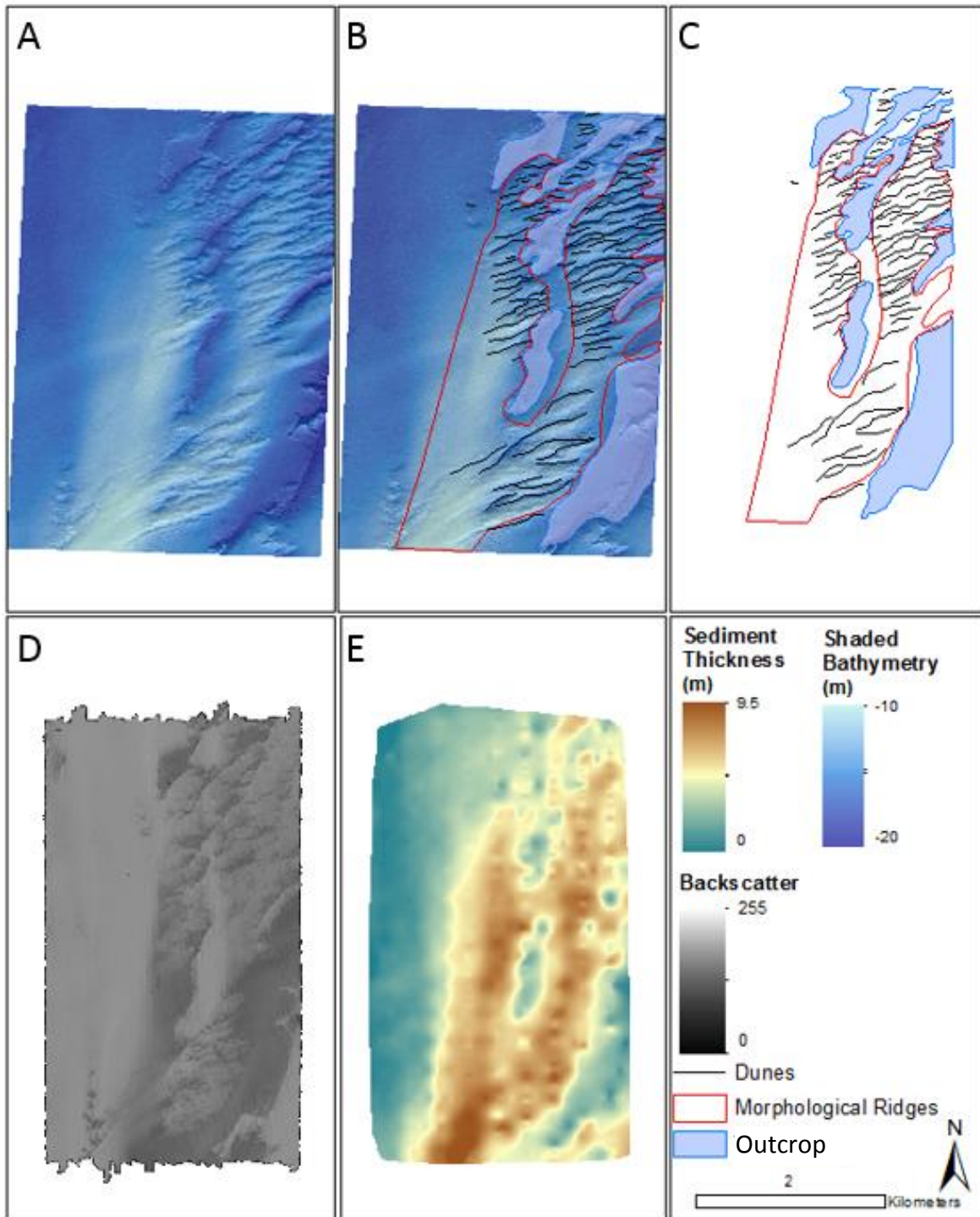
Figure 7. Data and interpretation for Survey Area "B". Boxes show: A) shaded relief bathymetry, B) shaded relief bathymetry with interpreted dunes, morphological ridges, and outcrops, C) only dunes, morphological ridges, and outcrops, D) backscatter (higher values indicating harder/rougher surfaces), and E) sediment thickness isopach. With the use of bathymetry and backscatter, areas of potential outcropping of the top of the indurated sediments and subaqueous dunes were delineated. Areas of potential outcrop are oriented in an N-S direction.

25
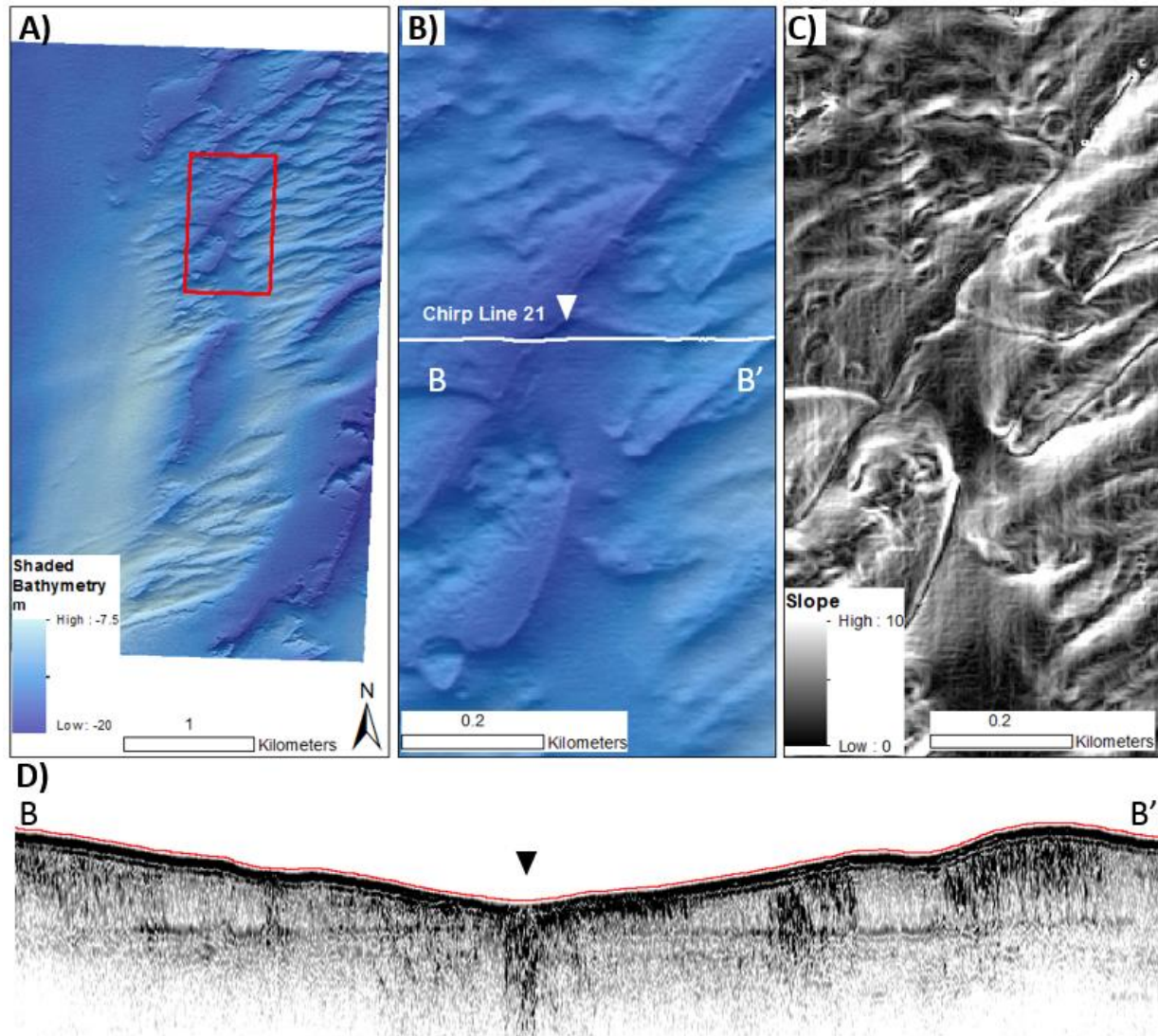
Figure 8. A) Overview map showing shaded bathymetry with area of interest (red box), B) Area of interest showing detailed shaded bathymetry and chirp line 21 and a triangle pointing out an area of little deposition between the ridge, C) Map showing slopes of corresponding features on the seafloor and D) Chirp line 21 with potential outcropping labeled with black triangle.

Comparison of the USGS and Geodynamics datasets in two areas of overlap reveals significant differences (Fig. 9). Elevation offsets in the datasets indicate either: 1) spatial or vertical mapping error in one of the datasets or 2) bathymetric change (i.e., erosion or accretion). Because both datasets were collected with sophisticated swath mapping, where offsets are substantial (>0.5 m) it is assumed that there has been erosion or accretion. While some of the differences between the two datasets can be assigned to different methods, techniques,

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equipment, and survey extent of each project, in general, there could be some migration of dune features. Several areas have negative difference between 2002 and 2013, indicating there was an increase in depth (erosion). For example, the location of largest difference is within the southern area ("B") where there is a difference (up to five meters) on the northern side of the ridges (Fig. 9). Areas of significant positive change (>3 m) are also observed, shown in the northern grid and in the southern grid along the southern faces of the ridges (Fig. 9). Values of offset are generally within 3 meters within the study area. The overall mean change between the time steps was -1.05 m with a standard deviation of 0.97 m. The maximum amount of negative and positive change was -5.16 m and 3.03 m, respectively (Fig. 9).

To complement the evaluation of recent morphological change, historical bathymetry was compared to the USGS bathymetry. Following the approach of Thieler et al. (2014), the 11 m depth isobath was used for comparison, and a similar timescale of comparison was made (Thieler 1870-2002; this research 1902-2002) Analogous to the findings of recent morphological change, the contours exhibit an overall landward shift of the shoreface (labelled B in Fig. 10), a shortening of the ridges by 2 to 4 kilometers (labelled A in Fig. 10), and a seaward migration of around 500-800 meters (labeled C in Fig. 10).
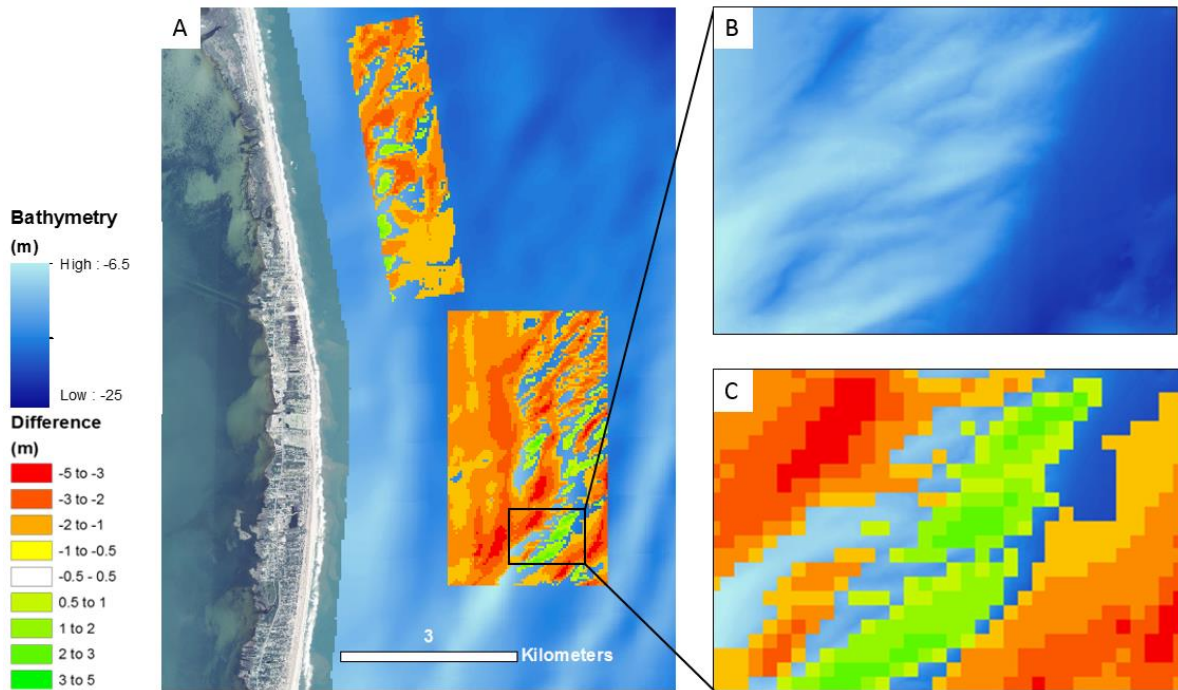
Figure 9. A) Map showing the comparison between the Geodynamics and USGS bathymetric surveys. All negative values (warmer colors) correspond to a loss of sediment where cooler (green) colors indicate accretion. B) A close up of the Geodynamics bathymetry showing a ridge feature. C) The same extent as shown in box "B", but with a difference map overlain showing more erosion on the north side of the ridge with accretion on the south.
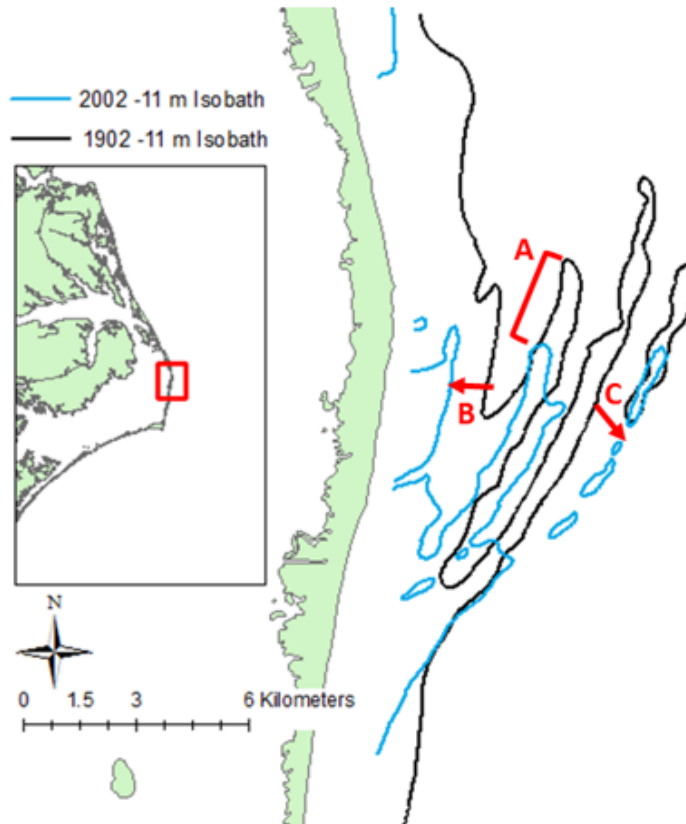
Figure 10. Historical chart analysis where the -11 m isobaths were traced in ArcGIS. The line labelled "A" represents a reduction in ridge length of about 2 km. Arrow labelled "B" identifies a shoreward shift of ~1 km and shoreface steepening, and "C" points to a seaward migration of about 650 m.

4.2 Shoreline Change

Many factors can explain long-term shoreline change rates including sea-level rise, sediment supply, inner shelf morphology, storms, and human impacts (Carter et al., 1987; Hequette and Aernouts, 2010). The average long-term shoreline change rate using an EPR (end point shoreline change rate) approach (1873-2009) was -0.5 m/yr (SD=1.4) for the study area, but transect measurements ranged from -4.6 m/yr to 2.2 m/yr. During this 136 year time step, 54.6% of transects showed a negative change (erosion). The area to the north of Rodanthe, including the S-Curves, has shown the most severe historical erosion (mostly >1.5 m/y) while

the area to the south has shown more accretion (generally > 1 m/yr; Figs. 11 and 12). Transects

adjacent to the attachment point of Wimble Shoals show the most accretion over time, although

the spatial and temporal extent varies.
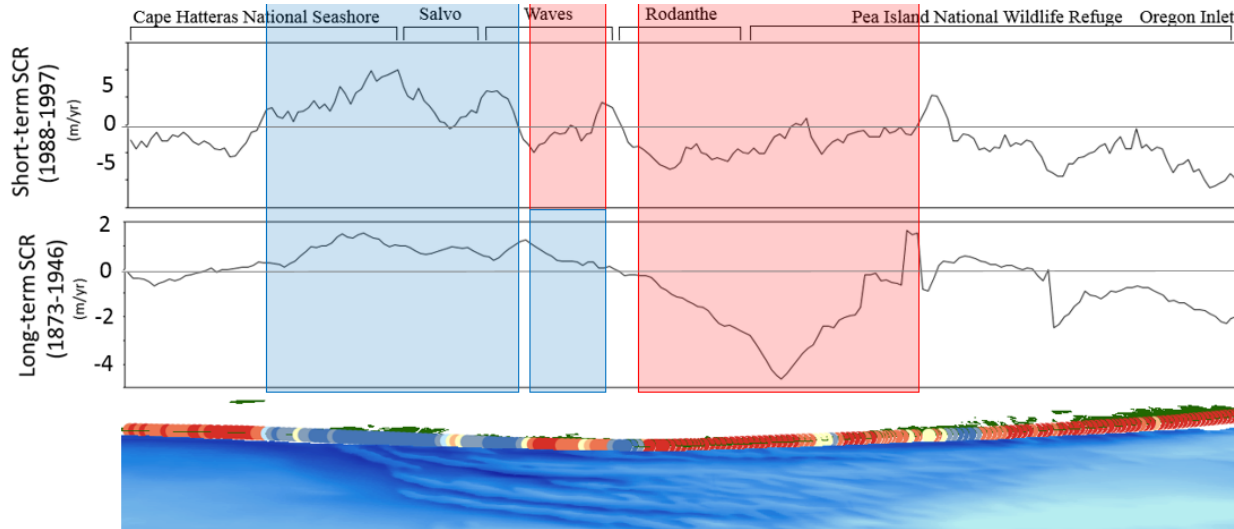
Figure 11. Alongshore (from South to North) recent (1988-1997) and historical shoreline change rates. The locations of different towns and park areas are shown, and regions of historic paleo-inlet channels are highlighted in grey and labeled. Included below the shoreline change rate charts is an oblique view of Wimble Shoals with the 1988-1997 shoreline change rates. Note that areas of blue shading on the graphs indicates accretion while red indicates erosion.

From 1873 to 1946, erosion occurred on 38.5% of transects and had a mean change rate of

-0.14 m/yr (SD=1.5). From 1946 to 1988, the percent of transects showing erosion is higher

(62.9%), and the mean rate of change is also greater (-0.36 m/yr). For the last two timesteps

even more erosion ensued, although it should be noted that the timescale used to calculate rates

was considerably less. From 1988 to 1997 the mean change rate was -1.8 m/yr (SD=4.4), and

71.4% of transects were deemed to be eroding. In the most recent time step, 1997-2009, erosion

was seen along 84.5% of transects, and the mean change rate is -1.82 m/yr (SD=1.9; Table 2).

Visually, the data suggest an increase in erosion with time. Also, specific areas of erosion and

accretion migrate southward through time (Fig. 12).

Table 2. AMBUR results from respective shoreline change analyses

Year	Mean Change (m)	Mean Change Rate (m/yr)	Percent of Transects Showing Erosion	Percent of Transects Showing Accretion
1873-1946	-9.7	-0.14	38.5%	45.3%
1946-1988	-14.8	-0.36	62.9%	36.6%
1988-1997	-15.9	-1.8	71.4%	28.2%
1997-2009	-21.8	-1.82	84.5%	15.5%

Shoreline Change Rates

- Severe Erosion (> 3 m/yr)
- Erosion (1 - 3 m/yr)
- Mild Erosion (0.6 - 1 m/yr)
- No Detectable Change
- Mild Accretion (0.6 - 1 m/yr)
- Accretion (1 - 3 m/yr)
- Severe Accretion (> 3 m/yr)
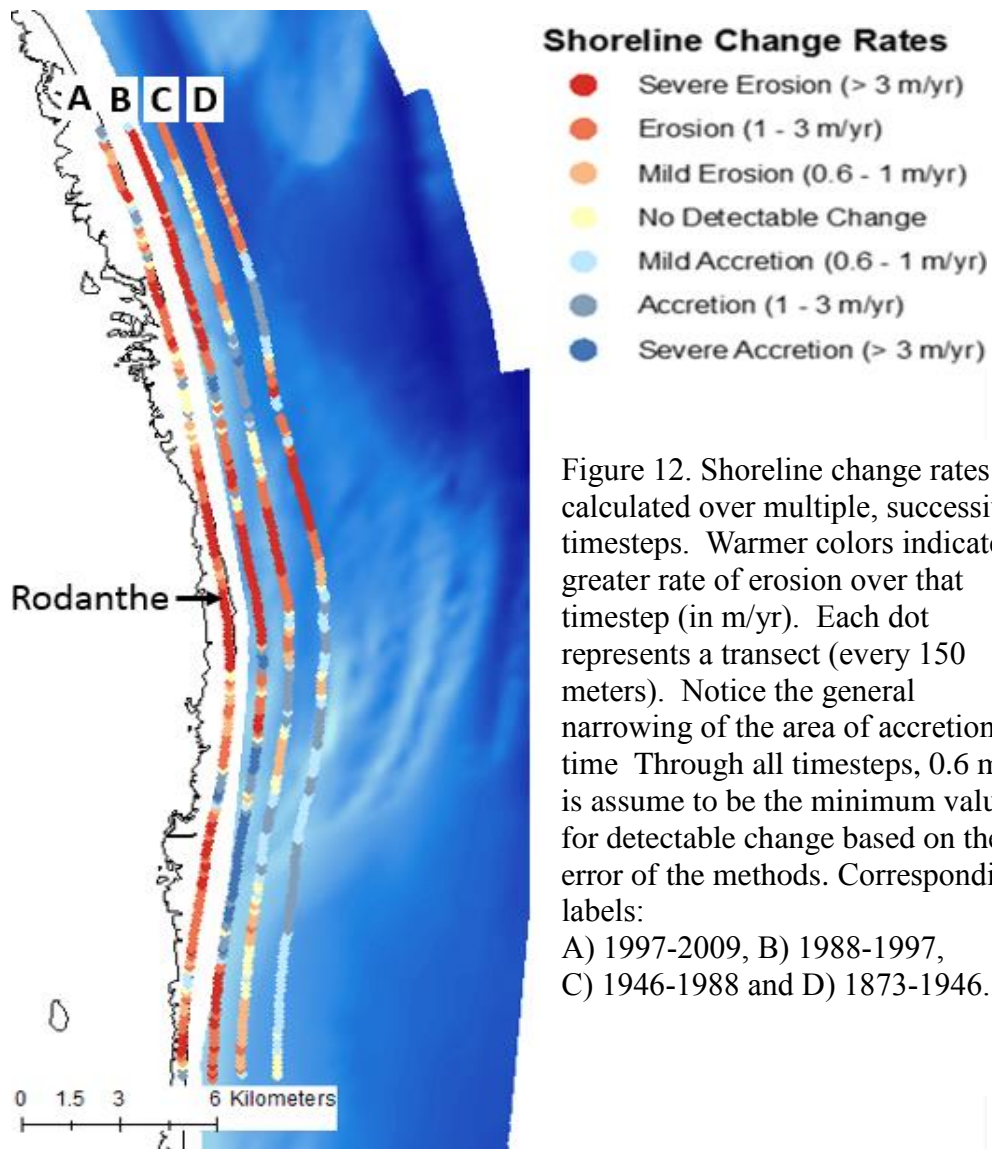
Figure 12. Shoreline change rates calculated over multiple, successive timesteps. Warmer colors indicate a greater rate of erosion over that timestep (in m/yr). Each dot represents a transect (every 150 meters). Notice the general narrowing of the area of accretion as time Through all timesteps, 0.6 m/yr is assume to be the minimum value for detectable change based on the error of the methods. Corresponding labels:
A) 1997-2009, B) 1988-1997,
C) 1946-1988 and D) 1873-1946.

4.3 Seismic Investigation

Wimble Shoals is underlain by a thick (~30-50 meter) Pleistocene sequence that has

relief of several meters at its surface, and the morphological ridges sit above these strata (Thieler

et al., 2014). Analysis of the Geodynamics chirp data revealed a shallow and deep reflector

(denoted by SS1 and SS2, respectively) prevalent across all of the study area (Fig. 13).

Following the work of others (Schwab et al., 2000; Boss et al., 2002; Denny et al., 2013), the

deeper reflector (SS2) is interpreted as the transgressive surface (i.e., Transgressive Ravinement

Surface). SS2 is a relatively flat-seaward dipping surface ranging from 15 to 30 m below sea

level (Thieler et al., 2014). The shallower reflector (SS1) is thought to be the top of the

reworked transgressive deposits, or the Maximum Flooding Surface (MFS) (Snedden et al.,

1994; Schwab et al., 2000; 2014; Chaumillion et al., 2010; Denny et al., 2013). Between the

reflectors SS1 and SS2 is the Transgressive Systems Tract (TST). The SS1 reflector is not

perfectly flat and may reflect some variability of the LST upper surface (Fig. 14). Deposition

between LST and the TRS occurred during sea level rise as the barrier system was transgressing.

Above the MFS lies the Highstand Systems Tract (HST) that is composed of active and modern

sand deposits (typically dunes). Schwab et al. (2000; 2014) demonstrated that modern bedforms,

such as Wimble Shoals, can lie unconformably above the Holocene flooding surface (SS1) and

thus can illustrate the formation of a transgressive erosion surface. The stratigraphy of the region

closely resembles the model that Chaumillon et al. (2010) proposed for a barrier system with an

enclosed lagoon and another that Snedden et al. (1994) proposed for a nearshore sand ridge

system (Fig. 15). The sediment in the HST was deposited during the Holocene and is likely

being reworked in the modern environment (Snedden et al., 1994; Schwab et al., 2000; 2013;

2014; Denny et al., 2013; Warner et al., 2017). This interpretation is consistent with studies in

NY, NJ, NC, and SC (Snedden et al., 1994; 2011; Schwab et al., 2000; 2014; Boss et al., 2002; Denny et al., 2013). Thus, assuming this interpretation is correct (no dating is available), sediment comprising Wimble Shoals is a combination of both HST and TST deposits, and is thickest in the HST layers.
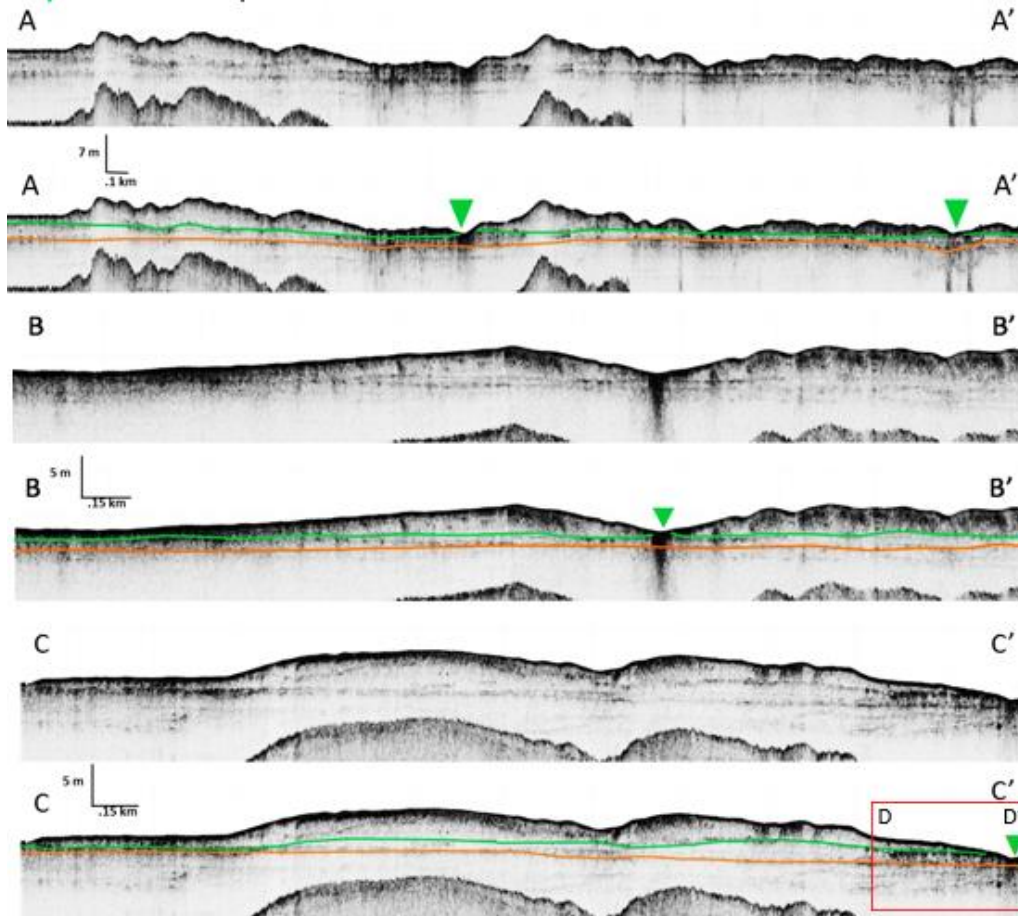
Figure 13. Maps and seismic data for Wimble Shoals. A) Shaded bathymetry and locations of seismic data. B) Map of depth to the top of the interpreted Pleistocene-Holocene unconformity. C) Interpreted sediment thickness. Green lines represent the reflector SS1 (i.e., MFS), orange lines represent reflector SS2, (i.e., TRS). Note where the SS1 crops out (green triangles) at the surface. Red box in C-C' is shown in figure 15.
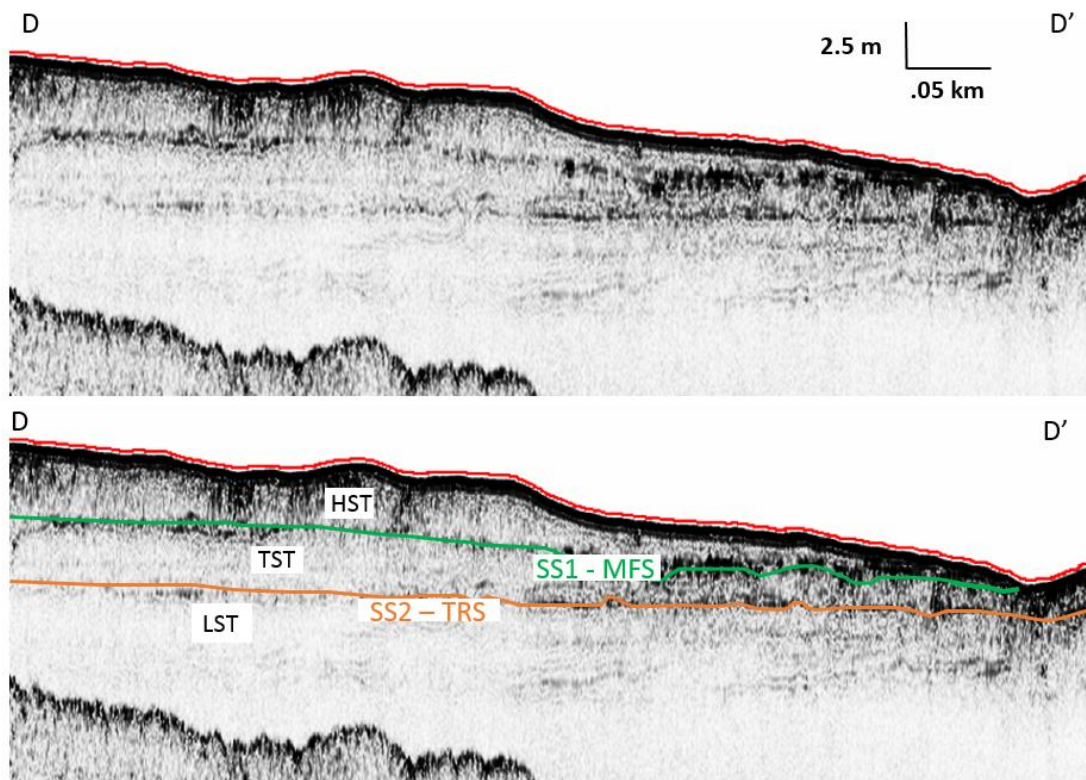
Figure 14. Seismic line "D – D'" with SS1 (green line) and SS2 (orange line) interpreted. Notice the subtle relief on both of the reflectors and where SS1 (MFS) crops out against the seafloor towards D'. Labeled are the Highstand Systems Tract, Transgressive Systems Tract, and the Lowstand Systems Tract.

A

B
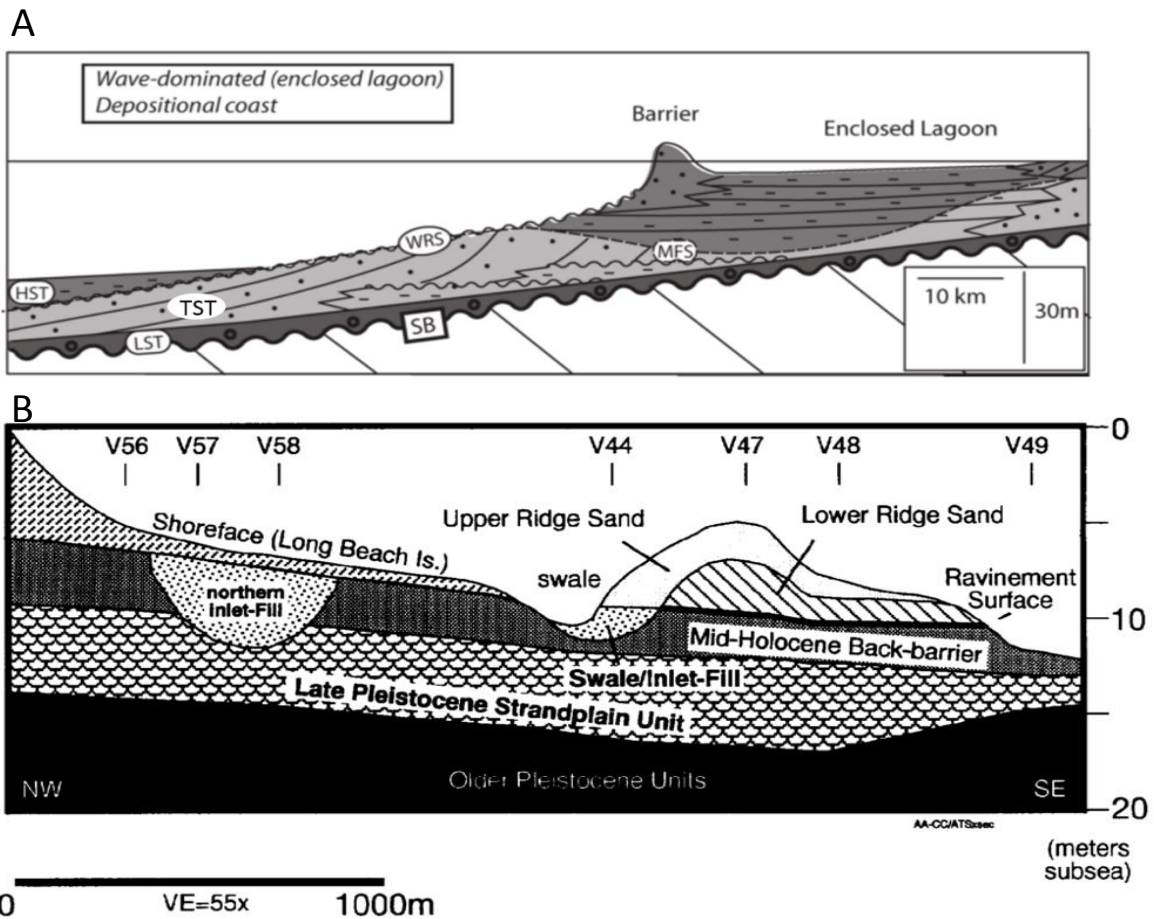
Figure 15. A) Wave dominated barrier system with an associated closed lagoon system behind the barrier. Figure includes multiple stratigraphic boundaries including the Highstand Systems Tract (HST), Lowstand Systems Tract (LST), Wave Ravinement Surface (WRS), Maximum Flooding Surface (MFS) and Transgressive Sequence Tracts (TST) (Modified from Chaumillon et al. 2010). B) Figure from Snedden, et al. (1994) showing interpretation of a nearshore ridge underlain by a locally erosional but generally flat surface (Transgressive Ravinement – e.g., this studies' SS2 reflector).

To better understand the underlying geology of Wimble Shoals, cores collected by the

U.S. Army Corps of Engineers (USACE) in association with the Geodynamics data were

analyzed. Cores were evaluated for sand thickness and georeferenced in ArcGIS. The sand

thickness values were then projected onto the modern sediment thickness isopach map provided

by Geodynamics to qualitatively compare to the seismic interpretation data (Fig. 16). In general,

most cores were composed primarily of well-sorted sand (mean grain size of 2.17Φ) with some

intermittent clay and silt layers. The clay and silt layers were typically observed in cores where

little sediment existed above SS2 (e.g., off a morphologic ridge). Between SS1 and SS2 is well

sorted-fine sand. Cores taken on top of the morphological ridges and within the subaqueous

dune typically had sand (most often logged as "well-sorted sand ") throughout the core, and thus

it may have continued past the coring depth (>5 m of sand thickness in some cases). Results

from the USACE cores agreed with the cores reported in the Boss and Hoffman (2000) study that

found an average total core grain size of 2.29Φ across Wimble Shoals.
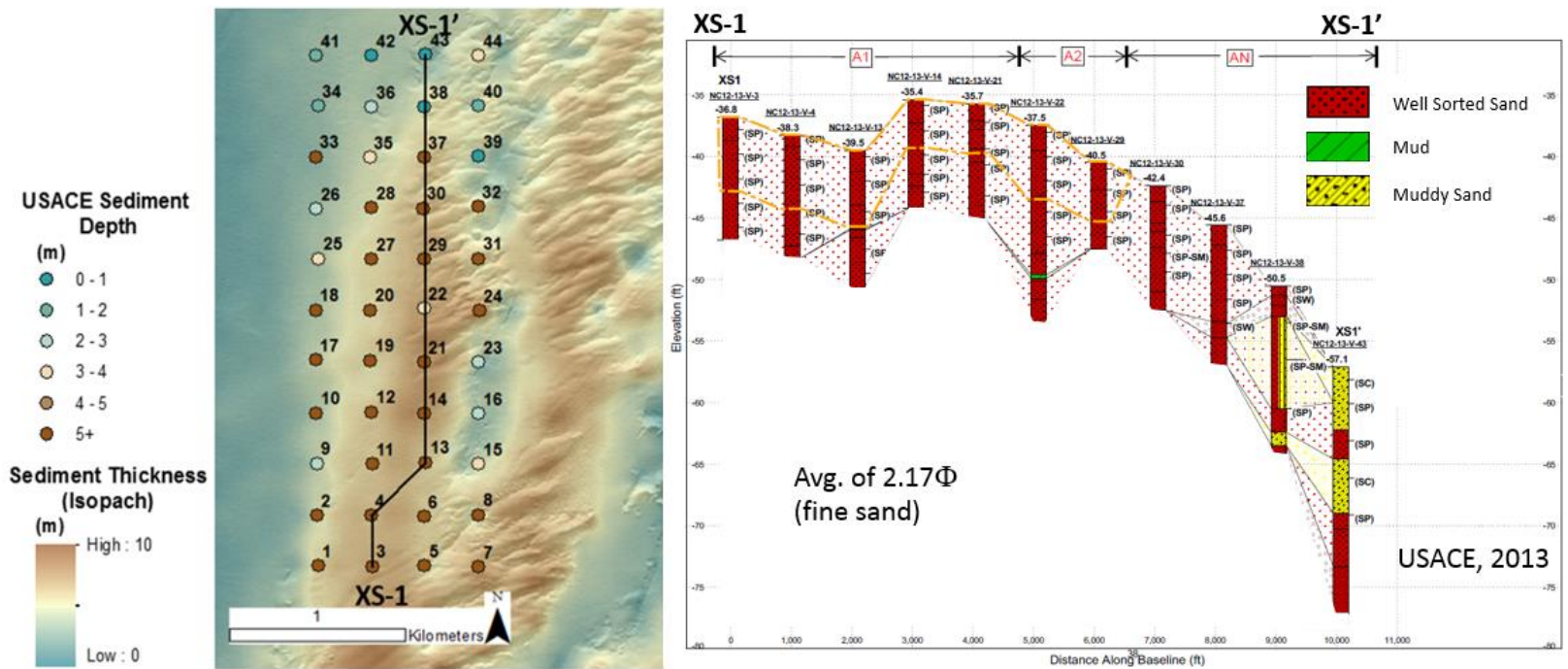
Figure 16. Surface sediment thickness isopach with interpreted sand depths from cores overlain (any cores that did not reach a non-sand layer were denoted at over 5 meters of sediment thickness). Also included is a fence diagram of the USACE core investigation. Note the overwhelming red within the fence diagram (sand) and that any muds (green and yellow) are typically off the ridge.

Differences in sediment thickness between datasets were evaluated at 235 intersection points of the Geodynamics and USGS data and values were extracted with ArcGIS (Fig. 17). If both datasets mapped out the same horizon to get sediment thickness, then a 1:1 relationship would be expected.   The results of the comparison are statistically significant (P-value <0.01) according to a two-sample T-test. A linear regression (Fig. 17) gives an R-squared value of 0.47 and a slope of 0.50 showing a poor correlation between the two datasets. Another analysis to determine differences between the two datasets was a quantitative comparison of each respective isopach compared with one another. While the USGS and Geodynamics isopachs show a similar pattern, the latter dataset has large differences in the amount of sediment, with an average depth of unit thickness being three times deeper than the USGS findings (Average Geodynamics = 4.9, Average USGS = 1.6).
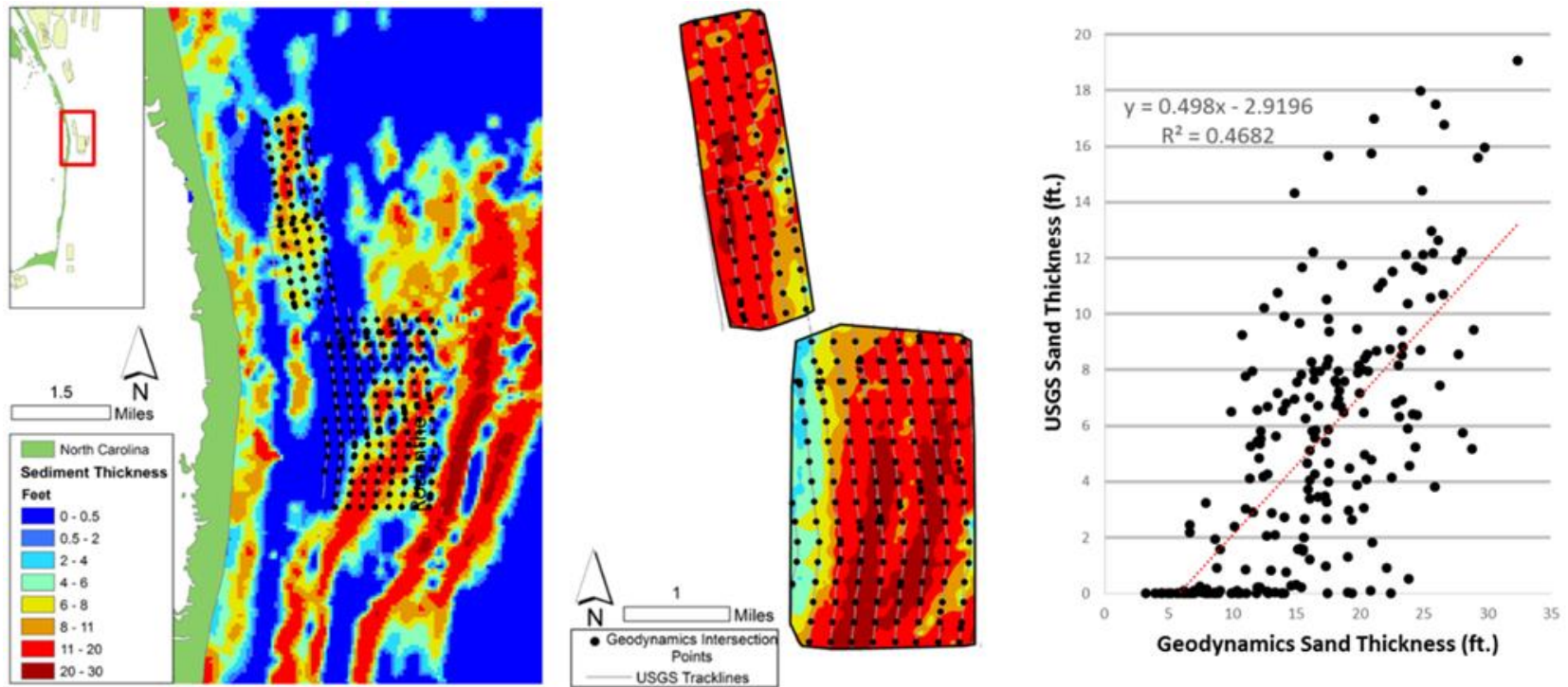
Figure 17. Map showing the isopachs from Geodynamics and USGS along with the comparison between the two. Each black dot corresponds to an intersection between a Geodynamics and a USGS Chirp line. These average thickness around these points were then plotted and compared in the graph on the right.

4.4 LiDAR/Volume Change rates

Multiple time steps of LiDAR data were compared qualitatively and quantitatively to assess beach volume changes in the study region. Analysis shows areas of onshore accretion and erosion, and indicates areas with an onset of erosion within a typically accretionary regime (Fig. 18). Error was calculated to be 0.2 m for the time period of 2012 to 2014, so differences less than 0.2 are hypothesized to be in the error of the data. Overall, the study area contains some areas of extreme accretion (> 1 m; perhaps from human intervention) and other areas of severe loss (> 2 m), highlighting the vulnerability and variability of the Outer Banks.
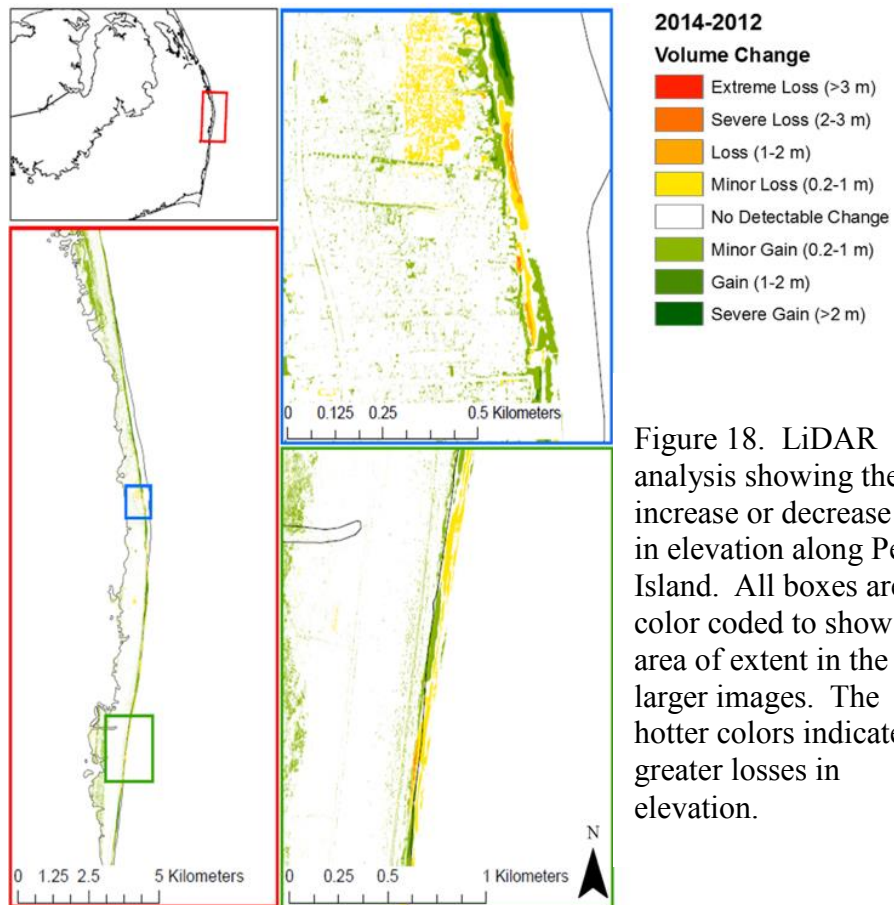
Figure 18. LiDAR analysis showing the increase or decrease in elevation along Pea Island. All boxes are color coded to show area of extent in the larger images. The hotter colors indicate greater losses in elevation.

To evaluate morphologic change, two transects across the study area were examined; the

northern profile is from an area where storm-induced erosion and road and dune construction

occurs frequently, and nourishment has since occurred; while the southern transect is from a

relatively disturbed and developed area. Generally, the profiles are similar with greatest

differences seen in the dune structures. Over time, the southern profile dune peak on all transects

shows some difference in position and height due to human intervention. On the southern

profile, the trend in dune change between 2012 and 2014 is inconsistent (Fig. 19), while for the

northern area the dune peaks remain relatively stable. For both transects, the dune peak from the

most recent survey (2014) is more landward than 2009 (~20-30 m).
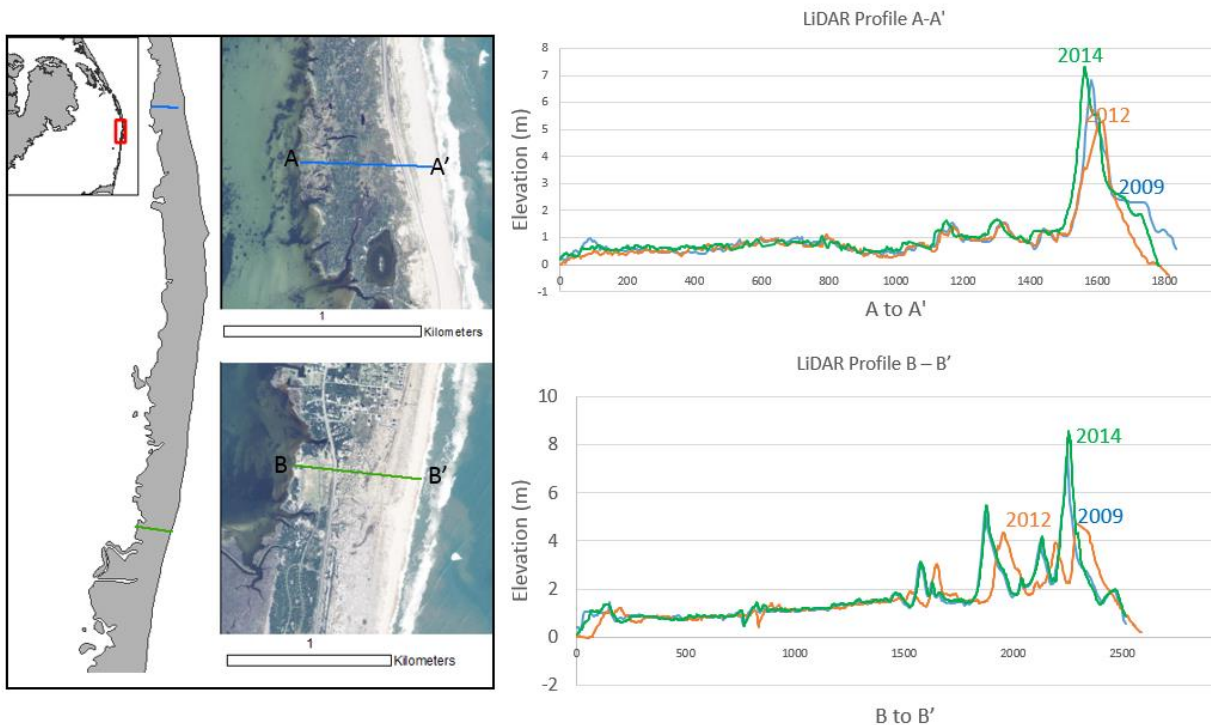
Figure 19. Selected transects showing the elevation of each location during 2009, 2012, and
2014 (based on LiDAR data). Notice the lateral shifts in the dune ridge locations as well as
moderate progradation along the beach front.

4.5 Sediment Characteristics

Results from the grain size analysis of Wimble Shoals, Platt Shoals, and Kinnakeet Shoals show that the mean of the surface samples were fine sand (2.24 Φ) (Fig. 20). However, several (i.e., 9 of 67) samples from each of the three shoal complexes were mud (5 samples) or gravel (4 samples), and these are generally located in areas of low mapped sand thickness (Fig. 20). Samples on the morphological ridges from all three shoal complexes had an average grain size of 1.73Φ (e.g., medium sand).

While the USGS-mapped sediment thickness generally is less than the amount estimated in the more recent data, this dataset is used to evaluate the sand stored in each shoal because of its extensive coverage. Wimble Shoals, Kinnakeet Shoals, and Platt Shoals have average sediment thicknesses of 1.40 m, 0.78 m, and 4.32 m, respectively. Platt Shoals has the largest estimated volume at just over 360 million m^3; Wimble Shoals has a volume of 180 million m^3, and Kinnakeet Shoals has a volume of 75 million m^3(Table 3). Grain size statistics were also calculated using the total recovered sediment from each of the 67 cores available in the shoal complexes. Samples from Platt Shoals had a mean grain size of 1.73Φ with a minimum grain size of 3.66Φ and a maximum grain size of -0.16Φ. Wimble Shoals samples had an average grain size of 2.29Φ, a minimum of 3.74Φ, and a maximum of 1.22Φ. Kinnakeet Shoals had sediment with a mean of 2.00Φ, a minimum of 3.10Φ and a maximum of 0.52Φ (Table 3). Interestingly, the cores taken on the morphological ridges of the three shoal complexes were similar and had an average grain size of 1.95Φ (e.g., medium to fine sand). The fact that the ridges of each shoal complex had medium sand is likely due to hydrodynamic sorting on top of the ridges. This sorting is due to the fact that energy would typically be higher on those ridges (shallower water) and thus, medium sands persist along the bathymetric highs. Adjacent to the

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shoals is Pea Island, which has a mean beach grain size of 2.0Φ (USACE, 2013). This suggests

that Wimble Shoals is composed of beach quality sand that could be used for further

nourishment.

Table 3. Results from grain size analysis for Platt, Wimble and Kinnakeet Shoals.

Inner Shelf Region	Mean Grain Size (Ø)	Minimum Grain Size (Ø)	Maximum Grain Size (Ø)	Area (m²)	Mean Modern Sediment Thickness (m) (USGS)	Holocene Sediment (m³)
Platt Shoals	2.04	3.41	-0.53	86,549,651.62	4.32	373,894,495
Wimble Shoals	2.02	4.31	0.12	132,783,626.20	1.40	185,897,076.68
Kinnakeet Shoals	2.14	2.99	0.54	96,028,193.85	0.78	74,901,991.20
Totals				315,361,471.7		634,693,562.88
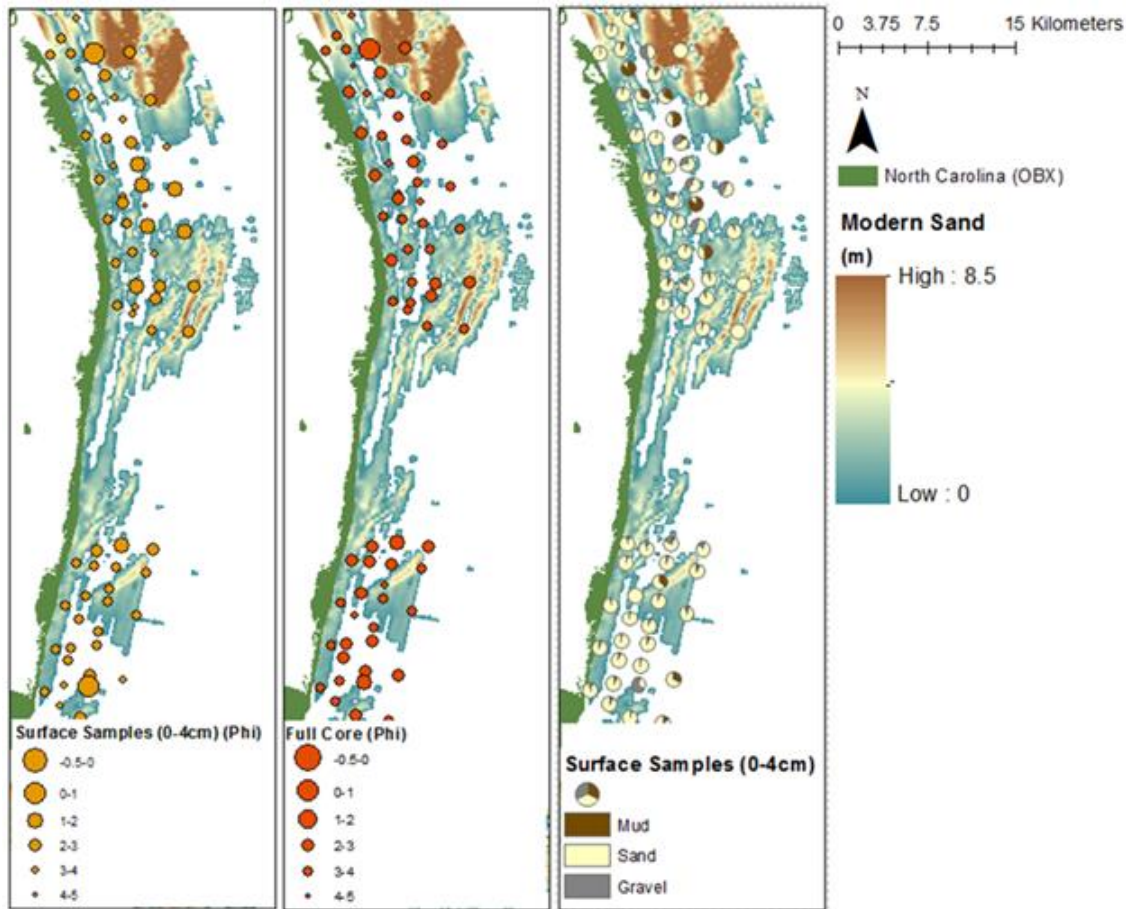
Figure 20. Selected cores showing both grain size and mud/sand/gravel percentages within the first 4 cm of sediment. Also shown is the average grain size throughout the entirety of each core. Notice that the majority are composed of medium sized sand and could potentially be developed as borrow sites and most mud/gravel is within low bathymetric relief regions.

4.6 Volumetric Analysis of Borrow Area

The USACE permitted the use of 1.5 million m³ of sand from Wimble Shoals to be used as a nourishment source for the neighboring S-Curves nourishment. It has been reported that 1.3 million m³ was actually taken from Wimble Shoals for the project (USACE, 2013). Results from a volumetric analysis show that there is a large range in the estimated amount of sediment taken from Wimble Shoals. The values of the depth of cuts from the dredge are based off of the

USACE report from the nourishment project. The cut depths ranged from minimum values of 2-4 feet, median values of 4-6 feet, and maximum values of 6-8 feet. From these values, the minimum calculation used the smallest of each bracket (2, 4 or 6 feet), median of each bracket (3, 5 or 7 feet) and the maximum of each bracket (4, 6 or 8 feet). Then, the total area of each representative cut area was used to calculate the total amount of sediment taken from Wimble Shoals for the nourishment of Pea Island National Wildlife Refuge. The results of this analysis show that the minimum amount of sediment taken from Wimble Shoals was 3.4 million m^3, and the maximum was 5.5 million m^3 (Fig. 21). While these values are clearly above what was reported as being borrowed, they are only estimates and provide a measure of how much potential sand could have been borrowed. Also, it is worth noting that the dredge might not have dredged the entire extent permitted.
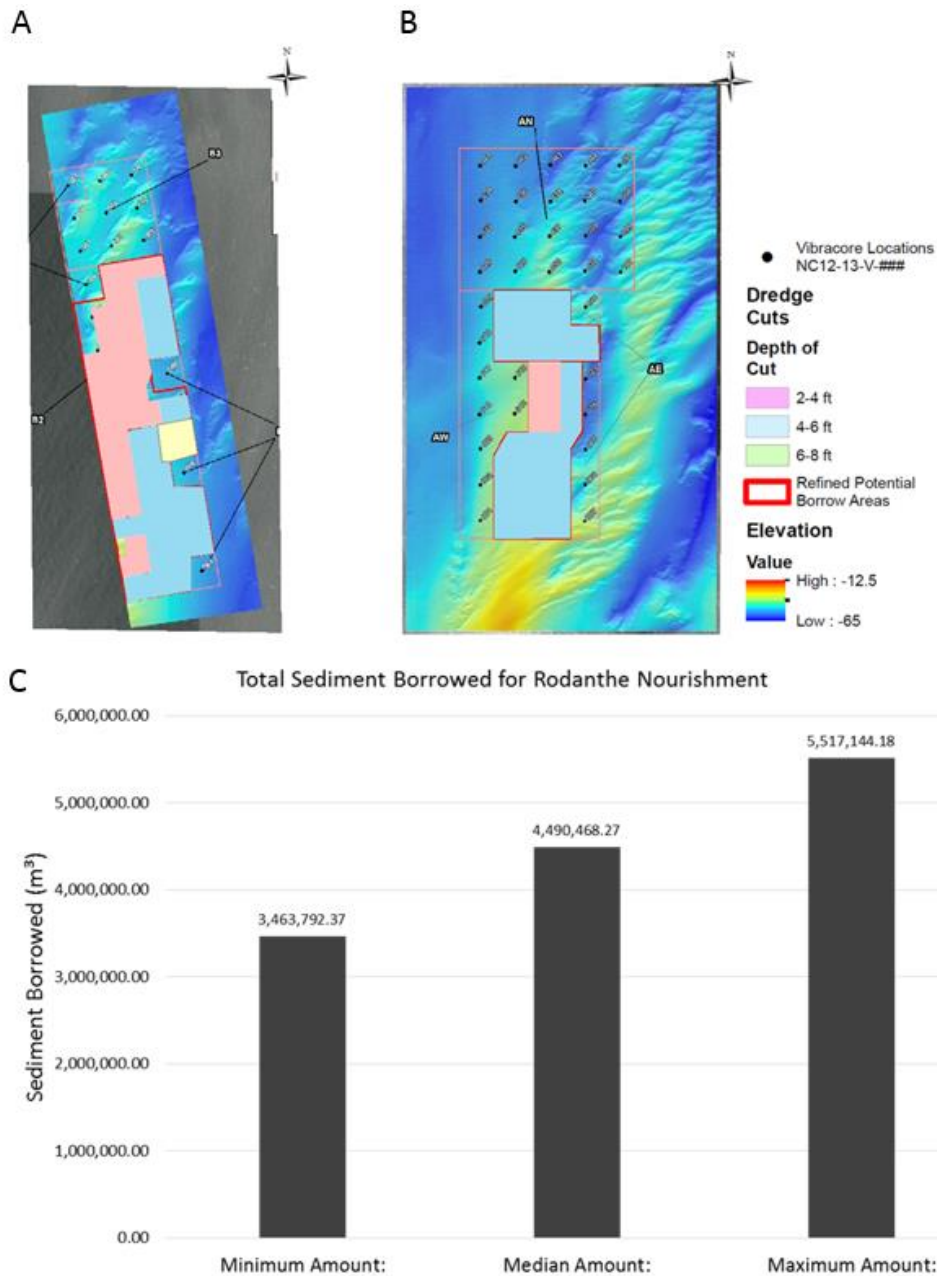
Figure 21. Dredge cut locations and depth ranges for the north (labelled A) and the south (B) survey areas. C) Graph of representative cut depths and amount of sediment mined from Wimble Shoals for the minimum, median, and maximum amount that could have been taken.

5. DISCUSSION

5.1 The Geology and Importance of Wimble Shoals

Nearshore sedimentary features such as Wimble Shoals are important with respect to coastal morphology, nourishment borrow sources, and habitat. Based on the existing data, Wimble Shoals is a morphological ridge complex that lies upon a gently sloping Pleistocene surface (Figs. 7, 8, 13, 22, 23). Forming the top of these morphological ridges are second order bedforms, subaqueous dunes. In between the morphological ridges, the seafloor has a varied, somewhat complex morphology. Seismic, backscatter and bathymetry data suggest that these are outcrops, which can provide essential habitat to a variety of benthic, pelagic, and hemipelagic marine species (Vasslides and Able, 2008; Kendall et al., 2009; Dubois et al., 2009; Slacum et al., 2010).

The underlying strata have subtle relief that most likely developed as erosional features, which control the location and persistence of the morphological ridges. Seismic lines shown in Figures 6, 8, 13, 14, 22 and 23 illustrate how a variably thick sediment body caps a relatively flat underlying older surface. This sediment body is the Highstand Systems Tract which was deposited when sea levels were near or at their current stage. The HST composes the ridges of the shoals and is where the majority of the sediment is located. The Transgressive Systems Tract was deposited as sea-level was rising and cutting across the previously exposed surface. The sediment composing the TST is interpreted as re-worked sands. The Lowstand Systems Tract lies beneath both the HST and TST and is interpreted as being mostly mud, potentially from a back-barrier environment when sea-level was at a low stand. Cores indicate the sediment body is largely composed of well-sorted sand (mean grain size of 2.17 Φ) with interbedded silt and clay layers, while beneath is clay, indurated sediments and gravels (Fig. 16; USACE, 2013). Findings

from this study also agree with those of Boss and Hoffman (2000) who found that cores within the Wimble Shoals area had an average of 78 percent sand (mean grain size of 2 Φ), 16 percent mud, and 5 percent gravel.

Wimble Shoals is persistent due to the geologic framework, but the dunes that sit atop the large ridges have likely experienced some migration (southward shift of about 1 km; Fig. 10) over time which is in line with general trends along the Outer Banks (spits, inlets, capes, etc.) due to the dominant longshore transport of this region driven by storms and waves (McBride and Moslow, 1991; Lazarus and Murray, 2011). Since the dunes do not show typical lee- or stoss-sides, it is interpreted that these dunes are a product of varying current directions and speeds due to fairweather conditions and storm conditions. The persistence of Wimble Shoals is noted by Riggs et al. (1995) whom provided that the geologic framework of these features controls their shape, orientation, and longevity.

Compared to other complex bathymetric features around the world, Wimble Shoals has similar properties such as the composition of the ridges (e.g., medium to fine sand) and orientation to the shoreline (e.g., 25-30°) (McBride and Moslow, 1991; Denny et al., 2013; Mazieres et al., 2015). Wimble Shoals differs from other bathymetric features around the world by having much more distinct ridges that are longer and wider than most found throughout North America, South America, and Europe (Swift et al., 1978; Dyer and Huntley, 1999; Li and King, 2007; Snedden et al., 2011; Denny et al., 2013). Perhaps Wimble Shoals distinct size and complexity results from the fact that the underlying geology (i.e., TST/LST) exhibits variable relief and structure which created a framework for the shoals. Wimble Shoals lies on top of a paleo-interfluve high ground that was between two paleo-channels. This paleo-high surface is thought to provide the geologic framework for which Wimble Shoals formed over. Maintaining

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both the morphological ridges and the subaqeous dunes is a phenomenon that is poorly

understood, although storms, rising sea level, and tides have been discussed as a primary factors

in their maintenance (Trowbridge, 1995; Hayes and Nairn, 2004; Son et al., 2012; Mazieres et

al., 2015; Warner et al., 2017). Findings from this study suggest that both the ridges and the

dunes experience migration to the south. It is also noted that there could be some potential

deflation (loss of sediment) throughout Wimble Shoals.
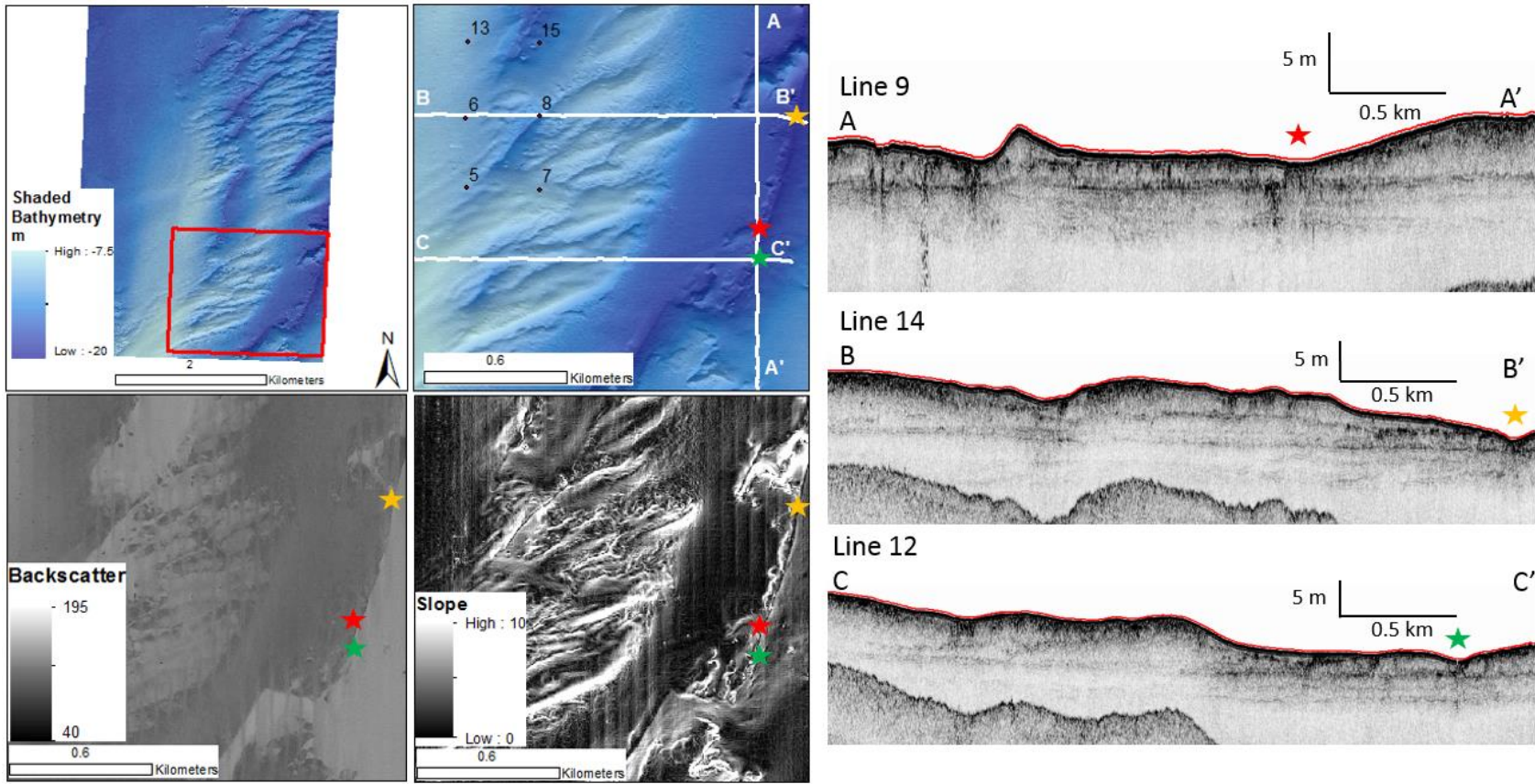
Figure 22. Southeast corner of South Survey Box. Along the chirp seismic lines, denoted by stars, you can see an increase in TST relief where it approaches the seafloor. This scarp is denoted by contrasting backscatter value, high slopes (~10°), and in Chirp data where the reflector has very little sediment overlying it. The scarp is hypothesized to be an area of hardbottom where indurated material is cropping out.
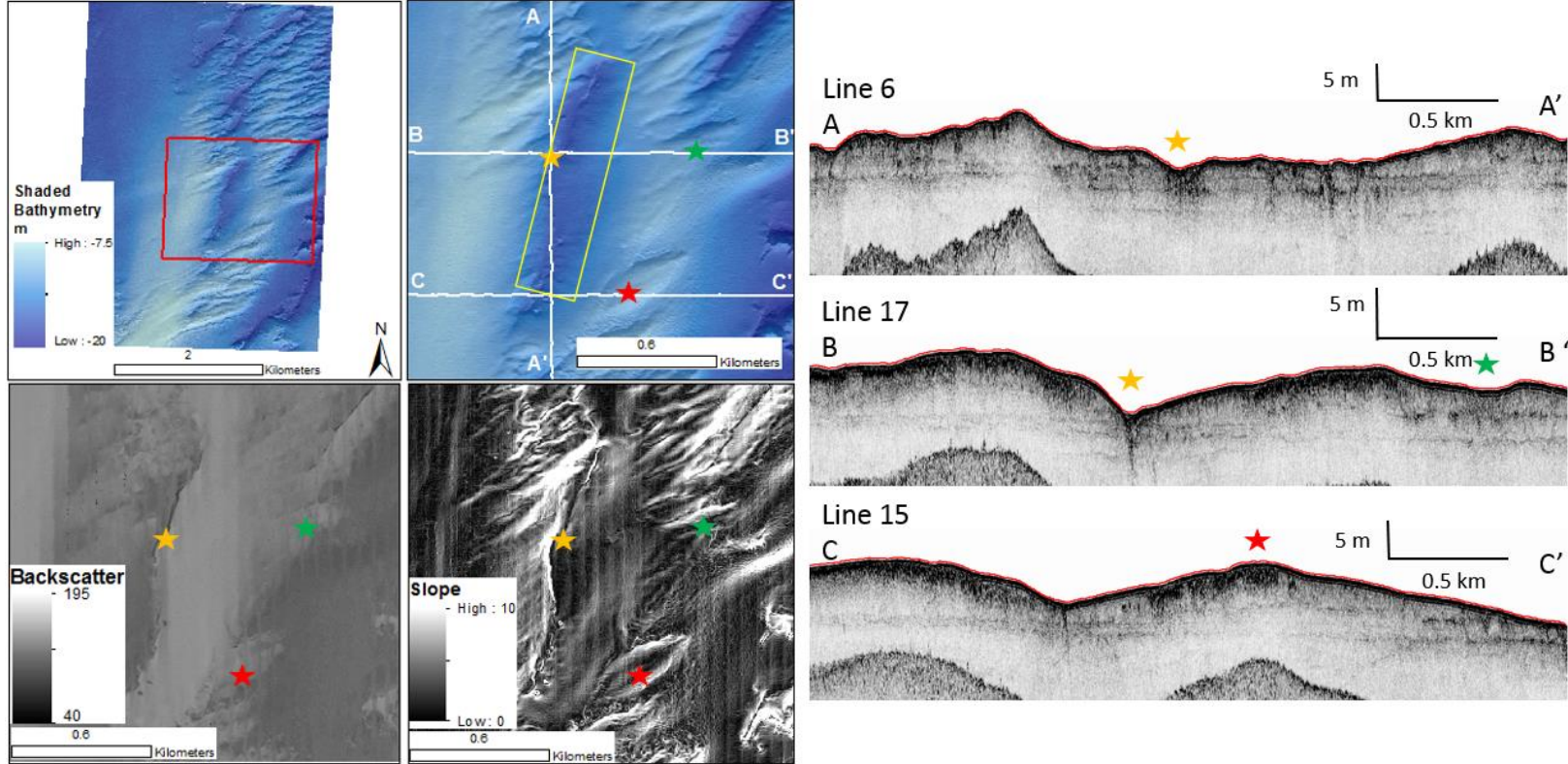
Figure 23. Two separate ridges separated by a trough in between them within the South Survey Box. This area does not contain as many subaqueous dune features as other areas adjacent to it. The trough, denoted by the yellow box, is likely composed of indurated TST/LST sediments that are outcropping. This area is hypothesized to have formed at a different time and from different processes than the sand ridges. Perhaps this Pleistocene outcrop influences current speeds and directions at this location, thus preventing the development of the ridge at this location. This is evidenced by the fact that the dune features on the western side of the trough cease at the scarp. The left side of this trough has a steep scarp feature (>10°) on its western side. The relief across this scarp is 2 m.

Wimble Shoals has been and will continue to be a navigational hazard, accounting for multiple shipwrecks within the "Graveyard of the Atlantic". The wrecks in the area of Wimble Shoals are important cultural resources that must be accounted for when mining this feature (Fig. 24). One of the most famous wrecks near Wimble Shoals is the "Mirlo", a British tanker that went down after hitting a mine off of the shoals. This wreck was the subject of the famed "Mirlo Rescue", which is considered to be one of the most dramatic operations in U.S. Coast Guard history (Bearss, 1968). Wimble Shoals is not only home to cultural resources, but is considered by some to be an essential habitat (Vasslides and Able, 2008). In areas of complex seafloor morphology, habitat for marine species, including a variety of annelids, crustaceans, and fishes is abundant (Steimle and Zetlin, 2000; Diaz et al., 2004; Vasslides and Able, 2008; Dubois et al., 2009). Nearshore sedimentary features provide a unique habitat resource for both pelagic and benthic marine species as well as increased forage opportunities for predators and refuge for prey species (Slacum et al., 2010). Wimble Shoals is likely an area of excellent habitat structure for benthic, hemipelagic and pelagic marine animals due to its complex morphology and areas of potential hard bottom (Figs. 6, 7, 22 and 23; Riggs et al., 1995). While nearshore geologic features, like Wimble Shoals, may be potential sources for nourishment borrow material, it is important to understand how mining of these resources can affect the biological communities, cultural resources, wave field properties, water and current flow, and turbidity adjacent to these borrow sites.

Figure 24. Map showing shipwrecks within the vicinity of Wimble Shoals. The amount of cultural resources around this area is evidenced by the amount of wrecks (National Geographic Map #1020676).

5.2 Spatial and Temporal Variability of Wimble Shoals

Some potential reasons for the differences seen in the bathymetric comparison lie within the resolution, accuracy, and location of the surveys as well as the resolution of the seismic data produced. Both USGS and Geodynamics mapped the same sedimentary features, but with different technology. Positioning of seismic lines also plays a part in determining where features are identified; for example, while one survey line may have crossed a peak of a sedimentary ridge, another may cross a trough or low region. Also, due to the large area that USGS gridded to form their bathymetry, it was inherently lower resolution.

Even with differences in resolution, Wimble Shoals appears to have a pattern of southward migration, and potentially a loss of some volume on the northern parts of the ridges (e.g., deflation; Fig. 9). These observations agree with the findings of Thieler et al. (2014) (Figs. 9 and 10). The migration direction also agrees with research of New York and New Jersey sediment ridges (Snedden et al., 2011; Goff et al., 2015). Migration of the ridge crests a few meters is hypothesized due to large storm events including hurricanes, such as Irene (2011) and Sandy (2012), and many nor'easters that create seafloor sediment mobility. Boczar-Karakiewicz et al. (1990) predicted that in 30 m of water, sand ridges could migrate up to 2 m/yr and upwards of 16 meters over 100 years. This study also provided that in 60 m of water that there would be no yearly migration and only 5 m of migration over 100 years. Another study by Li et al. (2003) showed that sand ridges may migrate at an average of 5m/year over time periods of one to two years. Goff et al. (2015) had similar findings on ridges off of Fire Island, New York where they reported migration of 10's of meters over two years. Dalyander et al. (2013) have reported that the area of Wimble Shoals experiences that critical shear stress that exceeds "mobility" standards on the bed occurs 15% of time throughout the year (with summer being the lowest, ~1% and winter being the highest, ~25%). This sheds light on the fact that the shallower areas of Wimble Shoals could display higher rates of migration than the deeper areas, potentially due to wave refraction and more bed mobility. This could potentially be important in the overall shape of Wimble Shoals as well as how it impacts the shoreline. Where Wimble Shoals is the shallowest (along the attachment point just south of Salvo), there could be more migration and thus there could be a higher control on shoreline variability along the attachment point as the ridge features migrate south.

5.3 Shoreline Evolution and Impacts Onshore

Throughout the project area over more than a century (i.e., 1873-2009), the ocean shoreline of Pea Island has experienced more erosion than accretion (mean change rate = -0.47 m/yr, or -62.7 m total). The study area on Pea Island shows relatively similar erosion rates to those of adjacent areas including Kitty Hawk and Nags Head, which was to be expected as these areas experience similar storm frequency, have similar bathymetric anomalies in the nearshore, and are experiencing similar magnitudes of human-induced development (Tables 1 and 4). As Miselis (2006) and McNinch (2004) have discussed, nearshore sedimentary features can be an important factor in altering the severity and onset of erosional hotpots. The rates of erosion in the study region reach up to 4.62 m/yr and 6.9 m/yr over the long- (century-scale) and short-term (decadal-scale), respectively.

While an erosional regime is present throughout most transects within the study area, especially over the last two decades, there is also a persistent area of accretion where Wimble Shoals attaches to the shoreline. An interesting finding from this study is that the northward extent of the area of accretion appears to have migrated south at the same rate and magnitude as the northern most part of Wimble Shoals. This co-migration indicates that Wimble Shoals plays an important role in the morphology of the beach and adjacent nearshore areas (Figs. 25). From 1873 to 1997, both the area of accretion and the northern extent of the 11 m isobaths have migrated 4,500 meters. It is worth noting that the overall length of the accretionary area on the beach has also decreased during this time. These changes suggest that the offshore ridges may shield the onshore environment from increased energy through refraction during storms or could potentially focus wave energy onto other areas of the beach causing higher rates of erosion. For example, Bender and Dean (2003) found that wave transformations provided by bathymetric

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highs in the nearshore environment had some control over shoreline change rates in Louisiana. This study agrees with multiple studies that found that the offshore bathymetric complexity is directly related with onshore erosional hotspots and severity of accretion and erosion (McNinch, 2004; Barnard and Hayes, 2005; Schupp et al., 2006; Park et al., 2009; Hequete and Aernouts, 2010).

Table 4. Shoreline change rates for Dare County and major beach towns within Dare. Time interval was 60+ years. As shown in the table, the study area has a high average shoreline change rate as well as the highest maximum shoreline change rate within the county.

Area/Town	Average Shoreline Change Rate (m/yr)	Max Shoreline Change Rate (m/yr)
Study Area	**-0.84**	**-4.21**
Duck	-0.15	-0.73
Kitty Hawk	-0.58	-0.91
Kill Devil Hills	-0.12	-1.22
Nags Head	-1.04	-3.32
Dare County	**-0.58**	**-4.21**

Combining the LiDAR data with AMBUR analyses, there is a persistence of erosion (e.g., 0.13 m loss of elevation and 2.4 m/yr of shoreline erosion) along the entire beach within the last decade, with only a few areas of accretion (Figs. 11, 12, 25 and 26; Tables 2 and 4). LiDAR analysis was used to evaluate recent change in the beach and dune, and provided similar results to the shoreline change analyses in that the beach is losing sediment. Generally, the LiDAR analysis shows a considerable amount of erosion throughout the entire island with isolated pockets of enhanced erosion or minor accretion (Fig. 18). Typically, the beach is losing volume while the dunes are increasing in volume, based on LiDAR analysis, potentially due to human maintenance of the dune structures. In the areas of the beach adjacent to the attachment point of Wimble Shoals, there is much less severe erosion and some areas of accretion. This demonstrates

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the importance of offshore sand volume in influencing and potentially preventing shoreline

erosion.
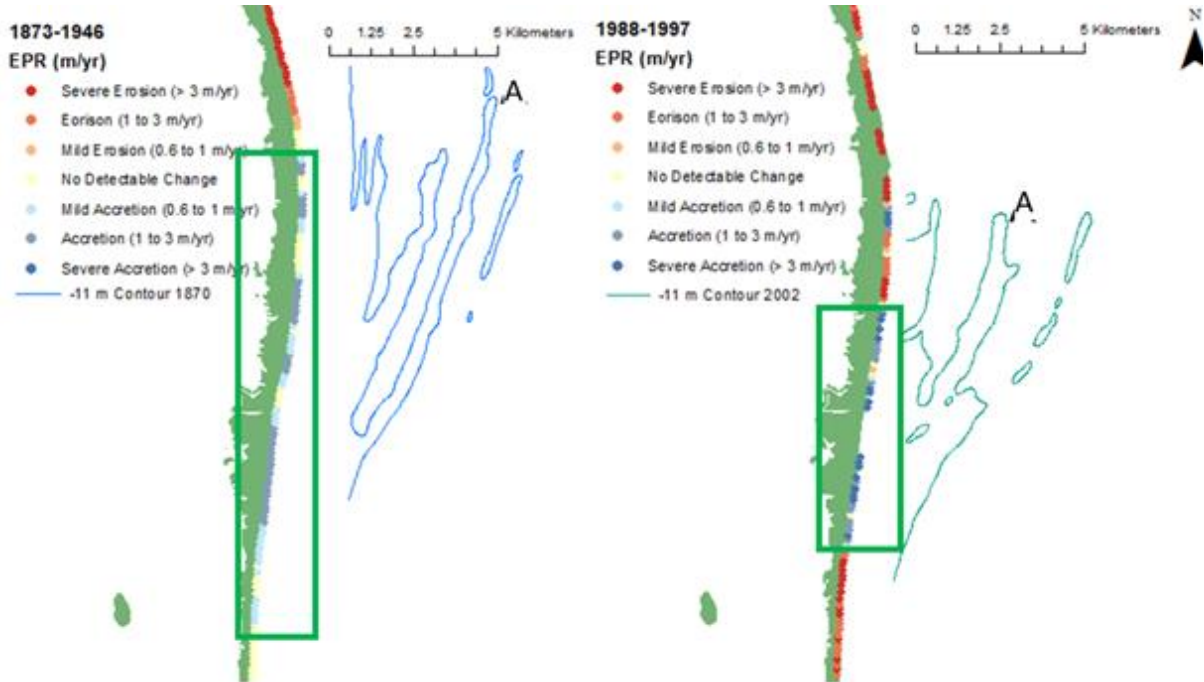
Figure 25. Map showing pre-development (1873-1946) and post-development (1988-1997) shoreline change rates along Pea Island and Rodanthe. Notice that both the onset of accretion and the extent of the shoal (A) migrate about 4500 m. This migration matches the migration of the 11 m isobath of Wimble Shoals, perhaps indicating some shielding effect that Wimble Shoals has on the adjacent beach.
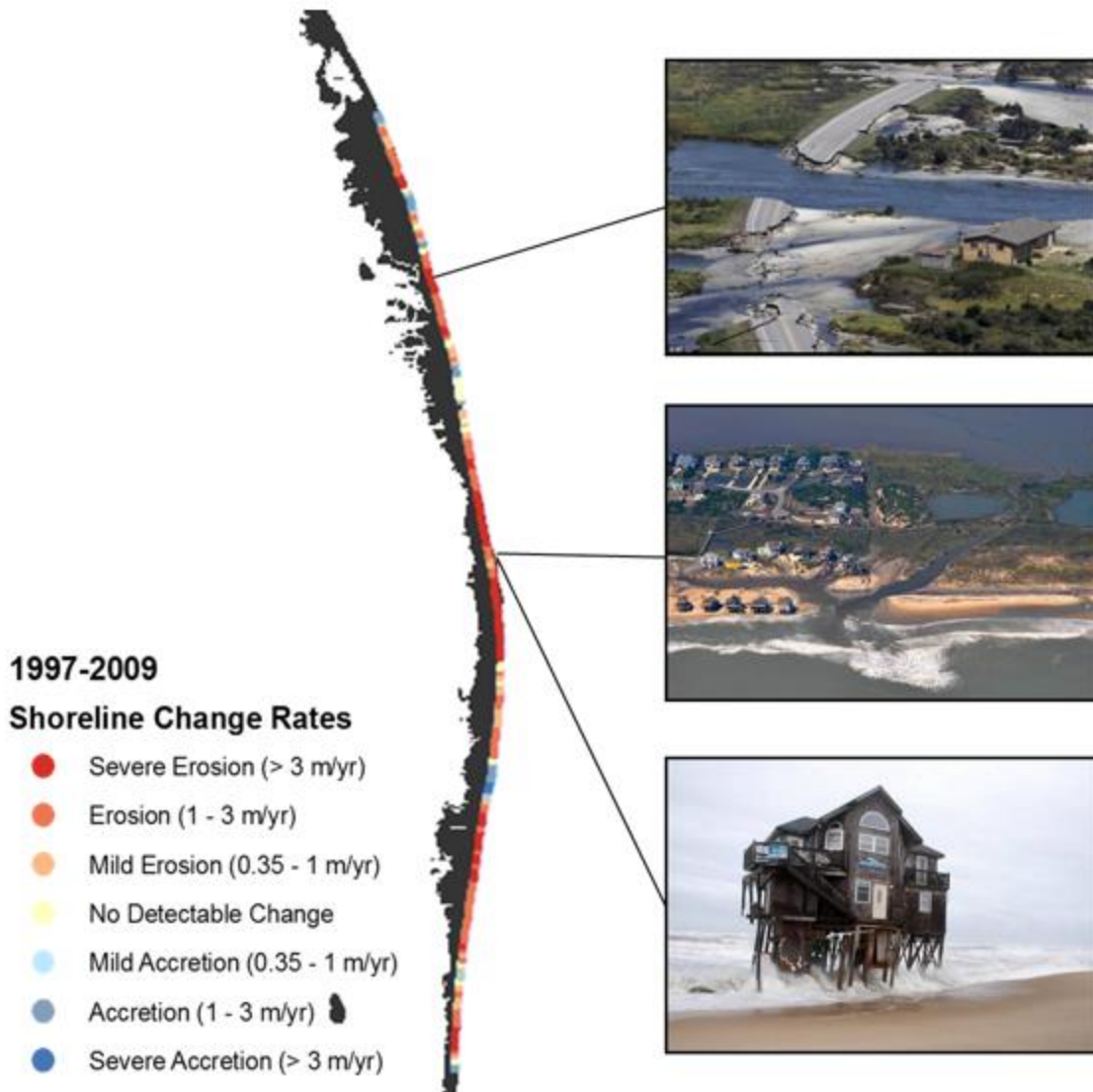
Figure 26. Recent shoreline change rates along Pea Island with hotter colors indicating more erosion. The pictures show glimpses into the extreme erosional areas where breaches have occurred and where homes are being washed to sea.

5.4 Implications for Nourishment Borrow Source

While areas around the world are losing beaches to erosion, many communities are responding by using beach nourishment to protect infrastructure, homes, and businesses. From 1923 to 1999, 573 beach nourishment projects have been conducted at 154 locations using 350 million cubic yards of sand throughout the East Coast of the U.S. alone (Valverde, et al., 1999). Nearshore sediment resources are commonly mined to provide material for beach nourishment

projects which can cause serious impacts to the borrow site and its ecology (Hayes and Nairn, 2004; Kelley et al., 2004; Finkl et al., 2007; Hobbs, 2007). While the USGS dataset is not high-resolution and does not show as much available sediment as the Geodynamics dataset, it is an excellent resource for discovering potential areas of sediment sources (Fig. 27).

Shoreline change analysis along the study area in this project indicates that erosion has been occurring at continually higher rates throughout the last 50 years, with a variance (southward migration) of areas of erosion and accretion (Fig. 12). Higher rates more recently are probably related to recent strong hurricanes and nor'easters, in particular Isabel (2003), Irene (2011) and Sandy (2012) (NC BIMP, 2011; Conery et al., 2014) With storms and sea-level rise expected to continue, beaches throughout the Outer Banks including the study area are expected to continue a landward migration (Riggs et al., 2009). The towns of Rodanthe, Salvo, and Avon are likely to be in need of shoreline protection in the future based upon shoreline change rates and nourishment trends (Tables 1 and 4, Figs. 11, 12, 25 and 26; NC BIMP, 2011). A recent report by Walsh et al. (2016) suggests that 2.3 billion cubic yards of potentially viable sand is available off of the Outer Banks. Assuming the need to nourish every 5 years and using similar volumes to recent or planned projects, in theory there is enough sand to nourish our beaches for the next 900 years. However, much of this material is not located adjacent to communities in need, so the cost of usage would be high. This study shows that Wimble Shoals may have enough sand (182 million m³) for 150 nourishments similar to the last project on Pea Island. However, if the sand is mined too heavily, deflation of Wimble Shoals could occur and thus directly impact the shoreline due to the loss of the shielding effect the Shoals provide the beach (Hayes and Nairn, 2004). If conducted at 5-year intervals, there would theoretically be enough sand within Wimble Shoals to nourish the adjacent area of Pea Island up to 750 years. Of

course, environmental conditions are not likely to remain the same; recent data show increasing waves, sea level, and storms will likely lead to a higher need for nourishment projects (Valverde et al, 1999; ASBPA, 2007). Also, while this sand estimate sounds comforting, the reality is that it is undoubtedly an overestimate because all of the material is not likely suitable. Dredging requires not only sufficient quality but also sufficient thickness and size to get enough sediment out of the borrow sites, but not too large or deep so as to protect the sediment transport regime, biological communities, and geological environment in the region (Hobbs, 2007). Also, as the number and scale of nourishment projects continues to increase and the availability of sediment sources decreases, there will be greater demands on nearshore sediment sources and thus, a need for better understanding of how these sources are affected by mining or dredging.

Hayes and Nairn (2004) proposed that there is likely a limit beyond which the removal of sand from a bathymetric high could result in the deflation or disappearance of the feature. Depletion of Wimble Shoals could induce more wave energy on the shoreline, potentially causing higher erosion rates alongshore. Aside from physical impacts that mining sand from these resources cause, there is also need for ecological and cultural consideration. Mining these features can disturb benthic communities directly and indirectly through sediment resuspension and loss of habitat/structure as well as disturbing pelagic species that depend on hierarchical relationships with benthic species (Diaz et al., 2004; Dubois et al., 2009; Slacum et al., 2010). Destruction of habitat within nearshore sedimentary features can drastically change species richness and diversity and thus also be harmful to recreational and commercial fishing (Diaz et al., 2004). Slacum et al. (2010) recommend mining sand in the winter months while biological communities are usually smallest, mining only parts of the shoal so that some portions remain viable habitat, and mining shoals in rotation to allow for both biological and physical recovery of

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the habitats. In the future, nourishment will continue to be a widely used method to mitigate loss

of beach in communities throughout the world; understanding how sand mining impacts the

ecology, cultural resources, and oceanographic/geological properties of a region is imperative.
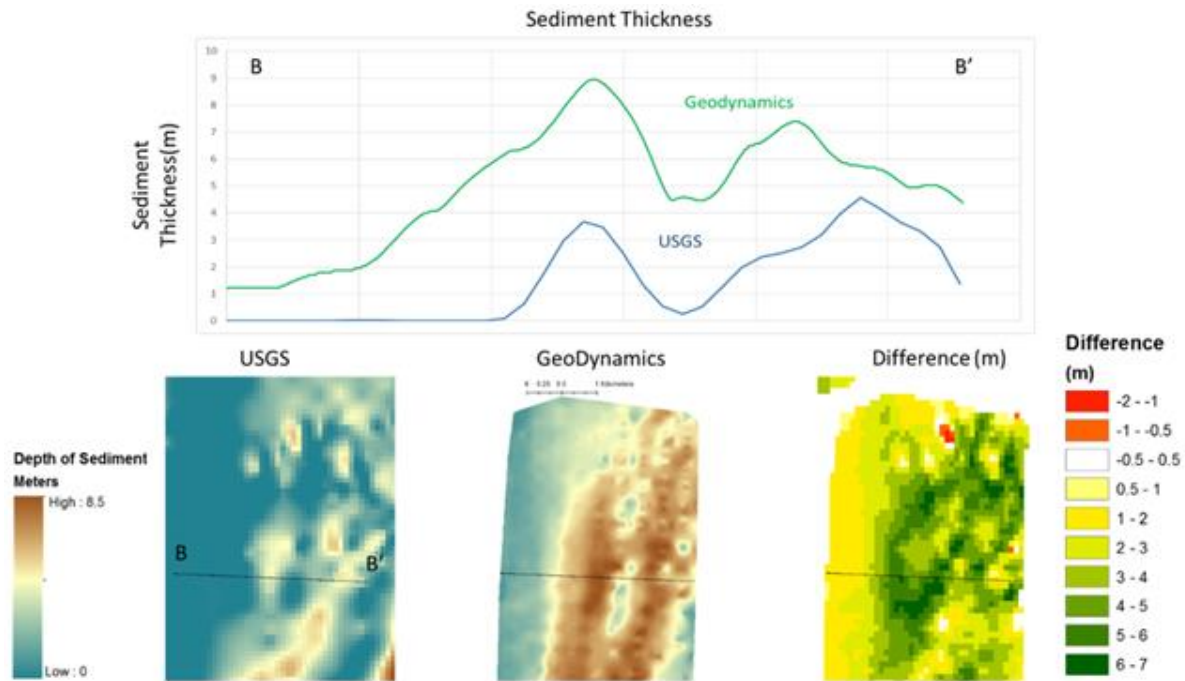
Figure 27. Transect highlighting differences between both datasets both quantitatively and qualitatively. Notice that general trends between the datasets align, but Geodynamics consistently reports higher values of unconsolidated sediment.

6. CONCLUSIONS

This study gives insight into the dynamics of a shoreline system with a shoreface-attached morphological ridge complex. The findings of this study can inform managers, researchers, and the public of the dynamics, processes and concerns about nearshore environments. Furthermore, this study evaluates the history and morphology of Wimble Shoals as well as the impact that this nearshore sedimentary deposit can have on future sand needs for beach nourishment projects. Several specific conclusions are:

1) Wimble Shoals is a morphological ridge complex that lies upon a gently sloping Pleistocene surface. On top of the morphological ridges second order bedforms exist (subaqueous dunes). There are some areas of complex morphology where the TST sediments are outcropping. Based on this interpretation, the sediments composing Wimble Shoals is a combination of both HST and TST deposits and are thickest within the HST deposits along the ridges. The presence of the sand within the HST could be derived from a paleo-cape feature that was once in the location of Wimble Shoals.

2) The sand bodies of Wimble Shoals are composed of medium to fine sand. These sand deposits are underlain by discontinuous layers of silt, mud and gravel. Wimble Shoals could potentially be a nourishment borrow source for many projects in the future (based on rough estimates, enough for 150 nourishment projects assuming similar sized projects that were recently completed on the Outer Banks), but more design-scale work is needed to fully understand how much sediment is available to borrow.

3) Wimble Shoals shows southerly migration of bedforms. This migration is in agreement with other studies and general trends along the Outer Banks. Wimble Shoals' spatial variability is hypothesized to be due to large storm events including multiple hurricanes

and many nor'easters. The southerly migration of Wimble Shoals is also connected to a similar migration of shoreline erosion and accretion areas, suggesting that the spatial variability of Wimble Shoals influences the adjacent beach morphology. This area of the Outer Banks is known to have a high number of storm events impact it each year, resulting in an average seafloor sediment "mobilization" of 15% of time throughout the year.

4) The island adjacent to Wimble Shoals is experiencing increasing rates of erosion with time. From 1873-2009, the average shoreline change rate was -0.5 m/yr where in more recent times (1997-2009), the average shoreline change rate increased to -1.8 m/yr. With the increase in shoreline erosion, sea level rise, storms, and human intervention there will likely be an increasing need for beach nourishment projects within the study area.

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