

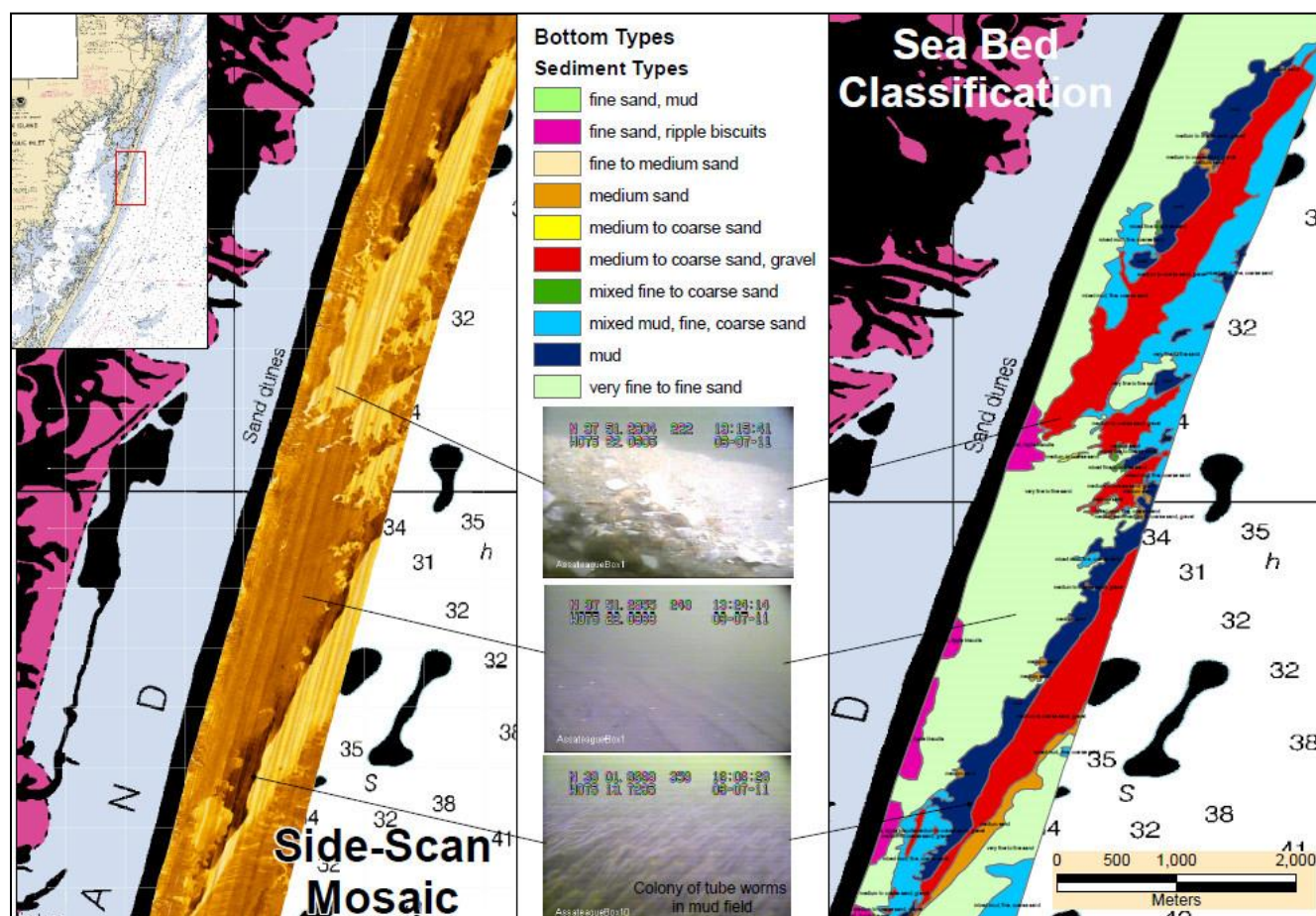


Assateague Island National Seashore

Inventory of Physical and Benthic Habitats and Ocean Resources within the Nearshore Boundary of Assateague Island National Seashore

Part I-Geophysical Framework

Completed 2013



ON THE COVER

Side scan sonar mosaic image and associated sea bed classification map of an area off Assateague Island. Also shown are several underwater images of sea floor. Images and map represent various GIS data produced by the Maryland Geological Survey as part of the study described in this report.

Inventory of Physical and Benthic Habitats and Ocean Resources within the Nearshore Boundary of Assateague Island National Seashore

Part I-Geophysical Framework

Completed 2013 – Edited June 2019

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Executive Summary

In order to obtain basic information about the shallow marine environment within the boundary of Assateague Island National Seashore (ASIS), the Seashore contracted the Maryland Geological Survey (MGS) and Versar, Inc. to conduct remote sensing surveys, and sediment and benthic sampling along the entire length of Assateague Island's ocean side. The geophysical and biological data from this project will provide baseline marine information that ASIS can use to identify critical benthic habitat locations. This information will be used to effectively manage these sensitive areas and protect them from destructive commercial fishing practices, and to clarify to the public the need for these restrictions.

The primary objective of this project is to create baseline inventories of submerged marine resources within and immediately adjacent to the Seashore boundary, in order to answer the following questions:

1. What are the types, locations, and extent of subaqueous sediment types and benthic habitats (including gravel and peat outcrops, sand shoals, hard bottom features, and other benthic habitat classifications)?
2. What is the existing bathymetry of the Seashore's shoreface and nearshore areas, and where are the major geomorphic features (such as shoals and shore attached-bars)?
3. What is the character of the shallow sub-bottom, such as shoreface sand thickness and locations and widths of relict inlets?
4. What benthic communities are found in the nearshore areas of the Seashore, and how do these benthic communities vary between locations and habitat types?

The study area includes the nearshore area extending out to 1 km offshore, along the 58-km Assateague Island oceanside shoreline. This offshore distance encompasses the jurisdictional boundary of ASIS and major adjoining bathymetric features indicated by regional surveys done farther offshore. A significant portion of the project area lies within the closure depth of the nearshore profile, and thus is considered highly dynamic.

The Maryland Geological Survey (MGS), part of the collaborative team, conducted remote sensing surveys with ground truthing to address the geological and geophysical task components in fulfilling objectives 1, 2 and 3 for this project. The surveys were conducted during May and June of 2011. The data provided by these surveys were used to select sites to sample for benthic invertebrate inventory (Objectives 4), which was conducted by Versar, Inc. in the fall of 2011.

The remote sensing surveys were done onboard the DNR *R/V Kerhin*. MGS collected side scan sonar, seismic, bathymetric sounding and magnetometer data, as well as sediment samples and underwater videos. Track lines (boat path) for the surveys ran parallel to the shoreline.

Primary instrumentation included:

- Side scan sonar - EdgeTech 4200 FS @ 120 and 410 kHz
- Seismic profiler – EdgeTech SB 216 @ 2 – 16 kHz, 10ms
- Seabed classification system - QuesterTangent QTC 5.5 VIEW @ 200 kHz
- Magnetometer – Geometric 881 Marine Magnetometer
- Echosounder - Dual Frequency Transducer 200 kHz and 28 kHz with 4 degree beam angle

Survey parameters were:

- Vessel speed – 5.5 knots
- Track line spacing – 100 meters
- Side scan sonar range – 75 meters
- Side scan fish depth – 1.5 meters
- Seismic profiler fish depth – 2 meters
- Seismic profiler depth range – 25 meters

Bottom sediment grab samples were obtained using a Van Veen sampler with a 10 centimeter depth capacity. Sampling sites were chosen based on the side scan sonar and seismic data. MGS took samples on distinct bottom types to confirm estimates of those types. Underwater video and still photographs were taken at select locations to get a better idea of bottom conditions and delineate boundaries between the sediment types.

The side scan mosaics show harder, strongly acoustically-reflective bottom in light shades. These are areas where shell, sand and coarse-grained sediments would most likely be found. The darker shades indicate less acoustically reflective surfaces such as muddy sediments or materials which would strongly scatter the acoustical signal away from the sensors.

The side scan acoustic data was analyzed with QuesterTangent's SWATHVIEW software to further characterize the seafloor according to subtle variations in the acoustic signal. SWATHVIEW analysis identified ten bottom bed types. Once the acoustic classes were determined, they were correlated with ocean bottom sediment samples and video images, and seismic profile data to clarify the seabed classification interpretation. Polygons based on the interpreted acoustic data were constructed to produce a bottom classification map. GIS data were compiled with ESRI ArcGIS Desktop 9.3.1. Final map products and data layers are available in various ArcGIS and graphic formats.

The nearshore along Assateague Island consists of a variety of bottom types based on a range of small scale (*i.e.*, 0.2 to 2 meter range) bed forms and sediment texture. The distribution of the bottom types correlates to bathymetry and delineates the shore-attached shoals located within the study area, as described below. These shoals are adjacent to historical inlets sites.

Sub-bottom seismic profiles provided information on the shallow stratigraphy in the nearshore area. The study area is mostly underlain by Holocene back barrier lagoonal and basal peat sediments and inlet-channel fill. Paleochannels visible in the seismic profiles were mapped and found to be clustered in several areas corresponding to historical inlets sites.

The dominant sediment type is well sorted, very fine to fine sand, found primarily in the broad flat areas between shore-attached shoals and the inner nearshore. 'Mixed mud, fine to coarse sand' is mapped in shallower areas of the inner-shoal area, and adjacent to the mud fields. The bottom sediment type progresses from 'medium sand' to 'very fine to fine sand' along the up-drift flank of the shoal and crest. This sorted distribution pattern of bottom sediment types is repeated on the three shore-attached shoals north of the inflection point (*i.e.*, shore-attached shoals near South Beach; Little Levels, and Fox Hills). 'Medium to coarse sand, gravel' class

was mapped primarily along the up drift flank of the three northern three shoals; this class was not identified south of the inflection point. The gravel is thought to be reworked relict channel fill.

Extensive linear fields of mud and mixed mud and poorly sorted sand were mapped in some of the inner troughs between shore-attached shoals in the northern half of the study area and along deeper areas seaward of the shore-attached shoals in the southern end. Based on seismic profiles, the mud fields correspond to areas where subsurface stratigraphic units, interpreted to be either Holocene back barrier sediments or Pleistocene shelf mud, are exposed. Underwater videos show that the bottom fringing the mud fields supports a vibrant benthic community (tube worm colonies). The patchy mud fields mapped of the north end of Assateague may represent exposed outcrops of back-barrier marsh. Sediment samples collected with these areas contained peat.

The geophysical framework for the habitat classification is presented in terms of the Coastal and Marine Ecological Classification System (CMECS). Eventually this information will be incorporated with the biological information for resource management by the NPS.

Acknowledgments

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The authors thank Keith Lindemann, First Mate on R/V Kerhin, for his invaluable assistance in various field operations. RY Enterprises provided the underwater camera system and magnetometer used in the study. The magnetometer analyses and results presented in this paper rely on data collected at magnetic observatories. We thank the national institutes that support them and INTERMAGNET for promoting high standards of magnetic observatory practice (<http://www.intermagnet.org>). The authors extend their thanks to Elizabeth Sylvia for analyzing the sediment samples, and to Neil Winn of the National Park Service for his assistance with setting up backup GPS onboard the R/V Kerhin and with report preparation.

Reviewed by Courtney Schupp (NPS Geologic Resources Division).

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Introduction

Background

Assateague Island National Seashore (ASIS) was established in 1965 to preserve the natural resources and recreational value of Assateague Island and its adjacent coastal waters in Maryland and Virginia. The Seashore's ocean boundary extends 1 km offshore from the island's 58-km long shoreline (Figure 1). The Seashore encompasses 19,400 hectares (48,000 acres), 20% of which are oceanic waters. Every year, 2 million visitors are able to experience one of the few remaining undeveloped barrier islands on the mid-Atlantic coast, and the majority (80%) of recreational visits to ASIS involves the direct use of Seashore aquatic habitats (Eppley Institute, 2007). In addition to the recreational uses (swimming, birding, fishing, surfing, boating) of the beach and nearshore areas, the oceanic habitats within the Seashore boundary are ecologically significant.

Marine resources are fundamental to the Seashore's ecosystem and purpose. Nearshore benthic habitats support a diversity of marine life that is commercially, recreationally, and intrinsically valuable. Nearshore sand movement controls every single aspect of the Seashore, including ecosystem health; visitor use; infrastructure management; an annual \$1.5 million federal project to restore coastal processes at ASIS (Schupp et al. 2013); and habitat availability for shorebirds, commercial finfish and shellfish, and six federally-listed threatened and endangered species (including sea turtles and marine mammals).

To better manage the park's marine areas, managers needed baseline data about the submerged geological and biological resources within the nearshore. The goal of this data collection effort was to support future management efforts to protect resources to limit ongoing habitat destruction; to assess and prepare for future resource threats (e.g., offshore development, nearshore infrastructure); to prepare for the impacts of sea level rise; to design research programs; to evaluate changing resource conditions; and to develop long-term marine resource monitoring protocols. ASIS needs to know the locations and extent of its sensitive benthic habitats in order to limit commercial fishing areas and to create benthic habitat protection strategies.

To accomplish the surveys, ASIS worked with the Maryland Geological Survey (MGS) and Versar, Inc. to design and conduct remote sensing surveys, sediment and benthic sampling along the entire length of Assateague Island's ocean side.

Objectives

The primary objective of this project was to create baseline inventories of submerged marine resources within and immediately adjacent to the Seashore boundary, in order to answer the following questions:

1. What are the types, locations, and extent of subaqueous sediment types and benthic habitats (including gravel and peat outcrops, sand shoals, hard bottom features, and other benthic habitat classifications)?
2. What is the existing bathymetry of the Seashore's shoreface and nearshore areas, and where are the major geomorphic features (such as shoreface-attached, and nearshore detached shoals)?
3. What is the character of the shallow subbottom, such as shoreface sand thickness and locations and widths of relict inlets?
4. What benthic communities are found in the nearshore areas of the Seashore, and how do these benthic communities vary between locations and habitat types?

The Maryland Geological Survey (MGS) conducted remote sensing surveys with ground truthing to address key task components in fulfilling objectives 1, 2 and 3, which focused on the physical framework for benthic habitat classes. The data provided by these surveys were used to select sites to sample for benthic invertebrate inventory (objective 4), which was conducted by Versar Inc.

This project incorporates the Coastal and Marine Ecological Classification Standard (CMECS), recently approved by the Federal Geographic Data Committee (FGDC, 2012). The CMECS offers a standard ecological classification system that is universally applicable for coastal and marine systems and complementary to existing wetland and upland systems.

Presented in this report is a summary of the methods used by MGS and their findings. The deliverables from this project include a series of GIS products presenting raw and interpreted remote sensing and ground-truthing data.

Other Studies

There have been several studies investigating portions of the Delmarva Atlantic coast and shelf, including the evolution and geomorphology of southern Assateague Island, and the stratigraphy and morphological character of the mid-Atlantic inner continental shelf and the adjacent shoreline. An in-depth discussion of the various studies is beyond the scope of this report, but can be found recent publications (Hobbs et al, 2008; Wikel, 2008; Krantz et al, 2009). However, several studies that are particularly germane to this report are discussed briefly in this section.

The origin and morphological characteristics of shore oblique linear shoals (also referred to as ridge and swale topography) have been the subject of numerous investigations.

Duane et al. (1972), Field (1976; 1979), and Swift and Field (1981) examined the orientation, distributions, and morphologies of linear shoal fields on the Atlantic inner shelf. Based on geophysical, sedimentological and hydrologic data, they concluded that shore-attached shoals form in response to nearshore storm generated currents and eventually become detached as a result of sea level rise. Detached shoals continue to respond to the modern shelf hydrodynamic regime. McBride and Moslow (1991), using a computer mapping system, correlated the distribution of shore-attached and detached shoals with locations of historical and active inlets along the U.S. Atlantic coast. They found a genetic relationship between shore-attached shoals and certain inlets and concluded that these shoals initially formed from ebb tidal deltas associated with inlets. Shore-attached shoals off the Outer Banks, North Carolina and Ocean City, Maryland have been linked to shoreline behavior (Kraus and Galgano, 2001; Schupp et al, 2006).

Linear shoals have been studied in terms of their importance as potential sand and gravel resources (Anders and Hansen, 1990; Conkwright and Gast, 1995; Wells, 1994). As part of an environmental study on the impact that sand mining may have on linear shoals, U.S. Department of the Interior, Mineral Management Service (MMS) funded studies to investigate how these linear shoals maintain their form (Hayes and Nairn, 2004) and to map benthic and fish habitats associated with the offshore shoals (Diaz et al, 2004).

Other studies utilized seismic surveys and sediment cores to document lithostratigraphic relationships and reconstruct paleodrainage on the mid-Atlantic shelf (Shideler *et al.*, 1972; 1984; Field, 1976, 1980; Sheridan *et al.*, 1974; Belknap and Kraft, 1984). MGS conducted an integrated study investigating the shallow stratigraphy of the inner shelf, between 2 and 40 km, off Assateague Island and developed the Quaternary geologic framework for the Maryland inner continental shelf (Toscano *et al.*, 1989). Based on data from high resolution seismic surveys and vibracores, four significant reflectors and five distinct stratigraphic units were identified on the inner shelf off Assateague Island (Figure 2). A most prominent and persistent reflector (M1) was identified between -21 meters to -36 meters MSL and correlated to the Tertiary-Quaternary unconformity onshore. The Q1/Q2 depositional units, characterized by parallel to subparallel internal reflectors, immediately overlie the M1 reflector. A persistent, but weaker reflector, M2, identified approximately between -15 meters to -31 MSL, separates the Q1 from the Q2. The M2 reflector is interpreted to represent an erosional surface formed between 190 - 130 thousand years ago. Sediments from vibracores that penetrated the upper portion of the Q1 unit were sands and gravelly sands containing shells; the Q1 unit is interpreted to be 250 -200 thousand years old or older. The overlying Q2 unit consists primarily of dewatered, fossiliferous mud. Amino acid racemization data from the genus *Mulinia* indicate that the Q2 unit was deposited between 75 and 128 thousand years ago. The Q2 mud unit, interpreted to be open-shelf muds deposited during the 50 thousand year period (oxygen-isotope stage 5) of slightly depressed sea levels, represents a depositional environment unique to the Maryland shelf (Toscano, 1992). The Q1/Q2 units were correlated to the Sinepuxent Formation on shore. Unit Q3 represents fluvial fill deposits of an ancestral St. Martin tributary system. The tributary system was incised into the shelf during the Wisconsin glaciation (oxygen-isotope stages 4 through 2; ~74 -17 thousand years ago). No deposits equivalent to oxygen-isotope stages 4, 3, and 2 were

identified on the Maryland inner shelf. Both Q4 and Q5 depositional units are Holocene in age. The Q4 unit is interpreted to be transgressive leading edge deposits (lagoon/marsh sediments) and overlaps Q3 and Q2 depositional units. Unit Q5 represents modern shelf shoal deposits.

Wikel (2008) studied the relationship between the shoreline behavior and the offshore geologic character of southern Assateague Island and Wallops Island. Wikel used, as part of his data set, over 400 km of side scan sonar and sub-bottom data collected in the nearshore along the southern end of Assateague Island and Wallops Island (Figure 2). The seismic data revealed a series of deep paleochannels interpreted to be the ancestral Potomac River, possibly accounting for the offset between Assateague and Wallops Islands (Wikel, 2008; Hobbs et al, 2008; Krantz et al, 2009).

As part of the monitoring of the sand-bypassing operation to restore the natural longshore transport of sediment to the north end of Assateague Island (see **Study Area** discussion), the U.S. Army Corps of Engineers (USACE) and ASIS collect beach profile, shoreline and nearshore bathymetric data along the northern 2 km of the island on an annual or semi-annual basis (Schupp et al., 2007). Monitoring has shown that the by-passing effort has been successful in slowing the erosion rate at the north end of the island (Carruthers *et al.* 2013).

Concurrent with the field work for this study, MGS collected similar data off southern Ocean City. That study was funded by the Maryland Coastal Zone Management (CZM) agency.

Study Area

The study area of this project includes the nearshore subtidal area extending out to 1 km offshore along Assateague Island's oceanside, a total of 58 km, from the Ocean City Inlet to Chincoteague Inlet. The offshore distance encompasses the jurisdictional boundary of ASIS (Figure 1). A significant portion of the study area lies within the shoreface zone and the nearshore depth of closure, and thus, is considered highly dynamic.

The study area is classified as a microtidal, wave dominated shoreline. Tides are semidiurnal with a mean tide range of 1.2 to 1.4 meters. Mean wave height ranges from 1.2 to 1.3 meters above mean sea level (MSL) (Seminack and Buynevich, 2013). Wind and wave patterns along the Assateague Island coast vary seasonally, with moderate winds blowing from the south and southwest in the summer months and higher average wind speeds occurring in late fall, winter and early spring. The higher winds, typically from the northern direction, occur during extratropical storms, and drive waves from the northeast to east direction. Because the higher wave energy is from the north and northeast, the net longshore transport of sand is to the south for most of the study area except the north end of Assateague Island. Wave refraction around the ebb tidal shoal at the Ocean Inlet results in a net transport to the north with a nodal point located at approximately 0.5 km south of the inlet.

Geologic Setting

Assateague Island and inner continental shelf is underlain by unconsolidated Coastal Plain sediments, the upper-most 60 meters of which are Cenozoic in age. The island itself is composed of Holocene transgressive sediment sequences, consisting of several facies which correlate to present day depositional environments. The barrier sands are light-colored well sorted fine to very coarse quartz sand with gravel and shell fragments, representing beach, dune, and overwash deposits. Tidal marsh deposits consisting of watery, highly organic silt and clay, represent back barrier, fringing marsh. Lagoonal deposits consist of mixed very fine sand and organic, sandy, silty mud, representing a back bay deposits similar to those seen in the Coastal Bays today. Marking the base of the Holocene deposits are peat and peaty mud. These deposits occasionally are exposed on the island or along the bay and ocean side after a strong storm.

The back barrier lagoonal and basal peat deposits extend into the nearshore area and are covered with modern shoals and sheet sand, represent trailing edge Holocene deposits. The wave ravinement marks the lower boundary of the modern nearshore sandy deposits. The wave ravinement processes actively rework the Holocene sequence,

Directly beneath the Holocene barrier island deposit is the Sinepuxent Formation (Pleistocene), a marginal marine deposit consisting of poorly sorted, silty, fine to medium sand with thin layers of peaty sand and dark clay. The deposit contains abundant heavy minerals, and micas, the latter making the Sinepuxent Formation lithologically distinct from older deposits (Owens and Denny, 1979). The Sinepuxent Formation is correlated to the offshore Q1/Q2 units described by Toscano et al. (1989). The Q2 unit, consisting of fine-grained sediment (mud), is exposed on the seafloor in seaward of the 15-m isobath..

An erosional unconformity marks the top of the Sinepuxent Formation and is referred to as the Holocene/Pleistocene (H/P) unconformity. Based on well boring logs along Assateague Island, the depth to this boundary ranges from approximately -4 m to more than -25 m MSL (Halsey, 1978). Areas where the boundary is deep correspond to historic inlets and paleochannels. Wikel (2008) identified the H/P unconformity (R3) at -16 MSL along southern end of Assateague Island.

Geomorphic Setting

Assateague Island is a transgressive barrier island, part of the barrier island/spit unit of the Delmarva coastal compartment (Fisher, 1967; McBride and Moslow, 1991). The barrier island is estimated to have formed approximately 5,000 years ago. Assateague Island has evolved into its present day geometry, in response to sediment source and supply, local wave and wind dynamics, and sea level rise (Kraft, 1971; Halsey, 1978; Leatherman, 1979; 1984; Oertel and Kraft, 1994). The current island configuration

reflects the antecedent topography, defined largely by paleodrainage and paleo-barrier/shoreline features (Wikel, 2008; Kranz et al, 2009).

Historically, numerous inlets have been documented along Assateague Island (Hite, 1924; Truitt, 1968; Gawne, 1966; Amrhein, 1986) (Figure 3). These inlets formed during storms. Although some inlets may have persisted for longer periods of time and often migrate slowly to the south, eventually all were filled in as a result of natural processes. These historical inlets have played an important role in shaping Assateague Island. Remnant features of the more recent inlets are evident in aerial photographs. Features include longitudinal sand ridges bracketing the former inlet channel, and lobate features and islands on the bay side of the island.

The present day Assateague Island is separated from Fenwick Island to the north by Ocean City Inlet. The Inlet was formed during a hurricane in 1933 and was immediately stabilized by the U.S Army Corps of Engineers to keep it open. This stabilization resulted in immediate changes in the shoreline configuration south (downdrift) of the inlet. The stabilized inlet interrupted the longshore transport of sediment, essentially "starving" northern Assateague Island of sand, causing accelerated erosion. A significant volume of sand has been trapped by the north jetty, and the flood- and ebb-tidal deltas of the inlet. Since 1933, the zone of accelerated erosion has expanded more than 10 km south along Assateague Island. Portions of the northern end of Assateague Island have migrated landward, as much as 500 meters along the northern-most 2 kilometers since 1943. At the same time, the north end has become flatter due to the loss of sand volume, making it more vulnerable to overwash. During two storms in 1998, a 2.4 km section of the north end experienced prolonged periods of overwash, resulting in the significant removal of sand and exposure of the underlying peat. To mitigate the erosional effects of the stabilized inlet, the Army Corps of Engineers initiated a restoration project, implemented in two phases. Phase I, completed in 2002, consisted of a one-time beach nourishment to repair the damage from the 1998 storms and stabilize the north end of the island. The second phase, which began in 2004, involved a long-term sand-by-passing operation to restore the natural flow of sand to the north end of Assateague Island. Twice a year, sand is dredged from the ebb tidal shoal at the Inlet and from other predetermined sites within the inlet and placed seaward of the nearshore bar in an area between 2.5 and 5 km south of the inlet. Wave and longshore processes rework and redistribute the placed material along the active surf zone. Between January, 2004 and April, 2011, 841,000 m³ (1.1 million yd³) of sand were placed in the nearshore along the north end of Assateague Island (Toepfer, 2011).

The middle portion of Assateague Island, from the Maryland State Park south to Green Run Bay near the Maryland-Virginia border, is an example of a wave-dominated barrier island. In terms of shoreline changes, this portion of the island has been stable over the past 100 years. However, this section of the island has been punctuated with numerous historic inlets (Figure 3). Two of the more prominent inlets, Sinepuxent Inlet and Green Run Inlet, persisted for more than a half century (Truitt, 1968).

Near Green Run Bay, the Island changes orientation and the southern end of the island is offset about 1 km (0.6 mi) seaward of Pope Island and Chincoteague Island. This inflection point marks where the modern barrier island intersects an earlier Holocene precursor to the modern barrier island (Halsey, 1978; Krantz et al, 2009) (Figure 4). Assateague Bay Inlet cut through Assateague Island seaward of the north end of Chincoteague Island during the Colonial period (1600s and 1700s) (Amrhein, 1986). By about 1800, this inlet was closed by the first of a set of spits extending south and wrapping around the eastern side of Chincoteague Island (Goettle, 1978).

The southern end of Assateague Island is a spit complex, informally named Toms Cove Hook. The Hook is an accretionary spit that has grown as much as 6 km since the mid-1800s (Figure 5). This growth is a result of the annual longshore transport of 1.5 million cubic meters of sand to the Hook from the Bethany headland (Wikel, 2008). The spit's rapid growth also may have been accelerated by the closure of the historic Green Run inlet and possible other inlets and subsequent reworking of the respective ebb-tidal deltas in the late 1800s (Halsey, 1978; Demarest and Leatherman, 1985; McBride, 1999).

Nearshore features within the study area include shore-attached shoals, or ridges defined by the 12 m (50-ft) isobath (Swift and Field, 1981). These features are part of the well-developed ridge and swale topography which is somewhat unique to the Middle Atlantic bight. These shoals have been associated with historical inlets as well as erosional hot spot on the adjacent shoreline (McBride and Moslow, 1991; Schupp et al., 2006; Kraus and Galgano, 2001).

Methods

In order to accomplish the first three objectives of this study, the approach consisted of four major tasks:

1. Map subaqueous sediment types and extent, including gravel and peat outcrops, sand shoals, hard bottom features, and other benthic habitat classifications.
2. Map the bathymetry, including shoreface profiles and major geomorphic features such as shoals;
3. Map the shallow sub-bottom, including a map of shoreface sand thickness and locations and widths of relict inlets.
4. Collect sediment grab samples and underwater videos to verify acoustic textural classification and small scale bottom features.

Field Methods

Remote sensing data were collected simultaneously using multiple instruments and integrated systems (Figure 6), described below. Remote sensing instruments were mounted on or towed from R/V Kerhin, a 51-ft shallow draft (1.3 m [4.2 ft]), steel hull research vessel owned by the Maryland Department of Natural Resources.

The field surveys were conducted in May 2011. Survey vessel speed was approximately 5 knots. Track lines were spaced 100 meters apart and were roughly shore-parallel (northeast to southwest). The shoreward-most track lines were between 200 and 300 meters seaward of the shoreline. A longshore bar limited how close the research vessel could get to the shore. Based on shore perpendicular profile data (Fulford and Bass, 1991), the longshore bar can be between 50 to 150 meters offshore (from mean water line) in the spring months, depending on the wave and weather conditions. Likewise, the Ocean City ebb shoal and offshore shoals at Toms Cove Spit at Chincoteague Inlet marked the northern and southern extents of the surveys, respectively.

The 58-square km study area was surveyed with 9 to 10 shore-parallel track lines and 33 cross track lines, totaling to over 607 km of survey track lines (Figure 7). Track lines were numbered according to the sequence that they were collected (Table 1). The positional order in which the track lines were surveyed was dictated by a number of factors including wind direction and wave conditions on the day of the survey, and if a particular line had to be resurveyed.

Navigation for the R/V Kerhin was supplied using the onboard Simrad MX512 Differential Global Positioning System (DGSP) system and a Furuno depth sounding system. Horizontal coordinates for the remote sensing equipment were collected using a Leica MX412 scientific –grade DGPS and integrated with remote sensing equipment using Hypack and Chesapeake Tech software. DGPS differential corrections broadcast by the United States Coast Guard (USCG) provided sub-meter horizontal accuracy; however, incorporating movement of the research vessel and DGPS signal latency, the

practical horizontal accuracy is ± 3 meters. DGPS horizontal position was output in geographic coordinates, World Geodetic System 1984 (WGS84) and converted by the various recording instruments to Universal Transverse Mercator (UTM) Zone 18N (WGS84) meters. A third GPS unit, Trimble 4800 RTK GPS system, provided by the NPS, served as a backup navigation system as well as the heave system.

Side Scan Sonar Surveys

EdgeTech 4200 FS side scan sonar (SSS) system, using dual frequencies of 120 and 410 kHz, was used to image the seafloor. The system was adjusted to a depth range of 1-15 meters and a horizontal range of 75 meters. At a line spacing of 100 meters, this range allowed for 33% overlap with 100% coverage of the sea floor within the study area. The underwater sensor (fish) was placed approximately 1.5 meters below the waterline, off the port bow. Side scan sonar data was logged using EdgeTech's proprietary "Discover" software in the proprietary ".jsf" file format.

Bathymetric Surveys

Raw bathymetric data were collected using Leica MX412 survey-grade Differential Global Positioning System (DGPS) and a Knudsen 320BP echosounder. DGPS differential corrections broadcast by the United States Coast Guard (USCG) provide a horizontal accuracy of 2 to 4 meters. Horizontal position was recorded 5 times a second (5 Hz) in Universal Transverse Mercator (UTM) position with a timestamp to the hundredth of a second. These navigational data were collected and stored in Hypack, an industry standard oceanographic data logging software package.

A Knudsen 320BP echosounder was used to determine depth from the water surface to the ocean sediments. The echosounder transducer was located at center hull, directly below the DGPS antenna. The keel offset between the transducer and water surface was determined by a bar check using known vertical measurements (Appendix A, Table A2). This echosounder generates repetitive acoustic pulses, two soundings per second, at 200 kilohertz (kHz) for bottom recognition. The acoustic wave reflects off the density gradient, differentiating the water column from the bottom sediment. The reflections are then filtered and integrated within the echo-sounder to produce an accurate digital measurement from the transducer to the water/sediment interface two times a second. A correction for the draft of the vessel was applied by the data logging software, as determined by the "bar check". Heave data collected by a TSS 320B/321 sensor were also collected and applied to the bathymetric data. At the survey speed of the vessel, a data point was collected approximately every 2 meters along the survey track lines. Raw soundings, heave data, and heave-compensated bathymetry were logged to a personal computer using Hypack. The bathymetric data were georeferenced with the navigational data in the Hypack software. Knudsen Engineering's echosounder computer program also collected the navigation and bathymetric data as a backup logging platform.

Seismic (Sub-bottom) Surveys

An EdgeTech SB 216 seismic profile system running at chirping frequencies from 2 to 16 kHz and a 10ms pulse width was used to collect sub-bottom profiles. The system was set to a 25 meter range. The sensor fish was submerged from the port stern to a depth of about 1.5 meters below the water line and approximately 8 meters behind the boat.

Magnetic Surveys

Magnetic field data were collected using a Geometrics G-881 marine cesium-vapor magnetometer and spatially positioned with the onboard Leica 412 DGPS. Magnetometer was towed from starboard stern, approximately 30 meters behind the R/V Kerhin, a distance to minimize any signal interference from the boat. The location for the magnetometer data were taken from the on-board navigation (Simrad MX512 DGPS). The magnetometer was operated at 10 Hz (10 samples collected per second) and a sensitivity of 0.5 nanoTeslas (nT). Data was logged to laptop computer using the manufacturer's provided software (MagLOG).

Underwater Videos and Sediment Sampling (Ground-truthing)

As part of the ground truth process, videos and still photographs were taken of the nearshore bottom surface, and sediment grab samples were collected to assist in and/or confirm the interpretation of SSS and seismic data, and to define the sediment types for the seabed classification. Video images of the ocean bottom were collected on June 7, 2011, using a custom underwater camera system equipped with a Panasonic underwater video camera, LED lighting (350 lumens, 5500 kelvin color temp), and GoPro YHDC5170 camera (Figure 8). The videos were recorded on a personal laptop. Pinnacle hardware and software were used to transfer the video signal to the computer top-side, allowing viewing during recording. GeoStamp +® (Intuitive Circuits, LLC), an on-screen composite video overlay device, was used to title and stamp the video frames with location (geographic coordinates, WGS84, from R/V Kerhin navigation: Simrad MX512 DGSP system), vessel heading (degrees from cardinal north), and time (UTC). Factoring in the offset of the camera with respect to the ship's navigation GPS antenna (which would vary depending on the amount of cable layout and how fast the research vessel was drifting) during deployment, the accuracy of the video stamped coordinates is estimated to be ± 5 m. The GoPro still photographs were post processed, attaching GPS coordinates, from the R/V Kerhin navigation GPS system (Simrad MX512 DGSP system) using Zoner Photo Suite software.

Twenty-six sites for the underwater videos were selected based on features seen in the side scan waterfalls and preliminary mosaic images (Figure 9). Each site was defined by ~150-meter square box. In order to travel slowly enough to get good images, and to minimize turbulence on the sea floor, the R/V Kerhin stopped engines and drifted across the target box while recording the underwater video. The exact boat path (*i.e.*

track line) depended on the direction of the wind and currents. During the video taping, still photographs also were taken every 2 seconds with the GoPro Camera.

Bottom grab sediment samples were obtained using a Van Veen sampler with a 15 cm depth capacity. Samples were collected along shore-perpendicular transects. Locations of the transects and sampling sites were chosen based on preliminary side scan data. A second set of sediment samples was collected along video track lines; the exact sampling sites were determined by what was seen in the video. A total of 136 sediment samples was collected (Figure 9).

Upon collection, sediment grab samples were photographed, and description of their textural characteristics, color and presence of benthic organisms were noted. To verify field descriptions, select samples were placed in a Whirl-Pak bag and transported to the laboratory for textural analysis and carbon, nitrogen and sulfur content analyses. An additional 18 sediment samples were collected by Versar during benthic surveys and given to MGS for analyses.

Location data and field descriptions of the sediment samples are presented in Tables B3 and B4 in Appendix B.

Analytical Methods and Data Processing

Bathymetry

The sounding data from the bathymetric surveys were processed to remove noise and invalid depth readings. The ASCII comma-delimited text files (kea files) generated by the Knudsen echosounder were imported into spreadsheets. A series of sorting routines was used to filter out invalid HF depth data (invalid HF flag), “out of sequence” depths (*e.g.*, fish, water column noise, multiples, etc.), invalid heave correction, and invalid location coordinates (GPS latency values > 500 msec). For soundings having the same geographic coordinates, the sounding with the higher latency was removed.

The sounding data set was tidally adjusted by subtracting an interpolated tidal offset from each sounding (see Appendix A). The tidal offset was interpolated from tide data obtained from the National Oceanic and Atmospheric Administration/National Ocean Service (NOAA/NOS) tide gauges at Lewes, Delaware (NOAA Sta. # 855-7380) and Wachapreague, Virginia (NOAA Sta. # 863-1044), and the slope array wave gauge offshore south Ocean City, Maryland, operated by the Army Corps of Engineers (Earle et al., 1995). This interpolated tidal offset was calculated using an inverse distance weighted average of the nearest two tide stations’ tidal offsets, based on the horizontal location of the tide stations and the collected data.

These tidally corrected depths were then filtered using a 7 sample (3.5 second) moving average to attenuate the effect of waves (short period chop). The filtered data set was output as a point file (easting, northing, and depth, in comma delimited ASCII format) and imported into ArcMap 9.3 as a point shape file, and used to create a bathymetric surface

grid (raster image). Depth contours, at 1 meter intervals, were generated from the surface grid.

The bathymetric data presented in this study were referenced to NAVD88 vertical datum. Based on comparison of corrected sounding point pairs (where survey tie in lines crosses shore parallel lines), the depth repeatability (precision) was determined to be 0.2 ± 0.2 m (see Appendix A).

Side Scan Sonar Mosaic

Side scan sonar data were processed using Chesapeake Technology's SonarWiz 5 software. Although 120 and 410 kHz data were collected, only the 410 kHz set was used for this project because of the higher detail presented in the imaging. During processing, location offsets due to layback were corrected. The software generates georeferenced side scan sonar mosaics and track line geometry. The mosaics (.tif format) represent an image of the seafloor, based on surface sediment acoustic reflectivity. Track line data, presented in ESRI shape file format, represent the "smoothed" navigation path for the SSS sensor fish which was towed from the port bow. These track lines are offset from the sub-bottom survey, bathymetric survey, and magnetic survey lines, the amount of offset determined by position of the respective instrument relative to the side scan sonar fish. The smoothed, track lines for the SSS surveys are shown in Figure 8. These track lines serve as the reference for the other geophysical data collected for this project.

Side scan sonar images (.bmp format) of the seafloor along each individual track line also were produced, but not georeferenced. These "waterfall" images are free of the typical distortions introduced by georeferencing, and are the highest resolution seafloor imagery available from this software.

Seabed Classification

QuesterTangent's SWATHVIEW seabed classification software was used to post-process the 410 kHz side scan sonar raw backscatter data. This software analyzes the side scan sonar return signal to produce a classification map based on the seafloor's acoustical reflectivity characteristics. Two factors that influence the acoustical reflectivity (back scatter) of the SSS signal are the roughness of the sea floor and the density difference between the overlying water and the sea floor material. Seabed roughness can occur on many scales from the grain size of the bottom sediment, which is on the scale of millimeters, to larger bedforms that can be up to several meters in length. The density of the seabed material (sediments) also influences the back scatter signal. A soft mud will have less density difference with the surrounding water than dewatered, compact mud. Employing proprietary algorithms, SWATHVIEW uses multivariate analysis to find patterns in the side scan acoustic backscatter signal, which reflect bottom textural parameters. Cluster analysis is used to group together regions of similar acoustic backscatter characteristics, or classes.

The acoustic seabed classification software produces a raster image that represents bottom classes with graded colors; the bottom classes are differentiated based on the acoustic characteristic of the sonar back-scattered signal. Figure 10 (Panel B) shows an example of the SwathView classification rendering raster. Striped patterns indicate either noise in the water column or transitional areas between bottom classes. This raster was digitized in ArcGIS to indicate the areas of distinct bottom acoustic classes. By grouping some similar classes together, eliminating signal noise, and integrating small, distinct classes into surrounding larger classes, major bottom acoustic types emerged.

The bottom acoustic classification data were layered over the side scan mosaics and bathymetry. These data sets were used to correlate side scan reflectivity with acoustic seabed classes and detect any influences that abrupt changes in seafloor slope may have on the acoustic data. Steep slopes tend to scatter the acoustic signals and produce anomalous data. The acoustic classes were correlated with bottom sediment samples and imagery, and seismic profiles to define further the acoustic classes with descriptive definitions regarding sediment type (*i.e.*, texture), small scale bed forms (*e.g.*, ripples), and apparent biogenic components (*e.g.*, shells and shell fragments, worm colonies, etc.). During this refining process, polygons were drawn and redrawn to define the boundaries and distribution of seabed bottom classes (Figure 10 Panel C).

The classification process attempted to select the dominant acoustic class best representing a given area, which may contain several other acoustic classes at a smaller scale. The seabed classification layer provided the basic framework for the benthic sampling scheme and the development the final benthic habitat classification which was completed by Versar, Inc. (2013).

Seismic (Sub-bottom) Profiles

Data from the seismic profile system were processed with EdgeTech's "Discover" (SB 3200-XS) software. The sub-bottom data are stored in a binary format and output in proprietary .jfs format and as a series of un-georeferenced grayscale images (.jpg format). The images, or seismic profiles, depict subsurface reflectors below each track line, representing changes in subsurface sediment acoustic transparency. Each image has horizontal fix marks overprinted at 100 meter intervals, and these intervals are labeled with geographic (WGS84) coordinates, the location of which represent the position of the research vessel, not the sub-bottom sensor fish. The horizontal distance between the sub-bottom sensor fish and the research vessel was approximately 6 meters, the direction of displacement depending on the track heading. Vertical (depth) scale on the seismic profile image is marked with 2 meter interval tic marks, displaying a total depth of 25.5 meter. The depths represent the distance between the seafloor bottom (or subbottom reflective horizon) and the bottom of the sensor fish, not the water surface. Therefore, the tic marks can be as much as 4 meters shallower than tidally corrected depths. The average vertical exaggeration displayed in the seismic profile images ranges between 11x and 14x, depending on the length of the survey line.

The profiles are correlated with the side scan mosaic to provide a 3-dimensional model of the seafloor, and further define/verify the boundaries of seabed classification polygons. Seismic profiles revealed shallow subsurface structures, and where these structures meet the surface. Seismic data were useful in showing where the seafloor was firm or soft and, in some areas, used to estimate thicknesses of overlying Holocene deposits (shoals).

Magnetic Anomaly Mapping

Geometrics software, MagMap2000, was used to process the geomagnetic data. Processing included adjustment for position layback and removal of background magnetic signals (diurnal variations, solar flares, large-scale ocean currents, etc.). Horizontal positioning data of the towed sensor were adjusted 3 meters starboard and 30 meters aft of the DGPS sensor. Background field data recorded at the Fredericksburg, Virginia, National Geomagnetic Observatory were subtracted from the recorded geomagnetic data. The resulting points are the local magnetic variations, presented in nanoTeslas (nT), at the differential GPS encoded location.

The magnetic field strength data were gridded and processed using a second order, non-directional differential algorithm, the results of which highlight abrupt changes in the recorded magnetic field. The differential magnetic data are presented as ERSI raster and contour shapefiles. Contour lines correspond to the level of deviation (integers from 1 to 5) from the background magnetic field. A list of the magnetic anomalies is presented in Appendix C.

Sediment Analysis

Textural Analyses

Sediment grab samples were analyzed for water content, bulk density, and grain size (sand, silt, clay contents, as well as gravel, when present- refer to Table 2 for definition of size classes). Two homogeneous splits of each sample were processed, one for bulk property analyses and the other for grain-size characterization. Analyses were performed as soon as possible after sample collection, and all samples were refrigerated in sealed Whirl-Pak™ plastic bags prior to analysis.

Water content was calculated as the percentage of water weight to the weight of the wet sediment using Equation 1.

$$\%Water = \frac{W_w}{W_t} * 100 \quad \text{Equation 1}$$

where: W_w is the weight of water; and
 W_t is the weight of wet sediment.

Water content was determined by weighing 20-30 g of sediment, drying the sediment at 65°C, and then re-weighing the dried sediment. Dried sediments were saved for nitrogen, carbon, and sulfur (NCS) analyses.

Bulk density (ρ_B) is calculated from water content utilizing Equation 2 by assuming an average grain density (ρ_s) of 2.72 g/cm³ and saturation of voids with water of density $\rho_w = 1.0$ g/cm³. This method was adopted from the work of Bennett and Lambert (1971):

$$\rho_B = \frac{W_t}{W_d / 2.72 + W_w} \quad \text{Equation 2}$$

where W_d is the weight of dry sediment.

Gravel, sand, silt and clay contents were determined using the textural analysis detailed in Kerhin and others, (1988). Grain size analysis consists of cleaning the samples in solutions of 10 percent hydrochloric acid and 6 or 15 percent hydrogen peroxide (determined by water content) with subsequent rinsing with deionized water. This process removed soluble salts, carbonates, and organic matter that could interfere with the dis-aggregation of the individual grains. The samples were then treated with a 0.26 percent solution of the dispersant sodium hexametaphosphate ((NaPO₃)₆) to ensure that individual grains did not re-aggregate (floculate) during analysis.

The separation of gravel-sand and silt-clay portions of the sample was accomplished by wet-sieving through a 4-phi mesh sieve (0.0625 mm, U.S. Standard Sieve #230). The gravel-sand fraction was dried and weighed. This fraction was then dry sieved through a -1 phi mesh sieve (2 mm) to separate gravel from sand. Standard pipette method was used to determine silt and

clay portions on the fine fraction (Carver, 1971; Folk, 1974). From these data the percentages by dry weight of sand, silt, and clay were calculated for each sample and classified according to Shepard's (1954) or Folk's (1974) classifications, depending on the gravel content (Figures 11 and 12).

MGS conducted sieve analyses on those sediment samples having more than 75 % sand and gravel. The sand/gravel fractions of the samples were passed through a series of 3-inch sieves, at whole phi intervals. The largest sieve used corresponds to -2 phi (4 mm mesh). The resulting whole phi size fractions were converted to cumulative weight percentages and incorporated the silt and clay components of the sediment sample, extrapolating the fine-grained end to 14 phi (6×10^{-5} mm)).

Grain size is given in phi units, a scale devised by Krumbein (1938) where phi is defined as negative log (to the base 2) of the particle diameter (mm). For example, 4 phi corresponds to a particle with a diameter of $1/2^4$ mm (=1/16 mm, or 0.0625 mm or 62.5 microns).

Based on the cumulative weight distributions of the size fractions, the following Folk (1974) graphic statistical parameters were calculated for each sample. However, some samples contained more than 5% gravel (pebbles- greater than 4 mm), so the inclusive graphic statistics may not be representative for those samples.

The graphic mean (M_G) is defined by equation 3.

$$M_G = \frac{\phi_{16} + \phi_{50} + \phi_{84}}{3} \quad \text{Equation 3}$$

where ϕ_{16} (or 50, 84..) is the phi class corresponding to 16th percentile (or 50%, 84%...) on the cumulative weight curve.

This graphic mean corresponds very closely to the mean as computed by the method of moments, yet is much easier to find. Inclusive Graphic Standard Deviation (SD_{IG}), defined by equation 4, gives the best overall measure of sorting (Table 3).

$$SD_{IG} = \frac{\phi_{84} - \phi_{16}}{4} + \frac{\phi_{95} - \phi_5}{6.6} \quad \text{Equation 4}$$

Inclusive Graphic Skewness (Sk_{IG}), defined by equation 5, measures the asymmetry of the distribution as well as the direction of the skewness (*i.e.*, excessive coarse tail (-) or excessive fine tail (+)).

$$Sk_{IG} = \frac{\phi_{16} + \phi_{84} - 2 * \phi_{50}}{2 * (\phi_{84} - \phi_{16})} + \frac{\phi_5 + \phi_{95} - 2 * \phi_{50}}{2 * (\phi_{95} - \phi_5)} \quad \text{Equation 5}$$

Graphic Kurtosis (K_G) is defined by equation 6. This statistic defines the degree of peakedness or departure from the "normal" frequency or cumulative curve

$$K_G = \frac{\phi_{95} - \phi_5}{2.44 * (\phi_{75} - \phi_{25})} \quad \text{Equation 6}$$

Results of the textural analyses are presented in Tables B5 and B6 in Appendix B.

Nitrogen, Carbon and Sulfur Analyses

The sediment samples containing significant fine fraction were analyzed for total nitrogen, carbon and sulfur (NCS) using a Carlo Erba NA1500 analyzer. Untreated dried sediments were analyzed for total nitrogen, carbon and sulfur (NCS) contents. Approximately 10-15 mg of dried sediment was weighed into a tin capsule. The exact weight (to the nearest µg) of the sample was recorded. To ensure complete combustion during the analysis, 15-20 mg of vanadium pentoxide (V₂O₅) was added to the sediment. The tin capsule containing the sediment and vanadium pentoxide mixture was then crimped to seal and stored until analysis.

The sediment sample, contained in a tin capsule, was dropped into a combustion chamber where the sample was oxidized in pure oxygen. The resulting combustion gases (N, C, H, and S), along with pure helium used as a carrier gas, were passed through a reduction furnace to remove free oxygen and then through a sorption trap to remove water. Separation of the gas components was achieved by passing the gas mixture through a chromatographic column. A thermal conductivity detector was used to measure the relative concentrations of the gases.

The NA1500 Analyzer was configured for NCS analysis using the manufacturer's recommended settings. As a primary standard, Sulfanilamide was used. Blanks (tin capsules containing only vanadium pentoxide) were run at the beginning and end of sample set. Replicates of every fifth sample were run. As secondary standards, one or more standard reference materials (SRMs) were run every 8 to 10 samples. The SRMs used were National Institute of Standards and Technology (NIST) SRM #1646a - Estuarine Sediment and NIST SRM #8704 – Buffalo River Sediment. Results of the analyses of the SRMs and sediment samples are presented in Appendix B.

Data, Maps, and GIS Products

GIS data were compiled with ESRI ArcGIS Desktop 9.3.1. All GIS coordinate data are projected to UTM 18N (WGS 1984). Final map products, data layers, and images are available in various ArcGIS and graphic formats described in Appendix D.

Results

Bathymetry

The 2011 bathymetric data from this study are displayed as color coded contours, overlain on the side scan sonar mosaics (left panel) in Figures 13 through 20. The closest survey track line was 200 meters offshore, seaward of the longshore bar. The 2011 bathymetric grid was extrapolated to the shoreline, but did not account for the longshore bar (Figure 21). Based on individual soundings, depths measured ranged between 1.2 and 14.9 meters (NAVD 88 datum). Generally, the inner-most 1.5 km of the Assateague Island nearshore becomes less steep going south. The bathymetric contours define the landward end of several shore attached shoals. The shoals become attached to the shoreface between -6 to -7-meter depth (NAVD88). Shallower contours (≥ -6 m) generally are parallel to the shoreline.

Shore-attached shoals, as well as other features defined by the irregular bathymetry, occur at seven areas (identified by place names on Assateague Island- see Figure 1): 1) North end; 2) South Ocean Beach; 3) Little Levels; 4) Fox Hill Level; 5) Pope Bay; 6) Morris Island; and 7) Toms Cove. In between these five areas, the nearshore bathymetry is generally featureless, characterized by shore-parallel contours (Figures 18 and 19). The bathymetric data generally do not capture features less than 50 meters in length.

At the north end of the study area, the nearshore bathymetry is very irregular with a series of sand waves, which have maximum length of 400 meters and height of 2 meters. These waves are slightly oblique (~60 degrees) to the shoreline (Figures 13 and 14). These waves are most pronounced at approximately 5 km south of the Inlet. This area corresponds to the nearshore placement site for the biannual sand bypassing project (Schupp et al, 2007).

In areas 2, 3, 4, 5 and 6, the bathymetry defines the shoreward end of several oblique shore-attached shoals and intershoal swales, or troughs (Figures 15, 16 and 18). The shoals range from 250 m to over 400 meters in width. The shoals intersect the shore face at an angle between 30° and 45°. South of the inflection, the orientation of Assateague Island shifts to more westerly direction, and the shore-attached shoals intersect the shoreface at slightly more oblique angle. Maximum relief (difference between depth in inter-trough and shoal crest) is approximately 3 meters. Shoal flanks are gently sloping (between 1 and 2 % slopes).

The bathymetry at the south end along Toms Cove defines a series of incipient spit shoals that are still attached to the shore face. This portion of the nearshore is very dynamic as evident from recent shore line changes (Figure 5).

Comparison with the most recently available NOAA bathymetry (1977/78) indicate that the shore-attached shoals along the middle section (areas 2, 3, and 4) of the Assateague Island are fairly stable and have not migrated in the last 33 years. Conversely, the shoals and inter-shoal troughs south of the island inflection point appeared to have moved as much as 800 meters to the south.

Side Scan Sonar Imagery

The side scan sonar mosaics show a varied pattern of acoustic characteristics of the seabed within the study area. A variety of factors, including sediment texture, small scale topographic features, presence of living organisms, and the angle (slope) of the seafloor to the side scan unit, control the acoustic backscatter recorded by the side scan record. Figures 13 through 20 present the side scan sonar mosaics overlaid with one-meter bathymetric contours to illustrate the relationship between bottom topography and prominent mosaic features.

The darker areas in the mosaics, corresponding to low backscatter, are interpreted to be finer grained sediments. Underwater videos and bottom sediment samples collected within these dark areas confirmed this interpretation (Figure 22). Many of these dark areas correspond to the deeper trough areas between the shore-attached shoal (or sand ridges), or confined to areas deeper than the -9 m contour. The light areas, seen along the base of the shoal flanks, and along the shoreward edge of the study area, mark the higher reflective bottom, usually composed of coarser grained material such as coarse sand, gravel and shell. Broad, intermediate-shaded areas are seen, along the large expanses of relatively featureless nearshore, defined by the shore parallel contours (Figure 16, 18, and 19). Sediments collected in these areas ranged from fine to very fine sand to mixed mud, sand (Figure 22).

In the Assateague Island nearshore area, a variety of bed forms occurs, from sub-meter ripples to kilometer long sand shoals (Table 4). These bed forms provide some information on hydrodynamic processes operating within the study areas. These bed forms also play an important role in assessing potentially important habitats of benthic organisms and demersal finfish populations.

Ripples are the most common bed form observed, occurring in many areas within the study area. These small-scale bed forms account for the higher backscatter return observed in side scan imagery taken along the shoreward most areas. Ripples are considered an active bed forms as their orientation generally reflected the current wave direction at the time the surveys were collected

Bed forms, particularly those of less than a few meters in extent or wavelength, are most easily identified in side scan sonar waterfall imagery, which has better resolution than the georeferenced mosaic. Often there is a very sharp boundary between the bottom bed forms. Controlling factors in bed form development include bottom topography, sediment type, tidal and wave energy and benthic faunal activity.

Figure 23 features an example of several bed forms. Details seen in the side scan sonar waterfall imagery reveal in the lighter areas, straight to sinuous, symmetrical to asymmetrical ripples, ranging from less than 50 cm to a meter in length. The field of view in the underwater image (C) is too narrow to capture the entire width of the sand ripple; the image is focused on the crest of the sand ripple, and shows fine to medium sand with occasional shell and coarse sand. Ripples usually do not form in sediments with a grain size coarser than 0.6mm (0.75 phi or coarse sand) (Hayes and Kana, 1977). Ripples fields are most visible when the ripple face is perpendicular to

the side scan sonar signal, resulting in maximum backscatter or reflection. Examples of these ripple fields are seen along the shoreward edge of the side scan sonar mosaic. The fields most likely are formed in response to shore perpendicular rip currents (Figure 21). The light green areas of the mosaic (A), which show up as darker areas in the waterfall image, correspond to very fine to fine sand. The video image reveals low amplitude, sinuous sand ripples, too small to be visible in the side scan waterfall image.

Seabed Sediment Classes

Ten seabed sediment classes were mapped in the study area. Seabed sediment class maps are shown in the right panel in Figures 13 through 20. The physical and select chemical parameters of each seabed class are listed in Table 5.

The seabed classes were initially identified based on acoustic properties of the seafloor. The classes were further refined by correlating the acoustic classes with sediment grab samples and under water imagery, resulting in a map of bottom seabed classes, largely defined by dominant sediment types (*i.e.*, sediment grain size). Thus, the terms ‘seabed classes’ and ‘sediment types’ are used interchangeably in this discussion. The sediments often range from mud and muddy sand to coarse sand and gravel over an area of a few meters. The seabed class polygons delineate areas that are dominated by a single sediment type, but will have small areas or patches of other types. Although the seabed classes are distinct with regard to acoustic properties, the textural characteristics of the classes often overlap. Bottom areas having similar sediment types can appear different acoustically. The difference in acoustic properties is attributed to presence of bedforms and/or biogenic components.

The most common class is ‘very fine to fine sand’, found primarily on the shoal crests and seaward flanks, in the broad flat areas between shore-attached shoals (Figures 14, 16, 17 and 18) and the inner nearshore (*i.e.* at depths less than 6 meters). This class covers approximately 66% of the study area (Figure 25). This bottom class consists of moderately to well sorted, very fine to fine sand (mean size= 0.1 mm), with varying amounts mud and shell, and little or no gravel (Figure 24). The small grain size can allow firm packing with minimum water content (~20%), resulting in a very firm bottom. This bottom class may be flat, or exhibits low profile, symmetrical or asymmetric ripples with a wavelength of a meter or less, lending to the faintly mottled appearance in the side scan sonar images. These sediments are fine enough to be readily mobilized by water column energy. They tend to migrate in the direction of prevailing currents and wave propagation, and can overrun underlying muddy beds or coarser sediments.

The second most common class is ‘mixed mud and fine to coarse sand’, cover 19% of the study area. This class contains moderately to very poorly sorted, fine to coarse sand (Figure 26). Mud contents range from trace to >40%. Gravel may be present. Bedforms within this class range from complex ripple patterns on a scale of a few meters or less, to ‘lumpy-like’ appearance. On the side scan sonar imaging, this class appears as medium to light areas with varying degrees of mottling. This class is the dominant class along a 6 km section at the north end of the study area; this area corresponds to the placement sites for the sand bypassing effort (Schupp, 2007). This

class also occurs as linear fields along the steeper flanks of the shore-attached shoal (Figures 14,15, 16 and 19), and as smaller patches in the southern end of the study area (Figure 20).

‘Mud’ class represents the third most common seabed sediment class, covering 6% of the study area. The ‘mud’ class consists mostly of dark colored, organic, silt and clay, with varying amounts of sand (Figure 27). Many of the samples collected within this class contained tube worms and worm tubes (polychaetes). This class occurs between the shore-attached shoal, or confined to areas deeper than the -9 m contour. Based on seismic profiles, the mud fields correspond to areas where older subsurface units, interpreted to be either Holocene back barrier fine-grained sediments or Pleistocene shelf mud, are exposed (see following **Seismic Sub-bottom Profiles** section). Muddy sediments tend to be cohesive below the seafloor surface and probably do not migrate much. Near-surface mud is often loosened and mobilized by infaunal and epifaunal processes, and subsequently resuspended by water column energy. The suspended sediments were noted in the underwater videos, particularly in areas near or over mud fields where extremely high turbidity conditions resulted in poor imaging of the seafloor. This resuspended fine sediment is deposited in the adjacent areas during periods of low energy (minimum or no wave activity). Eventually the fine sediment is transported out of the nearshore and deposited in deeper, lower-energy habitats further offshore.

Typically the ‘mud’ class does not display obvious bed forms, but most often presents a dark, mottled appearance in side scan mosaics. Some of the mottling may be attributed to the presence of benthic communities. Video imaging of one mud field revealed a vibrant tube worm colony (Figure 29). The patchy mud fields mapped in the north end of Assateague may represent exposed outcrops of back barrier fringing marsh. Sediment samples collected with these areas contained peat clumps.

The ‘medium to coarse sand’ class covers 5% of the study area. The class is predominately sand, but may include up to 5% gravel and trace amounts of mud. This class resembles the ‘medium to coarse sand, gravel’ but shows up as a distinct acoustic class in the side scan sonar mosaic (light areas). This class is associated with small mud patches along seaward edge of the study area off the State Park (Figure 14) and south of the inflection point (Figures 17-20). This class is not mapped as linear fields associated with the three shore-attached shoals north of the inflection point.

The ‘medium to coarse sand, gravel’ class describes a seafloor that is predominantly coarse to very coarse sediment, including coarse sand, gravel, pebbles and rock (Figure 28). Varying amounts of shells and shell hash were also observed. This class, which covers 3.4 % of the study area, occurs as linear fields along the updrift flank of the three northern shore-attached shoals, and is adjacent to the mud fields. The seafloor covered by this class is extremely reflective and shows up as very light areas (Figure 22- DBox 17). Curiously, this class was not mapped south of the inflection point. The ‘medium to coarse sand, gravel’ class is interpreted to represent lag deposits left behind when water column energy moves finer sediments out of the area. Muddy sediments may be present in small amounts, usually less than 5%, particularly where the coarse sediments form a relatively thin layer over underlying mud (refer to sample ASIS85- Table B4 in Appendix B). Bed forms in this class tend to be in the several-meter range, including mega-

ripples and sand waves. Often, bedforms are not well-developed, lending to this class appearing as a relatively featureless seafloor in the side scan image.

The ‘fine sand with ripple biscuits’ class is the only class defined by a bedform in addition to sediment type. The sediment type is fine sand, but may contain coarser sand and gravel (Figure 23). The class occurs primarily along the shoreward edge of the study area and is probably related to strong rip currents flowing across the nearshore bar, forming the well defined sand ripples (Figure 21). The term ‘biscuit’ describes the general shape of the ripple fields as they appear in the side scan sonar waterfall image. In the processed mosaic image, the fields are more linear, trending perpendicular to the shoreline and the direction of the rip currents. The ripple fields are transient, constantly changing and moving.

The remaining four classes (‘mixed fine to coarse sand’, ‘medium sand’, ‘fine to medium sand’, and ‘fine sand and mud’) combined cover less than 4% of the study area.

Seismic Sub-bottom Profiles

Seismic, or acoustic, sub-bottom profile data provide a third dimension to the seafloor data set, as well as additional information about the character of the seafloor sediments. Maximum depth of penetration of the seismic signal was less than 20 meters below MSL. Because of the shallow working depths which ranged between -4 and -16 meters, seafloor multiples often obscured details in the record, making it very difficult to trace the various reflectors across the study area.

Like the side scan sonar expression of the seafloor, the seismic signature of the bottom is controlled, in part, by the acoustic properties of the sediments. For example, the appearance, or attenuation, of the seafloor reflector can indicate whether the bottom is soft or hard. The presence of gas also indicates high organic fine-grained sediments. An example of this is seen in sub-bottom profile line 27x, collected at the north end of the study area (Figure 30). Both the mosaic and sea bed class maps are rotated so that north is to the right of the images. The blue line on the maps shows the track line (boat path) of the sub-bottom record which is lined up along the track line. The mud field, seen as dark area on side scan sonar mosaic (A) and blue polygon in lower panel (B) corresponds to the dark smudge on the seismic profile. This is typical of organic-rich, muddy sediments which often generate gas from bacterial decomposition of organic matter. The gas disrupts the acoustic energy, recorded as the characteristic dark, smudgy profile (Hill et al., 1992; Schubel, 1974). As a result, details of any underlying features are masked by the gas.

This figure also illustrates the effects of sediment thickness and grain size on seismic signal penetration. Line 27x tracks across the thick sand wedge of the inner nearshore and the shoal mantle consisting of fine to medium to coarse sand and gravel. The combination of coarse grain size and sediment thickness scatters the seismic acoustic signal, preventing much signal penetration into the sub-bottom. Although relict channels may exist under line 27x, they are not visible in the seismic profile record.

Figure 30 also is useful in illustrating the distribution pattern of the sediment types relative to the shore-attached shoals and bathymetry. Mud is found in the inner-shoal trough, below the 9-m isobath. 'Mixed mud, fine to coarse sand' is mapped in shallower areas of the inner-shoal area, and adjacent to the mud fields. The bottom sediment type progresses from 'medium sand' to 'very fine to fine sand' along the up-drift flank of the shoal and crest. This distribution pattern of bottom sediment type is repeated on the three shore-attached shoals north of the inflection point.

Shallow Nearshore Stratigraphy

Seismic sub-bottom profile data reveal several prominent reflectors and faint structure of the shallow stratigraphic units in the upper 10 to 15 meters beneath the seafloor along the nearshore of Assateague Island. The reflectors and interpreted stratigraphy are listed in Table 6 and correlated to seismic units described by Toscano et al. (1989), Wells (1994) and Wikel (2008). Figures 32, 35 and 37 present examples of selected seismic sub-bottom profiles with preliminary interpretation of prominent features. Locations of the selected seismic profiles are shown in Figures 31 and 36, along with the locations of on-shore borings/wells, logs of which were used by Halsey (1979) to determine depth to the Holocene/Pleistocene horizon; and locations of cores collected on and near the Ocean City ebb shoal (Wells, 1994).

The deepest reflector visible in the seismic profile data appears between -14 m in the northern end of the study area (Figures 32 and 35- Line 30) and -18 m at the Maryland/Virginia line (Figure 35 -Line 11x). The reflector was not visible in the seismic records collected in the southern end of study area. This reflector, identify as H4 in this study, is thought to be the continuation of the M2 reflector reported by Toscano et al. (1989) at depths less than -20 m approximately 3 km off Assateague Island. The M2 reflector represents oxygen-isotope stage 6 (190,000 to 130,000 years before present (B.P.)) erosional surface and has been correlated to the Eastville downcut of the Susquehanna River (Toscano et al., 1989; Toscano and York, 1992). Wells (1994) identified the M2 horizon between -16 and -20 m NGVD in the nearshore off Ocean City. This reflector and any internal stratigraphic features in the underlying units could not be distinguished in the seismic data from this study.

The H4 reflector marks the bottom of the C2 stratigraphic unit which is interpreted to be equivalent to the Q2 unit described by Toscano et al. (1989). The Q2 unit consists of an open shelf mud sequence deposited between 75,000 to 125,000 years B.P., and is interpreted to be a lateral facies of the Sinepuxent Formation (Toscano and York, 1992). Further north, this unit lies directly under the ebb shoal. Peat, recovered at -7.86 m NGVD from Core 1-3 collected south of Ocean City Inlet (see Figure 31 A), yielded a ^{14}C date of 31,190 $\pm$ 1330 yr B.P. (Wells, 1994). This date is at the limit of the ^{14}C dating technique, thus essentially 'carbon-dead;' the peat is considered to be much older, and the sequence in the core is interpreted as being Pleistocene in age.

The H3 reflector is a persistent, often high amplitude (thick), linear reflector, visible in some of the seismic profiles. This reflector marks the Holocene/Pleistocene unconformity and is equivalent to the R3 described by Wikel (2008). The H3 is distinct from the M3 reflector which

was described by Toscano et al (1989) as defining the geometry of early Holocene fluvial channels that were incised in the Pleistocene (Q2/Q1) stratigraphic units and filled with early Holocene fluvial sediments (Q3). The nearshore areas where the H3 reflector is absent may correspond to the shoreward extension of these fluvial channels.

The H3 reflector is identified at -9 to -10 m in the seismic profile records in the north end of the study area (Figure 32 - Line36x). The reflector is tentatively identified at -9 m in the nearshore south of North Ocean Beach (Figures 31B and 35-Line 30x). The Holocene/Pleistocene unconformity was mapped at depths shallower than -8 meters MSL on Assateague Island in the North Ocean Beach vicinity (Halsey, 1978). The reflector intersects the ocean bottom further offshore where the mud field is mapped. This particular mud field may be exposed Pleistocene sediments (C2 unit). The H3 reflector is identified at -16 meters offshore Green Run (Figures 36 and 37). In the offshore of Tom Cove, the H3 reflector is identified at -14 m in the subbottom data. (Figure 35 –Line 11x).

Above the H3 unconformity are Holocene transgressive back barrier deposits, identified in this study as B2, B3 and B4 facies. This sequence consists of interbedded layers of sands, muds and peats reflecting the successional deposition of different facies as the barrier island migrated westward. In the seismic profile, faint internal structure, including channel features, may be visible, but more often, gas obscures any details within and below the sequence. The presence of gas usually indicates that the sediments are high organic, fine grain mud, thought to be back barrier lagoonal facies (B2) or fringing marsh facies (B4). Numerous channel features (B3 facies) interrupt the B2 and B4 facies (Figure 37 –Line 3). These channels features are visible in areas not masked by gas. The locations of the buried channels that could be identified in the seismic data are shown in Figure 38.

One or more facies of the Holocene back barrier island sequence are exposed on the sea floor, generally at depth greater than -9 m and in the inner shoal troughs. These exposures correspond to most of the ‘mud’ and ‘mixed mud, fine to coarse sand’ bottom sediment class fields (polygons) mapped in the study area.

The H1 reflector is the upper-most reflector visible in most of the seismic sub-bottom profiles. This reflector represents the active shore-face erosional surface, or transgressive wave ravinement. The reflector intersects the seabed surface in the inner shoal troughs, and often is very faint or indistinct under the crest of the shoals. The reflector is absent in the inner-most shore face.

The H1 reflector marks the base of the top-most seismic stratigraphic unit, A1, defined as modern (Holocene) marine nearshore sediments consisting of very fine to coarse sand and small gravel. These sediments, which are continuously being rework by nearshore processes including wave-base erosion and longshore transport. This unit includes shore-attached shoals and sheet sand deposits found along the nearshore. This unit is discontinuous, absent in the intershoal troughs. The A1 unit includes the long-shore bar which marks the shoreward edge of the data coverage in this study. The long-shore bar was not delineated in the bathymetric model, but its presence was inferred by the numerous ‘fine sand, ripple biscuits’ class mapped along the shoreward edge of the study area. The A1 unit is generally wedged-shaped, the thicker portion adjacent to the inner shore area, and becomes thinner in the offshore direction. The unit is

thicker in the north end, where the south flank of the Ocean City ebb shoal represents the bulk of the A1 unit. The unit is over 7 meters thick here. Further south, the A1 unit appears in the sub-bottom record as a thin veneer, less than 0.5 meters thick in most areas seaward of the -4 or -6 meter contour.

A second unit, A1_A, defined as the poorly sorted, ‘mixed mud and fine to coarse sand’ field mapped along the northern end of the study area (Figure 13). These sediments are interpreted to be sand deposited shoreward of the longshore bar during the by-passing operation. The by-passed sand has been transported seaward of the longshore bar and reworked, mixing with the underlying back-barrier mud and peat unit (B2, B3, and B4 units). As a result, these sediments show up as a very distinct seabed class (Figures 13 and 14).

A second ravinement surface is visible in some seismic sub-bottom profile records at the southern end of the study area. Wikel (2008) describes a local ravinement (R2), at the base of the spit platform beneath Toms Cove, and postulated that the ravinement represents an erosional surface formed prior to or during to the initial extension of Tom Cove’s spit. Wikel interpreted the seismic unit between his R1 and R2 reflectors as representing regressive (prograding) shoreface sands deposits. The horizon identified as H2 in seismic line 11x is interpreted to be a local ravinement, equivalent to Wikel’s R2 (Figure 35).

Magnetic Anomalies

Twenty-one magnetic field anomalies were identified and mapped for this study. These anomalies, or abrupt changes in the magnetic field, are typical signatures of man-made objects containing ferric material (*e.g.*, pipe, chain, ship wrecks, etc.). Magnetic anomalies also may be associated with naturally occurring concentrations of heavy minerals (USC-OTA, 1987; Shah et al., 2012).

The locations of several anomalies are consistent with ‘obstruction’ or ‘wreck’ notations on the NOAA Navigation Chart 12211-1 (Fenwick Island to Chincoteague Inlet; February, 2011). One anomaly, in particular, corresponds to a documented ship wreck, the USS Despatch (Carl Zimmerman, pers. comm.). The wreck is clearly visible in the side scan sonar waterfall display and mosaic. For most of the anomalies, no defining features could be identified in the side scan sonar or sub-bottom seismic profile records. Refer to Appendix C for further discussion and locations of the anomalies.

DISCUSSION

Of the ten bottom sediment classes mapped in the nearshore along Assateague Island, ‘fine sand to very fine sand’ represents the dominant class, covering 66% of the study area. This class is found primarily in the broad featureless nearshore areas and the inner nearshore (*i.e.* at depths less than 6 meters), and on the crest and down-drift flank of the shoals. The remaining 9 classes are primarily associated with the shore-attached shoals, and the long-shore bar. The distribution patterns of the sediment types relative to the shore-attached shoals are a result of the interaction of the near-shore hydrodynamic regime with the underlying geology.

Mud class is mapped along the inner-shoal troughs, generally seaward of the 9-m isobath. Bottom currents are sufficiently strong to scour the bottom, exposing the underlying fine grained substrate, and keeping larger sediment particles from settling.

‘Mixed mud, fine to coarse sand’ is mapped in shallower areas of the inner-shoal area, and adjacent to the mud fields. The bottom sediment type progresses from ‘medium sand’ to ‘very fine to fine sand’ along the up-drift flank of the shoal and crest. This sorted distribution pattern of bottom sediment types is repeated on the three shore-attached shoals north of the inflection point (*i.e.*, shore-attached shoals near South Beach; Little Levels, and Fox Hills). South of the inflection point, shore attached bars become acutely oblique, almost parallel to the shoreline. The nearshore hydrodynamics are shifted due to the change in orientation of the barrier island.

‘Medium to coarse sand, gravel’ class was the mapped primarily along the up drift flank of the northern three shoals; this class was not identified south of the inflection point. The three northern shoals are located in the vicinity of the historical Sinepuxent Inlet, one of the most significant inlets, both in duration and size (Figure 3). Historical accounts indicate that Sinepuxent Inlet existed for nearly a half of a century, from 1794 to 1832, although it is not clear whether the inlet was opened continuously or that the frequent reports represent repeated storm-cut openings at that location (Truitt, 1968). It is very likely that even earlier inlets may have existed at this site. This site corresponds to a Pleistocene fluvial channel defined by the Pleistocene/Tertiary erosional surface (Figure). The gravel may be reworked relict channel fill (Browder and McNinch, 2006). Other studies along the mid-Atlantic have correlated oblique shore-attached shoals and coincident gravel outcrops with erosional hot spots onshore (McNinch, 2004; Schupp, *et al*, 2006; Wikel, 2008) and with paleo-channels (Browder and McNinch, 2006).

‘Mixed mud, fine to coarse sand’ is the dominant class along a 6 km section at the north end of the study area, corresponding to the placement sites for the sand bypassing effort (Schupp, 2007). This mixed mud and sand field is identified as anthropogenically disturbed unit (A1_A unit, Table 6). Over 800 thousand m³ of sand have been placed along the upper shoreface (*i.e.*, shoreward of the longshore bar) along the north end of Assateague Island since 2004. The side scan sonar data from this study and from 2008 NOAA data indicate that a portion of the bypassed sand has moved as much as 1.5 km offshore (Figure 39). The sand has been reworked, mixing with the exposed Holocene back barrier mud and peat deposits. Mud out-crops are interpreted to be primarily Holocene barrier island deposits. Interestingly, the southern boundary of this ‘mixed mud, fine to coarse sand’ class appears to have not moved between 2008 and

2011. The location of this boundary corresponds to the point at which 5-year trend (2005-2010) in shoreline change shifts from erosion (north of this point) to accretion (Psuty *et al.*, 2011).

Coastal and Marine Ecological Classification (CMEC) of Bottom Sediments

Table 7 lists the seabed sediment classes in terms of the Coastal and Marine Ecological Classification (CMEC) System. The study area is located within the Virginian Ecoregion. The study area is restricted to the nearshore, subtidal zone, within water depths ranging from 2 to 17 meters.

Conclusions

This study represents the first systematic effort to map the stratigraphy and benthic habitat in the subtidal nearshore along Assateague Island. The bathymetric, side scansidecan and seabed data provide a ‘snap shot’ characterization of the nearshore bottom conditions within the study area.

The nearshore seafloor along Assateague Island consists of a variety of bottom types based on a range of small scale (*i.e.*, 0.2 to 2 meter range) bed forms and sediment texture. The distribution patterns of the sediment class types relative to the shore-attached shoals are a result of the interaction of the near-shore hydrodynamic regime with the underlying geology. Bottom sediment composition is influenced by bottom geomorphology, water depth, substrate composition and biologic activity. The interaction of these factors with water column energy, such as waves and currents, determine in part the seafloor surface composition.

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