Hardbottom Characterization and Relationship to the Geologic Framework in Long Bay, South Carolina

Cathryn J. Wheaton
Coastal Carolina University

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Hardbottom Characterization and Relationship to the Geologic Framework in Long Bay, South Carolina

By

Cathryn J. Wheaton

Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science in Coastal Marine and Wetland Studies in the College of Science Coastal Carolina University 2018

Dr. Jenna C. Hill
Major Professor

Dr. Richard N. Peterson
Committee Member

Dr. Till J.J. Hanebuth
Major Professor

Dr. Michael H. Roberts
Dean, College of Science

Dr. Richard F. Viso
Committee Member

Dr. James O. Luken
Director of Graduate Studies
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ABSTRACT

Hardbottom seafloor is a common element among sediment-starved portions of the inner continental shelf along the U.S. Atlantic margin. These areas are characterized by indurated sediment surfaces that are heavily altered by biological and physical processes. Long Bay, in northeastern South Carolina, offers ideal environmental conditions for hardbottom exposure with only patchy Holocene sand deposits, interspersed with extensive hardbottom areas. Here we use high-resolution multibeam bathymetry, CHIRP subbottom profiling and electrical resistivity data, along with surficial sediment samples, hardbottom thin sections, and water column radioisotope (radon-222) analysis to investigate the origin and geologic framework of a region of hardbottom seafloor in central Long Bay. Based on petrographic analyses, Long Bay seafloor hardbottom is characterized as phosphatic glauconite sandstone, while loose beach hardbottom samples are characterized as quartz sandstone or fossiliferous limestone. The presence of glauconite and older foraminiferal species comprising the seafloor hardbottom samples suggest that the hardbottom within the study area likely formed during the Cretaceous and Tertiary. Correlation of bathymetry and CHIRP data suggests that the hardbottom is outcropping, truncated and tilted sedimentary rock strata that outcrop at the seafloor as a result of the location of the Mid-Carolina Platform High. As such, it appears that the underlying geologic framework does provide spatial control on the distribution of hardbottom, where hardbottom is often associated with ancient outcropping sedimentary strata. Mineralogical differences between seafloor hardbottom and loose beach hardbottom samples suggest that there may be other types of hardbottom within Long Bay that were not sampled. Lastly, electrical resistivity and radon-222 data show that there are indicators of groundwater discharge associated with regions of hardbottom, though no potential pathway could be identified at this time.
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1. INTRODUCTION

Marine hardbottoms are common among sediment-starved portions of the inner continental shelf and are found in carbonate and siliciclastic marine settings worldwide (Obrochta et al., 2003). While it is known that hardbottoms commonly form in warm, shallow-marine tropical seas, the processes leading to their formation remain poorly understood (Obrochta et al., 2003; Christ et al., 2015). Moreover, little effort has been set forth to examine the petrology of ancient and modern hardbottoms (Christ et al., 2015). Obrochta et al. (2003) postulate two models for formation: (1) scarped hardbottoms are erosional features of underlying bedrock, and (2) hardbottoms are younger, more recent features formed by processes unrelated to those of the bedrock. These models, respectively, would indicate that: (1) hardbottoms are much older, indurated seafloor, or (2) hardbottoms are forming in-situ, through processes that have not yet been identified.

Long Bay, in northeastern South Carolina, offers ideal environmental conditions for hardbottom exposure with only patchy Holocene sand deposits (Gayes et al., 2003; Denny et al., 2013). This region receives little fluvial sediment as no major rivers provide significant sediment discharge into the coastal zone north of Winyah Bay, which is located at the southern end of Long Bay (Fig. 1) (Barnhardt et al., 2009). Consequently, rocky outcrops, or hardbottoms, are found extensively throughout this region. The SEAMAP-SA (2001) study estimates that between 42 – 61 % of the South Carolina inner shelf is made up of hardbottom (Fig. 2). Though many studies have recognized hardbottoms as an important component to the modern coastal system (Riggs et al., 1996, 1998; Schroeder et al., 1998; Obrochta et al., 1998, 2003; SEAMAP-SA, 2001; Locker et
few studies have focused on the formation of hardbottom. To date, no research has documented the formation or composition of hardbottom in Long Bay.

The objective of this work is to characterize a portion of hardbottom seafloor in Long Bay to determine the petrographic composition and geologic context of this deposit. By characterizing the hardbottom, we aim to determine whether these hardbottoms are exposed bedrock or more recently indurated sediment deposits. Furthermore, this study aims to examine the potential impact of submarine groundwater flowpaths in providing the chemical precondition to facilitate hardbottom formation. Additionally, the underlying geology may provide important spatial control on the formation and distribution of hardbottom, such that these features may be more common in areas where buried fluvial or tidal paleo-channels incised the surrounding bedrock. These incisions potentially breach aquifers and emplace sections of variable porosity strata that may serve as a conduit for focusing submarine groundwater discharge to the seafloor.

The objective of this work will be met through investigation using high-resolution multibeam bathymetry, CHIRP subbottom profiling and electrical resistivity data, along with surficial sediment samples, hardbottom thin sections, and water column radioisotope (radon-222) analysis.

The research questions that will be addressed in this study include:

1. What is the composition of hardbottom in nearshore, central Long Bay?
2. Are hardbottoms in Long Bay exposed bedrock or recently indurated deposits?
3. Are there indicators of groundwater discharge near regions of hardbottom?

2. BACKGROUND

2.1. HARDBOTTOM NOMENCLATURE & CLASSIFICATION

Hardbottom terminology varies with scientific disciplines. Words often used to describe hardbottom, or associated with hardbottom, include hardground, reef, and livebottom. Additionally, submerged beachrock, which was not considered by Riggs et al. (1996), may also be a type of hardbottom in coastal zones (Scoffin and Stoddart, 1987). Hardbottom is a descriptive term for an indurated rock surface that does not exhibit any evidence of synsedimentary processes (a deformation accompanying deposition) or reef-building organisms. This term is used to describe all types of hardground, reef, and rock outcrops on the seafloor. Hardbottoms are characterized by indurated sediment surfaces that may be heavily altered by biological and physical erosive processes.

a. Hardground substrate is a rocky surface showing evidence of synsedimentary lithification (borings, encrustations, marine cementation) at the sediment-water interface. In order for hardground surfaces to be considered synsedimentary, they must show petrographic evidence of primary submarine cement. This evidence of synsedimentary lithification is what separates hardgrounds from hardbottoms.
b. *Reefs* are constructed by living, *in-situ*, skeleton-producing organisms that grow upwards toward the sea-surface. They are often characterized by positive relief and are somewhat resistant to hydrodynamic stress.

c. *Livebottom* is used to describe any hardbottom surface with persistent and reliant biological communities. This differs from reefs in that it hosts communities, rather than being fully composed of a skeleton fabric produced by organism communities.

d. *Beachrock* is a consolidated deposit from which unconsolidated sediment was lithified by calcium carbonate in the intertidal and spray zones. Beachrock is primarily found in tropical and subtropical environments (Scoffin and Stoddart, 1987).

A fundamental hardbottom classification scheme was developed by Henry and Giles (1980), Mearns (1986), and Mearns et al. (1988) based solely on the degree of scarp surface relief. Scarps are formed through erosional processes in which the less consolidated substrate underneath the indurated hardbottom seafloor is eroded. Alternatively, scarps can be formed by dipping subsurface units that outcrop out on the seafloor (Riggs et al., 1996). The Henry and Giles (1980) fundamental classification scheme, however, did not incorporate all of the components of hardbottoms, and was later modified by Riggs et al. (1996). Riggs’ (1996) newly developed morphology-based classification scheme now incorporates scarps and associated hardbottoms, the
morphology produced by erosional processes, and depositional morphology (i.e., rock rubble) (Table 1). This study uses this modified classification to catalog hardbottom morphology in Long Bay, SC.

2.2. HARDBOTTOM SIGNIFICANCE & MOTIVATION OF RESEARCH

Understanding type and formation of hardbottom is important for a broad range of disciplines. Riggs et al. (1996, 1998) and Obrochta et al. (2003) point out the importance of hardbottom as *sequence boundaries* and *condensed sections* in the long-term sedimentary record, constituting critical components of the stratigraphic record (Riggs et al., 1996). The persistence of hardbottom through large-scale sea level fluctuations means these features have often evolved through multiple stages of authigenic and diagenetic processes in both subaerial and submarine environments. These processes result in a complex paragenetic succession of cementation and induration, physical and biological erosion, sediment burial, and erosion with subsequent re-exposure (Riggs et al., 1996).

Other studies discuss the significance of hardbottoms as a source of sediment to sediment-starved continental margins (Riggs et al., 1996, 1998; Obrochta et al., 1998, 2003). Gayes et al. (2003), Ojeda et al. (2004), and Barnhardt et al. (2009) discuss the possibility of hardbottoms as a significant source of sediment to the Grand Strand, SC. Hardbottoms often form the framework for livebottom communities, which support biogenic erosional fauna. This fauna can physically and chemically degrade and erode seafloor lithologies (Riggs et al., 1998). Riggs et al. (1998) highlight the importance of
hardbottom lithology with respect to bio-eroding organisms, such that lithology dictates the species-specific attachment mechanisms and endolithic boring processes. Consequently, hardbottom lithology also dictates the type of fresh sediment delivered to the modern seafloor, i.e. rock and shell fragments, fossil shells, as well as sand and mud sized sediment.

Hardbottoms are also significant from an ecological standpoint in that they are morphologically complex and provide essential benthic habitat that can host a diverse community of marine life and fuel the regional food chain (SEAMAP-SA, 2001; NC-DEQ, 2015). Hardbottoms provide the foundation for attachment of sessile communities such as sponges and corals, creating a diverse benthic habitat. These habitats are a key source for associated reef fish, particularly in regions where they represent a large portion of the seafloor, such as along Long Bay. Additionally, scarped hardbottoms provide much of the only natural relief on the seafloor (up to 10 m in some regions), providing an additional high-relief habitat for marine life in otherwise sparsely populated regions (Riggs et al., 1998; Obrochta et al., 2003).

Though it is documented that hardbottoms are extensive along high-energy continental margins (Riggs et al., 1996, 1998) and provide a multitude of essential ecosystem services, little research has documented the formation of hardbottoms in Long Bay. This study aims to provide information towards better understanding the past and present environmental controls that influence their formation, which in turn can help predict how this framework will respond to processes such as coastal change, infrastructure development, and beach nourishment along the Grand Strand, South Carolina.
2.3. POTENTIAL MECHANISMS OF RECENT HARBOTTOM FORMATION

Some evidence suggests that groundwater plays an important role in diagenetic processes that lead to the formation of coastal and marine geologic features (i.e. beachrock and karst features) (Field, 1919; Hanor, 1978; Simms, 1984; Evans and Lizarralde, 2003). It has also been proposed that groundwater discharge may be an important process leading to the formation of hardbottom (Spence, 1993). These studies aid in our understanding of the potential implications that groundwater may have on hardbottom formation and distribution in Long Bay.

It was first hypothesized that degassing of carbonate-saturated groundwater could play a role in the diagenesis of beach sediment and formation of beachrock at the Dry Tortugas, Florida (Field, 1919). Hanor (1978) addresses this hypothesis by showing that degassing of groundwater at the water table and intertidal zone may be responsible for a significant portion of beachrock cements. After a series of experiments, the author discovered that calcite precipitates could form within one day when groundwater was exposed to the air-water interface and that the degree of precipitation decreased with increasing amounts of seawater. Hanor (1978) demonstrates that the degassing of CO$_2$-rich groundwater at the air-sea interface is sufficient to precipitate cements to form beachrock in tropical and subtropical environments. It is possible that hardbottoms in Long Bay, South Carolina may have formed during sea-level lowstands, via processes similar to those described by Field (1919) and Hanor (1978).

Subsurface dolomite, which has been studied extensively in the Bahamas (Field and Hess, 1933; Supko, 1977; Gidman, 1978; Kaldi and Gidman, 1982; Simms, 1984),
has been linked primarily to mixing zone diagenesis, and is considered a product of water-rock interaction (Simms, 1984). This mixing zone is characterized as the zone in which groundwater and seawater mix in the subsurface sediment. Seawater contains an available source of magnesium, which is needed for dolomitization. As seawater infiltrates and circulates through the seafloor, magnesium emigrates into the substrate, allowing for dolomite to diagenetically form from calcite and aragonite minerals. Furthermore, the geographic location of dolomite formation is a function of water chemistry, enrichment in magnesium, and platform characteristics (i.e. permeability). Simms’ (1984) study highlights the role of recirculated seawater (groundwater) in providing magnesium needed for dolomitization, and potentially hardbottom formation.

This study hypothesizes that the underlying geologic framework may control the spatial distribution of hardbottoms in Long Bay. Hardbottoms may be more common in areas of high permeability, such as sedimentary infills of fluvial or tidal paleochannels, which can provide a hydraulic connection between freshwater aquifers and the sea (Mulligan et al., 2007). During periods of lower sea-level, fluvial channels extended much farther off the modern shoreline. These channels potentially breached confining units of silts and clays in deeper aquifer systems, essentially acting as a conduit for groundwater-seawater exchange through the subsurface (Fig. 3). As sea-level rose, channels became infilled with unconsolidated sediments, allowing for a more permeable hydraulic connection between the seafloor and the underlying aquifer (Mulligan et al., 2007). Numerical modeling by Mulligan et al. (2007) shows that paleochannels can in fact act as a favorable pathway for offshore fluid exchange across the sediment-water interface. Russoniello et al. (2013) show similar findings with observational data, in that
paleochannels can act as a pathway for lower-saline groundwater discharge to the coastal zone. Numerous deep paleochannels have been identified in Long Bay, some of which extend across the study area offshore of Surfside Beach (Fig. 4). It is hypothesized that these paleochannels, which can act as a conduit for submarine groundwater discharge, may provide important spatial control on hardbottoms in Long Bay.

3. GEOLOGIC SETTING

The Grand Strand (Fig. 1) is a 100 km long crescent-shaped shoreline in northeastern South Carolina that lies within the apex of Long Bay and represents a transition zone of oceanographic processes that control geomorphology. The northern portion of the Grand Strand, located in North Carolina, is a wave-dominated, microtidal coast, while the southern portion of the Grand Strand in South Carolina is characterized as a tide-dominated, mesotidal coast (Hayes, 1994; Denny et al., 2013). Long Bay has a tidal range of < 2 m and mean near-shore wave heights of 1.25 m (Hayes, 1994; Denny et al., 2013). Winds vary seasonally, with yearly averages showing a dominant orientation of southwest/northeast origin, in rough alignment with the shoreline. Fall and winter are dominated by northerly winds, while the spring and summer are dominated by southerly and southwesterly winds. Consequently, waves and swells occur predominantly from the northeast and southeast, producing a dominant longshore current to the southwest (Blanton et al., 1985; Denny et al., 2013). The Grand Strand extends along southern and central portions of Long Bay from Little River Inlet to
Winyah Bay and is comprised of a series of nearly continuous sandy beaches that are welded to mainland Pleistocene barrier-island deposits, and (Ojeda et al., 2004; Barnhardt, 2009; Denny et al., 2013). Barrier islands and tidal inlets only occur in the northern and southern portions of the Grand Strand, limiting coastal drainage to small, local tidal creeks and channels (Denny et al., 2013).

The geologic framework of the Grand Strand consists of unconsolidated sediment, overlying a much older Cretaceous and Tertiary sedimentary rock foundation that influences the development of the modern coastal system. Barnhardt et al. (2009) identify three basic elements of this framework that play an important role in the evolution: (1) long-term non-depositional and erosional processes, (2) long-term cyclic sea-level changes, and (3) limited Holocene sedimentation. Due to the complex nature of tectonics and continental margin evolution, this region consists of a series of structural highs (platforms and arches) and lows (basins and troughs). Consequently, northeastern South Carolina overlies a structural high known as the Carolina Platform, summiting at the Cape Fear Arch or Mid-Carolina Platform High (MCPH), just underneath of the Grand Strand (Fig. 5). These morphological highs and lows dictate regimes of erosion and deposition. Numerous unconformities and hiatuses in the geologic record in this region illustrate these long-term erosional and non-depositional processes (Barnhardt, 2009).

This modern coastal system receives little fluvial sediment as no major rivers intersect the Grand Strand north of the Pee Dee River system, which discharges into Winyah Bay (Patchineelam et al., 1999; Baldwin et al., 2006; Denny et al., 2013). Despite the Pee Dee River system being the second largest source of riverine sediment
in the Georgia Bight, it is estimated that ~ 50% of the sediment is now trapped by dams upstream (Barnhardt et al., 2009). In addition, it is estimated that ~ 80% of the fine-grained sediment delivered to Winyah Bay is trapped within the bay and surrounding salt marshes, never reaching the open coast (Baldwin et al., 2006; Patchineelam et al., 1999). Sediment supply from the north is limited to the Cape Fear River, but is predominantly deposited in the Cape Fear spit and shoal complexes (Denison, 1998; Patchineelam et al., 1999; Park et al., 2009; Denny et al., 2013). Consequently, Holocene deposits are patchy and thin (< 0.5m) across most of the inner shelf (Fig. 6), allowing for hardbottom to be exposed and widespread.

Subsequently, the Grand Strand is essentially a closed littoral system with respect to sediment supply. Therefore, sediment may be derived from the recycling of material from other sources, such as erosion of the inner shelf (hardbottoms), modern shoreface, and/or paleo-shoreline deposits (Denny et al., 2013). Though the regional processes responsible for transporting sediment are poorly understood, some studies have identified long-shore transport of inner shelf sediment as the essential component for the coastal sediment budget (Riggs et al., 1996, 1998; Schwab et al., 2000; Denny et al., 2013).

3.1. STUDY SITE

The study area covers 1 square kilometer (km) of the inner shelf approximately 1.2 km offshore of Surfside Beach, SC (Fig. 1). This area has been previously identified as containing extensive hardbottom (Fig.6) (SEAMAP-SA, 2001; Barnhardt et al.,
extending offshore continuously for a minimum of 10 km (Barnhardt et al., 2009). Small, localized sand deposits are present in this zone (Fig. 6) and may be due to biological and mechanical erosion of the hardbottom (Riggs et al., 1998; Barnhardt et al., 2009).

4. METHODS

Existing data have been compiled from a variety of sources and include electrical resistivity profiles, acoustic-backscatter intensity measured from side-scan sonar, CHIRP subbottom profiles, and bottom type classification (SEAMAP-SA, 2001; Barnhardt et al., 2009; Viso et al., 2010). These data sets, however, are limited spatially and do not fully characterize the study area offshore of Surfside Beach, SC. New data collected through this current study to better characterize the study site are broken down into three categories: (1) seabed morphology and subbottom architecture, (2) surface geology and hardbottom characterization, and (3) indicators of groundwater discharge.

4.1. SEABED MORPHOLOGY AND SUBBOTTOM ARCHITECTURE

A bathymetric survey was conducted to better characterize the distribution of hardbottoms in this region and to catalog their morphology based on Riggs et al. (1996). Multibeam bathymetry and backscatter intensity data were acquired aboard Coastal Carolina University’s R/V Coastal Explorer on March 16 – 17, 2017, using a shallow water Kongsberg 3002D dual head multibeam echo sounder (300 kHz) (Figs. 7 – 8). This
system generates high-resolution data with a swath width of 200° (approximately 10 times the water depth) (Kongsberg, 2018). Motion of the vessel and navigational data were acquired with a Seatex Seapath 200 RTK-DGPS system. Multibeam data were processed using CARIS HIPS and SIPS 9.0 hydrographic processing software at 0.5 m resolution, while a backscatter intensity mosaic was created using FMGT v.7.5.3. Due to an unknown technical error with the RTK-DGPS system, tidal elevation data could not be extracted and used for processing. To circumvent this issue, tide data were extracted from NOAA Tides & Currents for Springmaid Pier (3 – 5 km from the study site) and imported into CARIS.

CHIRP subbottom data does exist throughout the study area, however these data are limited spatially and are low resolution. In effort to provide a higher resolution map of the geologic framework within the study site, three kilometers of CHIRP subbottom profile data were acquired (Fig. 9). Data were acquired aboard the R/V Coastal Explorer on March 17, 2017 using an Edgetech SB-0512i CHIRP subbottom profiler (0.5-12 kHz) at a ship speed of 4 – 5 knots. CHIRP subbottom data were processed using SIOSEIS (Henkart, 2006) and Seismic Unix (Cohen and Stockwell, 1999) seismic processing software packages. Additional CHIRP subbottom profiles used in this study were extracted from the SC Coastal Erosion Study and Nancy Foster Cruise 1005 cruise (Hill et al., 2000; Viso, unpublished data).
4.2. SURFACE GEOLOGY AND HARDBOTTOM CHARACTERIZATION

To characterize the modern sediment veneer within the study area, 16 surficial sediment samples were collected (Fig. 10). Eight samples were collected aboard the R/V Coastal Explorer on March 17, 2017 using a Petite PONAR sediment grab sampler. Divers collected the remaining eight samples from six sites on September 28, 2017. Duplicate surficial sediment samples were collected at sites D-1 and D-3. Grain size was measured for all sixteen samples with vertical stacking sieves at mesh sizes of 0.5 Φ intervals from -2 Φ to 4 Φ (4 mm to 63 μm, respectively). In each case, 17.5 to 20 grams of dried material was placed on top of the 4-mm sieve column and was shaken for 5 minutes. Data were run through GRADISTAT v.8.0, a particle size analysis software, to determine grain size, sorting, kurtosis, and skewness. Samples were plotted in ArcGIS to determine spatial distribution of mean grain size. Mean grain size for site D-1 and D-3 is an average of the duplicate samples. Additionally, surficial sediment samples were analyzed with a Carl Zeiss Stemi 2000-C stereomicroscope to compare with hardbottom sedimentology and petrographic properties such as mineralogy, grains size, and color.

Petrographic analysis of hardbottom rock samples was employed to determine the composition as well as optical and mineralogical properties of Long Bay hardbottoms. Orientation of the outcropping samples (D- samples) was recorded (e.g. NW, SE, top, bottom). Two additional samples (DS-1 and DS-2) collected from the seafloor by SCUBA divers during projects unrelated to the scope of this work were included to provide insight to more large-scale variability in hardbottom characteristics throughout
Long Bay. Since the collection of these two samples was unrelated to this current project, only petrographic characteristics have been analyzed from these samples.

In addition to the collection of seafloor hardbottom samples, a series of beach surveys were conducted between May – July 2017 to collect subaerial fragments of loose hardbottom rock samples (B- samples) from Surfside Beach and Garden City Beach (Fig. 10). Loose hardbottom beach samples were collected to provide insight into the relationship between outcropping rocks offshore and rock fragments that wash ashore.

All rock samples were visually sorted into categories based on properties such as color, texture, and lithology. Once sorted, 17 representative samples were cut into billets at the University of North Carolina Wilmington (UNCW) hard rock lab. For each sample that had an orientation recorded when collected, a small notch was cut in the top, north corner of the billet so that orientation could be preserved in the thin sections. Billets were sent to Quality Thin Sections (QTS) in Tucson, Arizona, where the samples were impregnated with blue resin to enhance pore space visibility and prepped for thin sections at 30-µm; no coverslip was applied. Thin sections were examined and photographed with a Leica DM 2700P polarizing microscope with a DFC 450 camera at the University of North Carolina Wilmington.

In an effort to determine if Long Bay hardbottoms are exposed bedrock or more recently indurated sediment deposits, benthic and planktonic foraminifera were picked from 10 representative samples. Rock fragments were crushed with a mortar and pestle to roughly centimeter chunks and soaked in 3 – 10 % hydrogen peroxide and borax for at least 24 hours, then washed over a 63-µm sieve. Dried samples were picked for foraminifera and photographed with a Carl Zeiss Stemi 2000-C stereomicroscope and
Dino-Lite Premier2 Digital Microscope, respectively. Planktonic foraminifera were used for age diagnostic analysis.

4.3. INDICATORS OF GROUNDWATER DISCHARGE

Marine electrical resistivity is a geophysical method that is useful for detecting conductivity variations of the water column and shallow subsurface pore-fluids. Principally, different rock and sediment types exhibit unique resistivity values. First, sediment (grain lithology and pore fluid) resistance is calculated using Ohm’s Law (resistance = voltage / current). Resistivity is then derived from the resistance and electrode geometry of the streamer cable (Johnson et al., 2015). One caveat, however, is that the calculated resistance values may produce inconsistencies, which makes it difficult to distinguish between sediment properties (i.e., porosity, connectivity or pores, fluid solutes). In an effort to further detect indicators of groundwater discharge, natural isotopes such as radon-222 can be utilized. Radon-222 is a useful tracer of active groundwater seepage due to its high enrichments in groundwater relative to seawater (approximately 1000-fold or higher) (Santos et al., 2008) (Fig. 11). This short-lived isotope has a half-life of 3.82 days and has been widely used to identify areas of submarine groundwater discharge (Burnett and Dulaiova, 2006; Burnett et al., 2008).

Electrical resistivity and radon-222 (\(^{222}\text{Rn}\)) survey methods were used in an attempt to better understand dynamic geological controls on modern groundwater movement between the subsurface and overlying ocean. This in turn may provide insight into the relationship between hardbottoms and submarine groundwater discharge in
facilitating or constraining flowpaths. An electrical resistivity survey was conducted on April 6th and 12th, 2018 using Coastal Carolina University’s research vessel R/V Privateer. Intentions were to survey after a significant rainfall event and on a falling tide to enhance the likeliness of detecting indications of groundwater, however weather and time constraints did not permit. Refer to Figures 12 and 13 show tidal conditions during the April 6th and 12th surveys, respectively, and Fig. 14 illustrates monthly rainfall preceding the surveys.

Marine electrical resistivity values were recorded with a SuperSting R8 IP meter and steamer cable from Advanced Geosciences, Inc. Data were collected with a 120-meter streamer cable with 12-meter electrode spacing, allowing for penetration of approximately 30 – 40 meters below the sea-surface. The survey consisted of 11 shore parallel lines, and one shore perpendicular tie-line (Fig. 15). Five of the shore parallel electrical resistivity lines coincide with CHIRP subbottom profiles collected through the SC Coastal Erosion Study, cruise 99044 (Hill et al., 2000). Navigation and water depth data were collected and recoded with a Lowrance HDS5 depth finder and GPS unit. For more detailed information on similar marine electrical resistivity data collection methods, see Manheim et al. (2004).

Raw resistivity and navigation data files were merged and converted to linear coordinates with the SuperSting Marine Log Manager (MLM) software to create a straight two-dimensional data set. Each navigation-merged line segment (Line 1 – 12) was extracted in MLM and inverted in 2D EarthImager v.2.4.0 to create separate continuous resistivity profiles (CRPs) for each line, using default CPR saltwater processing parameters. An unknown issue arose with the Lowrance HDS5 GPS system
during a portion of the electrical resistivity survey (Line 5 and one-half of Line 6), and
the navigation data was not useable. To circumvent this issue, NMEA navigation data
were extracted from HYPACK. Due to the GPS error, there is no water depth information
associated with survey Line 5 and one-half of Line 6, so the seafloor could not be traced
on the CRPs. For more detailed information on similar processing methods, refer to Cross
et al. (2010). To better compare lateral changes in the resistivity data set, data were
extracted from 10 m and 15 m depth (i.e. 10 m and 15 m from sea surface) and
interpolated in ArcGIS. Due to the Lowrance GPS error, Line 5 and one-half of Line 6
were not included in the interpolation.

A bottom water $^{222}\text{Rn}$ survey was conducted in concurrence with the electrical
resistivity survey. Radon-222 can be measured with a continuous multi-detector radon
system (Dulaiova et al., 2005), which requires that a constant stream of water pass
through an air-water exchanger to distribute radon to a closed air loop. A stream of air
circulates through the air-water exchanger and a desiccant column before reaching a
commercially-available radon-in-air monitor (RAD-7; Durridge Co.) for measurement
(Fig. 16). For this study, a submersible pump attached to a bottom sled was towed along
the seafloor and pumped water to a RAD AQUA (Durridge Co. accessory) air-water
exchanger. Air was pumped to three RAD-7 (Durridge Co.) radon-in-air monitors
arranged in parallel which measured for $^{222}\text{Rn}$ activity (Bq/m$^3$). In general, each RAD-7
detector was set to a 10-min cycle, resulting in a new, integrated, data point for every 10-
min phase with an average of three data points per survey line. For more detailed
information on multi-detector continuous monitoring of $^{222}\text{Rn}$, see Dulaiova et al. (2005).
We compute the solubility coefficient for radon (Burnett and Dulaiova, 2003), which is
based on water temperature measured by a HOBO temperature data logger was attached to the sled.

A series of statistical methods was used to determine any outliers within each data set and to determine whether a significant difference exists among $^{222}$Rn concentrations between each survey day. A t-Test was used to determine statistical significance of $^{222}$Rn concentrations between survey days in which a two-tail p-value was calculated. In addition, temporal $^{222}$Rn concentrations were plotted with standard deviation bars to further investigate potential outliers within each data set, per survey day. Surface and bottom water properties including temperature, salinity, and dissolved oxygen (DO) concentrations were measured to provide insight to indicators of groundwater discharge within the study area (Table 2). These data were recorded with a YSI 6600 V2 multiparameter water quality sonde on March 17 and September 28, 2017.

5. RESULTS

5.1. SEABED MORPHOLOGY AND SUBBOTTOM ARCHITECTURE

Water depths within this study site range from 7.7 to 10.2 meters below sea level, where depth generally increases with increasing distance from shore (Fig. 8). Shallowest depths (7.7 m) are observed at the SW and NW portion of the survey grid, while deepest depths (10.2 m) are observed in the NE portion of the study area. Overall, the seafloor within the study area exhibits rugose bathymetry with maximum relief of 0.5 m and high variability in backscatter intensity.
The northern portion of the study site is made up of shore-oblique sorted bedforms that are 70 – 170 m wide and 0.5 m in relief relative to the surrounding seabed (Fig. 8). The sorted bedforms are somewhat asymmetric, with smooth, flat surfaces and are characterized by uniform low backscatter intensity. These low backscatter intensity features extend outside of the study area from the shoreface to approximately 2 km offshore. The sorted bedforms cross the apex of shore-parallel – shore-oblique, arcuate ridges located in the central, northwestern portion of the study area. Ridges are 10 – 20 cm in relief above the seabed, where the steepest relief ridges are located towards the south (Fig. 17). The expression of this arcuate ridge system becomes less prominent where the ridges lose elevation at the intersection of the sorted bedforms. Attached and adjacent to these arcuate ridges is a rocky ledge 200 m in length and 0.5 m in relief that runs shore-perpendicular (Fig. 17).

Inshore of these ridges is a group of oblong mounds with lengths and widths of 9 – 10 m and 7 – 9 m, respectively, and relief of 10 – 20 cm above the seabed (Fig. 17). This mound system follows an almost identical curvature as the adjacent arcuate ridges. Linear, shore-perpendicular ridges to the north that trend NW – SE have similar elevation (10 – 20 cm) but extend farther offshore. These linear ridges are gently sloping and are characterized by variable backscatter intensity. Alongside these linear ridges in the northeastern portion of the study area exists a cluster of seven small semi-circular depressions. These depressions have diameters of 9 – 11 m and relief of approximately 10 cm below the surrounding seabed (Fig. 18).

The southwestern region of the study area is made up of irregular, somewhat sinuous, shore-perpendicular features, with variable backscatter intensity, and relief of 10
cm above the seabed (Fig. 19). This seafloor feature loses elevation with increasing distance from shore and intersects with a complex sinuous ridge system in the southeastern portion of the study area. This complex sinuous ridge system is made of tightly spaced, variable backscatter intensity, sinuous ridges with an average relief of 10 cm above the seabed (Fig. 20). The variable backscatter intensity that aligns with both bathymetric features extends outside of the study area. The backscatter intensity characteristics of the somewhat sinuous feature extend inshore to the shoreface, while those of the complex sinuous ridge feature extend just outside of the study area.

The mosaic of backscatter intensity collected with the Kongsberg 3002D multibeam system is illustrated in Fig. 21, while the 100 kHz mosaic collected by Barnhardt et al. (2009) is shown in Fig. 22. Backscatter intensity within the study area is characteristic of (1) uniform low backscatter intensity, and (2) variable backscatter intensity, while outside the study area exist areas of uniform high backscatter intensity. Backscatter intensity corresponds well with bathymetry data (Fig. 21). For example, bands of uniform, low backscatter intensity bars in the northern portion of the study site correspond to bathymetric highs associated with the shore-oblique sorted bedforms. Furthermore, the varying patterns of variable backscatter intensity correspond to areas of high rugosity, or the rugose bathymetry within the study area. For example, the spines of bathymetric highs associated with the arcuate ridges in the northwestern area are characterized by high backscatter intensity while the troughs are characterized by low to medium backscatter intensity (Fig. 22b).

In general, the rugose seafloor within the study area with bathymetric complexity is often characterized by variable backscatter intensity. The backscatter intensity mosaic
from Barnhardt et al. (2009) shows that much of the nearshore seafloor within Long Bay is characterized by similar variable backscatter intensity (Fig. 22), particularly regions with little to no sediment cover. Regions of uniform low backscatter intensity similar to those found within the study area are also abundant within the nearshore of Long Bay.

CHIRP profiles collected during the USGS 99044 cruise are of limited resolution and show very little to no structure in the subsurface, which is likely results from acoustic attenuation from the hardbottom. As such, primary structures are inferred from the CHIRP profile collected on March 17, 2017. Angled reflectors are observed in the northeastern and northwestern regions of the study area and outcrop at the seafloor (Figs. 23 – 24). In the northern portion of the most distal CHIRP profile, the strata are gently tilted with a predominately southward dip (Fig. 23). In the central, northern portion of the most proximal CHIRP profile, the strata are steeply tilted with a predominantly northward dip (Fig. 24). Strata in the north portion of the proximal CHIRP profile are gently tilted with a predominantly southward dip. Separating the steeply tilted and gently tilted strata in the proximal CHIRP profile is an acoustically transparent package of sediment approximately 350 m wide and 2.5 m thick (Fig. 24). The sediment cover is underlain by a high-amplitude reflector, which appears to connect the tilted strata. The remainder of the CHIRP data is acoustically transparent beneath the seafloor.

The tilted strata in both profiles appear to be truncated and outcrops frequently at the seafloor. These outcropping tilted reflectors align with bathymetric highs, primarily the arcuate and linear ridges in the northern portion of the study area. The steeply tilted strata dipping to the north align with the arcuate ridges which have the most prominent features in bathymetry and backscatter intensity data (i.e. steep relief and high backscatter
intensity at the spine of the ridges) (Fig. 25a). The gently tilted strata dipping to the south align with the shore-perpendicular linear ridges in the northeast and northwest portions of the study area (Figs. 25b – 25c). The linear ridges are more gently sloping and characterized by lower backscatter intensity than the arcuate ridges. The thick sediment package aligns well with the shore-oblique sorted bedforms that intersect at the apex of the arcuate ridges (Fig. 25c).

5.2. SURFACE GEOLOGY AND HARDBOTTOM CHARACTERIZATION

Spatial distribution of mean grain size from 14 locations within the study area is shown in Fig. 26. Mean grain size ranges from fine to very coarse sand, while textural groups range from slightly gravelly sand to sandy gravel, most likely made up of shells or shell fragments in these large classes. Folk and Ward mean grain size ranges from 189.5 μm to 1.32 mm, while sorting ranges from moderately well sorted to poorly sorted. For more detailed information on GRADISTAT calculations, refer to Table 3. Mapped data shows that the largest mean grain size is concentrated in the northern portion of the study area, and mean grain size decreases towards the south. Microscopic analysis of sediment samples show that the sediment is primarily composed of quartz grains and carbonate shell fragments, with small amounts of dark glauconite, opaque minerals, and carbonate grains (Fig. 27).

Seafloor hardbottom samples are made up of a breccia with clasts ranging from coarse sand to pebbles. Samples have a clastic texture and are moderately indurated to well indurated but can be broken somewhat easily with a rock hammer. Samples are very
dark grey to light grey with large green clasts (coarse sand to pebble size). Loose hardbottom samples collected on the beach are primarily sandstone with moderately sorted grains and are well indurated. Beach samples show a range of colors from tan to dark grey, though most samples collected were dark grey with similar lithologies. Similarly, samples show a range in textures, but mostly clastic to microclastic, and some fossiliferous. Seafloor hardbottom samples showed evidence of sessile organism attachment, while loose samples did not. All samples showed evidence of bioerosion through processes such as borings, drillings, and scrapings.

Petrography shows that seafloor hardbottom samples D-1, D-2, D-3, and D-6 are largely composed of carbonate, quartz, glauconite, and phosphorite grains, along with abundant bioclasts (e.g., foraminifera) (Fig. 28). Glauconite is the most abundant accessory mineral and exhibits many different morphologies and a wide range of green shades. Rhombohedral dolomite and chalcedony are also present in some instances. Sediment grains range from subangular to well-rounded but are primarily subrounded and are supported by a mud dominated matrix or calcite cement. The grains are moderately well sorted and are loosely packed together with abundant pore space. Samples D-4 and D-5 have a similar mineralogical make-up of the above, however they contain much less glauconite and are rich in quartz, supported by a muddy matrix or calcite cement (Fig. 28). Sample DS-2, collected outside the study area, contains relatively little glauconite, but rather is composed of angular quartz grains, phosphate, and carbonate grains with a mud dominated matrix or calcite cement (Fig. 28). Beach hardbottom samples are largely composed of quartz grains and carbonate shell fragments, along with abundant bioclasts. Small amounts of glauconite and phosphorite are present. The sediment grains range
from moderately well to poorly sorted and are mostly subangular with a muddy matrix or calcite cement (Fig. 29).

Of the 10 hardbottom samples picked for foraminifera, two of the four beach samples had no foraminifera. Foraminifera were abundant and well preserved in all other samples. Preliminary results suggest that sample B-7 may contain *Thalmaninella greenhornensis* (Fig. 30) which is a Cretaceous species. Due to the poor resolution of the photographs, no other identifications could be made; however, initial identifications suggest that the remaining foraminifera may be Paleocene species. Further work needs to be done to identify and classify foraminifera, so these ages remain speculative.

5.3. INDICATORS OF GROUNDWATER DISCHARGE

Electrical resistivity tomograms (ERTs) show complexity in the subsurface resistivity characteristics. Bulk resistivity values range from less than 1 Ω-m to greater than 11 Ω-m, suggesting entirely saline and partially fresh porewaters, respectively. In general, highest resistivity values are observed on the most proximal survey lines and decrease with increasing distance from shore. In the offshore portion of the study area, the highest values appear to be associated with the southwestern and northwestern corners of the survey area (Fig. 31), which align with bathymetric highs, or the shallowest depths observed. Moreover, the highest resistivity values align with the somewhat sinuous feature in the southwestern portion of the study area and the sorted bedforms and arcuate ridges in the northwestern portion of the study area. Interpolated grids of resistivity values at 10 m and 15 m below the sea surface (Figs. 32 – 33) show
similar results in that highest resistivity values are constrained to the southwestern and northwestern portion of the study area.

Results from water sampling show that comprehensive bottom water $^{222}$Rn concentrations ranged from 0.58 to 2.01 dpm/L, though the ranges varied on each survey day (Fig. 34). Radon concentrations measured on each survey day can be seen in Fig. 35 and Fig. 36 when concentrations on April 06, 2018 ranged from 0.58 to 1.59 dpm/L, and concentrations on April 12, 2018 ranged from 0.67 to 2.01 dpm/L. Highest $^{222}$Rn concentrations are constrains to the most distal survey lines but are primarily associated with the sinuous ridge system in the southeastern portion of the study area. A t-Test was run to determine whether there a significant difference exists in $^{222}$Rn concentrations between the two survey days. Results show a very significant difference ($p << 0.05$) between the two days, with a $p$-value of 0.0017 for the two-tail test. This significant difference could potentially be a result of the difference of tidal phase between the two days (i.e. April 6th survey occurred during a rising tide, while April 12th survey occurred during a falling tide). Plots of temporal $^{222}$Rn concentrations with standard deviation bars (Figs. 37 – 38) show two enriched outliers during the April 6th survey, and three enriched outliers during the April 12th survey.

6. DISCUSSION

For the purpose of this discussion, surface geology and hardbottom characterization will be discussed first, then seabed morphology and subbottom
architecture, and finally indicators of groundwater discharge. This order is done to provide context to understanding the morphological and subbottom components.

6.1. SURFACE GEOLOGY AND HARDBOTTOM CHARACTERIZATION

Surficial sediment samples, which are composed primarily of quartz and shell fragments and contain very little glauconite, differ substantially in mineralogy compared to the sediment comprising the hardbottom samples, which are characterized as phosphatic glauconite sandstone. This finding is interesting as hardbottoms were previously assumed to be a major source of new sediment to the coastal zone within Long Bay (Gayes et al., 2003; Ojeda et al., 2004; Barnhardt et al., 2009). Loose hardbottom samples collected on the beach also do not resemble the seafloor hardbottom samples, but rather are characterized as quartz sandstone or fossiliferous limestone. The differences in lithology between seafloor hardbottom and beach hardbottom suggests that there are other types of hardbottom within Long Bay that were not sampled during this study.

This new finding suggests that modern sediment in the study area, and potentially at a larger geographic scale, is not being sourced from the type of hardbottom associated with the study area. This discovery also suggests that the source of modern sediment to the coastal zone may potentially be sourced from other types of hardbottom, if present, within Long Bay. In addition, Long Bay hardbottom can be classified as flat hardbottom (FHB), and in some instances, low relief scarped hardbottom (SHB) as maximum seafloor relief within the study area is 0.5 m. This classification is interesting when
compared to Onslow Bay, North Carolina, where hardbottom is associated with up to 10 m of relief in some locations (Riggs et al., 1998).

Glauconite is a sand to pebble-sized potassium and iron-rich clay mineral that forms under weak oxidative to weak reducing conditions of the medium (Odin and Matter, 1981; Mingxiang et al., 2008; Banerjee et al., 2016). Glauconite is considered a marine authigenic mineral primarily associated with transgressive deposits and condensed sections (Odin and Matter, 1981; Banerjee et al., 2016). It has been recognized as a product of dissolution-precipitation and later maturation, in which the host grain being replaced is most often fecal pellets produced by filter feeding organisms that may be composed of clay minerals, calcite, mica, quartz, or feldspar. Due to the range of host grain minerals, glauconite often exhibits a wide array of morphologies (Fig. 39) (Chafetz and Reid, 2000).

It has widely been accepted that glauconite forms at mid-shelf and upper continental slope environments in low sedimentation regimes between 50 m and 1000 m water depth (Chafetz and Reid, 2000; Mingxiang et al., 2008), but commonly between 200 m - 300 m water depth (Odin and Matter, 1981; Chafetz and Reid, 2000). Due to the unique nature of glauconite formation (i.e., at depth and under slow sedimentation), glauconite has widely been used as a proxy for inferring past environmental conditions. More recent studies, however, dispute this understanding, suggesting that these samples represent modern glauconite, but that formation may have differed in geologic history and in other parts of the geologic column (Chafetz and Reid, 2000; Mingxiang et al., 2008). A growing number of studies show that glauconite may have formed in high-energy, shallow water environments during the Late Mesoproterozoic and Cambro-
Ordovician, when high rates of sedimentation are typical (Chafetz and Reid, 2000; Mingxiang et al., 2008).

Though glauconite is an authigenic mineral, the presence of glauconite in a substrate does not necessarily indicate that glauconite was formed in-situ. More recent studies discuss other scenarios for the presence of glauconite in a substrate, and glauconite origin. Fischer (1999) discusses four modes of glauconite genesis: (1) authigenic, (2) perigenic, (3) allogetic, and (4) meta-allogenic (Fig. 40), though for this research we are primarily concerned with authigenic vs. allogetic glauconite. Authigenic glauconite forms in-situ primarily through the replacement of fecal pellets or from a variety of other host minerals. The primary optical criterion for identifying authigenic glauconite is the presence of mature cracks on the grain surface, which often exhibit many morphologies. Allogenic glauconite refers to glauconite that has been transported, or deposited, away from its original place of formation. The primary optical criterion for identifying allogenic glauconite is the presence of well rounded, ovoidal, and ellipsoidal grains. Though these terms provide context to glauconite genesis, it is important to note that they tell nothing about the formation process itself, nor of the parent minerals (Fischer, 1999).

In most instances, the glauconite observed in the in-situ samples is loosely packed together and bioclasts (e.g., foraminifera) have remained mostly intact and undamaged. Authigenic growth of glauconite is suspected here as the grains are not well rounded or ovoidal and have well-developed cracks (Fischer, 1999), though glauconite has not been observed having replaced bioclasts which would undoubtedly suggest authigenesis.
6.2. SEABED MORPHOLOGY AND SUBBOTTOM ARCHITECTURE

Barnhardt et al. (2009) show that the geologic framework of the Grand Strand consists of a relict sedimentary rock foundation which is overlain by younger, unconsolidated sediment. Since modern sediment is patchy in Long Bay, the older sedimentary rock foundation is frequently exposed at the seafloor. This layered and tilted sedimentary rock foundation is believed to have been deposited as sandy and muddy sediments under continental shelf settings during the Cretaceous and Tertiary periods, 70 to 55 million years ago. A combination of bio- and geo-chemical processes cemented this loose unconsolidated material, though exact processes leading to cementation were not investigated (Barnhardt et al., 2009). Through tectonic evolution of the Grand Strand and the formation of the Mid-Carolina Platform High, these sedimentary rocks have been uplifted close to the modern surface. They have since been sharply truncated by widespread erosion, creating an unconformity that spans approximately 70 million years in areas where Cretaceous strata outcrop at the seafloor (Barnhardt et al., 2009). Baldwin et al. (2004) and others have postulated that Cretaceous and Tertiary strata intersect with the coast just offshore of Surfside Beach, though the location of the unconformity separating the strata remains uncertain (Colquhoun et al., 1983).

New CHIRP profiles across the study area suggest that the source of hardbottom here is associated with outcropping, angled reflectors that correspond to bathymetric highs along the series of arcuate and sinuous ridges observed across much of the study area. Combined with the results of the petrographic analyses, which suggest authigenic glauconite formation within these strata, this finding implies the hardbottom observed
here are likely outcropping beds of tilted sedimentary bedrock strata. The presence of ancient foraminiferal species, along with the common occurrence of glauconite in Cretaceous and Tertiary strata of this region (Horton and Zullo, 1991), suggests that the hardbottom strata within the study area formed during the Cretaceous or Tertiary.

As such, seafloor morphology can be categorized as modern and relict. The modern morphology exists as unconsolidated sediment that is mostly associated with the shore-oblique sorted bedforms in the northern portion of the study site. The sorted bedform that intersects the rocky arcuate ridges appears to be cutting across, or overprinting, the underlying fabric, as the expression of these ridge features is not as prominent in that area (Fig. 8). This behavior explains why the arcuate ridges and mounds lose elevation relative to the surrounding seabed at the point of intersection where the ridge features become buried. The sand lobe in the northeastern portion of the study area, just north of the complex sinuous ridge system, also appears to be overprinting the underlying geologic framework as it cuts across the shore-perpendicular linear ridges. Young sediment also appears to be concentrated in a bedform characterized by small sorted bedforms in the central portion of the study area (Fig. 41). These sorted bedforms run shore-perpendicular with relief of 20 – 30 cm relative to the seabed.

The relict seafloor morphology manifests as bathymetric highs and ridges that are associated with areas of truncated, outcropping tilted strata and is characterized by variable backscatter intensity. Correlation of the subbottom and bathymetry data suggests steepest relief of the arcuate ridges is linked to the more steeply tilted strata, while the gently tilted beds are linked to more subtle ridges. The high-amplitude reflector just underneath the sediment package identified in the proximal CHIRP profile appears to be
connected to the steeply dipping and gently dipping strata, suggesting that these features represent one geologic unit. It is likely that this unit forms a structural syncline that was truncated through erosional processes. Since this region has been predisposed to periods of low sedimentation and deposition, these truncated dipping strata now outcrop at the seafloor, providing some of the small-scale relief seen throughout the study area.

Though the remainder of the CHIRP data is acoustically transparent, it is likely that the sinuous ridges in the southeastern portion of the study area are also truncated, deformed sedimentary bedrock strata. The irregular, somewhat sinuous ridges in the southwestern portion of the study area are somewhat convoluted as they exhibit relief but are not organized ridges like the adjacent sinuous ridges to the east. It is possible that this region is a different expression of the hardbottom, where there may be higher sediment cover interacting with the hardbottom.

Backscatter intensity data show that much of the seafloor within Long Bay is similar to that within the study area, with rugose bathymetry and shore-oblique sorted bedforms that are present across much of the region (Fig. 23). This similarity suggests that much of the seafloor with Long Bay is exposed, deformed sedimentary bedrock, superimposed by more recent unconsolidated sediment. Moreover, hardbottom is likely abundant within Long Bay with a similar origin to that within the study area. Furthermore, these data suggest that the underlying geology does in fact dictate locations of hardbottom, such that the exposed hardbottom is likely sourced from the uplifted, deformed sedimentary rock foundation that has been truncated through periods of erosion.
6.3. INDICATORS OF GROUNDWATER DISCHARGE

Electrical resistivity values within the study area are similar to findings reported for the nearshore in Long Bay by Viso et al. (2010) where resistivity values ranged from less than 1 Ω-m to greater than 40 Ω-m. Electrical resistivity values are likely lower in this current study as this study area is farther from shore, and thus farther from a source of fresh groundwater. Data show the presence of groundwater discharge indicators associated with regions of hardbottom within Long Bay. While an inverse relationship exists between ERTs and ²²²Rn concentration, it is possible that the relationship can be explained by the underlying geology and the source of groundwater. Highest resistivity values appear to coincide with the location of the mapped paleochannel within this region, suggesting that paleochannel infill may be dictating regions of high resistivity (Fig. 42). Electrical resistivity is a highly variable geophysical property of a geologic material and can vary by several orders of magnitude (Fig. 43) (Palacky, 1987).

Bloss and Bodrosian (2013) explain that four factors control bulk electrical resistivity: (1) mineralogy, (2) porosity, (3) pore-space saturation, and (4) conductivity of pore fluid. The dominant factors that control bulk electrical resistivity in sedimentary environments are clay content, type of pore water, and the degree of saturation, though clay content has been found to be the major driver governing sample conductivity (Bloss and Bodrosian, 2013). Clay particles are positively charged, and thus very conductive to an electrical current. As such, increased clay content would have a negative effect on bulk electrical resistivity properties, and thus lower resistivity values. Though the composition of Long Bay channel-fill deposits is uncertain, electrical resistivity and
radon-222 data suggests that channel-fill is potentially more coarse material with little clay content. This interpretation agrees with results by Viso et al. (2010), which suggests that channel-fill in Long Bay may be characteristic of coarser lag deposits.

To provide some context for the measured $^{222}\text{Rn}$ concentrations from this study within this region, these data are compared to $^{222}\text{Rn}$ concentrations collected along the coastline of Long Bay (Fig. 44) (Peterson, unpublished data). Comparison indicates that our observed radon concentrations are within the range previously found and similarly decrease with increasing distance from shore. The general distribution of $^{222}\text{Rn}$ concentrations within this current study appears to be highest in the southeastern portion of the study site, corresponding to an area of complex backscatter intensities (Fig. 34). This finding is interesting as it departs from the general trend of $^{222}\text{Rn}$ concentrations decreasing with increasing distance from shore, suggesting that there could potentially be some areas of groundwater discharge (e.g. hot spots) associated with regions of hardbottom.

As previously mentioned, ERTs and $^{222}\text{Rn}$ concentrations show an inverse relationship, where $^{222}\text{Rn}$ concentrations are highest in the eastern portion of the survey. As such, the ERTs suggest that either the pore fluid is saline or that the subsurface geology has some clay content. Based on results by Peterson et al. (2016), it is highly likely that the subsurface pore fluid, and thus groundwater, is actually saline within the study area. Li et al. (2009) state that when fresh submarine groundwater discharge is low or absent in a coastal system, recirculated marine submarine groundwater discharge becomes the main contributor to total submarine groundwater discharge. Such behavior would explain why the ERTs do not show increased resistivity (i.e. less saline pore
fluids) associated with areas of increased $^{222}$Rn activity. Another possibility for this discrepancy could be an external source of groundwater discharge contributing to elevated $^{222}$Rn concentrations. With a half-life of 3.82 days, it is possible for a groundwater body enriched in $^{222}$Rn to have traveled some distance and still show higher than ambient concentrations.

To assess whether paleochannels influence the presence of groundwater discharge indicators, $^{222}$Rn concentration distributions were compared to mapped paleochannels within the study site (Baldwin et al., 2006) (Fig. 45). Surprisingly, the overlays show that the highest concentrations are not located within the mapped paleochannel, but rather it appears that highest concentrations are just outside, or along the channel flank. It does appear, however, that highest resistivity values coincide with the mapped paleochannel (Fig. 42), which further suggests that paleochannel fill may control resistivity characteristics.

The very significant difference ($p = 0.0017$) in $^{222}$Rn concentrations between survey days is most likely a result of the difference in tidal phase during surveys. Groundwater discharge, and thus water column radon concentrations, is highly variable and is known to respond to external forcing such as tides (Burnett et al., 2008; Li et al., 2009; Moore, 2008). Simulations by Robinson et al. (2007) suggest that tidally driven recirculation accounts for upwards of $>70\%$ of total submarine groundwater discharge in subterranean estuaries. Tidal pumping causes an oscillating flow where during rising, or high tide, seawater is pumped into the subsurface sediment, and during falling, or low tide, seawater is pumped back into the near-bottom ocean. Surface and bottom water YSI
measurements show very little difference, thus no conclusions could be drawn from these data.

7. SUMMARY

New evidence from geophysical surveys and seafloor sampling suggests that Long Bay hardbottoms are not recently indurated deposits, but rather outcrops of the ancient sedimentary rock foundation underlying the Grand Strand (Fig. 5). Long Bay seafloor hardbottom is characterized as phosphatic glauconite sandstone, while loose hardbottom samples collected on the beach are considered quartz sandstone and fossiliferous limestone. This difference in composition between seafloor hardbottom and loose beach hardbottom samples suggests that there are other types of hardbottom within Long Bay that were not sampled during this study. In addition, the surficial sediment samples collected alongside the seafloor hardbottom have a mineralogy substantially different from the sediment comprising the outcropping hardbottom samples. These new findings indicate that the seafloor hardbottom within the study area is not a major source for new sediment to the coastal zone, as previously thought (Gayes et al., 2003; Ojeda et al., 2004; Barnhardt et al., 2009), though it is possible that there are other types of hardbottom within Long Bay that contribute to new sediment but are not present in the study area offshore of Surfside Beach.

Petrographic analyses of the seafloor hardbottom samples suggest authigenic glauconite formation within these strata, indicating that they formed during pervious times as modern glauconite forms in mid-shelf to upper continental slope environments
Glauconite is a very common mineral in Cretaceous and Tertiary strata within this region (Horton and Zullo, 1991), while older foraminiferal species identified in the hardbottom samples suggest a similar age for formation. Since examination of the Cretaceous and Tertiary geology is hindered by a paucity of outcrops within the low-relief Coastal Plain (Horton and Zullo, 1991), this study could serve as a gateway for understanding South Carolina Cretaceous and Tertiary geology.

Bathymetry data show that these hardbottom are flat hardbottom, and in some instances, low relief scarped hardbottom and provide some of the only natural seafloor relief in Long Bay. The hardbottom is related to the truncated deformed sedimentary strata, while these older strata likely outcrop at the seafloor as a result of low sedimentation, tectonic deformation and uplift in association with the Mid-Carolina Platform High uplifting just underneath of the Grand Strand. Backscatter intensity data suggest much of the seafloor within Long Bay shares similar morphologies and outcrop exposures as seen within the study area. This comparison suggests that much of the seafloor within Long Bay is exposed hardbottom, superimposed by more modern unconsolidated sediment.

Electrical resistivity and radon-222 data suggest indicators of groundwater discharge are associated with hardbottom, however no specific flowpaths could be determined at this time given the available data. Future studies should focus on finding sites of possible modern hardground formation, on geochemical and isotopic (strontium, oxygen, etc.) analyses of cements to potentially constrain the mechanism and driver of modern lithification, and on age determination of Long Bay hardbottoms. Additionally,
studies should consider sampling a larger area to capture any other potential types of hardbottom.
REFERENCES


Burnett, W.C., Peterson, R., Moore, W.S., Oliveira, J., 2008. Radon and radium isotopes as tracers of submarine groundwater discharge – Results from the Ubatuba, Brazil SGD assessment intercomparison. Estuarine, Coastal and Shelf Science 76, 501-511.


## Tables

**Table 1.** Classification of U.S. Atlantic continental margin hardbottom morphology. Morphological position describes the position of FHB in relation to the bounding surfaces of low- and high-relief scarped hardbottom, as these features can be temporarily or permanently buried by modern sediment. Extracted from Riggs et al., 1996.

<table>
<thead>
<tr>
<th>Hardbottom Morphology</th>
<th>Morphological Position</th>
<th>Relief</th>
<th>Morphology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat Hardbottom (FHB)</td>
<td>Upper (U-FHB)</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Middle (M-FHB)</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>Lower (LFHB)</td>
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<td></td>
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<tr>
<td>Scarped Hardbottom (SHB)</td>
<td>Low Relief = &lt;0.5 m (LR-SHB)</td>
<td>-</td>
<td>Sloped = 50-75° (SL-SHB)</td>
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<td>High Relief = &gt;0.5m (HR-SHB)</td>
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<td>Vertical = 75-90° (V-SHB)</td>
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<td></td>
<td></td>
<td>-</td>
<td>Undercut/Overhang (U/OH-SHB)</td>
</tr>
<tr>
<td>Erosional Ramps (ER)</td>
<td>Block (B-ER)</td>
<td>-</td>
<td>Stepped (ST-ER)</td>
</tr>
<tr>
<td></td>
<td>Stepped (ST-ER)</td>
<td>-</td>
<td>Solved = 50-75° (SL-SHB)</td>
</tr>
<tr>
<td>Rubble Ramps (RR)</td>
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<td>-</td>
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Table 2. Physical water property measurements of surface and bottom waters from several locations in Long Bay, South Carolina.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Name</th>
<th>Longitude</th>
<th>Latitude</th>
<th>YSI Depth (m)</th>
<th>Surface Temp (°C)</th>
<th>Surface Salinity (%)</th>
<th>YSI Bottom Temp (°C)</th>
<th>Bottom Salinity (%)</th>
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Data were collected on March 17 and September 28, 2017.
<table>
<thead>
<tr>
<th>Sample</th>
<th>Texture</th>
<th>Sorting</th>
<th>Skewness</th>
<th>Kurtosis</th>
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<td>S1</td>
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<td>Coarse Sand</td>
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<td>Poorly Sorted</td>
<td>Coarse Sand</td>
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<td>Coarse Sand</td>
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<td>Coarse Sand</td>
<td>0.736</td>
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<td>0.820</td>
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<td>Sandy Gravel</td>
<td>Poorly Sorted</td>
<td>Coarse Sand</td>
<td>1.017</td>
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Table 3. GRADISTAT calculations of all fourteen surficial sediment samples collected with a PONAR and by scientific SCUBA divers. Samples show a range of mean grain sizes and textures. Note that replicate samples were collected at sites D1 and D3, so the calculated mean used for analysis and interpretation is an average of the two samples.
Figure 1. Geography of the study area within Long Bay, South Carolina. The study area (bottom left - red box) is located offshore of Surfside Beach, which is along the Grand Strand (right - dashed box). Red lines in study area figure indicate 1-m depth contours.
Figure 2. Classification and distribution of bottom types offshore of South Carolina and North Carolina. The study site, indicated by the black box, is located within grids that have been identified as hardbottom. Modified from SEAMAP-SA (2001).
Figure 3. Cross-section of a highly permeable paleochannel that has incised a confining unit (red arrows), allowing for a preferential pathway for submarine groundwater discharge to the coastal zone. As such, this paleochannel acts as a conduit for groundwater-seawater exchange. Modified from Xia et al. (2012).

Figure 4. Paleo-channel reconstruction showing various relic fluvial channels of different shapes and sizes formed during periods of lower sea-level. Study site is shown by the black box. Modified from Barnhardt et al. (2009).
**Figure 5.** Underlying geologic framework of the southeast U.S. coastal margin. Note that the Grand Strand is located near the summit, or apex, of the Mid-Carolina Platform High (MCPH). As a result, Cretaceous and Tertiary strata are uplifted very close to the modern system, potentially outcropping at the seafloor. Modified from Barnhardt et al. (2009).
Figure 6. Holocene sediment distribution and thickness on the inner shelf in Long Bay, South Carolina. Study site is shown by the black box, where modern sediment is mostly absent. Modified from Barnhardt et al. (2009).
Figure 7. Multibeam bathymetry track lines collected on March 16 – 17, 2017. Data were collected with a Kongsberg 3002D multibeam echo sounder (300 kHz).
Figure 8. Map showing bathymetry within the study area, which was collected March 16 – 17, 2017. Depths range from 7.7 to 10.2 m and seafloor relief is limited to 0.5 m. See subsets for more detailed bathymetry.
Figure 9. Track line of CHIRP data collected on March 17, 2017 with an Edgetech 512i subbottom profiler.
Figure 10. Map showing the location of the collected hardbottom and surficial sediment sample. Hardbottom samples indicated by the red circles were collected during this study, while DS-2 (green circle) had previously been collected. Note that one additional sample collected while diving (DS-1) was collected from an unknown location and could not be mapped.
Figure 11. Isotope enrichments in groundwater, relative to seawater. Graph shows that radon-222 is significantly enriched in groundwater, relative to seawater, by almost two orders of magnitude relative to the other isotopes tested. Modified from Santos et al. (2008).
Figure 12. Plot showing timing of the electrical resistivity and radon-222 survey on April 06, 2018 with respect to the tide. Survey was conducted on a rising tide.

Figure 13. Plot showing timing of the electrical resistivity and radon-222 data survey on April 12, 2018 with respect to the tide. Survey was conducted on a falling tide.
Figure 14. Monthly rainfall recorded at Springmaid Pier leading up to the electrical resistivity and radon-222 surveys on April 06 and 12, 2018.
Figure 15. Electrical resistivity and radon-222 track lines collected on April 06 and 12, 2018. Six proximal survey lines were run on April 06, while five distal and one shore-perpendicular line were run on April 12.
Figure 16. Schematic of the three-stage radon measurement system used for this study. Dashed lines represent water inflow and outflow, while solid lines represent the closed air loop. Adapted from Dulaiova et al. (2009).
Figure 17. Bathymetry data showing arcuate ridges and mound system that run shore-parallel – shore-oblique. Ridges appear to be outcropping titled bedrock that can be seen as angled reflectors in the CHIRP profiles (Fig. 24). The rocky ledge and sorted bedforms are examples of maximum relief (0.5 m) observed within the study area.
Figure 18. Bathymetry data showing semi-circular depressions that are 9 – 11 m in diameter with 10 cm of relief below the seabed. Formation mechanism remains uncertain.
Figure 19. Bathymetry data showing somewhat irregular, sinuous ridges observed in the southwestern portion of the study area. These ridges run shore-perpendicular and intersect with a sinuous ridges system farther offshore (Fig. 20). These ridges have similar relief to arcuate (Fig. 17) and sinuous ridges (Fig. 20) within the study area, however they are not as organized.
Figure 20. Bathymetry data showing complex, tightly spaced sinuous ridges with 10 cm relief above to the seabed, located within the southeastern portion of the study area.
Figure 21. Comparison of backscatter intensity and multibeam bathymetry data collected on March 16 – 17, 2017. Backscatter intensity shows complexities in the seafloor texture that appear to align with bathymetric features. Notice low backscatter intensity bars running WNW – ESE aligning with bathymetric highs. For location reference refer to Fig. 8.
Figure 22. Backscatter intensity mosaic measured with side-scan sonar along the Grand Strand. The mosaic shows complexities in the seafloor texture along the whole portion of Long Bay that was surveyed. (A) The northern portion of the mosaic appears to depict several shore-perpendicular sorted bedforms and rugose backscatter intensity, characteristic of that seen within the study area. (B) The study area shows rugose backscatter intensity associated with the arcuate and sinuous ridges identified in the bathymetry data. Sorted bedforms are also present and have been identified as bathymetric highs in the bathymetry data. (C) The southern portion of the mosaic appears to depict rugose backscatter intensity similar to that seen within the study area, along with possible areas of patchy sediment.
**Figure 23.** Uninterpreted (top) and interpreted (bottom) CHIRP subbottom profile. Profile runs shore parallel from northeast (shot point 0 x 10^4) to southwest (shot point 0.30 x 10^4) and shows gently dipping strata with a southward dip (red). See Fig. 9 for location reference.
Figure 24. Uninterpreted (top) and interpreted (bottom) CHIRP subbottom profile. Profile runs shore parallel from southwest (shot point $0.95 \times 10^4$) to northeast (shotpoint $1.20 \times 10^4$) and shows steeply dipping strata (red) to the north and gently dipping strata (red) to the south. Sediment cover is indicated by the blue line. See Fig. 9 for location reference.
Figure 25. Correlation of CHIRP and bathymetry data suggests that the sources of the arcuate ridges (A) and shore-perpendicular ridges (B) is outcropping truncated, tilted sedimentary strata. (A) Steepest relief associated with the arcuate ridges appears to be attributed to the steeply dipping strata. (B) More subtle relief associated with the shore-perpendicular ridges appears to be attributed to more gently dipping strata, observed both in the northeastern and northwestern portion of the study area. (C) Sediment package 2.5 m thick located between outcropping, tilted strata. This package aligns with the shore-oblique sorted bedforms.
Figure 26. Mean grain size distribution of 14 surficial sediment samples collected from offshore of Surfside Beach. Mean grain size is highest in the northern portion of the study area and decreases towards the south.
Figure 27. Photographs of surficial sediment (left) and ground hardbottom sediment (right) collected while diving. Surficial sediment is primarily composed of quartz and shell fragments with small amounts of glauconite (green mineral). Ground hardbottom sediment is composed primarily of quartz and glauconite, with some shell fragments. Photographs suggest that the hardbottom sampled within the study area is not a major source of new sediment to the coastal zone.
Fig. 28. Photomicrographs of hardbottom thin sections (left – plain polarized light, right – crossed polarized light) of samples collected while diving. Explanations are from top to bottom. Sample D-2 was collected from the arcuate ridges and is characterized as phosphatic glauconite sandstone with a mud dominated matrix or calcite cement. Glauconite ranges in color and morphology. Sample D-4 was collected while diving, though the sample was not collected from outcropping strata. D-4 is characterized as phosphatic glauconite sandstone with a mud dominated matrix or calcite cement. Dolomite is also present in some instance. Sample DS-2 was collected outside of the study area and is characterized as a quartz sandstone with very little to no glauconite.
Figure 29. Photomicrographs of hardbottom thin sections (left – plain polarized light, right – crossed polarized light) of samples collected on the beach. Explanations are from top to bottom. Sample B-1 is largely composed of quartz with small amounts of glauconite and is characterized as quartz sandstone. Samples B-10 has abundant bioclasts and small amounts of quartz grains with a calcite cement. B-10 is characterized as a fossiliferous limestone.
Figure 30. Foraminifera picked from sample B-7. Foraminifera looks suspiciously like Thalmaninella greenhornensis, though more work needs to be done to confirm this assertion. If correct, this finding could be used as an age diagnostic tool, suggesting that sample B-7 is Cretaceous in age.
Figure 31. Screen capture from Fledermaus showing electrical resistivity tomograms (ERTs). Highest resistivity values are observed in the northwestern and southwestern portion of the study area and decrease with increasing distance from the shore. This increased resistivity nearshore is likely a result of the lithologic properties, rather than pore fluid salinities.
Figure 32. Gridded image showing electrical resistivity measurements (Ohm-m) extracted at 10 m below the sea surface, which is just underneath the seafloor. Electrical resistivity track lines are plotted on top to provide a reference to the data points used for interpolation. Note that Line 5 and half of Line 6 were not included in the interpolation as there was an unknown technical issue with the Lowrance GPS.
Figure 33. Gridded image showing electrical resistivity measurements (Ohm-m) extracted at 15 m below the sea surface. Electrical resistivity track lines are plotted on top to provide a reference to the data points used for interpolation. Note that Line 5 and half of Line 6 were not included in the interpolation as there was an unknown technical issue with the Lowrance GPS.
Figure 34. Gridded image showing bottom water $^{222}$Rn concentrations (dpm/L) collected over the survey area. Data points and track lines are plotted on top to provide a reference to the distance each data point encompasses (each data point is an average over a 10 min cycle). Notice that the highest radon concentrations are associated with the sinuous ridge feature in the southeastern portion of the study area.
Figure 35. Rn-222 concentrations (dpm/L) collected on April 06, 2018. Error bars represent the analytical uncertainty of each data point.

Figure 36. Rn-222 concentrations (dpm/L) collected on April 12, 2018. Error bars represent the analytical uncertainty of each data point.
Figure 37. Rn-222 concentrations (dpm/L) collected on April 06, 2018. Error bars represent the standard deviation of the dataset. Two high outliers exist, suggesting areas of enhanced radon activity, relative to the surrounding waters.

Figure 38. Rn-222 concentrations (dpm/L) collected on April 12, 2018. Error bars represent the standard deviation of the dataset. Three high outliers exist, suggesting areas of enhanced radon activity, relative to the surrounding waters.
Figure 39. Images of glauconite grains showing many different morphologies and a range of colors from light to dark green. The morphology of glauconite grains depends on the host mineral that was replaced by glaucontie. Modified from Smaill (2015).
Figure 40. Explanation of four potential modes of glauconite genesis and a summary of synonymous terms often used in the literature. Authigenic and allogenic are the primary modes of genesis that are of interest for this study. Modified from Fischer (1999).
Figure 41. Bathymetry data showing shore-perpendicular sorted bedforms with relief of 20 – 30 cm. Sediment cover within the study area is patchy and often concentrated to certain areas such as the small sorted bedforms located in the central portion of the study area.
Figure 42. Map showing gridded electrical resistivity values (Ohm-m) extracted at 10 m below the sea surface in relation to a mapped paleochannel within the study area. Blue lines represent the margins of the mapped paleochannel. Notice that the highest resistivity values are located within the mapped paleochannel.
Resistivity of geologic materials. Modified from González-Álvarez et al. (2014).

Figure 43. Resistivity-conductivity values for various rock forming materials, showing large variability in the electrical properties of different rock types.
Figure 44. (Left) Map showing $^{222}$Rn concentrations collected by Peterson (unpublished data) in 2010 along the Grand Strand, SC. (Right) $^{222}$Rn concentrations compared to $^{222}$Rn concentrations measured during this study. This serves as a reference for what concentrations should be expected within Long Bay. Note that there are two different scales for each dataset.
Figure 45. Map showing gridded $^{222}$Rn concentrations (dpm/L) in relation to the location of a mapped paleochannel. Blue lines represent the margins of the mapped paleochannel. Notice that the highest $^{222}$Rn concentrations are located outside of the paleochannel, or along the channel flanks.