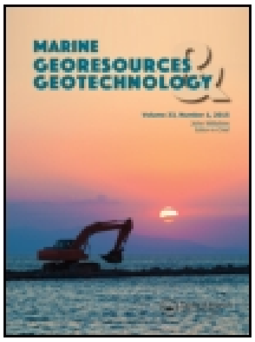

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ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/umgt20

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To cite this article: Ian Conery, John P. Walsh, David Mallinson & David R. Corbett (2021): Marine Geology and Sand Resources of the Southern North Carolina Inner Shelf, Marine Georesources & Geotechnology, DOI: 10.1080/1064119X.2021.1967531

To link to this article: https://doi.org/10.1080/1064119X.2021.1967531

Published online: 26 Aug 2021.

MARINE GEORESOURCES & GEOTECHNOLOGY
https://doi.org/10.1080/1064119X.2021.1967531

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Marine Geology and Sand Resources of the Southern North Carolina Inner Shelf

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ABSTRACT

Beach nourishment is a popular engineering-with-nature (EWN) strategy used globally for shoreline stabilization and coastal storm damage reduction. Large-scale projects require dredging from offshore sand borrow sources. However, suitable sands for nourishment are not ubiquitous offshore, especially in sediment-starved southern NC. In 2015, >300 nautical miles (555 km) of sub-bottom, sidescan, bathymetry and 38 cores/grabs were collected in data gaps offshore southern NC and interpreted for geologic horizons and potential nourishment-compatible sand thickness. In addition, hundreds of paleochannels were mapped and evaluated for fill patterns and resource potential. Various forms of hardbottom were delineated, sometimes in close proximity to sand resources. Results show high spatial variability in the distribution of beach-compatible sands across the southern NC shelf, where only a thin sand veneer is observed in many locations, although some regions contained continuous deposits exceeding 3 m. The thickest shoal deposits (>5 m) were observed offshore New Hanover County Region. Underlying strata and bathymetry appear to affect channel shape and distribution. Channels with acoustically transparent fill may be suitable as nourishment sources, yet many channels show complex and variable fill suggestive of tidal and estuarine environments. Seafloor reconnaissance data are valuable in preventing multi-use conflicts on the shelf as shelf areas are increasingly being explored for other functions (e.g, wind farms, oil/gas, fish habitat). These findings provide a useful starting point for coastal managers seeking sufficient offshore sediment resources for nourishment in response to future storm events and sea-level rise.

ARTICLE HISTORY
Received 10 October 2020
Accepted 9 August 2021

KEYWORDS
N Atlantic shelf; quaternary stratigraphy; sand resources; geophysics; beach nourishment; paleochannels

1. Introduction

Like many areas around the world, the North Carolina ocean coast is experiencing widespread erosion as a result of reoccurring storm events (Luijendijk et al. 2018). The shelf geomorphology and geology play a key role in shoreline changes (e.g., Miselis and McNinch 2006) and also hold sand resources to mitigate against erosion. Beach nourishment is used worldwide as a strategy to combat erosion of sandy coasts (e.g., de Schipper et al. 2021). Often described as a "soft-engineering" strategy, nourishment is designed to dissipate wave energy and minimize storm surge to protect infrastructure and to sustain recreational beaches that are economically essential in tourism-driven areas. Along some sections of the U.S. Mid-Atlantic Coast nourishment occurs every few years. For example, since 1939, nearly $850 million has been spent in North Carolina (NC) on nourishment of > 250 projects and > 250 miles of coastline (PSDS 2018).

Beach nourishment is typically a multi-pronged process involving multiple stakeholders, permitting steps and geologic reconnaissance, surveys, and engineering (ASBPA 2007). In the case of dune maintenance and small-scale beach projects (e.g., <50,000 cubic yards), trucked sand is often economically effective (Dobkowski 1998). However, large-scale beach nourishment projects, typically involve the dredging of sand and pumping it from offshore borrow sites (i.e., with a hydraulic dredging system). While beach nourishment is simple in theory, suitable sediment, i.e., material that is compatible with the natural beach, is not ubiquitous offshore. Thus, project costs fluctuate with distance to the borrow area. Costs are also dependent on the geological nature of the borrow source and the efforts needed to extract the beach quality sand (Leatherman 1989; Dobkowski 1998). Regional sediment management (RSM) is a strategy highlighted by the U.S. Army Corps of Engineers, and in keeping with this management philosophy, use of navigational dredged material is considered when possible. But, the persistence of storms and chronic erosion has triggered an increased demand for diminishing sand resources in State waters (Drucker, Waskes, and Byrnes 2004), making it necessary to target material from the Outer Continental Shelf (OCS) under federal jurisdiction.

Following the detrimental impacts of Hurricane Sandy (2012) along the east coast of the U.S., the Bureau of Ocean Energy Management (BOEM) recognized that establishing a

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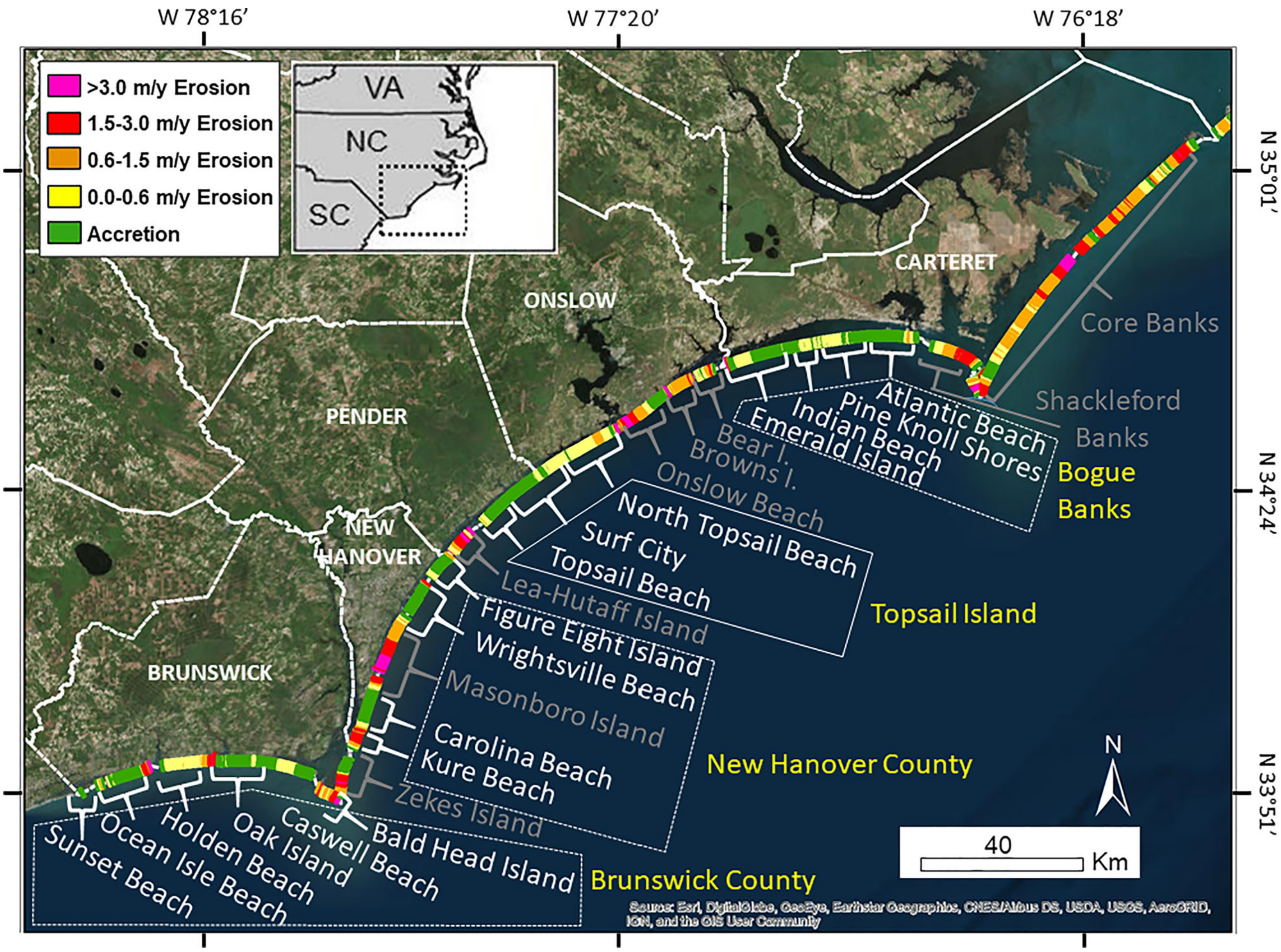

Figure 1. Site map of southern North Carolina and focus areas (labeled yellow). White labels indicate incorporated towns that are managed with beach nourishment. Gray labels signify undeveloped zones that include state and federal lands which are unlikely to be nourished. Long-term DCM (2017) shoreline change rates are shown by colors (see legend) and show the variability of erosion along the state.

central hub for existing geologic knowledge relevant to potential borrow sources would increase response efficiency and provide a better understanding of the distribution, character and volume estimate of known suitable sands (Walsh, Conery, Mallinson, et al. 2016). In response, research was funded in thirteen states to collect and synthesize data on marine sand resources. Based on this and earlier research here and elsewhere around the world, it is understood that offshore sand bodies persist in a variety of morphosedimentary forms depending on varied complex geologic history, and often require multiple survey and sediment sampling techniques (e.g., sub-bottom profiling, vibracoring) to sufficiently map and characterize them.

Widespread surveying has been conducted in northern NC (e.g., Thieler et al. 2014; NCDCM 2016), but there was a lack of broad-scale data coverage in the southern NC OCS as work has been conducted primarily in NC State waters (0-3 mi). To address this deficiency, reconnaissance sub-bottom geophysical data and vibracores were collected in 2015 based on data coverage gaps, as part of the Atlantic Sand Assessment Project, a post-Sandy BOEM-funded sand resource assessment effort (Walsh, Conery, Mallinson, et al. 2016). The work herein stems from this project, and specific objectives are to: 1) examine the geomorphology and geology of the southern NC shelf, 2) evaluate the distribution of sand resources offshore southern NC and its relationship to geologic context, and 3) assess the variability in form and classification of paleochannels and hardbottom.

2. Study region

The underlying geologic framework varies significantly along NC and has a strong control on the modern configuration of the coastline (Riggs, Cleary, and Snyder 1995; Zaremba et al. 2016). The northern part of the State is characterized by long, narrow barrier islands with few inlets and large estuaries, whereas the southern portion has shorter barrier islands, more inlets and smaller estuaries (Riggs, Cleary, and Snyder 1995) (Figure 1). Differences in tectonics, sea-level rise and sediment supply influenced the long-term basin evolution. As sea-level rose following the Last Glacial Maximum and into the Holocene, shorelines retreated and transgressive ravinement by wave action eroded and exposed subsurface sedimentary strata consisting of shelf, coastal, and fluvial lithofacies (e.g., relict barrier complexes, tidal deltas and fluvial deposits) (Rutecki et al. 2014). The northern coastal zone contains a thick wedge (up to 90 m) of Quaternary strata that has been reworked during sea-level change (Mallinson et al. 2005; Mallinson et al. 2010; Culver et al. 2011; Thieler et al. 2014; Culver et al. 2016). Offshore

Table 1. Beach nourishment data from the Beach and Inlet Management Plan (NCDENR 2016).

Location	First year of record	Number of times nourished	Total volume nourished (cy)
Atlantic Beach/Ft. Macon	1958	14	17,525,228
Bald Head Island	1991	12	11,186,190
Cape Hatteras	1966	3	1,812,000
Cape Lookout	2006	1	75,700
Carolina Beach	1955	36	19,803,048
Caswell Beach	2001	2	256,600
Emerald Isle	1984	19	4,571,214
Figure Eight Island	1977	26	6,113,852
Hatteras Island	1974	7	887,801
Holden Beach	1971	49	4,661,045
Indian Beach/Salter Path	2002	3	1,385,692
Kill Devil Hills	2004	1	38,016
Kitty Hawk	2004	1	143,000
Kure Beach	1998	6	5,964,932
Masonboro Island	1986	6	3,234,686
Nags Head	2001	3	4,800,000
Oak Island	1986	9	6,545,287
Ocean Isle Beach	1974	18	4,479,790
Ocracoke Island	1986	5	516,062
Onslow Beach	1990	4	405,829
Pea Island	1990	20	9,673,228
Pine Knoll Shores	2002	6	2,969,185
Rodanthe	2014	1	1,618,083
Topsail Island	1982	20	5,394,479
Wrightsville Beach	1939	26	14,709,157

sand bodies, which can serve as potential borrow areas, are present but localized (Swift 1976; McBride and Moslow 1991; Snedden and Dalrymple 1999; Walsh, Conery, Gibbons, et al. 2016). Southern NC, however, is characterized by even more limited sand bodies (i.e., "sediment-starved") along with exposed Cretaceous through Pliocene rocks along much of the seafloor (Meisburger 1979; Snyder, Hoffman, and Riggs 1994; Riggs, Cleary, and Snyder 1995). Ultimately, with chronic shoreline erosion rates (often less than 1 m/yr; NCDCM 2016), sand resource demands may pose problems along many parts of the NC coast, but considering the geological setting, a number of communities are facing long-term challenges.

3. Background

3.1. Shoal and sediment sources

Sand resources exist in a variety of geologic forms, ages and locations. In North Carolina, moderate volumes are extracted at several localities from navigational channels for "beneficial reuse" in nourishment projects (NCDCM 2017). The work presented here, however, focuses on the shelf, where sand bodies are in the geomorphic form of ridges, rippled scour depressions, shoals/sediment banks, channel fill and shoal complexes and fields. Shoals are generally divided into relict shoals (e.g., Oregon Shoals; Thieler et al. 2014), cape-associated shoals (e.g., Frying Pan Shoals) and sorted bedforms (e.g., Wrightsville Beach; Thieler et al. 2001). In northern NC, the ample Quaternary sand supply has led to the formation of shoal fields that are kilometers wide with relief up to 10 meters (e.g., Oregon Shoals; Swift 1976; Snedden and Dalrymple 1999; Thieler et al. 2014). In contrast, in southern NC unconsolidated sediment has been reported to be less abundant on the shelf (Riggs, Cleary, and Snyder 1995), and sources are typically small-scale sorted bedforms or thin modern veneers (Hine and Snyder 1985; Gutierrez et al. 2005; Thieler et al. 2001).

3.2. Paleochannel background

Buried paleochannels also may contain sand fill useful for nourishment. Fluvial and tidal processes are the primary channel-carving mechanisms (Gutierrez et al. 2003). Major paleo-river systems on the U.S. East Coast that have been extensively surveyed include the Hudson (Carey, Sheridan, and Ashley 1998), the Delaware (Fletcher, Knebel, and Kraft 1992), the Susquehanna/Potomac (Colman et al. 1990), the Pee Dee/Waccamaw (Baldwin et al. 2006) and the Roanoke/Albemarle Rivers (Riggs, Cleary, and Snyder 1995; Boss, Hoffman, and Cooper 2002; Mallinson et al. 2005). Commonly referred to as incised valleys, these systems generally exhibit dendritic drainage patterns with a large trunk channel. The preservation potential of a paleo-channel is contingent upon the initial channel morphology, tidal enhancement, depth of wave ravinement and burial (Belknap and Kraft 1981). The best preservation potential for channel morphology has been suggested to occur in outer shelf areas of rapid transgression during the late Pleistocene/early Holocene, as shown by seismic data collected along the paleo-Delaware River (Belknap and Kraft 1981; Childers et al. 2019; Brothers et al. 2020). As such, the rate of sea-level rise is believed to be critical to the depth of ravinement and channel preservation (Belknap and Kraft 1981).

3.3. Shelf habitat

Sediment bodies and hardbottom also may serve as critical habitat for fish and other benthic organisms in addition to being sources for beach nourishment (NCDEQ 2016; Rutecki et al. 2014). In order to best manage multi-use conflicts, an understanding of the effects of dredging on habitat is crucial. For shelf mineral resource extraction, projects must comply with NOAA fisheries and the U.S. Fish and Wildlife Service guidelines as outlined in the Endangered Species Act (ESA) and Magnuson-Stevens Fishery Conservation and Management Act (Magnuson-Stevens Act). Ridge and swale and cape-associated shoal complexes have been defined as essential fish habitat by NOAA Fisheries (NOAA 2014). Sand dredging has been shown to have several short- and long-term physical and biological impacts affecting habitats (Rutecki et al. 2014). Physical effects include alteration of sediment grainsize and transport, wave and current patterns and turbidity, which in turn have a biological influence (Drucker, Waskes, and Byrnes 2004; Hayes and Nairn 2004). Direct biological impacts include alteration or removal of benthic epifaunal and infaunal communities that are linked to higher trophic levels (Drucker, Waskes, and Byrnes 2004; Hayes and Nairn 2004). Spatially compiling all knowledge on potential borrow areas is important to determining habitat effects and for long-term, sustainable management of multi-use shelf resources.

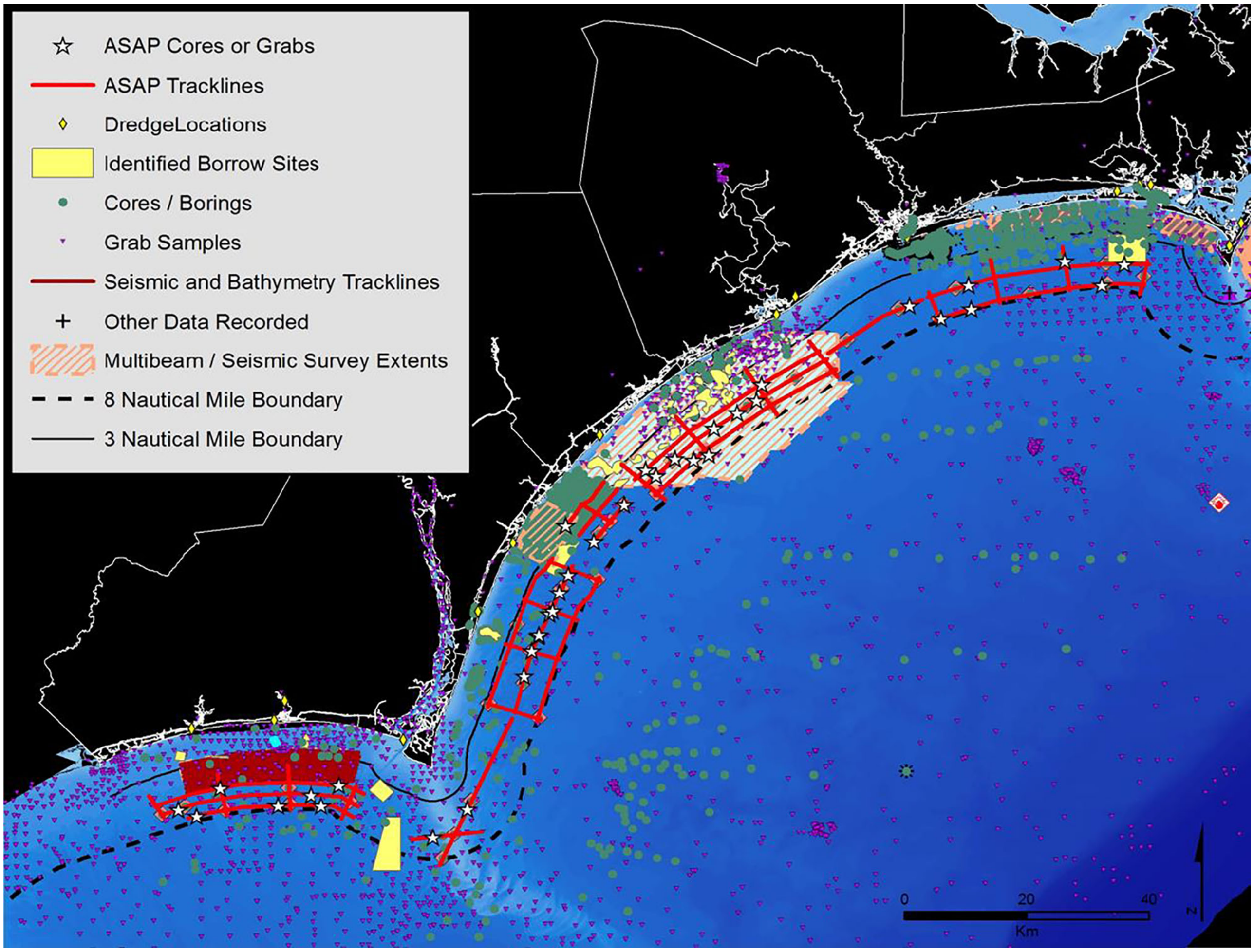

Figure 2. Survey lines (red lines) and core locations (stars) analyzed in this study. The ASAP data collection in 2015 targeted the Outer Continental Shelf offshore NC (3–8 nautical miles) and was strategically planned to fill gaps in available federal, state and private datasets (shown; Walsh, Conery, Mallinson, et al. 2016).

3.4. NC nourishment history

Wrightsville Beach, in the southern part of the State, conducted the first beach nourishment in NC in 1939 (NCDCM 2016) (Figure 1). Since then, dozens of nourishment and renourishment projects have taken place in NC (Table 1), totaling over $800 million (Program for the Study of Developed Shorelines 2018). Today, beach nourishment is being considered for about 75% (120 of 160 miles) of the developed NC oceanfront shoreline (NCDCM 2016).

In the Bogue Banks region (Atlantic Beach to Emerald Isle; Figure 1), the process of implementing a federally sponsored 50-yr Coastal Storm Damage Reduction (CSDR) project began in 1989 and was authorized in 2016. In addition, Carteret County adopted the Bogue Banks Beach Master Nourishment Plan in 2010 because future federal funding is not certain (BBMNP 2017). Atlantic Beach was recently nourished in 2017 with >650,000 cy of sand. In 2019, three areas of Bogue Banks (Emerald Isle, Indian Beach and Salter Path) will be nourished with 945,446 cy using sediment from the Offshore Dredged Material Disposal Site (ODMS) as part of the Post-Florence Renourishment Project (BBFRP 2019).

In the Topsail Region (Figure 1), a CSDR was authorized in 1992, but it did not proceed. Because federal projects were not ensuing, the Town of Topsail Beach 30-Year Beach Management Plan (2011) was developed. The most recent project in 2015 used 860,000 cy from inlet and other federal navigation channel sources.

In the New Hanover County Region, Wrightsville Beach was authorized for a CSDR in 1965 and was most recently nourished in 2014 and 2018 using sediments primarily from Masonboro Inlet (USACE 2015). Carolina Beach was authorized for CSDR in 1962, one of the first in the U.S., and was most recently nourished in 2016 (890,000 cy) using the Carolina Beach Inlet (USACE 2010). Kure Beach also was authorized for CSDR in 1965 and was most recently nourished in 2016 (655,000 cy) using an offshore borrow source.

In the Brunswick County Region, a CSDR was approved for Ocean Isle Beach in 2001 for a 3-year maintenance cycle that was most recently conducted in 2017 (270,000 cy) using sediment from Shallotte Inlet. Holden Beach was most recently nourished in 2017 (1,800,000 cy) using an offshore borrow site. Oak Island was nourished in 2015 (227,315 cy) using Eastern Channel sediments and again in 2018. Caswell Beach was nourished in 2018 using dredged sediments from the Wilmington Harbor entrance channel. Finally, the Village of Bald Head Island was nourished in 2015 (1,850,000 cy) from the Wilmington Harbor entrance channel.

Table 2. Calibrated ^{14}C ages and associated cores and depths.

Sample ID	Depth in core (cm)	cal y BP (2σ)
VC03	183	6661–6831
VC08	93	36,346–37,361
VC08	319	44,568–45,679
VC09	144	969–1134
VC09	292	8025–8196
VC09	436	44,979–46,075
VC09	495	38,745–39,663
VC09	523	33,583–34,001
VC13	140	7833–7978
VC15	201	42,253–42,892
VC17	46	5315–5519
VC17	61	2980–3177
VC17	373	7980–8143
VC18	497	10,540–10,735
VC19	124	8185–8338
VC23	67	42,119–42,755
VC23	183	45,030–46,134
VC24	30	1529–1677
VC24	241	8531–8744
VC25	21	4580–4795
VC25	247	4415–4598
VC25	328	4769–4892
VC27	26	20,866–21,268
VC31	26	1710–1858
VC31	43	9875–10,133
VC31	86	9917–10,156
VC31	122	10,500–10,683
VC31	170	34,435–34,952
VC32	23	32,415–33,268
VC32	27	42,274–42,933
VC32	61	45,083–46,351
VC33	30	563–668
VC33	117	9078–9313
VC33	197	48,446–50,000
VC34	140	45,407–46,737

All analysis used shells or shell fragments.

3.5. Existing data

Many different entities have conducted seafloor mapping and geological research offshore NC over the last half century. As a result, a wide variety of sediment, seismic, and bathymetric data are available; recent reports review available information (NCDCM 2017; Walsh, Conery, Mallinson, et al. 2016) (Figure 2). The largest data collections (many with large spatial coverage) are available from federal agencies, including the National Oceanic and Atmospheric Administration (e.g., the National Centers for Environmental Information, formerly the National Geophysical Data Center at https://www.ngdc.noaa.gov/), the U.S. Army Corps of Engineers and the U.S. Geological Survey (http://walrus.wr.usgs.gov), including information in usSEABED and from a large cooperative study conducted in the 2000s (Reid et al. 2005). Other data sources include information from academic, private, state and other federal efforts.

4. Methods

4.1. Priority target areas and data collection

As a result of a large USGS cooperative project (OFR 2011-1015) and earlier work, a relatively extensive amount of geophysical and core data, and thus geological knowledge, exist in northern NC (Thieler et al. 2013, 2014). In early 2015 with input from NC scientists, managers, and private consultants, it was agreed that reconnaissance data collection would occur in southern NC for the BOEM-funded Atlantic Sand Assessment Project (ASAP), where there was sparse data on the OCS (Figure 2). These data are the foundation of the research herein. CBI (currently APTIM) collected 317 nautical miles of sub-bottom data, interferometric sidescan sonar data (EdgeTech 6205), swath bathymetry data (EdgeTech 6205), magnetometer (Geometrics G-882) along with 24 vibracores and 14 surface sample grabs (Figure 2). High resolution seismic reflection data were collected with an EdgeTech 3200 chirp sub-bottom profiler system and an EdgeTech 512i towfish using a ping rate of 8 Hz and pulse frequencies between 0.7 and 12 kHz, resulting in a maximum vertical resolution of 10 cm. A speed of sound through water of 1500 m/s was used for sub-bottom data.

4.2. Core logging and ^{14}C dating

Cores were logged on the CBI vessel, and subsequently, logs were refined and verified by a team from East Carolina University. Cores were subsampled at lithologic boundaries, or at a minimum of 30 cm intervals. For grain-size analysis, a Rotap system was used with 12 sieves at 0.5 phi intervals from 2.25 to 4.0 phi. While relogging the cores, 29 *in situ* shells or shell fragments were extracted for ^{14}C analysis (Table 2). Samples were sent to the Center for Applied Isotope Studies, Univ. of Georgia for dating. The open source software Calib (Stuiver et al. 2019) was used to calibrate age ranges using the radiocarbon age, standard deviation in age, and MARINE13 curve. Two sigma values are reported in years before present (Cal y BP).

4.3. Sand thickness analysis

Chesapeake Technologies Sonarwiz software (Version 6.04) was used for sub-bottom processing and sand thickness calculations. SEG-Y Chirp files were imported and smoothed using the swell filter function. Vibracores and grab samples were added based on coordinate positions within seismic lines. The seafloor reflector was created using the automated bottom-tracker. For the purpose of this work, the interpreted base of reworked Holocene sand (H), the Quaternary Transgression surface (QT), the base of Quaternary channels (QC), and hardbottom (R) were interpreted and digitized. These reflectors are common in the study region. After digitization, the reflector thickness calculator was used to estimate sand thicknesses between the relevant reflectors and the seafloor (by subtracting elevation values). These thicknesses were exported as XYZ text files and imported to ArcGIS as points for analysis of the spatial distribution of the reflectors and related sand thicknesses.

5. Results

5.1. ASAP results and interpretations

This study focused on mapping key reflectors in the region that define important stratigraphic units. Properties of these

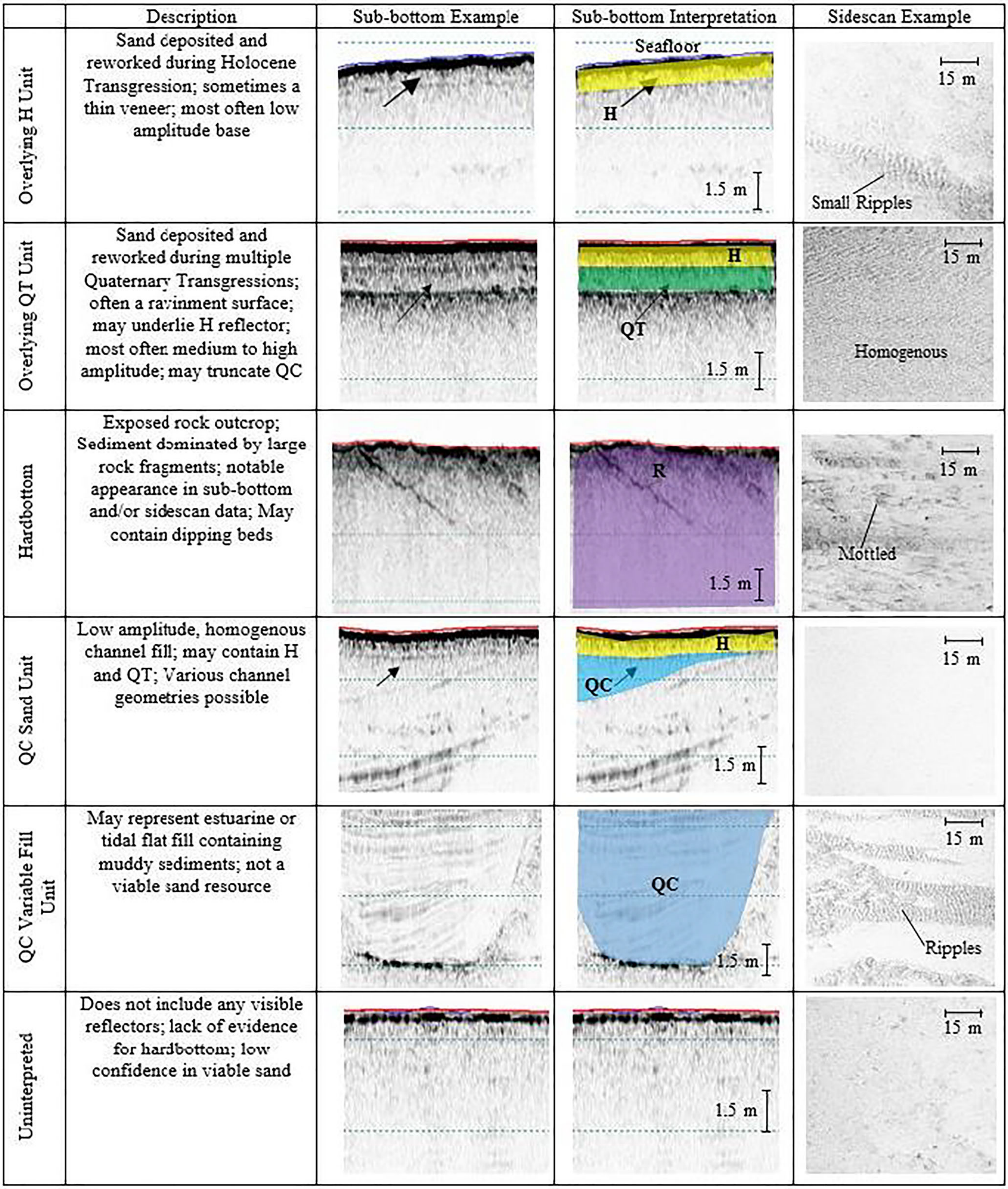

Figure 3. Interpretation guide depicting various seismic unit examples, descriptions and associated appearances in sub-bottom and sidescan data. Note, this is not all-inclusive and these lithologic units have a variety of geophysical signatures.

reflectors and the units they define are presented in Figure 3. Based on the core and seismic observations, units H and QT are the most likely sources for unconsolidated sands with potential for beach nourishment. Specific examples are provided below.

5.2. Bogue banks region

The Bogue Banks region of Carteret County (Figure 4) shoreline is oriented predominantly E-W and is bordered by Cape Lookout to the east. The survey lines are relatively shore parallel, contain four north-south shore-perpendicular

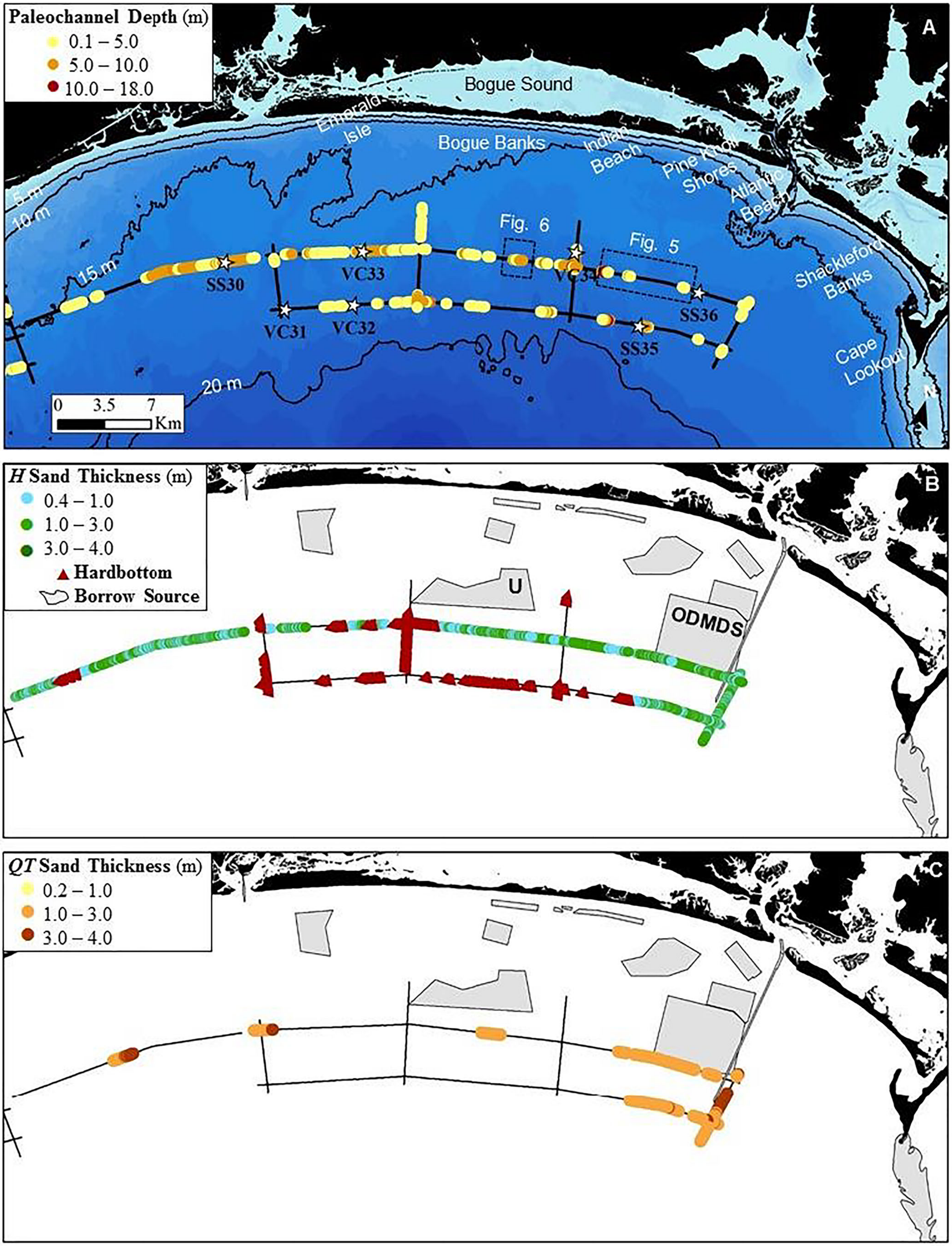

Figure 4. Bogue Banks Region ASAP interpretations. Irregular black lines in top panel represent 5 m isobaths. Vibracores (VC) and surface samples (SS) are represented by stars. Colors represent depth below seafloor of channels identified in Chirp data. Polygons are previously identified borrow sources; those labelled U and ODMS are discussed in text.

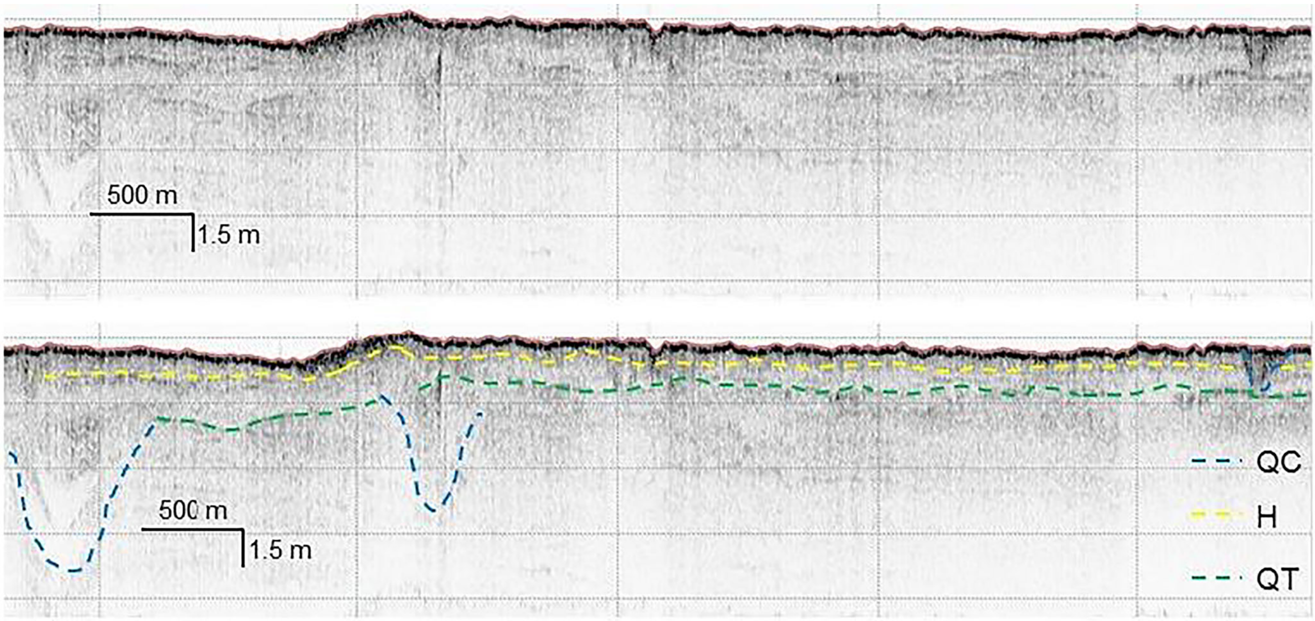

Figure 5. Example seismic line and interpretations from Bogue Region. Location indicated by black dashed box in Figure 4.

crossing lines, and are between 7.4 and 15.0 km offshore (Figure 4). Water depths range from 15.0 m (closest to shore) to 19.0 m at the seaward edge of the survey area. Seafloor gradients vary in the region, and slopes of 0.2 m/km occur to the east (seaward of the 17 m isobath). The steepest slopes of 2.5 m/km occur toward the center of the region (seaward of the 18 m isobath). The seafloor is generally low relief, and the highest relief of up to 1.5 m occurs at a ridge and depression in the SE quadrant. The eastern half of the region contains three small-scale, shore-detached ridges that extend NW-SE and are 1 m high, 0.5 km wide, range in length from 2.0 to 3.4 km and have little to no asymmetry.

The ASAP Bogue Region contains an extensive modern sand layer (Unit H) mapped in 49% of the total survey distance with unit thicknesses reaching up to 3.59 m in the northern and southeastern portions (mean = 1.06 m)(Figure 4). These observations are consistent with Hine and Snyder (1985) who also note the patchy presence of a 1-2 m thick Holocene veneer on the inner shelf. Extensive Holocene deposits are thought to be absent due to wave ravinement which removed much of the sedimentary record in Onslow Bay. Consequently, Tertiary rocks and sediments crop out at the seafloor in many locations (Hine and Snyder 1985; Freeman et al. 2012).

The deeper QT reflector is visible in the eastern third of this region (20% of the mapped linear distance) and the overlying unit contains thicker sands up to 4.7 m (mean = 2.5 m)(e.g., Figure 5). Paleochannels and hardbottom are frequently observed in the central region (Figure 4), and are present in 31% and 23%, respectively, of the total mapped distance. When ASAP interpretations are overlain on Hine and Snyder (1985), numerous areas of mapped paleochannels align that are interpreted as relict tidal inlets/lower coastal plain streams that can be identified by truncation in the Tertiary seismic stratigraphy (Figure 6). Radiocarbon ages from four cores within channels show two channels contain surficial Holocene sand and variable Pleistocene fill below (VC31 and VC33; Table 2; Figures 4 and 7), whereas the other two channels are filled with Pleistocene or reworked sediments (0.3 1.5 m depth) (VC32 and VC34; Table 2; Figures 4 and 7). The infilling of the paleochannels is variable and complex, and mostly appears to be representative of estuarine and fluvial fill (i.e., sands interbedded with muds and clay and gravel base) (Hine and Snyder 1985). While some buried channels may contain sands suitable for nourishment as shown by core and seismic appearance, more core validation is needed. Hine and Snyder (1985) show areas of especially thick (10 20 m) Quaternary sediments within channels that are corroborated by ASAP data (see black box focus area in Figure 7).

Several previously identified potential borrow sources are identified in the vicinity of ASAP data. For example, the USACE (2014) indicate the "U" borrow source contains an estimated 8.9 million cubic yards (mcy) or million cubic yards (6.8 million m^3) of beach compatible sand (Figure 4). The Offshore Dredged Minerals Disposal Site (ODMDS),where Bogue Inlet channel sands have been dumped since 1987, is estimated to contain 28.3 mcy (21.6 million m^3) (Figure 4). At the ODMS site, dredge spoil sand (up to 4.9 m thick) overlies fine and silty sand that is stratified as much as 9.2 m below the seafloor, although its base is not continuous throughout the Bogue region (Freeman et al. 2012).

ASAP reconnaissance data provide several potential high volume areas of beach compatible sand that represent a complex geologic history and are in reasonable proximity to a series of towns with a history of nourishment (Table 1). Based on future demand of sand for continued replenishment projects (NCDCM 2017) these are viable options, if the need for additional resources arises.

5.3. Topsail island region

The shoreline in the Topsail Island region is oriented NE-SW. Three survey lines are shore-parallel, along with five

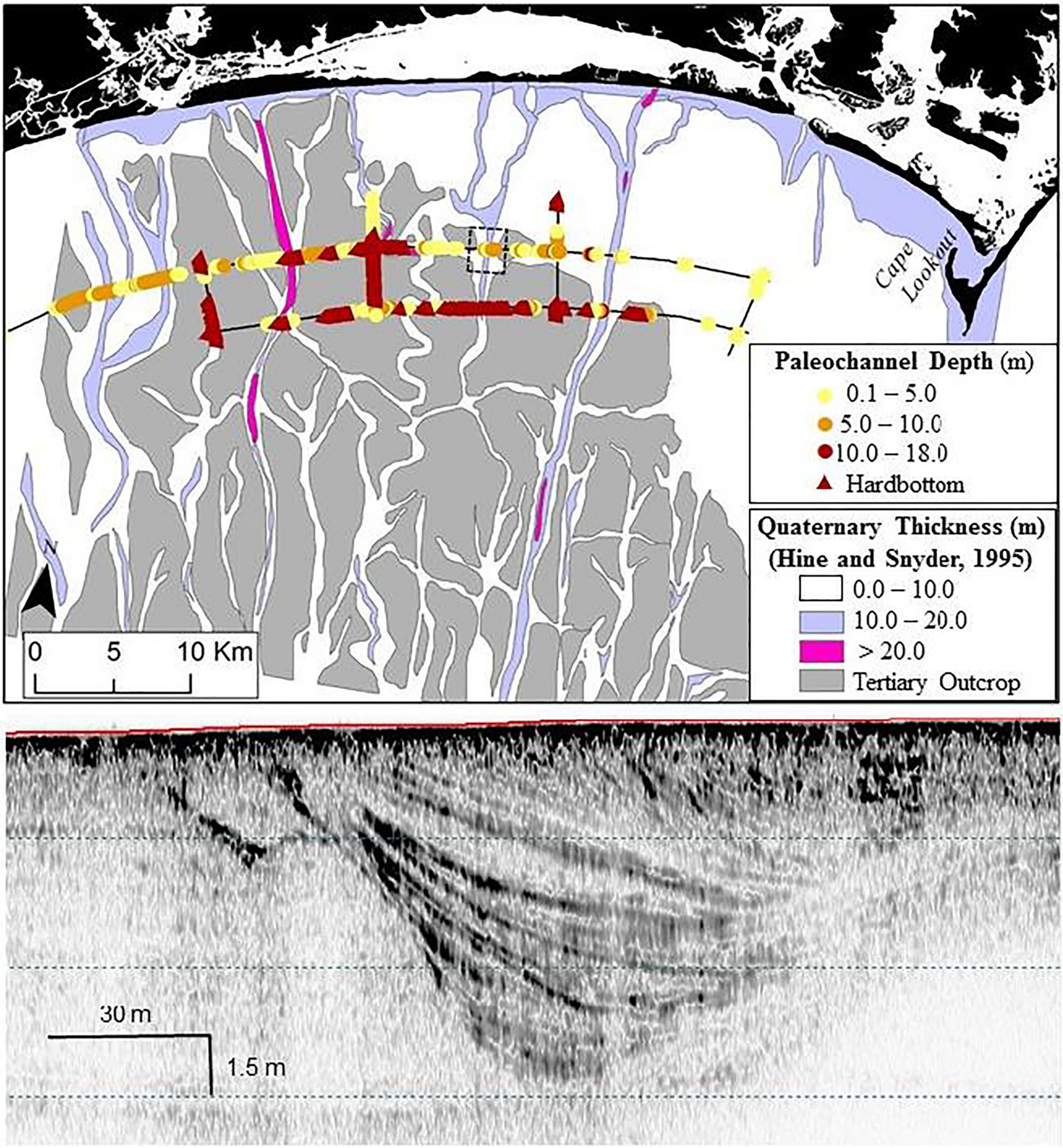

Figure 6. ASAP results draped over geo-rectified interpretations from Hine and Snyder (1985). Areas of thick Quaternary sediments and hardbottom as interpreted by Hine and Snyder (1985) often are corroborated by ASAP results. A channel example is shown (location is indicated black dashed box in top panel) where Hine and Snyder mapped particularly thick (10–20 m) Quaternary sediments.

shore-perpendicular crossing lines (Figure 8). Water depths range from 13 m closest to shore (5.4 km offshore) to 17 m at the seaward edge of the survey area (14.8 km offshore). The NE half exhibits a gently dipping seafloor (0.45 m/km slope) seaward of the 13 m isobath. The southern half of the region contains a valley-like feature with sidewalls up to 4 m/km in slope defined by the 20 m contour in Figure 8. The southern section of the region is characterized by a bathymetric fabric produced by a series of shore-detached, shore-oblique small scale ridges 1 m high, 1 km wide and ranging in length from 3.8 to 4.4 km. The highest local relief is 2.2 m. These ridge features become more pronounced seaward of the survey lines at the 15 m isobath.

Most of the Topsail region contains a sand unit (mean thickness = 1.0 m) reaching up to 2 m thick and visible in 73% of the total mapped linear distance (Figures 8 and 9). However, this modern sand unit is discontinuous and quite thin in most areas, making resource extraction by dredging unlikely. OSI (2004) and Snyder et al. (1988) indicated much of the region landward of the survey area is characterized by low relief Oligocene limestone and siltstone hardbottom overlain by a thin, patchy veneer of Quaternary sands

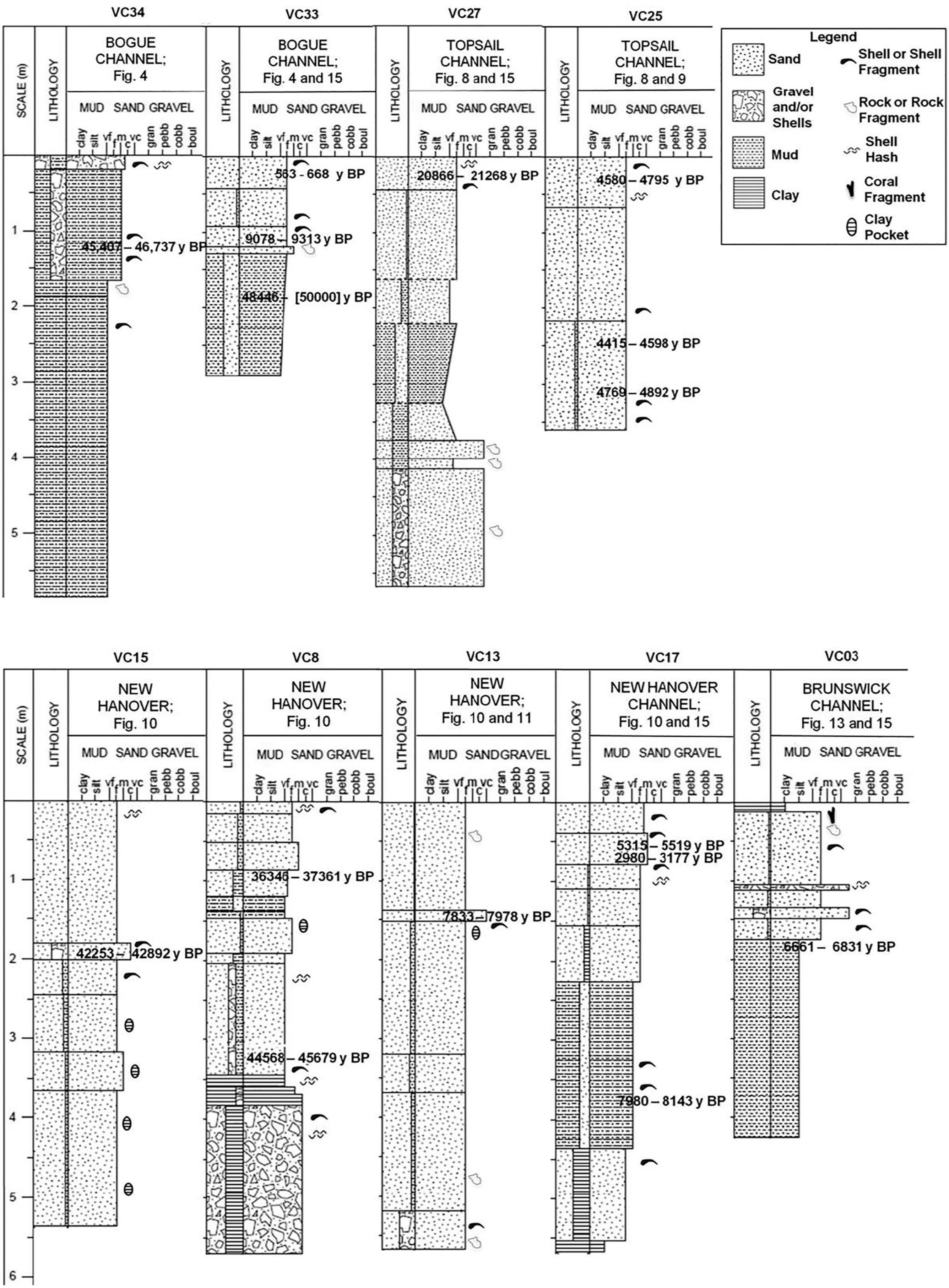

Figure 7. Core logs and associated ^{14}C age estimates at depth (calibrated years before present). Note, lithology column reflects relative percentages. Cores are in the order in which they are discussed in the text.

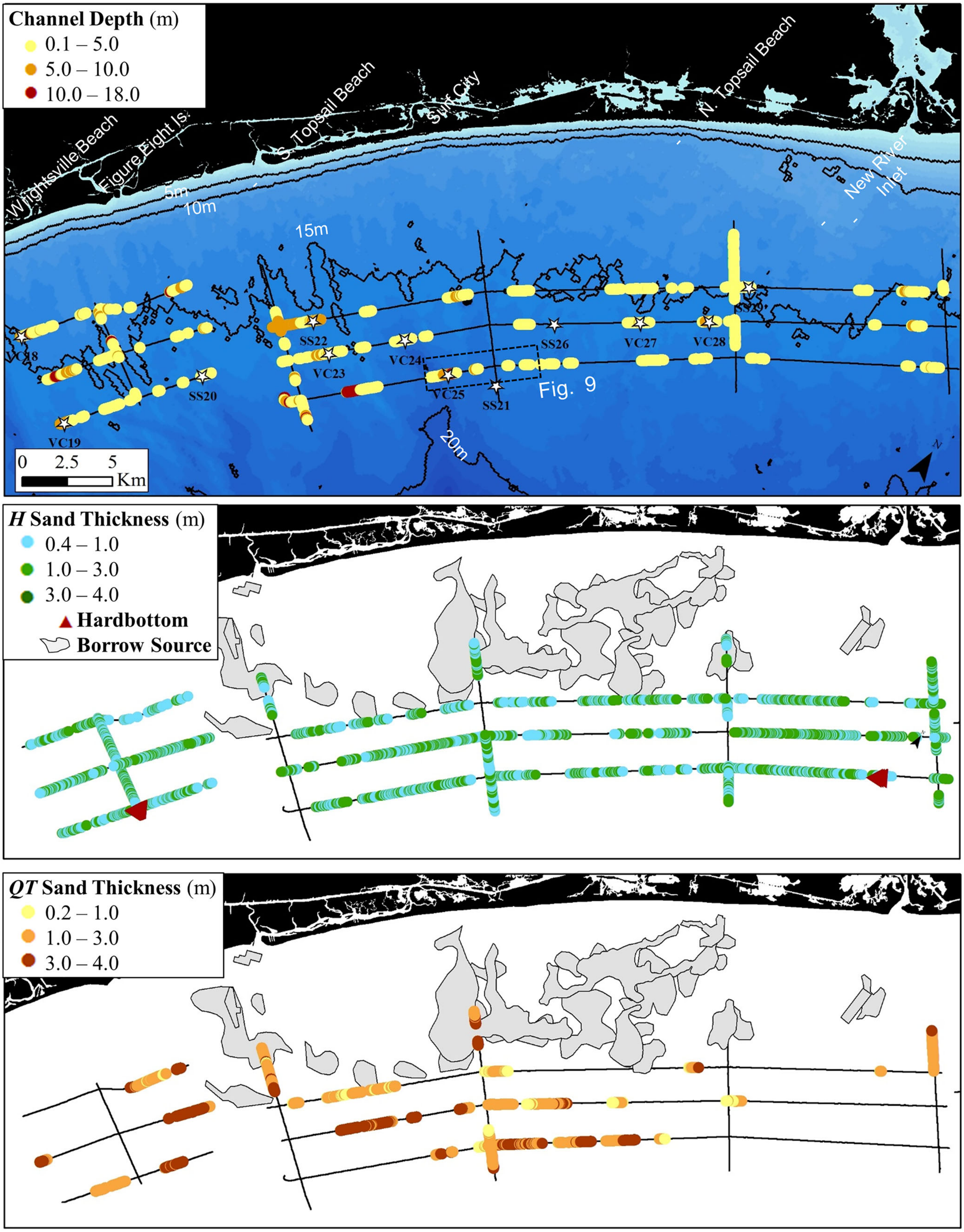

Figure 8. Topsail Island region ASAP interpretations. Irregular black lines in top panel represent 5 m isobaths. Vibracores (VC) and surface samples (SS) are represented by stars. Colors represent depth below seafloor of channels identified in Chirp data.Polygons are previously identified borrow sources; A1 is discussed in the text.

and gravels and numerous Quaternary channel-fill sequences. The QT reflector is interpreted in 29% of the total linear survey distance (mean unit thickness above QT= 2.6 m, range 0.2 to 6.4 m), and the unit above appears to be thicker

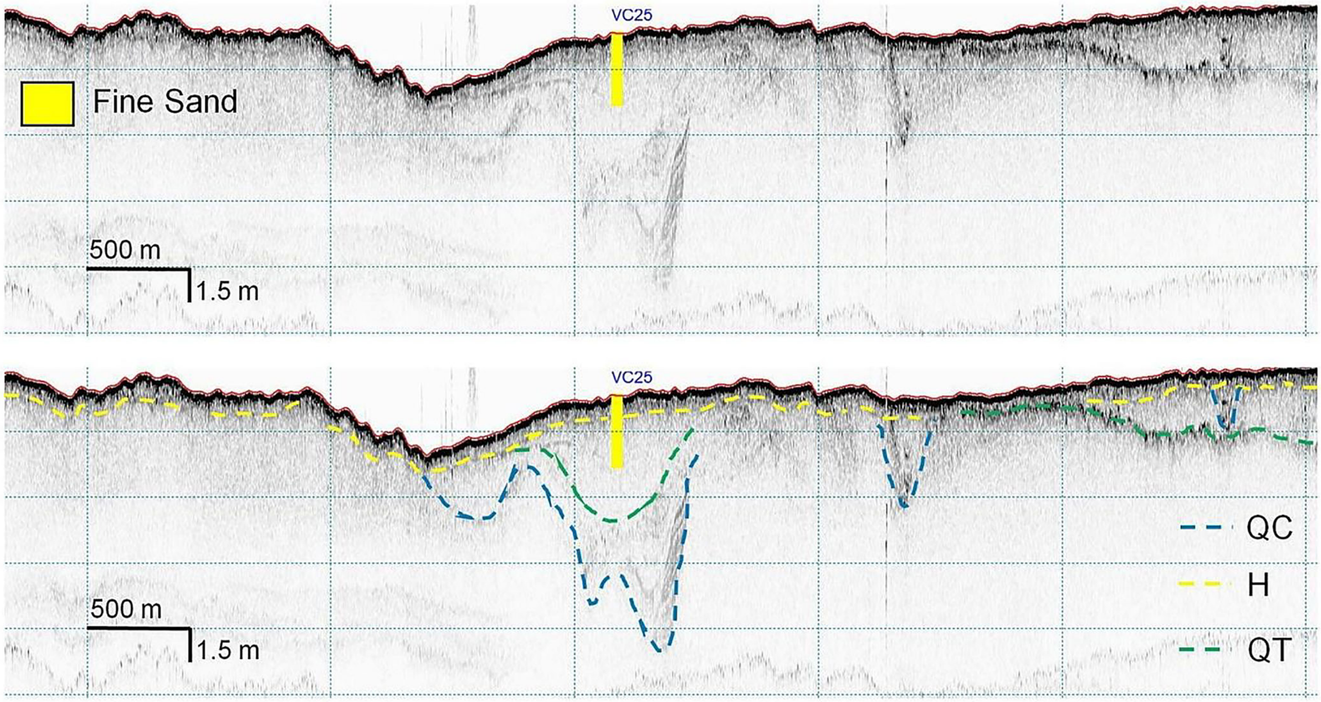

Figure 9. Example seismic line and interpretations from the Topsail region. Location indicated by black dashed box in Figure 8.

in the central section where many areas exceed 4 m (e.g., Figures 8 and 9).

Paleochannels also are widespread (31% of mapped distance) and are most common in the central areas (Figure 8). ASAP core data indicate some channels may contain usable sand (e.g., Figure 7), yet others are more heterogeneous and indicative of variable estuarine fill (i.e., silts and clays), also noted by OSI (2004). Radiocarbon ages from cores within four separate channels indicate two channels (VC23 and VC27; Figures 7 and 8; Table 2) are filled with shallow (< 2 m) Pleistocene (or reworked) sediments, whereas the other two channels are filled with Holocene sediments overlying the interpreted QT reflector (VC24 and VC25; Figures 7 and 8; Table 2). The Holocene channel fill is composed of a homogenous fine sand, while the Pleistocene channel fill consisted of variable estuarine lithofacies.

Mapped hardbottom is minimal in this region (1%) (Figure 8). Extensive low to high-relief hard bottom outcrops have been mapped nearshore of Surf City and New River Inlet, although a thin layer of sand covers much of the low relief hardbottom (Crowson 1980). Using sidescan, multibeam, and diver-collected ground truth data, HDR (2003) reported an irregular exposure pattern of hardbottom in this region extending from the 9.1 m contour to 8 km offshore. Much of the complexity of the exposure is likely due to the irregular burial of low relief hardbottom areas by sands.

An adjacent previously identified borrow source was recently examined by Coastal Planning and Engineering, Inc., (CPE) for Topsail beach projects. CPE conducted design-level surveys in the USACE-identified A1 potential borrow site, yet data collection stopped at 3 nm (i.e., State water boundary) (Figure 8). A1 contains an estimated 0.9 km^2 (214 acres) and 1.45 million m^3 (1.99 mcy) of potential beach compatible sand, although the town opted for a closer, less-expensive inlet-derived borrow source. The ASAP data reveal the extent of this potential borrow area into federal waters.

5.4. New Hanover County region

The New Hanover County region shoreline is oriented N/NE-S/SW. The survey lines are located between 5.6 and 15.8 km offshore and are near shore-parallel with four shore-perpendicular crossing lines. Water depths range from 8 m around Frying Pan Shoals (southern extent) to 18 m at the seaward survey extent. This region exhibits the most complex bathymetry of all the regions. Ridges with up to 1.9 m relief and moderate asymmetry are observed around Frying Pan Shoals. Multiple well-developed, shore-attached ridges are evident landward of the survey region. Most of the survey coverage is seaward of the 14 m isobath where ridges appear to be shore-detached with a relief of mostly 1-2 m in relief. These wide ridges have slopes up to 10 m/km, are up to 4 km long and 1 km wide. Localized shoals in the central and north sections have relief up to 3.1 m and hardbottom outcrop with relief up to 2.2 m is present in the southern extent.

The modern sand unit in this region has a mean thickness of 1.0 m with thicknesses up to 3.6 m (Figure 10). The H reflector is extensive in the region and visible in 71% of total mapped distance (Figure 10). Radiocarbon ages from two cores verify Holocene ages of the surficial modern sand (VC13 and VC17) (Figures 7 and 10; Table 2). Compared to other regions, this region has the most mapped QT reflector

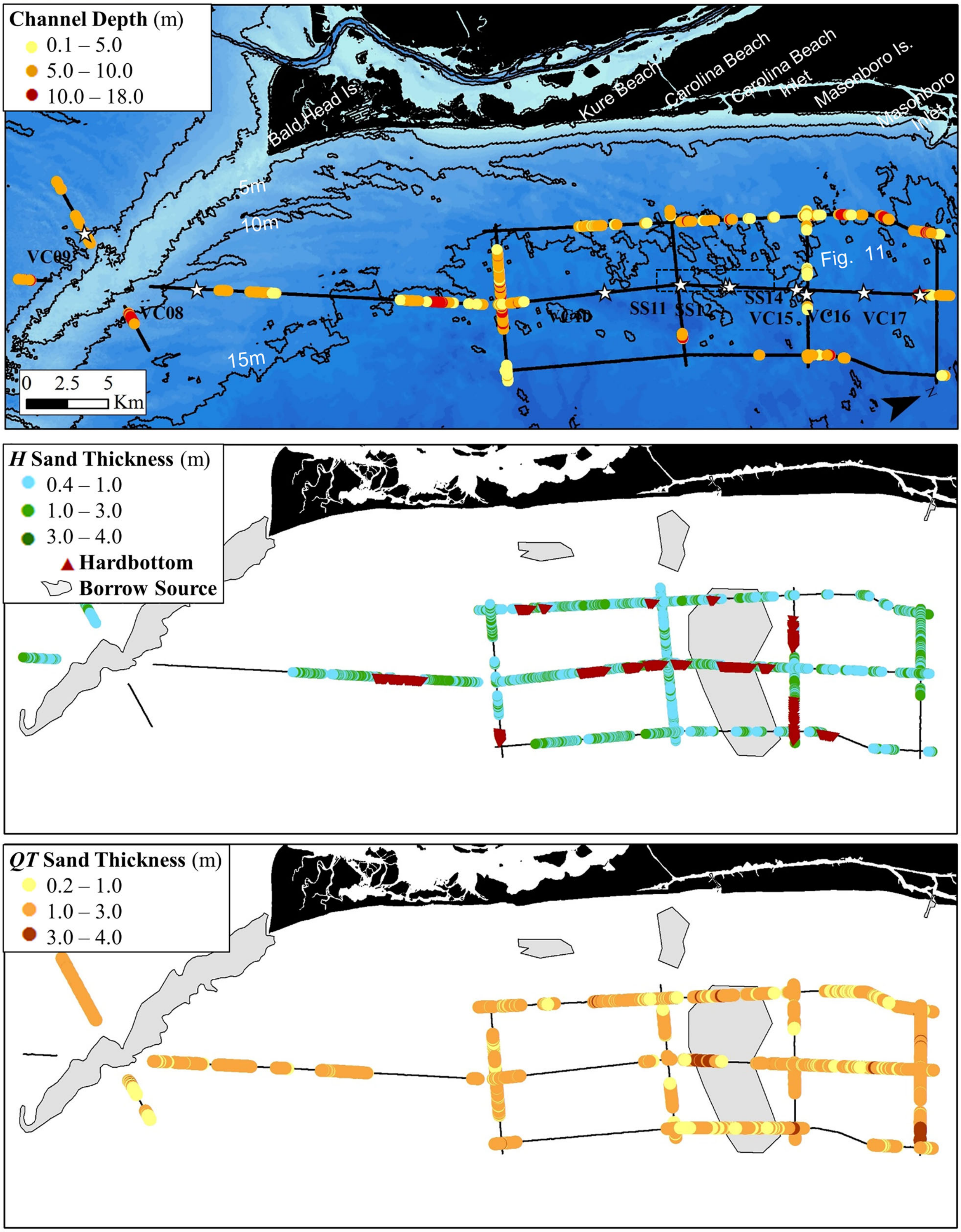

Figure 10. New Hanover Region ASAP interpretations. Irregular black lines in top panel represent 5 m isobaths. Vibracores (VC) and surface samples (SS) are represented by stars. Colors represent depth below seafloor of channels identified in Chirp data. Polygons are previously identified borrow sources.

(61%) with an overlying mean unit thickness of 1.7 m and reaching up to 5.3 m in thickness (Figure 10). The QT unit generally appears to thicken to the north. A ^{14}C age from a shell just below the QT reflector has a Pleistocene age (42,253 42,892 cal y BP; Table 2) (VC15; Figures 7 and 10). Core VC8 contains Pleistocene-aged surficial (1 m depth) sand based on a shell fragment (36,346 37,361 cal y BP; Table 2; Figure 7). The New Hanover County region

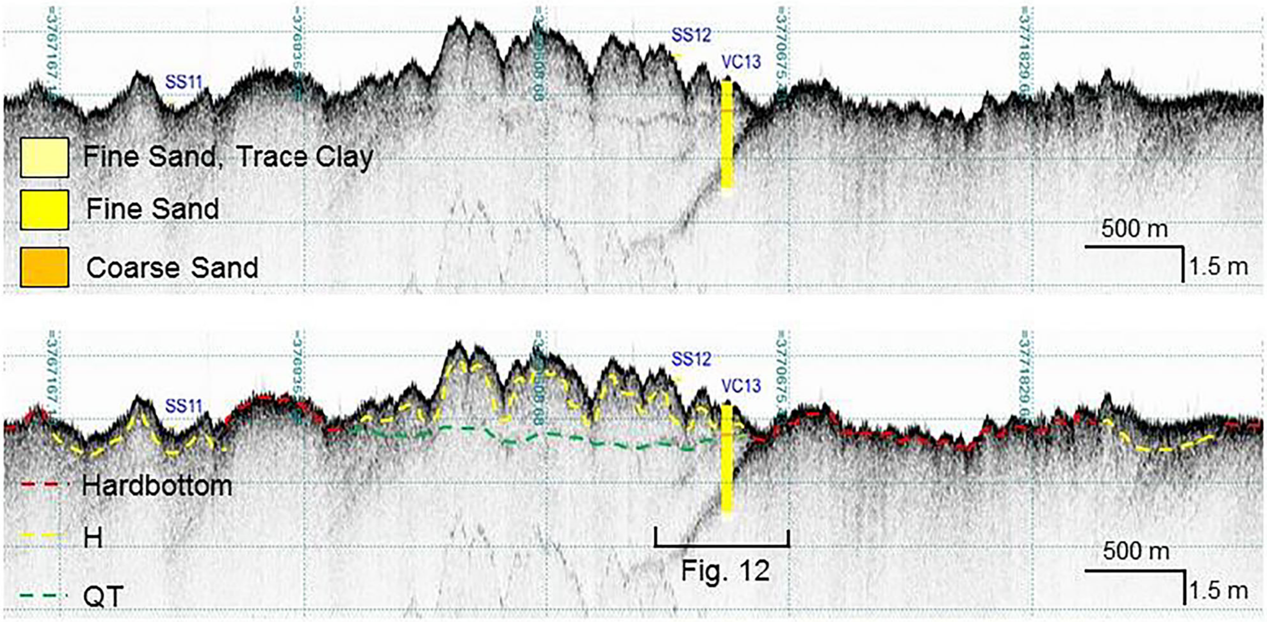

Figure 11. Example seismic line and interpretations from New Hanover Region. Location indicated by black dashed box on Figure 9.

region contains a lesser distribution of paleochannels (25%) and hardbottom (15%) than most of the other regions (Figure 10). A channel sampled by core VC09 contained a shell fragment dated to the Pleistocene (44,979 46,075 cal y BP; Table 2; Figure 10). Another channel (VC17) contained a shell fragment dated to the Holocene (5315 5519 cal y BP; Table 2; Figures 7 and 10).

According to the BIMP (2011), few offshore sand sources have been identified in this region, and most replenishment projects have used nearby inlets. However, the USGS seabed database indicates a region of possible beach compatible sand (Figure 10; large polygon intersecting with ASAP lines), although it is poorly characterized. ASAP data help to corroborate this possibility, showing extensive high relief shoal features with thicknesses exceeding 3 m in some areas (Figures 10 and 11). The shoals contain both the H and QT reflectors and are often laterally bound by hardbottom outcrop (Figures 10 and 11).

The New Hanover County region borders work conducted by several researchers (i.e., Meisburger 1979; Hoffman, Gallagher, and Zarra 1991; Zarra 1991) and several areas of ASAP sands intersect the lithosomes interpreted by Snyder, Hoffman, and Riggs (1994) as lower shoreface lithosome (LSL), the Inner Shelf Sand Shoal (ISSS), and Linear Shoreface Attached Shoal (LSAS), in addition to the Plio-Pleistocene Valley Fill and Sequence Orb-A (Figure 12). These lithosomes represent a variety of depositional settings including barrier, backbarrier, estuarine and fluvial environments that are now subject to erosion at the seafloor (Wren and Leonard 2005). Prior work, consistent with ASAP observations, has noted the presence of linear shoal features that are over a kilometer in length, hundreds of meters wide, and up to 5 m in relief that are likely "erosional remnants of partially preserved Pleistocene sections deposited during successive Quaternary sea-level fluctuations" (Snyder, Hoffman, and Riggs 1994).

5.5. Brunswick County region

The Brunswick County region shoreline is E-W oriented and bound by Cape Fear and Frying Pan Shoals at its eastern boundary. Survey lines run shore-parallel with four shore-perpendicular crossing lines (Figure 13). The water depths range from 12 m (7.8 km offshore) to 16 m (15.8 km offshore). The shelf in this region exhibits low-relief, gently seaward dipping seafloor (0.5 m/1 km slope) with the most uniform bathymetry of all the regions (i.e., aligned isobaths). The eastern portion contains the highest relief with ridges up to 1.4 m relief showing little to no asymmetry.

Half (50%) of the Brunswick region has a visible H reflector, which is most frequently mapped in the eastern section (Figure 13). H unit thickness also averages 1.0 m, but the range is smaller than other regions (0.2 to 1.8 m) (Figure 13). The QT reflector is not noted in the area likely because of the thinness of Unit H, making it difficult to resolve two reflectors. Hardbottom is widespread (39%) in the western area and is interwoven with paleochannels (20%) (Figure 13). Core and sub-bottom data suggest the presence of sand in the surficial layers of many paleochannel features, although the fill is variable. Figure 14 displays a good representation of the paleochannel and modern sand appearance. A core sample (VC03) at 2 m depth and below the H reflector shows a ^{14}C age of cal BP 6661 6831 (Figures 7 and 13), yet this age may not be representative of all channels in the region. Extensive hardbottom interpreted in the ASAP data is consistent with NCDEQ (2016).

The ASAP data are somewhat adjacent (1 km) to an estimated 5.3 mcy (4.1 million m^3) of sand source areas (ATM 2010). ATM (2010) reports four sites (Figure 13; 1-4 borrow source labels) that range in sand veneer thickness from 0.3 to 1.8 m. These additional sand sources identified in the ASAP data may be a viable and necessary resource option for coastal communities.

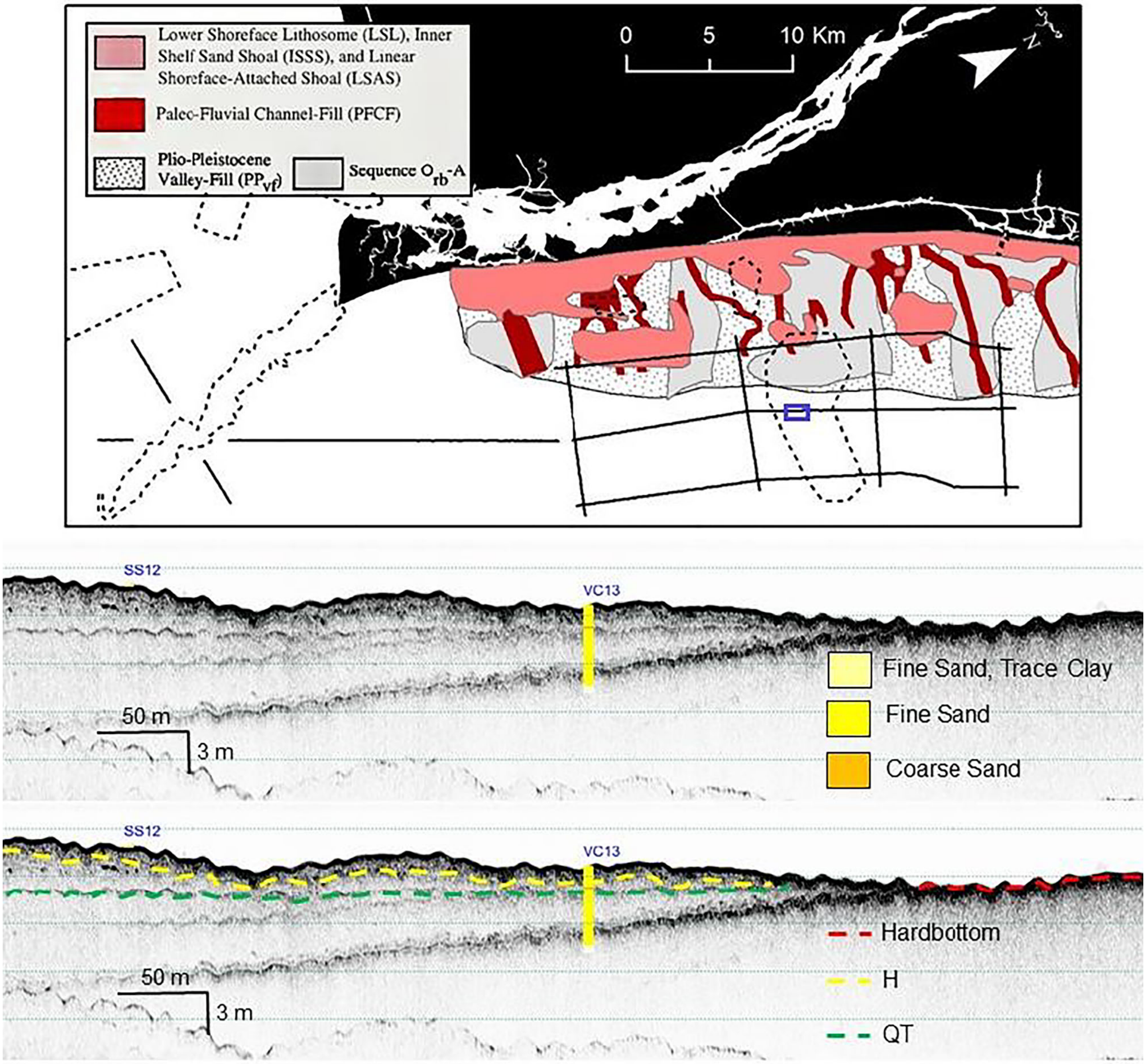

Figure 12. New Hanover Region ASAP interpretations relative to geo-rectified facies from Snyder, Hoffman, and Riggs (1994). The extent of the seismic line is indicated by the blue box and is also noted in Figure 10. Note, this area lies within a formerly identified potential borrow source and contains thick shoal deposits.

6. Discussion

6.1. Variability in channel distribution and architecture

Buried channels on the NC continental shelf represent important preserved environmental conditions and reflect a complex variety of transgressive and regressive physical processes (Oertel, Henry, and Foyle 1991). Due to the lack of fluvial sedimentation coupled with deep shoreface wave scour during transgression, preserved channels are anticipated to be the only depositional record of transgression in the region (Kraft et al. 1987; Oertel, Henry, and Foyle 1991). Because inlet channels are prone to erosion by wave ravinement during transgression in the wave-dominated system, most large, buried channels found within this region are hypothesized to be paleostream valleys (Hine and Snyder 1985; Oertel, Henry, and Foyle 1991), similar to the inner shelf adjacent to the Cape Henlopen headland of Delaware (Belknap and Kraft 1981). In other tide-dominated (as opposed to wave-dominated) shelf regions such as South Carolina, Georgia and Virginia, buried channels may be more reflective of lagoonal and inlet drainage patterns, in addition to paleostream valleys (Henry et al. 1981; Oertel, Henry, and Foyle 1991). Tidal-inlet channels are typically discontinuous and have rounded bases (Belknap and Kraft 1981; Oertel, Henry, and Foyle 1991; Riggs, Cleary, and Snyder 1995). According to Harris et al. (2005), however, tidal channels incising into less-resistant Holocene and Pleistocene sediments exhibit more angular bottom shapes with low width-to-depth ratios. In contrast, U-like shaped channels with flat bottoms and high width-to-depth ratios are characteristic of channels and valleys in Tertiary strata or compacted Pleistocene muds (Harris et al. 2005).

Hundreds of channels were delineated across the ASAP regions with high variability in form and fill. While

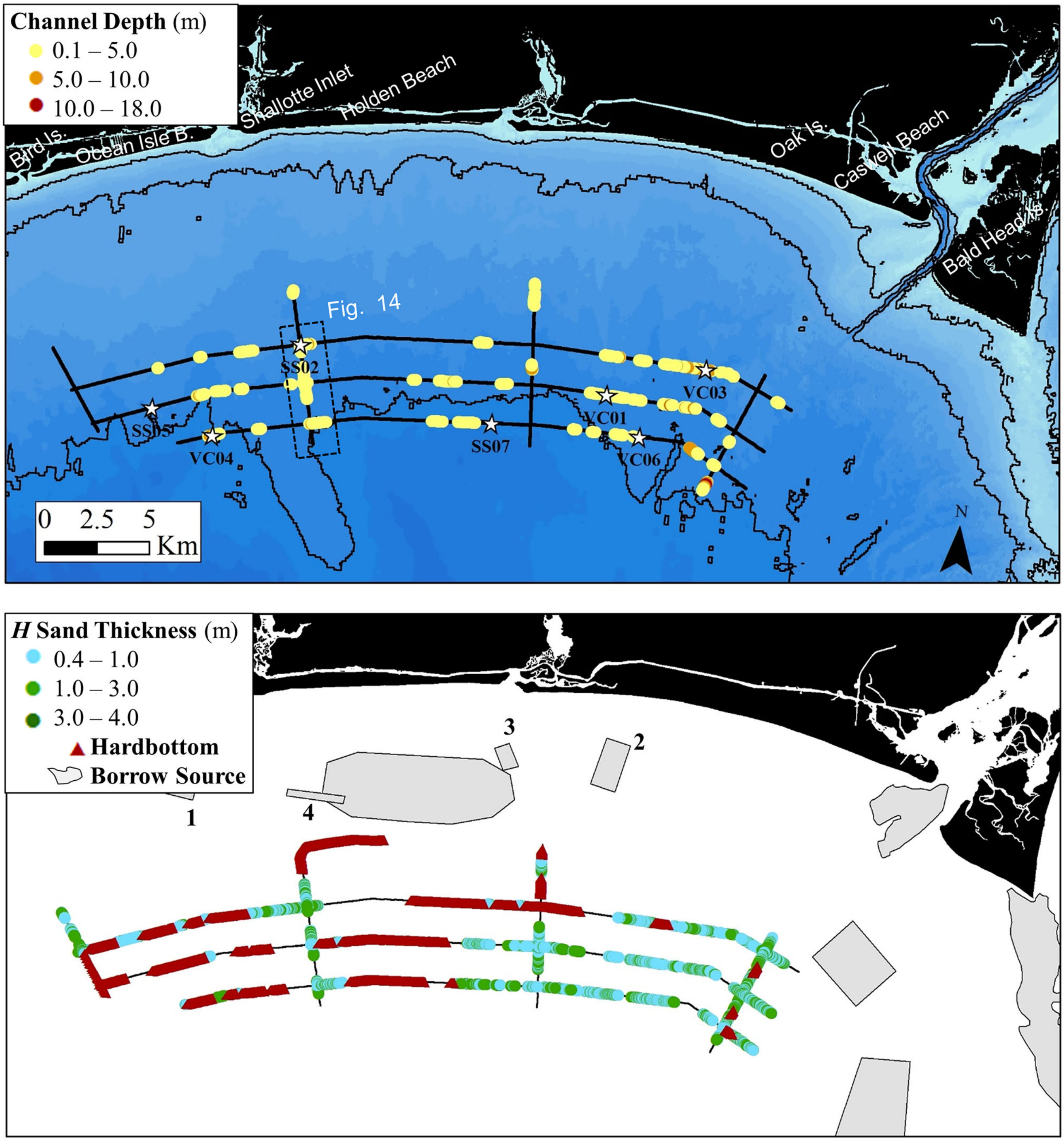

Figure 13. Brunswick County ASAP interpretations. Solid black lines in top panel represent 5 m isobaths. Vibracores (VC) and surface samples (SS) are represented by stars. Colors represent depth below seafloor of channels identified in Chirp data. Polygons are previously identified borrow sources; areas 1-4 are discussed in text.

characterizing each individual channel is beyond the scope of this work, Figures 14 and 15 (VC33, VC27, VC03) provide examples of channels characteristic of each region, and highlight the varied form and fill of the preserved paleo-channels. The Bogue Banks Region contains extensive mapped buried channels that may be associated with the paleo-New River Valley (Cleary et al. 1996). The deepest channels are concentrated to the west and may be related to the antecedent bathymetric depressions extending from the highly irregular 15 m isobath. The prevalence of hardbottom in the central region (Figure 4) appears to influence channel shape (i.e., more flat bottom forms evident) and limit channel distribution, as noted by Hine and Snyder(1985). Figure 15a shows an example of a Bogue channel with an asymmetrical rounded bottom, and complex fill including inclined heterolithic strata, representing multiple episodes of cut and fill suggesting tidal influence. Below a 1.25 m thick sand layer, the heterolithic fill as indicated by the core would not be ideal for beach nourishment (Figure 7; VC33). The western portion of the channel contains the highest amplitude reflections suggestive of lateral infill and reworking (Oertel, Henry, and Foyle 1991). Toward the eastern edge, there is

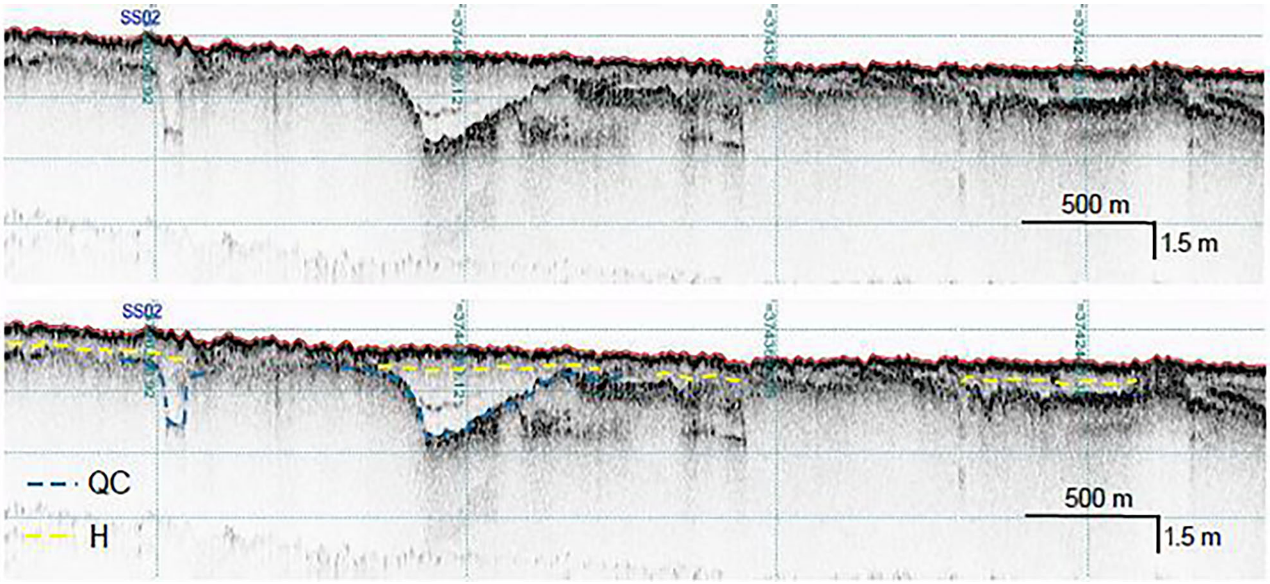

Figure 14. Example seismic line and interpretations from Brunswick Region. Location indicated by black dashed box on Figure 12.

acoustically transparent fill and low amplitude reflections that show bedding planes of upbuilding and constricting strata from flow inhibition (Oertel, Henry, and Foyle 1991). A Holocene sand cap, as seen in many studies (e.g., Nordfjord et al. 2006), is verified by a ^{14}C date (Table 1; Figure 15a). Many channels in the region are similar in incision depth (6 to 10 m) to the Folly and Kiawah rivers in SC (Harris et al. 2005).

The Topsail Region contains numerous mapped buried channels (Figure 7) that may also be associated with a paleo-pathway of the New River Valley (Cleary et al. 1996). To the west, the channels are deepest (> 5 m), with low width-to-depth ratios, and exhibit angular bottoms (Figure 8). The western-central area of the subregion also exhibits a deep incisional channel network possibly related to the valley-like feature apparent in the bathymetry to the south (Figures 8 and 9). Toward the east, the channels are generally shallower and wider suggesting incision into more resistant strata. High amplitude channel bases are also evident toward the east possibly indicating a coarse fluvial lag (Chaumillon et al. 2008). Sediment facies in VC27, VC33 and VC03 from the region are indicative of estuarine fill and are not ideal for nourishment (Figures 7 and 15b).

The New Hanover region contains the least amount of channels, yet they are among the deepest in all of the regions (>10 m) (Figure 10). Fewer mapped channels in the subregion are likely attributable to the absence of a major river system in the area - the Cape Fear River flows to the west (Cleary et al. 1996). Maximum channel depth below the seafloor locally is 18 m deep, similar to the incision of the Stono (15 m) and North Edisto (20 m) paleochannels observed in SC (Harris et al. 2005). Thieler et al. (2001) also observed "Quaternary fluvial channels" up to 18 m in the vicinity (offshore Wrightsville Beach). The central and seaward-most lines contain few to no channels which may be related to the bathymetry and hardbottom distribution. Some channels in the central region are topped by shoals above the QT reflector, suggesting the channel network provided a source for modern sediments (Figure 15c).

The Brunswick County region contains a number of shallow (< 5 m) channels as highlighted in Figures 12 and 13. Most channels are mapped on the eastern portion of the region and are likely related to the Cape Fear Valley (Cleary et al. 1996). These channels are predominantly constrained to areas where there is also a thin modern sand veneer. To the west, more hardbottom is visible, corresponding to a lack of buried paleochannels. Of all the regions, Brunswick likely was subject to the lowest amount of wave scour during transgression, and consequently, the numerous shallow channels (< 5 m) are indicative of tidal influence. Similar shallow channels have been mapped in tidally-dominated Georgia (Oertel, Henry, and Foyle 1991). Additionally, shallow channel incision in this region may be attributable to the differences in shelf slope and more uniform bathymetry (i.e., steeper slopes may have caused incision of deeper channels). The Brunswick channels also differ from the other ASAP regions and areas such as the New Jersey Outer Continental Shelf (Nordfjord et al. 2006), in that they are less likely to be truncated by a transgressive ravinement surface.

In general, the channel observations across the SE NC shelf reflect tidal vs. fluvial development (i.e., the distribution of different channel sizes) as well as the underlying geology into which the channels are incised. In Onslow Bay, the shape of the channels is hypothesized to be governed by the geologic strata (Hine and Snyder 1985). However, the fill and preservation is hypothesized to reflect the relationship between fluvial transport capacity, rates of sea-level rise and local geomorphic changes (which are no longer visible due to wave ravinement). These data show that channel-limited areas tend to be hardbottom-rich and the distribution and depth of large channels is related to paleovalley locations (e.g., Figures 7 and 8). It is reemphasized that channels may contain some sand suitable for beach nourishment where acoustically transparent fill and/or the surficial

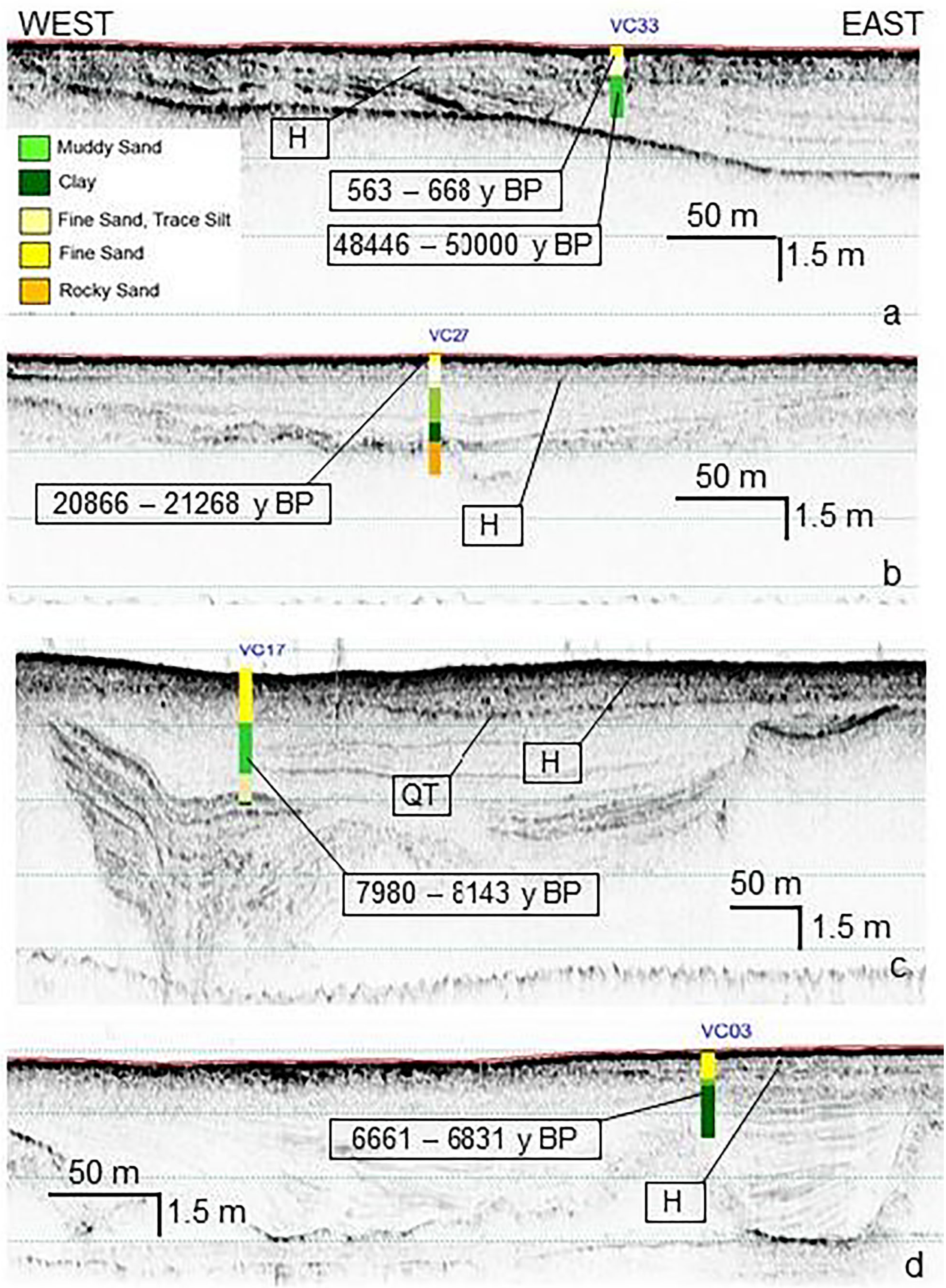

Figure 15. Channel examples, core logs and associated ^{14}C ages. Panel A is from Bogue Banks Region; B is from Topsail Island Region; C is from New Hanover Region, and D is from Brunswick Focus Region. Dimensions, fill architecture and geometry are highly variable and described in the text.

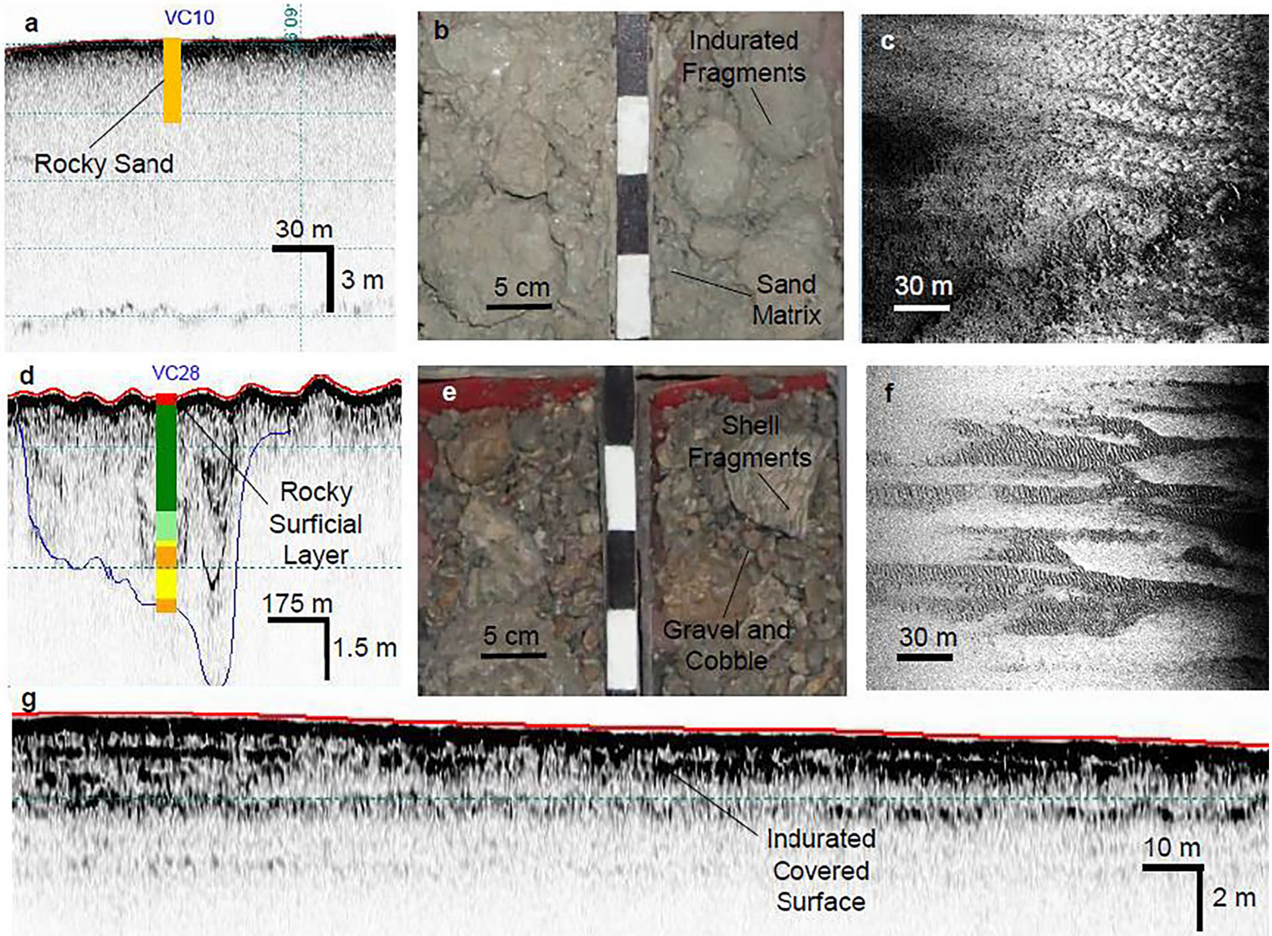

Figure 16. Seafloor examples of New Hanover region hardbottom (a–c) and Topsail Island region non-hardbottom (d–f) areas. Hardbottom interpreted in seismic data from New Hanover and Topsail Island, a and d respectively, with corresponding cores (b, e) and in sidescan data (c, f). Panel G shows the seismic appearance of a hardbottom buried by <1 m of sand, commonly observed in Brunswick County.

modern sand (H unit) is observed and validated by core data. However, many channels are complex indicating multiple incisions/processes, and are interbedded with heterolithic fill (i.e., shelly and muddy fluvial and estuarine) making its use for beach nourishment impractical.

6.2. Hardbottom variability

Hardbottom areas are widely viewed as key habitat, thus accurate maps of their distribution are important. However, determining their distribution is somewhat subjective and dependent on the method used and the interpretation of the data. Hardbottom may be indicated by the inability to acquire grab samples or the presence of large gravel. Alternatively, the geologic context in seismic or sidescan data may define areas without sediment cover. To divers, the actual presence of a rock outcrop may evidence a hardbottom area. Thus, the definition and classification of hardbottom varies and is inconsistent when synthesizing academic, government and private work (Riggs et al. 1996). *Hardbottom* has been defined by Riggs et al. (1996) as "a descriptive term for an indurated surface on the seafloor with no implications of synsedimentary cementation or growth of reef-building organisms; the term refers to all hardgrounds, reefs, and rock outcroppings on the seafloor" (Riggs et al. 1996). If the hardbottom serves as a persistent habitat it is often referred to as *live-bottom* (Riggs et al. 1996). More recently, Street et al. (2005) gave a more encompassing hardbottom description, "exposed areas of rock or consolidated sediments, distinguished from surrounding unconsolidated sediments, which may or may not be characterized by a thin veneer of live or dead biota, generally located in the ocean rather than in the estuarine system." Hardbottom may also be called *live rock* with colonization of algae, sponges, corals and invertebrates (NCDEQ 2016). According to studies from North Carolina to Florida, hardbottom types include "1) emergent hard bottom dominated by sponges and gorgonian corals; 2) sand bottom underlain by hard substrate dominated by anthozoans, sponges and polychaetes, with hydroids, bryozoans, and ascidians frequently observed; and 3) softer bottom areas not underlain with hard" (SAFMC 2008a).

Several other terms are often used interchangeably with hardbottom and these may produce confusion. *Hardground* includes rock surfaces that "show unmistakeable evidence (borings, encrustations, marine cementation) of synsedimentary lithification … " (Bromley 1975), although these are also hypothesized to not crop out in Onslow Bay (Riggs et al. 1996). This study has mapped hardbottom primarily using seismic and sidescan interpretation. While this is good for identifying larger areas of no or low sediment cover, resolution and positioning have their limits.

The interpretations of ASAP data apply a more broad classification of hardbottom (essentially following the definition of Street et al. 2005). This is useful from a habitat and sand resource perspective as it indicates where all forms of hardbottom are likely creating key habitat and dredging is not viable. Figures 3 and 16 show some of the variety of forms of hardbottom and non-hardbottom within the ASAP data. In Figure 16b, hardbottom is mapped based on the presence of large indurated fragments, although the matrix is sand. Distinguishing this hardbottom based solely on the acoustic signature is less evident, showing that a combination of geophysical and core data is needed to accurately classify the seabed and map benthic habitat (Harris and Baker 2012). Figure 16e shows seafloor with a mixture of surficial granule to cobble size lithoclasts and shell fragments, which would be classified by Riggs et al. (1996) as a *lag pavement*. Although not technically a hardbottom, from a habitat standpoint it is hypothesized that it would be similar to the seabed shown in Figure 16b. In this light, hardbottom classifications might require new considerations that clarify the geological nature of the substrate (e.g., rock vs. unconsolidated coarse sediments).

According to Snyder, Hoffman, and Riggs (1994) and Riggs et al. (1996), hardbottom character and distribution in Onslow Bay are determined by the outcropping of SE-dipping Tertiary indurated sedimentary strata. The morphology of hardbottoms is quite variable as a result. Past research has shown that hardbottom varies in relief with outcrops up to 10 m in vertical relief (farther offshore) to areas that are relatively flat (Riggs et al. 1996; NCDEQ 2016). The majority of the ASAP-mapped hardbottom is low-relief and shallow-sloped. Outcrops with vertical relief up to 3 meters were mapped mostly in the New Hanover region, which is consistent with past studies (e.g., NCDEQ 2016). Most of the ASAP hardbottom likely falls under the Riggs et al. (1996) classification of *flat hardbottoms* that are "smooth to slightly irregular, semi-indurated to indurated surfaces of great extent that form the upper, lower, and in some places middle bounding surfaces of low-relief and high-relief scarped harbottoms." In Onslow Bay, *flat hardbottoms* are generally composed of semi-indurated Tertiary muds to muddy sands, and are covered by a thin layer of mobile or permanent Holocene surficial sand that are difficult to map through remote sensing (Riggs et al. 1996; Schmid 1996).

The distribution of hardbottom is widespread on the southern NC shelf as highlighted by past research and this study, although it is subject to challenges relating to interpretation and definitions described above. From Cape Hatteras to Cape Fear, it is estimated that hardbottom represents 14% (or 500,000 acres) of the seabed between 27 and 101 m water depth (Parker, Colby, and Willis 1983). However, due to the discontinuous and patchy nature of hardbottom, as well as the vastness of the outer continental shelf, more recent efforts have refrained from estimating the overall distribution of hardbottom in NC (Rutecki et al. 2014). Hardbottom distribution is critical to better understand not just from ecological habitat and sand resource perspectives, but because they are an extensive part of the stratigraphic and paleoceanographic record on the Atlantic Shelf (Riggs et al. 1996; Riggs et al. 1998). The data from this work suggests hardbottom represents 23% of the seabed in the Bogue region, <1% in the Topsail region, 15% in the Hanover region and 39% in the Brunswick region, respectively.

Several factors make the delineation of hardbottom in the ASAP dataset challenging. Firstly, these areas contain a variety of hardbottom forms (Figures 3 and 16). Next, in some areas it is difficult to distinguish hardbottom using geophysical signatures alone (i.e., seismic, sidescan) and the sparseness of cores and samples prohibits validation in many cases. Finally, low relief hardbottom areas are subject to ephemeral burial and exposure by moving sand bodies (Cleary et al. 1996; Riggs et al. 1996). This is notable in the ASAP data, as evidenced primarily by sidescan (e.g., Figure 16f). Because the sand veneer covering hardbottom is often thin, the exposure of hardbottom fluctuates as sediments are transported and mobilized during storm events. Ultimately, these data and past research have shown that hardbottom definition, form and distribution is complex and variable on the NC OCS. Because of the described dynamics and interpretation challenges, it is our recommendation that a combination of geophysical and sampling is used to define hardbottom zones, and that a broad, inclusive definition be used.

6.3. Influence of geologic framework and management implications

Due to the drastic differences in framework geology across NC, each region is unique in terms of the characteristics of potential and historically used borrow sources. The northeast NC shelf has thick sand deposits, as shown by a host of researchers (e.g., Boss and Hoffman 2001; Thieler et al. 2014). As such, ASAP collection efforts were focused on the southern half of the state, where data are more sparse and there is much more nourishment demand (NCDCM 2017).

A primary control on the distribution of interpreted sand resources is the underlying geologic framework and consequent lack of sediment input to the region. As many researchers have emphasized, like other high-energy shelves on passive continental margins, the southern NC shelf and Onslow Bay are considered sediment-starved due to either lack of fluvial input, entrapment of sediment within estuaries or transport to slope environments, i.e., sediment bypassing (Emery 1968; Cleary et al. 1996; Riggs et al. 1996, 1998). Consequently, Onslow Bay is dominated by hardbottoms (Mearns, Hine, and Riggs 1988; Cleary et al. 1996; Riggs et al. 1996). Modern sands are limited to a discontinuous veneer as shown by the data in the ASAP regions (Cleary et al. 1996; Riggs et al. 1996, 1998). Similarities are noted on the SC shelf, where the modern sediment layer is patchy and thin due to lack of fluvial input and reworking over an irregular transgressive erosional surface, allowing for underlying strata to crop out at the seafloor (Gayes et al. 2003; Baldwin et al. 2007; Denny et al. 2013). Physical and bioerosion processes are hypothesized to be responsible for creating much of the modern sands in Onslow Bay and SC that reflect the composition of underlying Tertiary and Pleistocene hardbottom being eroded (Cleary et al. 1996; Riggs et al. 1998; Gayes et al. 2003; Putney, Katuna, and Harris 2004; Baldwin et al. 2007). While the majority of ASAP-delineated sand can be considered a *veneer,* in multiple areas two or more deeper reflectors (i.e., H and QT) are visible that represent thicker sand deposits. In addition, this ASAP effort has mapped numerous channels that may be a viable source of offshore sand in sediment-starved areas.

This new reconnaissance effort provides a broad starting point to search for offshore sand resources. As sand resources may diminish with increased demand (Jones and Mangun 2001), these data are critical for effective coastal management in response to storm events. Moreover, they provide some framework for advanced planning and/or long term RSM, as well as economic evaluations to help constrain costs relative to known volumes.

7. Conclusions

In sediment-starved southern NC, the distribution of potential beach-compatible sand is irregular and complex. Some areas contain especially thick (> 5 m) sand deposits (e.g., New Hanover), while others contain thinner (< 1 m) modern sand deposits impractical for dredging. Buried paleochannels provide important preserved records into past environmental conditions and hardbottom represents potential critical habitat. Paleochannels may also be viable sand sources when fill is acoustically transparent or validated by cores, but many locations show complex fill not useful for beach nourishment. Ultimately, design-scale surveys and sampling are needed to refine sand volume estimates when being considered as nourishment sources.

Reconnaissance data for seabed geology, habitat potential and resource evaluation is quite valuable not only in NC but also globally, as many sandy coastlines throughout the world experience similar erosion issues. Moreover, continental shelf areas are increasingly being used or considered for other resources and functions including wind farms, aquatic habitat, commercial/recreational fishing, hydrocarbon exploration/extraction, marine sanctuaries, etc. Because these OCS resources may overlap (in both space and time), multiuse conflicts may arise and protocol is still poorly developed to handle federal continental shelf rights (Jones and Mangun 2001; National Research Council 1995). Therefore, data collection and interpretation efforts like this work are important to ensure shelf value can be assessed before the areas are exploited for resources. Prioritization of vital habitats and/or potential sand borrow sources is essential, especially in regions where there is a high demand for nourishment but a shortage of shelf sand availability.

Acknowledgments

We would like to thank the faculty and staff at ECU's Department of Coastal Studies and Coastal Studies Institute, particularly Sid Mitra, Cindy Harper, Marie Magee, Kimberly Armstrong, Paul Paris and Liz Mason. We would also like acknowledge the Bureau of Ocean Energy Management (BOEM) for project funding.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the Bureau of Ocean Energy Management (BOEM) [BOEM Cooperative Agreement No. M14AC00009 and BOEM Cooperative Agreement No. MI4ACOOOI2].

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