SAND RESOURCES OF THE NORTH CAROLINA OUTER BANKS

2nd INTERIM REPORT: ASSESSMENT OF BUXTON STUDY AREA

Prepared for the

Outer Banks Task Force and the

North Carolina Department of Transportation

by

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EXECUTIVE SUMMARY

A review of available geophysical (single-channel seismic reflection and side-scan sonar records) and sedimentological (core descriptions, images, and textural analyses) data from an area offshore Buxton, North Carolina was undertaken on behalf of the Outer Banks Task Force and the North Carolina Department of Transportation to determine the potential of this area as a source of sand for possible beach nourishment programs on the North Carolina Outer Banks. Results of this review are presented as an outline of the stratigraphic architecture of the Buxton Study Area (BSA) derived from interpretation of seismic reflection and side-scan sonar data, description of the gross textural attributes of sediment in cores collected within the BSA, and assessment of potential sand reserves within the BSA that might be utilized for future beach nourishment programs.

Nine principal seismic reflectors (designated R_0 through R_8) were correlated throughout the BSA and form the upper and lower boundaries of eight principal stratigraphic units (designated S_1 through S_8) extending from the seafloor to approximately 60 m sub-sea. Individual seismic units are relatively thin, averaging 5.4 m throughout the BSA. The seismic signatures of units within the BSA are quite variable, ranging from acoustically "transparent" units (i.e. lacking internal reflecting horizons) to units with multiple, closely spaced parallel reflectors. These variations in seismic character are indicative of rather variable geologic or sedimentologic units.

Side-scan sonar records throughout the BSA indicate that seafloor over three-fourths of the study area is characterized by weak acoustic reflectivity. This phenomenon most commonly indicates very fine sand or finer sediment at the seafloor. In addition to imaging of fine-grained sediments, side-scan sonar data from the BSA scanned significant occurrences of low- to high-relief hardbottoms exposed on the seafloor over a good portion of the northernmost quarter of the study area (north of line 022).

Twenty- seven vibracores were collected within the BSA. These cores contain variable sediment types ranging from very fine-grained sand and mud to shell gravel. The variable nature of sediment contained within cores demonstrates the highly variable nature of stratigraphic units throughout the BSA. A cluster of five cores (189, 190, 192, 193, 195) are composed of greater than 97% sand and shelly gravel and appear to be associated with seismic unit S_7 in the southern portion of the study area.

Among the eight seismic units exposed within the BSA, only one, S_7, seems to satisfy the necessary conditions to be considered a candidate sand resource: 1) it crops out relatively close to shore within the southern portion of the BSA near a site of critical shore erosion, 2) it crops out in relatively shallow water and thus is accessible to presently available dredging technology, 3) its seismic signature and reflector geometry are indicative of a sand-rich depositional environment (fluvial channel or inlet fill), and 4) cores within this unit confirm the presence of appreciable quantities of sand. Unit S_7 is estimated to contain in excess of 375 million cubic yards of sand over the surveyed area. A smaller sand resource target within S_7 is identified with an area of 11 million square yards and an estimated sand volume of 60 million to 180 million cubic yards, depending on assumptions regarding thickness of unit S_7.

INTRODUCTION

Project Background

Following preliminary meetings and discussion of problems related to maintenance of North Carolina Highway 12 in 1993 and 1994, the Outer Banks Task Force agreed to conduct a large-scale geophysical survey of the northern Outer Banks from Oregon Inlet to Ocracoke Inlet. The primary intent of this survey was to collect reconnaissance data (single-channel, high-resolution seismic reflection and side-scan sonar profiles) over a broad area of the northern Outer Banks (Oregon Inlet southward to Cape Hatteras, then westward to Ocracoke Inlet; Fig. 1). These data were to be used to acquire baseline knowledge regarding the shallow (<100 m depth) stratigraphy, sea-floor characteristics, and sand resource potential of the continental shelf within waters under state jurisdiction (to 3 nautical miles offshore). The geophysical survey was conducted during July and August 1994 by Dr. Stephen W. Snyder (North Carolina State University) under contract to the North Carolina Department of Environment and Natural Resources with the North Carolina Geological Survey (NCGS) acting as contracting agency.

The following summer, a sampling survey was authorized to provide “ground truth” for geophysical data. Vibracores were collected during 8 weeks (July – August 1995) aboard the United States Army Vessel *Snell* from Oregon Inlet southward to Cape Hatteras, across Diamond Shoals, then westward to Ocracoke Inlet. Upon completion of the field-sampling program, all cores were transferred to the Coastal Plain Office of the North Carolina Geological Survey for processing. All cores were halved lengthwise, described, digitally imaged, and sampled to determine textural attributes. The digital images of each core were archived on CD-ROM and placed into the public domain at the Coastal Plain Office of the North Carolina Geological Survey. Core sediment samples were processed using standard methods by the Soils Testing Laboratory of the North Carolina Department of Transportation and textural attributes were compiled and archived on CD-ROM at the Coastal Plain Office of the North Carolina Geological Survey.

In December 1998, a contract was executed between the North Carolina Department of Environment and Natural Resources and the University of Arkansas (Dr. Stephen K. Boss, Principle Investigator). The purpose of this agreement was to complete analyses of existing geophysical data (single-channel seismic reflection and side-scan sonar profiles) and assess the sand resource potential of four study areas offshore of the northern Outer Banks (Fig. 1).

The following report is the second project deliverable, and is organized into several sections to facilitate understanding of the rather complex data. Section I describes the available geophysical data and presents results of interpretations of BSA stratigraphy. Section II documents textural attributes of sediment in vibracores collected within the Buxton Study Area (BSA) during 1995. Finally, Section III provides information pertinent to assessing the BSA as a potential resource of sand for beach nourishment along the critically eroding beach north of Buxton, NC.

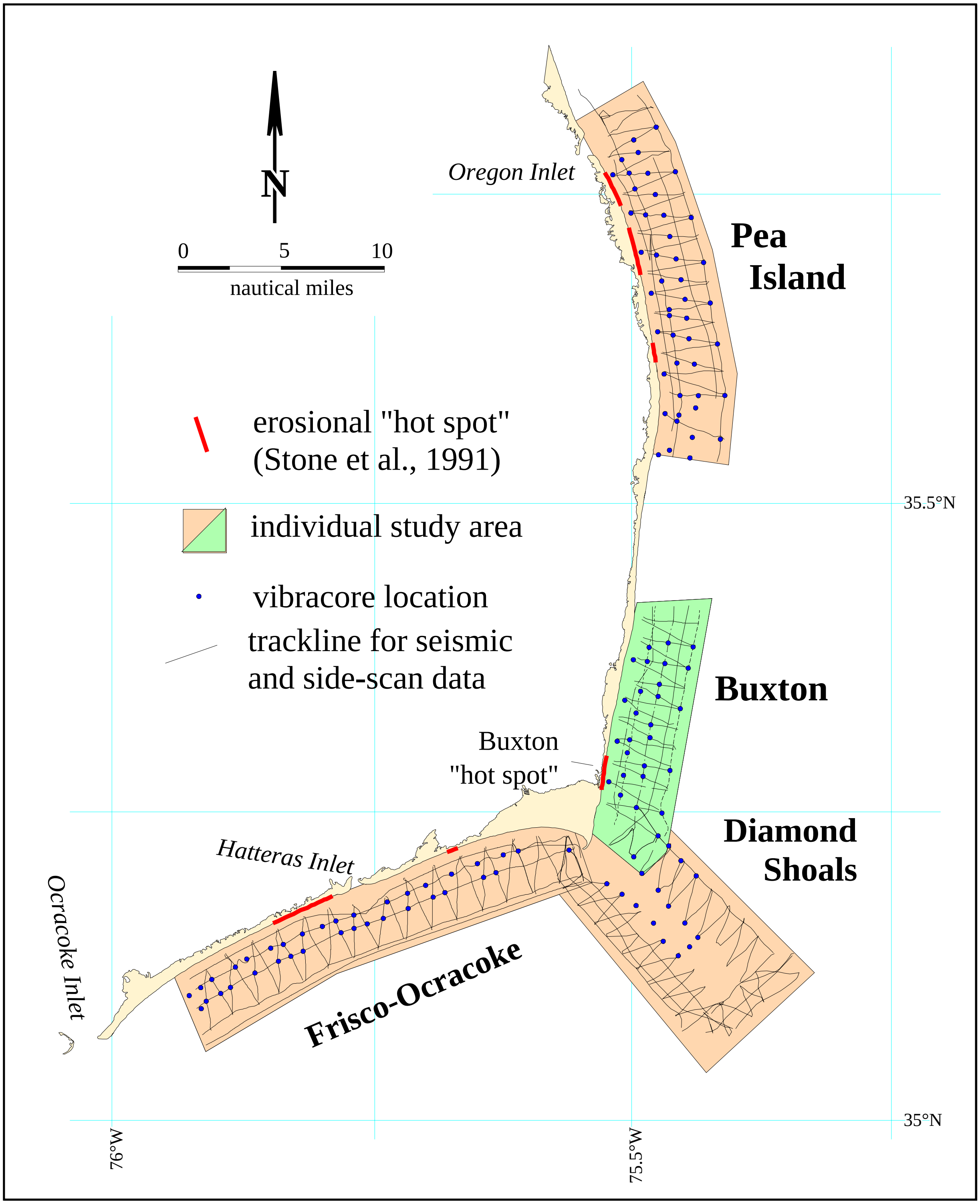

Fig. 1. Location map showing the Outer Banks Task Force sand resource project area. The four principal project areas are labeled along with locations of erosional “hot spots” (red line segments) with potential to impact NC Highway 12. Geophysical tracklines (seismic reflection and side-scan sonar profiles) are indicated by thin solid lines. Vibracore locations are shown as solid circles. Green study area is the subject of this report.

SECTION I: GEOPHYSICAL DATA

The BSA is approximately rectangular, measuring about 18.0 km x 7.3 km (9.9 nautical miles x 3.9 nautical miles) and occupying an area of 132 km^2 (39 nm^2). Geophysical data consist of single-channel, high-resolution seismic reflection profiles and side-scan sonar records from the BSA (Fig. 2). These data were collected simultaneously during the 1994 research cruise and are subdivided into 28 trackline segments constituting 204 km (110 nautical miles). Tracklines are oriented with 5 lines spaced at approximately 1 km (0.5 nautical mile) intervals parallel to the coast from 0.5 to 3.0 nautical miles (limit of state jurisdiction offshore). These shore-parallel lines are crossed by a series of zig-zag tracklines oriented approximately perpendicular to the coast and extending from near shore to approximately the 3-mile limit.

Seismic Reflection Profile Interpretation and Analysis

Seismic reflection data were archived as paper scrolls printed at the time of acquisition and in digital format on CD-ROM. Paper copies of these data printed at the time of acquisition were of limited utility because their quality is greatly influenced by physical sea-state at the time of the research cruise and by the acquisition software processing parameters. However, digital records of these data (archived on CD-ROM) were reprocessed using specialized software to enhance signal-to-noise relations and thus provide more interpretable versions.

Seismic reflection data were collected to a maximum "depth" of either 100 or 120 milliseconds two-way travel time (the standard vertical axis on seismic reflection profiles) during the initial survey. Seismic reflection profiles from the BSA were reprocessed and interpreted to a maximum "depth" of 60 milliseconds two-way travel time. This depth was chosen as a compromise providing sufficient depth to assess the geological architecture of the BSA while also enabling relatively fine-scale resolution of individual sedimentary units. In addition, data below 60 ms are of little value to the goal of assessing sand resources since sediments beneath this level are too deep beneath the seafloor to be considered for conventional dredging.

Precise conversion of two-way travel time to true depth requires knowledge of the velocity of *p*-waves through both seawater and sedimentary deposits, parameters that typically are not available during a survey. Thus, figures showing "depth" to a particular reflecting horizon (e.g. Figs. 3, 4, 6) are presented in milliseconds two-way travel time, the parameter recorded during data acquisition.

For this study, estimates of the thickness of stratigraphic units were obtained by assuming uniform *p*-wave velocity through the sediment column. A reasonable estimate of *p*-wave velocity of 1800 m/sec was obtained from published values of typical unconsolidated, surficial marine sand (Dresser Atlas, 1982), and this value was adopted for this study. This value was chosen as a conservative estimate, since it is likely that *p*-wave velocities in the subsurface are greater than 1800 m/sec. Thus, estimates of sediment thickness reported herein are considered to be minimum estimates since velocities of seismic transmission greater than 1800 m/sec will result in thicker deposits (Table 1).

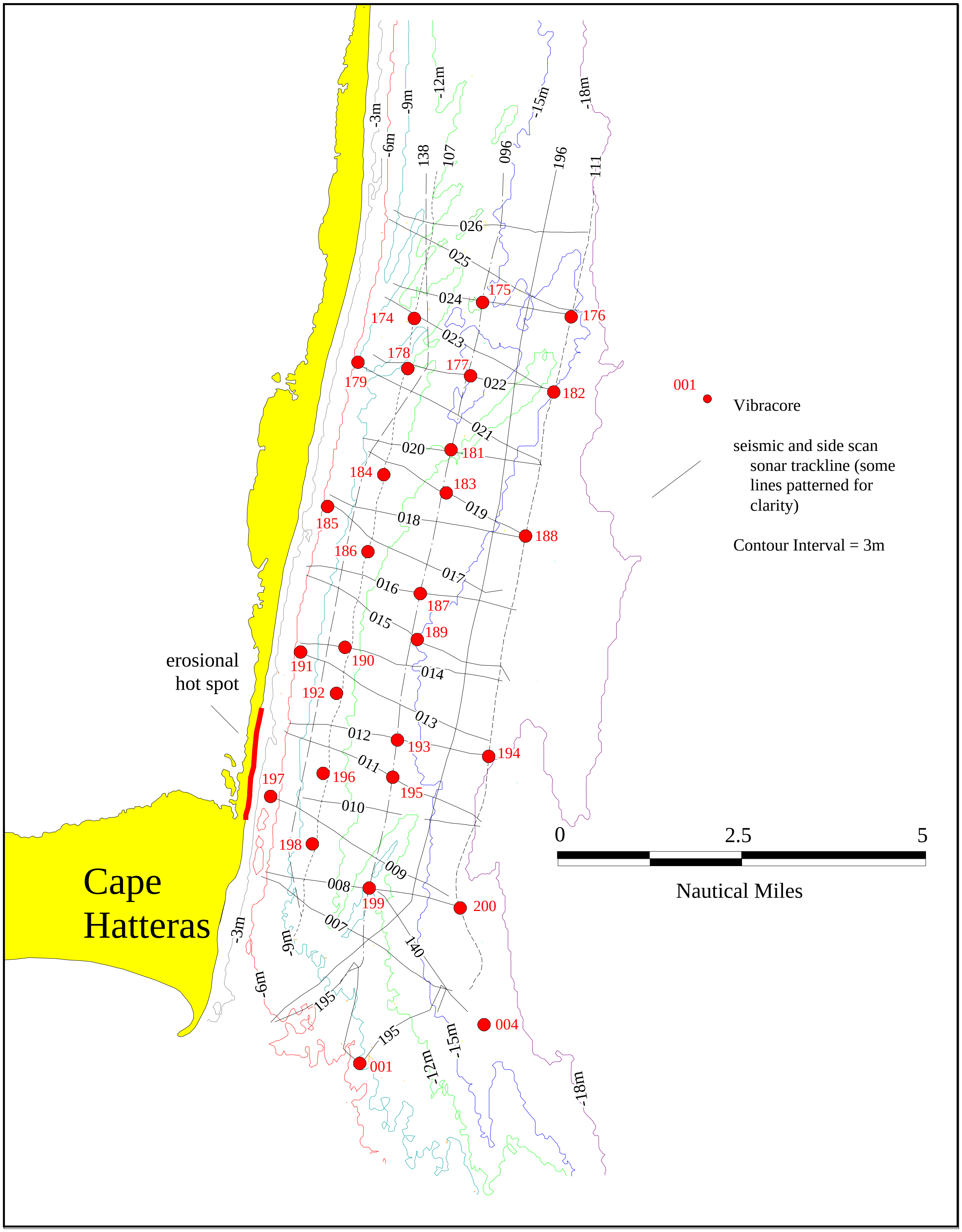

Fig. 2. Detailed location map of Buxton Study Area (BSA) showing tracklines of seismic reflection and side-scan sonar profiles (thin lines) as well as locations of vibracores (solid cirlces) used in this sand resource assessment. Bathymetry from NOAA hydrographic data (NGDC, 1999).

TWO-WAY TRAVEL THICKNESS (seconds)	p-WAVE VELOCITY (m/sec)	THICKNESS (m)
0.020	1500	15
0.020	1800	18
0.020	2100	21

Table 1. Example calculations showing the dependence of estimated deposit thickness on *p*-wave velocity. Example assumes a stratigraphic unit with measured "thickness" 0.020 seconds two-way travel time on a seismic reflection profile. The change in true thickness of the unit with increasing *p*-wave velocity is evident. For this study, a conservative *p*-wave velocity of 1800 m/sec was assumed to arrive at estimates of sediment thickness. The equation relating p-wave velocity, two-way travel time, and thickness is: $(t_2/2) \times v_p = z$ where t_2 = two-way travel time, v_p = *p*-wave velocity, z = thickness.

Seismic reflection profiles were interpreted using an iterative correlation method whereby prominent seismic reflectors are identified and correlated among closely spaced seismic profiles. An attempt is then made to extend these initial correlations throughout the entire surveyed area, cross-referencing and checking for appropriate "ties" frequently until the entire data set is interpreted. This process constitutes the first iteration through the data.

Following completion of the initial interpretation cycle, all profiles were reviewed, and refinements to the initial interpretations made. This process constitutes the second iteration through the data.

Finally, the geographic locations and depths of principal seismic reflectors are tabulated for each time-event mark (approximately every 500 seismic shot points) and line crossing. These data are compiled in a spreadsheet and checked for consistency; the position and depth of a reflector should be the same on crossing seismic profiles. Anomalous reflector depth pairs are noted, and the associated interpreted seismic profiles checked again for accuracy. This process constitutes the third iteration through the seismic data.

Once satisfied that correlations among major reflectors were reasonable, the digitized locations of seismic reflectors were updated using spreadsheet software and the results exported to Geographic Information System (GIS) software to generate maps of reflector surfaces and seismic stratigraphic unit thickness throughout the BSA. Mapping of reflector surfaces in three dimensions made it possible to estimate the volume of material contained within the major depositional sequences throughout the BSA.

Geologic Framework of the Buxton Study Area

Interpretations of seismic profile data indicate that the detailed geologic history of the BSA is more complex than that of Diamond Shoals. Seismic units can be grouped into eight principal depositional units. The major reflectors separating these principal units are labeled beginning with the seafloor reflector as R_0 and others designated R_1, R_2, R_3, R_4, R_5, R_6, R_7, and R_8 (Fig. 3).

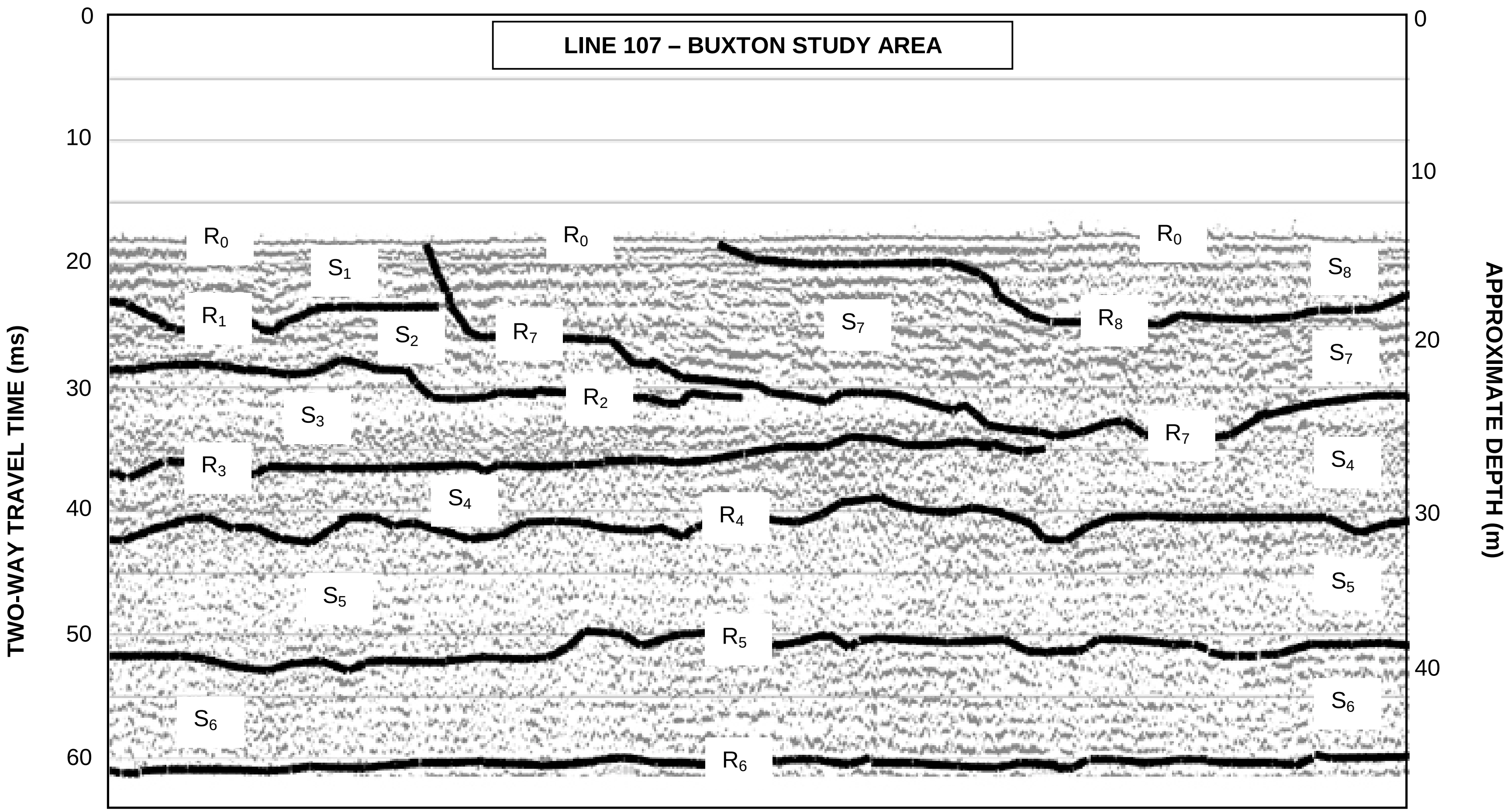

Fig. 3. Four kilometer segment (2.1 nautical miles) of seismic reflection profile 107 between shot points 52000 (left) and 56000(right). Segment trends parallel to shore of BSA from north (left) to south (right). The principal reflectors (R_0 through R_8) and stratigraphic units (S_1 through S_8) correlated throughout the BSA are indicated. Vertical scale in meters is approximate based on a sub-bottom *p*-wave velocity of 1,800 meters/second.

Within the seismic units defined by the nine major reflectors, the acoustic character of contained stratigraphic units is somewhat distinctive, aiding in the correlation of these units around the Buxton area. By convention, each unit (or sequence) is named according to the label of its basal reflector. Therefore, the ocean water column above R_0 could be labeled S_0, the sedimentary package between R_0 and R_1 is termed S_1, that between R_1 and R_2 is called S_2, etc. Brief descriptions of some of these seismic units are provided below.

Seismic Unit S_1

Unit S_1 is recognizable throughout the BSA. However, it is only continuous east (seaward) of line 096 (Fig. 2). West (or shoreward) of line 096, unit S_1 and its lower bounding reflector, R_1, are discontinuous from line 018 northward. Unit S_1 is missing altogether south of line 018, having been truncated by later erosion related to development of R_7. Unit S_1 has a tabular geometry and averages 4.1 m thick (range 0 m to 10 m) throughout the BSA. This reflector dips very gently seaward from the nearshore area where it occurs between 5 and 10 milliseconds two-way travel time and reaches maximum depth of about 25 milliseconds near the eastern (seaward) boundary of the survey area.

The basal reflector of Unit S_1 appears to crop out in the northernmost portion of the study area (north of line 022), and may be the horizon occurring as hardbottom throughout the northern portion of the BSA.

Unit S_1 is the uppermost stratigraphic unit within the northern and eastern portions of the study area, and it is a unit for which direct sedimentological data are available from cores. In addition to core sediment data, the surface expression of S_1 is represented on the side-scan sonar records north of line 018 and seaward of line 096. These data indicate that S_1 is of somewhat variable composition throughout its area of occurrence. Cores 181, 183, 184 show that the upper portion of unit S_1 is dominantly silty fine sand to silty very fine sand. However, down core, as one approaches the basal reflector of unit S_1, sediments become coarser and lithified. Occurrences of hardbottom composed of lithified coarse to medium sand (cores 174 to 177) correspond to areas where reflector R_1 crops out on the seafloor.

Seismic Unit S_2

The next seismic unit identifiable among the BSA seismic reflection data is also recognizable throughout the study area. Reflector R_2 is also somewhat discontinuous. North of line 017 and east of line 096, R_2 can be identified in all seismic data. However, south of line 017 and west of line 096 (Fig. 2), R_2 has been truncated by erosion during development of R_7. The R_2 reflector also dips gently seaward from 15 – 20 milliseconds two-way travel time in the nearshore area to about 30 ms near the eastern boundary of the BSA. The stratigraphic unit bound by R_1 and R_2 is termed S_2 in this report.

Unit S_2 is recognized and correlated throughout the BSA. S_2 also displays a tabular geometry, averaging 3.4 m thick (range 0 to 18 m) throughout the study area. The unit is missing in an area bound by lines 096, 107, 017, and 007. It is not clear whether any cores have penetrated this unit.

Seismic Unit S_3

Like reflectors R_1 and R_2, reflector R_3 has been truncated by erosion and development of R_7 in the southern, nearshore portion of the BSA. Unit S_3, therefore, is missing south of line 016 and west of line 096 (Fig. 2). Unit S_3 averages 6.5 m thick (range 0 to 30 m) where it can be found within the BSA. The unit is somewhat tabular, but shows evidence of some channel development, particularly in the northernmost part of the study area where it also displays the greatest thickness. In general, the unit dips seaward (east), with the basal reflector, R_3, occurring between 20 – 25 milliseconds two-way travel time nearshore and deepening to 35 milliseconds at the seaward (eastern) limit of the BSA. No cores penetrate unit S_3, so its sedimentary constitution is not presently known. However, its depth beneath the surface (20 – 35 m) is sufficiently great to preclude its consideration as a potential sand resource.

Seismic Units S_4, S_5, S_6

Reflectors R_4, R_5, and R_6 form the basal reflectors of units S_4, S_5, and S_6. Each of these units is too deep beneath the surface to be considered as potential sand resources, and are mentioned here only for completeness. Both R_4 and R_5 dip gently seaward. R_4 is recognized throughout the entire study area, occurring at about 35 milliseconds two-way travel time in the western part of the BSA and descending to 40 – 43 milliseconds along the eastern boundary of BSA. Unit S_4 has a uniform thickness averaging 8.8 m throughout the BSA. R_5 is also recognizable throughout the BSA, and dips gently eastward from about 40 milliseconds two-way travel time in the western (nearshore) portion to about 53 milliseconds along the seaward boundary of the survey area. S_5 also has a relatively uniform thickness averaging about 8.6 m.

Reflector R_6 is a very strongly reflecting horizon and easily correlated throughout the entire BSA. It is the deepest reflector observed within this study area and may correlate with R_5 observed within the Diamond Shoals Study Area. R_6 is a very stable reflecting horizon, and varies in depth between 50 and 60 milliseconds two-way travel time everywhere in the BSA. Once again, this unit is too deep beneath the surface to be exploited as a sand resource, but it is a good seismic/stratigraphic marker unit.

Seismic Units S_7 and S_8

Reflector R_7 is the most significant feature within the BSA. R_7 occurs only in the southern portion of the BSA, in an area bound by lines 007, 018, 096, and the shoreface. R_7 intercepts the seafloor in the vicinity of line 018 and rapidly descends to 24 - 27 milliseconds two-way travel time such that it truncates reflectors R_1, R_2, and R_3 throughout the entire southern area of the BSA shoreward of line 096 (Fig. 4).The average thickness of unit S_7 overlying R_7 is 12.4 m (Fig. 5).

Note that the northern edge of occurrence of R_7 is approximately coincident with a dramatic change in the width of Hatteras Island (Fig. 4). North of the occurrence of R_7, the island is sufficiently wide to accommodate the community of Avon. South of the occurrence of R_7, however, the island is much narrower and lower in relief. This area of the island is presently the focus of dune restoration efforts.

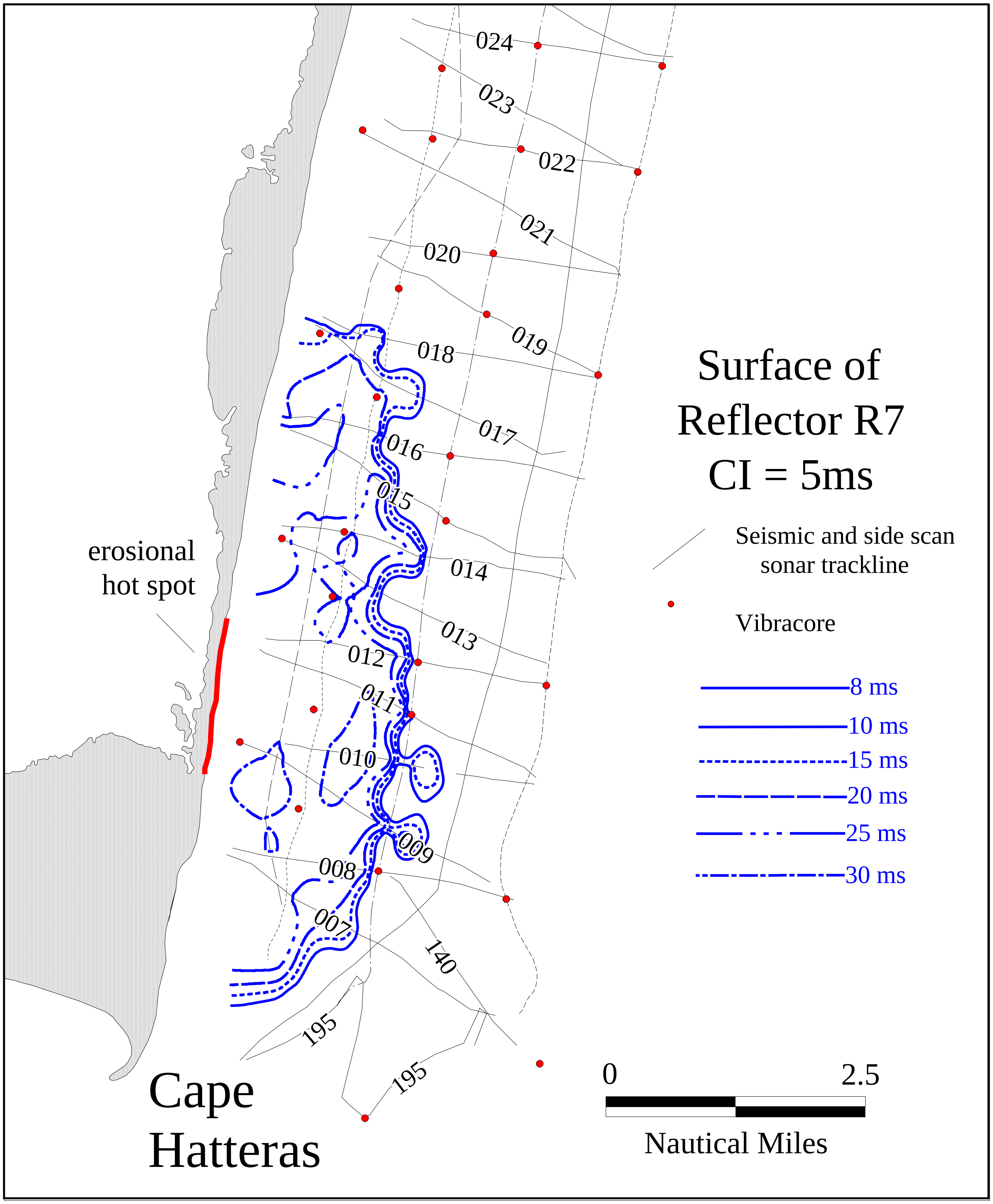

Fig. 4. Structure contour map derived from seismic reflection data showing depth (in milliseconds two-way travel time) from sea level to top of reflector R_7 within the BSA. Contours on surface of R_7 labeled with 5 ms contour interval (approximately 4 meters). Note that R_7 occurs only in the southern portion of the study area.

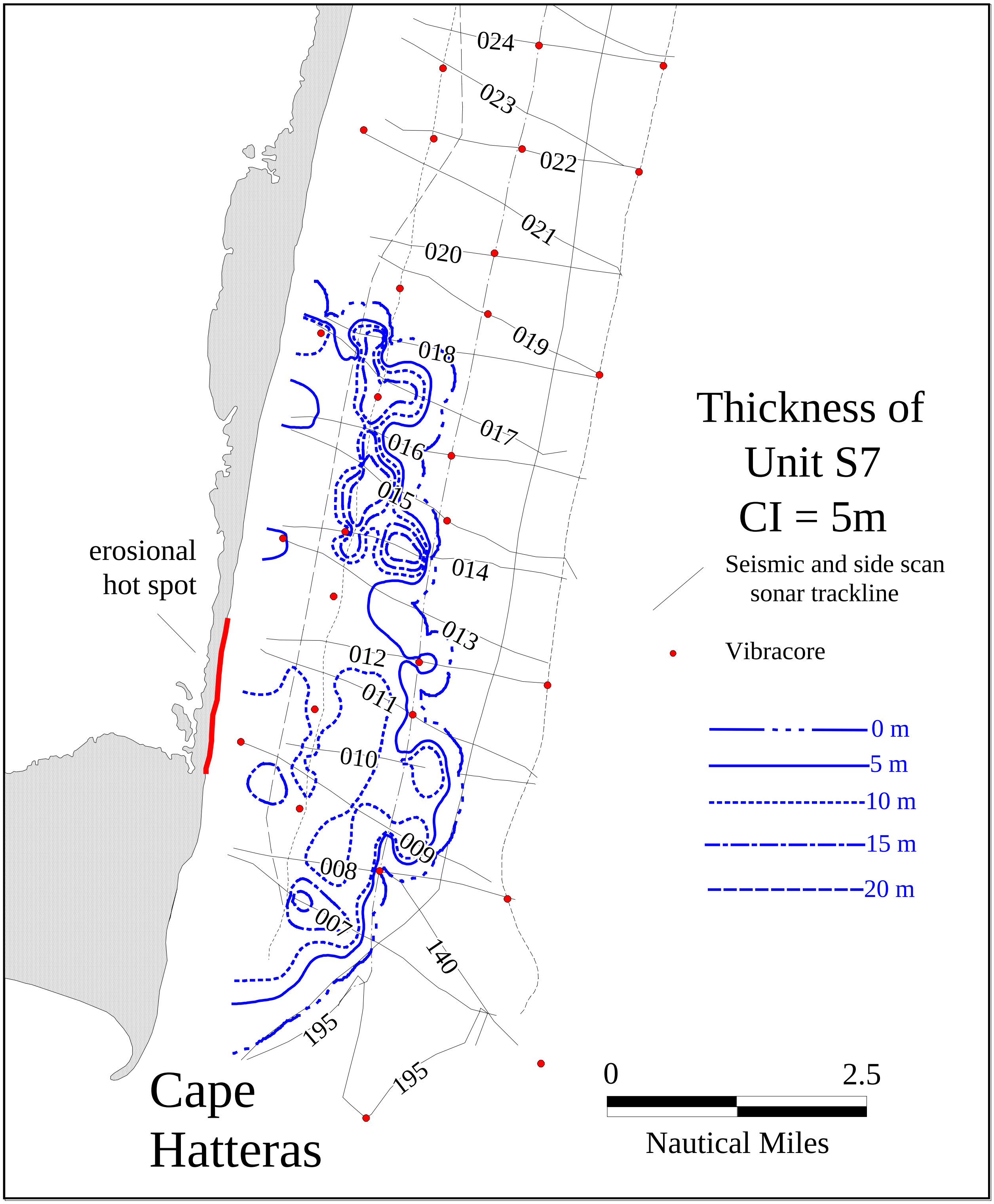

Fig. 5. Isopach map of unit S_7 in the southern portion of the BSA. The average thickness of S_7 is 12.4 m. Contour interval is 5 m.

On seismic profiles (e.g. Fig. 3), the northern boundary of R_7 appears as a concave reflector reminiscent of one sidewall of a channel. No similar sidewall has yet been located to the south. When viewed on shore-parallel seismic profiles (i.e. lines 107 and 138), the seismic appearance of sediments overlying R_7 (that is, sediments of unit S_7) is that of a continuous series of thin, tabular cross-strata, dipping to the south. When viewed on shore-perpendicular seismic profiles (i.e. Lines 007 to 018), the seismic character of S_7 is that of numerous small, superimposed channels. This seismic signature is interpreted to represent a migrating channel complex which initiated at the northern edge of R_7 occurrence and progressively migrated toward the south, perhaps to Cape Hatteras, before closing. As this channel system migrated, it eroded all pre-existing stratigraphy and redeposited channel-fill sediments (mostly sand and gravel). Riggs (personal communication, 1999) suggests that these channels evolve from fluvial systems that incise into the continental shelf during lowstands of sea-level. When sea-level rises again, the channels are inundated and back fill with estuarine sediments. During the next sea-level lowstand, channels may incise into estuarine sediments once more and rework or redeposit coarser channel-fill sediment.

An alternative hypothesis is that the migrating channel complex represents southward advance of a tidal inlet system. Under this scenario, an inlet opened at the northern limit of R_7 (indeed, R_7 represents the northern “wall” of this inlet). Over time, southerly longshore drift along the Outer Banks forced migration of the inlet toward Cape Hatteras and as it migrated, it eroded through all pre-existing stratigraphy (truncating reflectors R_1, R_2, and R_3) and redeposited inlet fill (mostly sand and shell gravel). A limitation of this model is that the breadth of R_7 offshore may be too great to be explained as migration of an inlet.

Like reflector R_7, R_8 also has a restricted areal distribution within the BSA (Fig 6). R_8 occurs as a horizontal reflector throughout most of the area of R_7, and S_8 occurs as a thin capping stratum over S_7. S_8 averages 2.9 m thick (range 0 to 10 m; Fig. 7) and appears to be composed of interbedded silty very fine sand, mud, and gravel (cores 186, 191, 196, 198). In areas where this unit is thick, cores are of highly variable quality, though relatively thick mud layers impart overall mud contents in excess of 10%. In areas where S_8 is thin (e.g. seaward of line 138), cores appear to penetrate through approximately 0.8 – 0.9 m of unit S_8 into unit S_7 and their overall textural attributes are very good. If one overlays a map showing the seaward limit of R_8 onto a map showing the seaward limit of R_7, and compares this map to the location of favorable cores, it is evident that the best cores sampled unit S_7 beyond the seaward limit of S_8 (Fig. 8). Thus, it appears that unit S_8 is the likely source of poor sediment quality observed shoreward of line 107 in the southern part of the BSA.

Side-Scan Sonar

Side-scan sonar data were collected concurrently with the seismic data using an EG&G (now Edgetech) DF-1000 system. The digital signal was processed through a deck control unit and then written to a thermal plotter as well as digital tape. For this study, the hardcopy records from the thermal plotter were reviewed. The thermal plotter records a gray-scale image of the seafloor, known as a sonogram, which is sensitive to the textural characteristics of the surface sediments. Higher reflectivity (darker record) is typically associated with coarser-grained sediments; lower reflectivity (lighter record) with finer grained sediments. Topographic

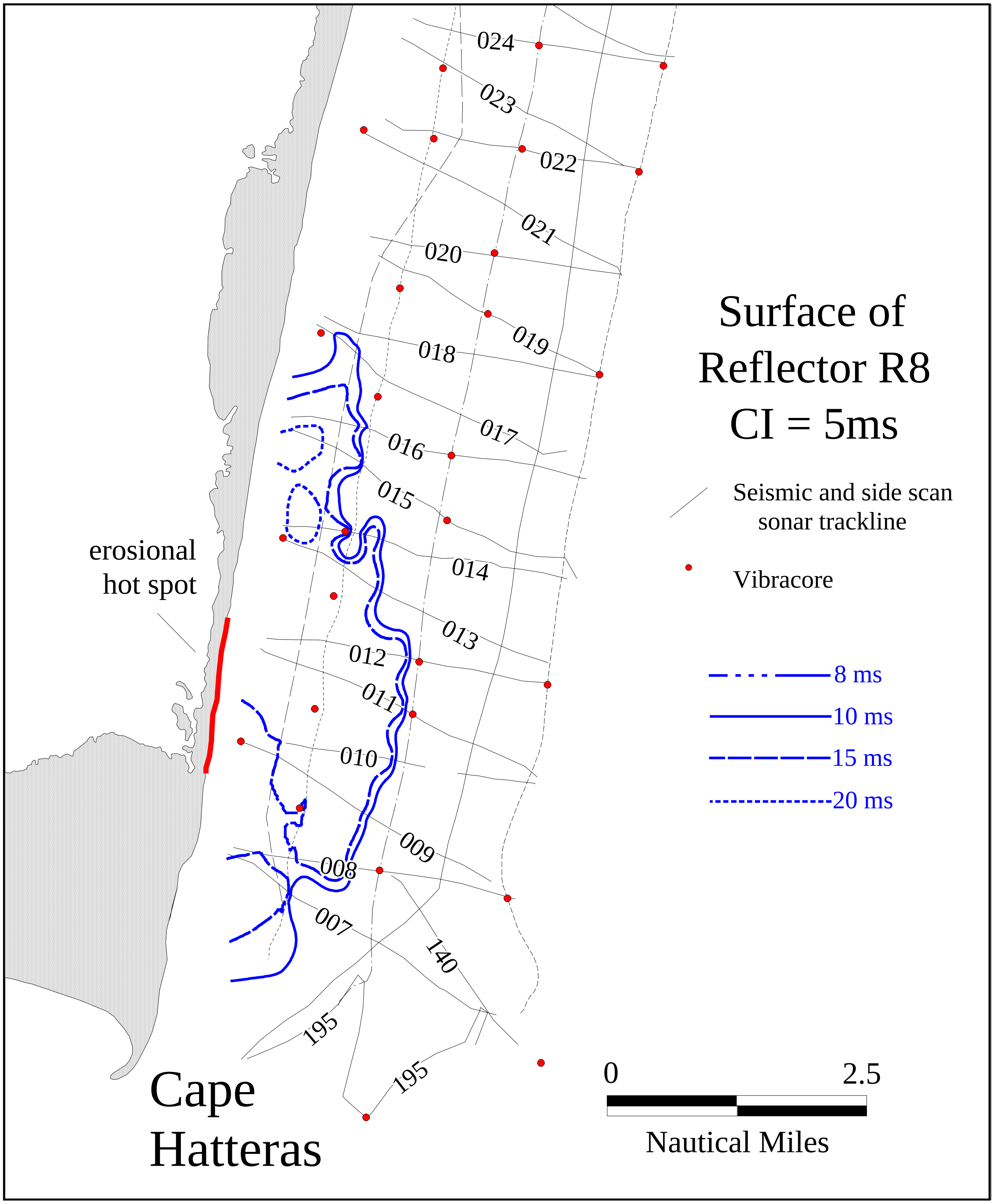

Fig. 6. Structure contour map derived from seismic reflection data showing depth (in milliseconds two-way travel time) from sea level to top of reflector R_8 within the BSA. Contours on surface of R_8 labeled with 5 ms contour interval (approximately 4 meters). Note the limited areal extent of R_8, occupying only the southern portion of the study area. Also note that R_8 occupies a more restricted area than R_7.

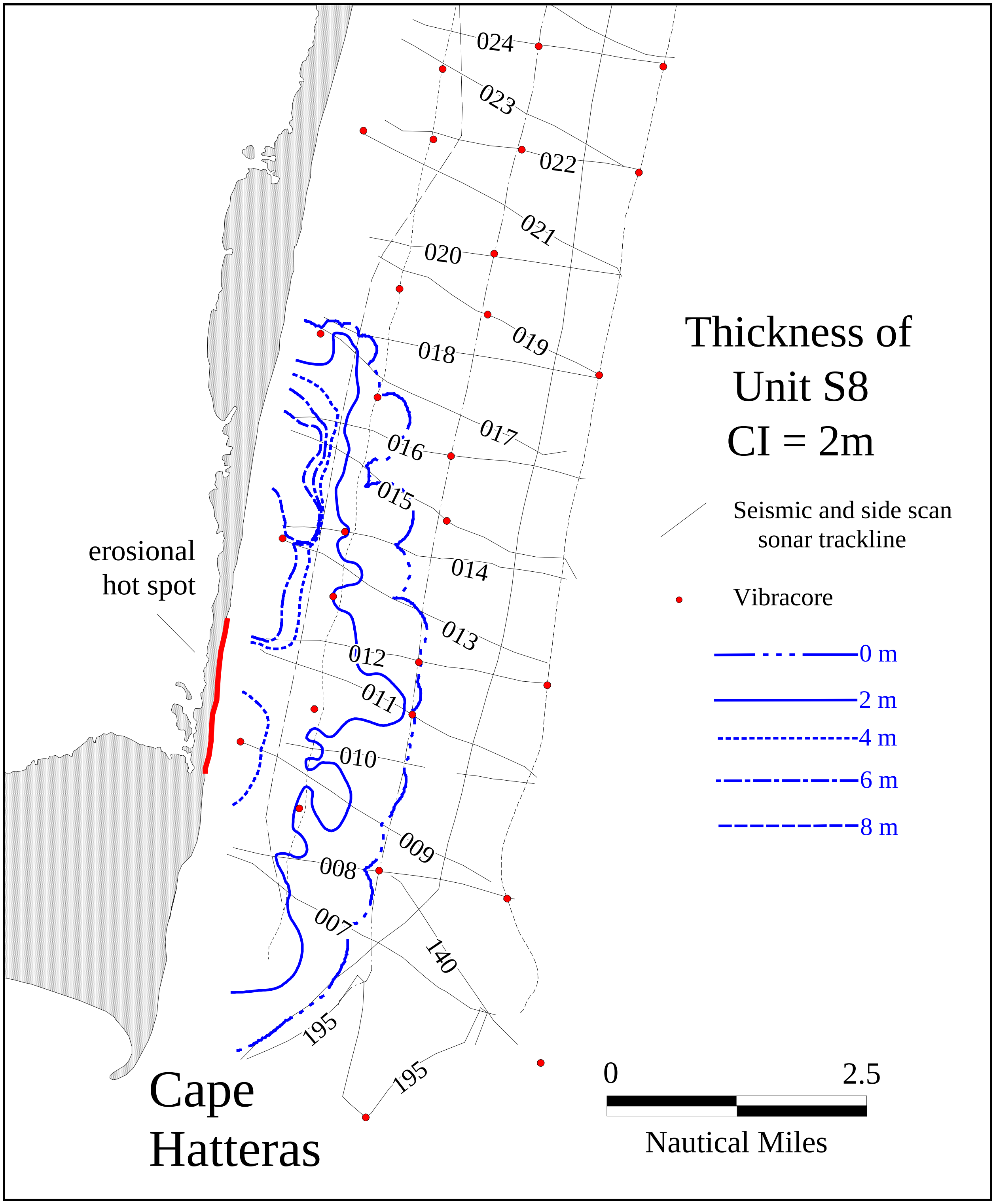

Fig. 7. Isopach map of unit S_8 in the southern portion of the BSA. The average thickness of S_8 is 2.9 m. Contour interval is 2 m.

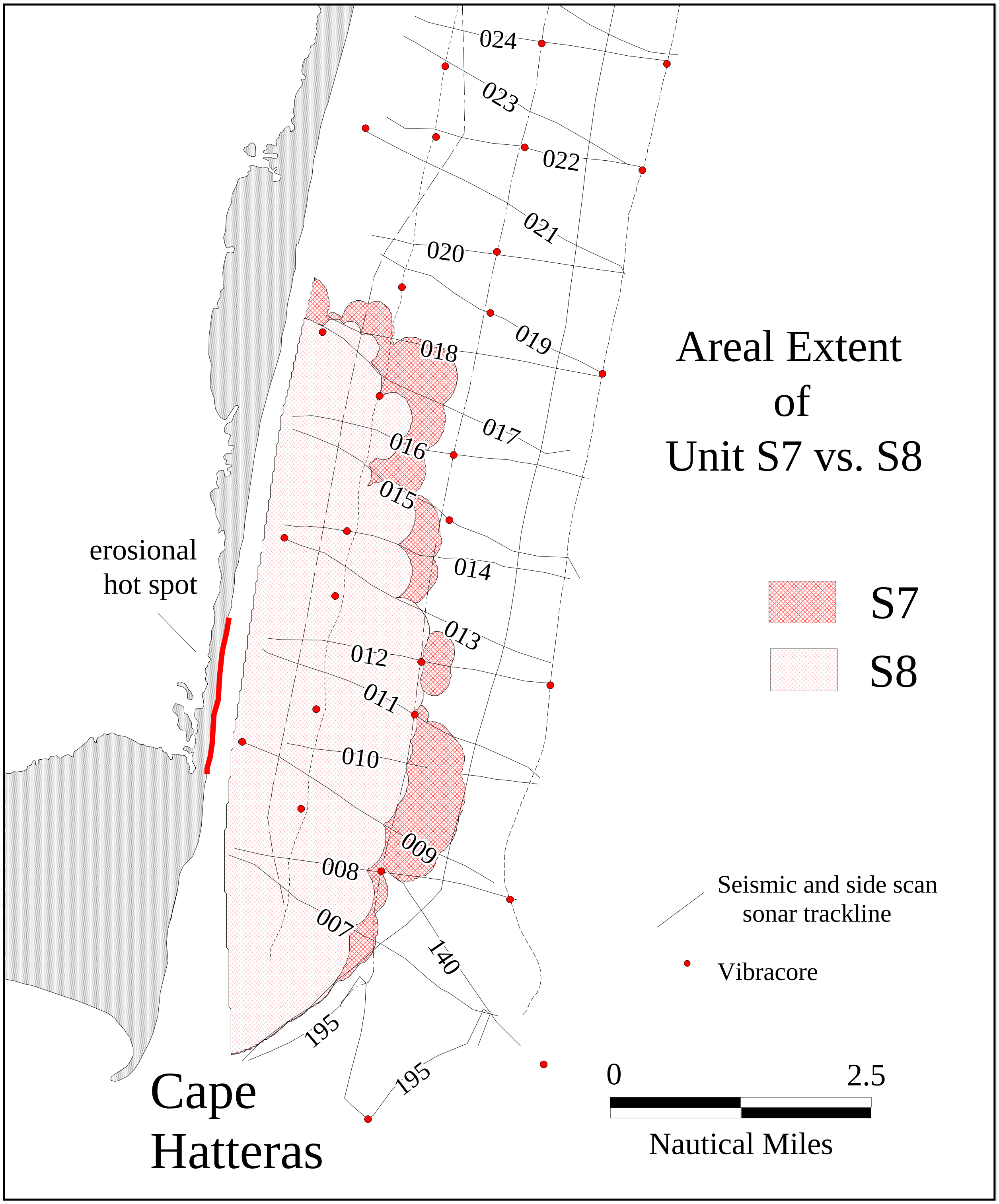

Fig. 8. Comparison of areal extent of units S_7 and S_8, illustrating that unit S_7 extends beyond the limits of S_8. Thus, cores in this area will sample S_7 with without penetrating poorer quality sediment of S_8.

irregularities in the seafloor such as escarpments, bedforms, or even man-made debris can impart character to the record as well. Time-event marks on the sonograms were cross-referenced to known navigation fixes taken during the data collection and could be referenced to the seismic data and GIS basemap.

All sonograms were recorded with a 400-meter swath width (200 m to each side of the towfish). Ideally, the towfish should "fly" at a relatively constant and recorded height above the seafloor. In the BSA, especially the lines running perpendicular to the shoreline, the fish would need fairly continuous monitoring and adjustment for optimal data capture. No such activity is noted on the data records or logs. The consequences of operating at an improper height typically include 1) the imaged seafloor swath typically is less than 400 m, 2) there are significant portions of sonograms where acoustic returns from the sea surface obscured seafloor data (especially in rough weather), and 3) it is difficult to maintain the bottom-track of the sonar fish in the shallowest portions of the survey area -- resulting in poor sonogram quality across these areas.

Furthermore, specific operating parameters of the side-scan sonar instrument during acquisition were not available. Thus, it was not possible to determine whether slight changes in acoustic character were related to actual variability of seafloor physical properties or to adjustment of operating parameters (such as gain) at the time of acquisition. Thus, careful evaluation of the record is necessary to differentiate "real" featureless data from poor data. Indeed, much of the BSA side scan record was fairly featureless and indistinct. On the other hand, several areas of hardbottom were imaged quite well, so it is apparent that the equipment was functional.

The southern three-fourths of the Buxton area side-scan record is dominated by a weak to moderate acoustic return (Fig. 9). This acoustic character of seafloor sediment suggests a predominance of very fine- or fine- to medium-grained sand as the surface sediment type. Along the shore-parallel lines, much of this bottom type is rippled to suggest further that sandy surficial material is mobile. Ripples are not imaged very well on the shore-perpendicular lines, even where these lines cross distinctly rippled sediments along the shore-parallel tracklines. This may be due to an unfavorable orientation in terms of imaging, but also may be due to the fact that the lines were collected several days to over a week apart from each other. The shore-perpendicular lines were collected under somewhat rough sea conditions and both the side scan and seismic data quality suffered as a result.

Figure 9 illustrates the extent of different generalized seafloor types throughout the BSA. Hardbottom areas are relatively common in the northern quarter of the surveyed area. The hardbottoms are very distinctive on the side scan sonograms (Fig. 10) and show relief along generally east-facing scarps. Some areas appear to be rock rubble. Whereas the presence of hardbottom (and more specifically the flora and fauna that develop and flourish on this bottom type) is a strongly negative factor in terms of offshore mining, the area north of line 022 should not be considered for mining even if it does prove to contain otherwise viable sand resources. Similarly, the inner mile extending south from line 022 to about line 017 should be disregarded.

Surprisingly, the hardbottom area has no characteristic signature on the single-channel seismic profiles, so seismic data alone would be insufficient to locate these features. They are

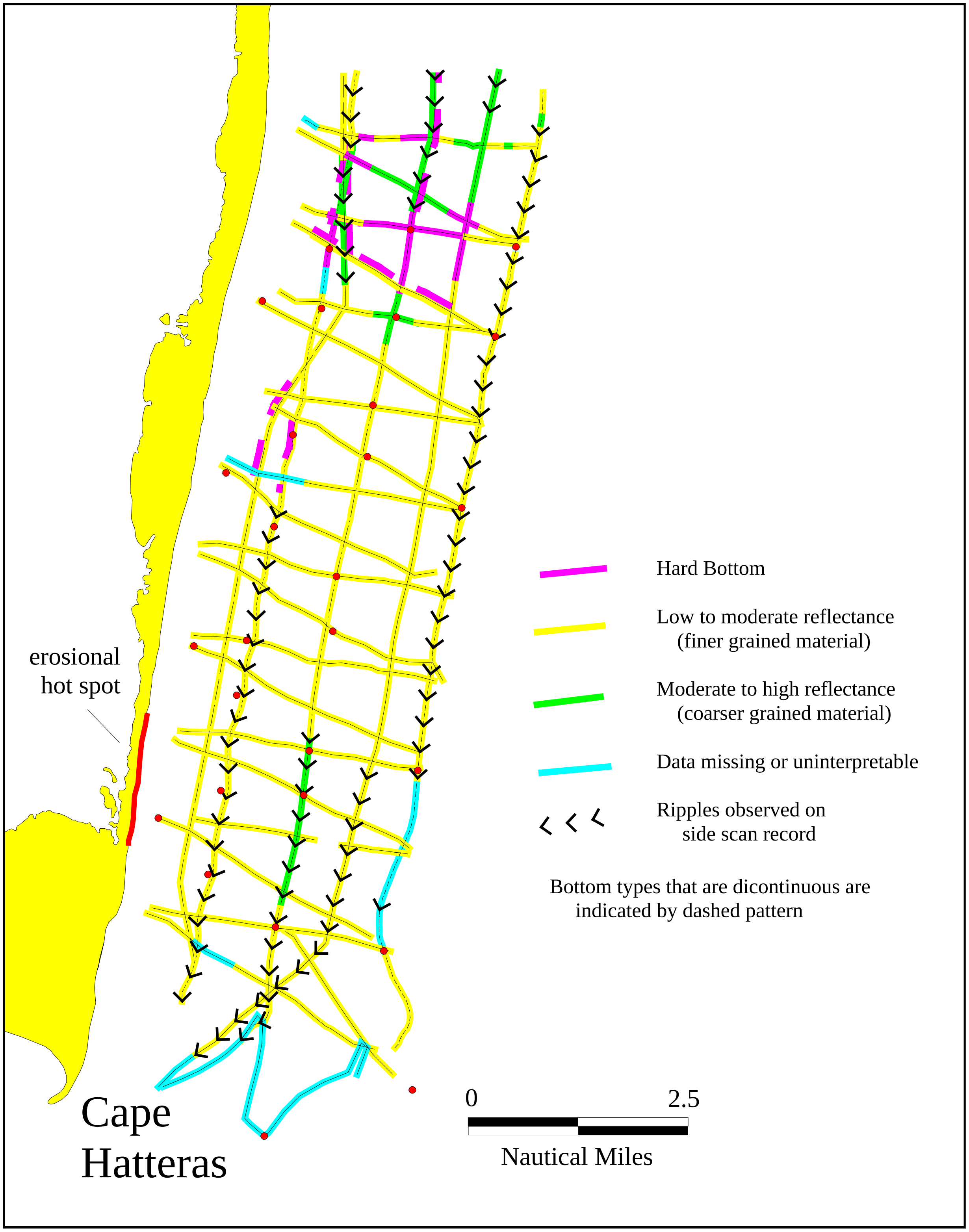

Fig. 9. Seafloor map derived from analysis of side scan sonar imagery.

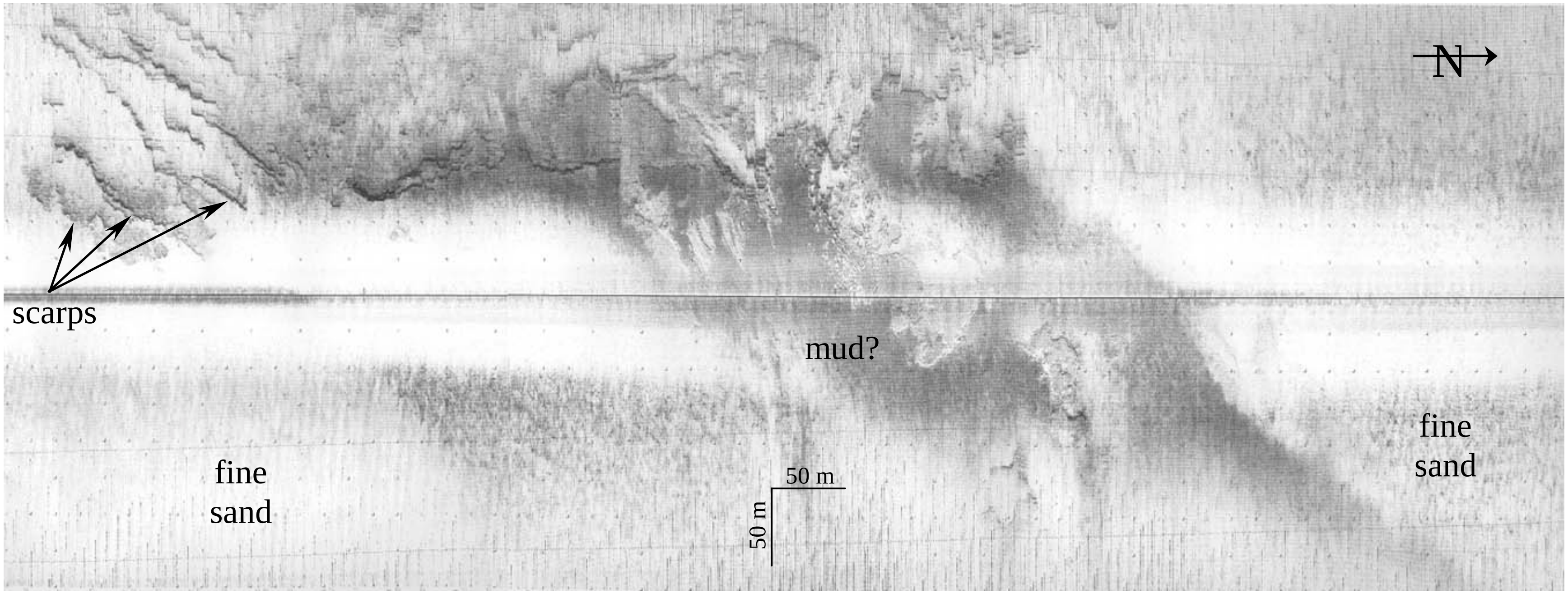

Fig. 10. Side scan sonogram along line 196 between lines 023 and 024.

best located using side-scan sonar. Cores 174 and 175 are located along trackline segments marked as hardbottom and contain clasts and zones of cemented shell debris (coquina) within medium- to coarse-grained sand and gravelly sand. Core 176, located further offshore from the other two and in an area mapped as a sandy bottom type, contains approximately 2.5 m of muddy fine-grained sand at the top of the core. But this overlies the sandy, cemented lithology. Thus, the hardbottom "unit" is buried beneath younger material further offshore.

In the southern portion of the BSA, side-scan sonar reveals areas of moderate acoustic reflectivity indicative of coarser sediment (medium to coarse sand or gravel). The principal area where this seafloor type is observed (Fig. 9) corresponds well to the mapped distribution of unit $S_{7.}$

SECTION II: SEDIMENT TEXTURAL CHARACTERISTICS FROM CORES

Twenty-seven vibracores were collected within the BSA during the summer of 1995 aboard the U.S. Army Vessel *Snell* (Fig. 11; Table 2). Core lengths range from 1.96 m to 6.11 m, with an average length of 3.97 m. The cores are distributed throughout the study area and range from approximately 0.5 miles to 3 miles offshore. These locations generally coincide with seismic line crossing or end points.

Using the *p*-wave velocity adopted for this study of 1800 m/sec, the average core length would be represented on seismic profile data by 4.4 ms two-way travel time. Minimum and maximum length cores would be represented on seismic profile data 2.2 ms to 6.8 ms two-way travel time. Thus, it is clear that cores penetrate to very shallow depths within the BSA sediment package.

Despite the fact that cores penetrate to relatively shallow depths, it was possible to sample different stratigraphic units within the BSA because the areal extent of stratigraphic units was limited. In particular, it appears that north of line 018 and east of line 096, unit S_1 was the likely stratigraphic unit sampled by cores. South of line 018 and west of line 096, cores appear to sample both units S_7 and S_8. (Figs. 5, 7, 11).

Sediment textural data (Table 2) are summarized from original core descriptions (composed at the time cores were opened in 1995). Images of cores archived on CD-ROMs (also composed at the time cores were opened), and textural analyses (standard textural parameters such as weight percent size fractions, mean grain size, sorting, etc.) were compiled by Hoffman and Boss on computer spreadsheets in 1996 (unpublished data). All of these data, including core halves, are archived at the Coastal Plain Office of the North Carolina Geological Survey in Raleigh, NC.

Within the BSA, sediment texture is varied within most individual cores as well as from core to core. Several sediment types, varying from mud to gravel, are present within the cores. The three northernmost cores (numbers 174, 175, and 176) all contain clasts and zones of cemented shell debris (coquina) indicative of hardbottom areas. These zones occur within medium- to coarse-grained sand and gravelly sand and are altered to a dull yellowish brown color. Approximately 2.5 m of muddy fine-grained sand overlies the sandy, cemented lithology in the

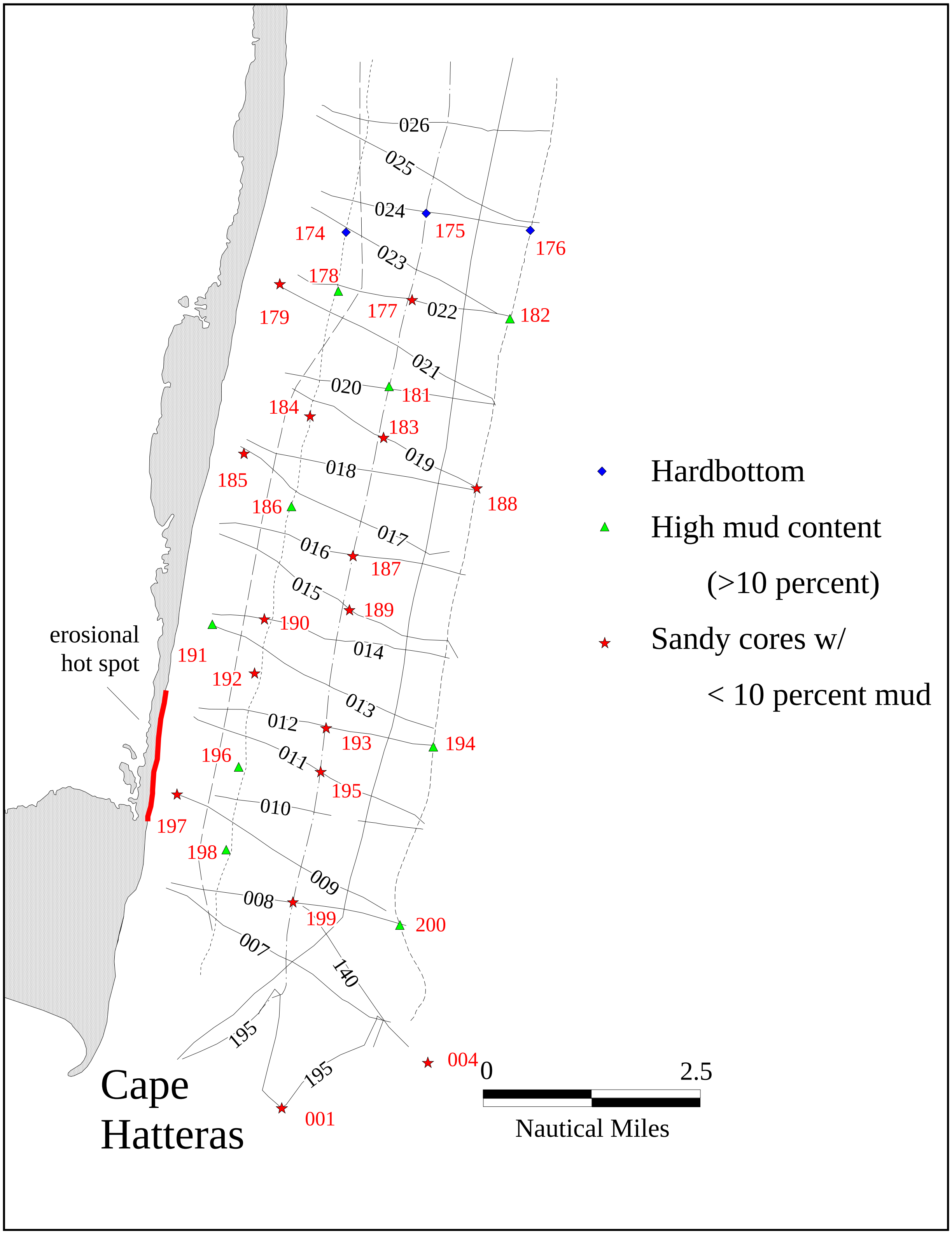

Fig. 11. Map showing distribution of cores coded to indicate quality of sediment with respect to suitability for beach nourishment.

Table 2. Summary textural data from vibacores.

CORE No.	Water Depth (m)	Length (m)	MUD (wt. %)	SAND (wt. %)	GRAVEL (wt. %)	Mean Grain Size(Ø)	Mean Grain Size(mm)	St. Dev. (Ø)	General Description
SNL-001	7.3	2.82	2.23	97.14	0.39	2.49	0.18	0.65	uniform fine-grained sand; laminae of very coarse skeletal sand 80-120 cm
SNL-004	17.4	2.18	6.86	84.75	8.08	2.10	0.23	1.63	finer-grained sand in upper meter and medium- to coarse-grained sand in lower meter; shell gravel at 1.5-1.9 meters
SNL-174	10.97	3.62	18.28	72.87	8.83	1.74	0.30	1.76	hardbottom area; 0-209cm--medium to coarse shelly sand with cemented zones (coquina); 209-256cm--mud; 256-362cm--muddy, fine burrowed sand grading down to clean medium to coarse sand
SNL-175	12.80	4.24	8.52	60.18	31.19	0.52	0.52	1.75	hardbottom area; uniform coarse sand and gravelly sand with abundant cemented clasts and zones of cemented shell debris (coquina)
SNL-176	16.15	4.81	6.85	77.70	15.30	1.83	0.28	1.71	0-250cm--dominantly muddy fine sand; 250-481cm--gravelly coarse and medium to coarse sand with cemented zones and clasts (hardbottom lithology)
SNL-177	15.85	3.62	3.79	76.99	19.12	1.15	0.45	1.65	sandy throughout core; dominantly fine to medium sand with zones also containing coarser sand and shell fragments
SNL-178	10.97	6.10	12.24	73.89	13.80	1.59	0.33	1.83	dominantly medium sand; 0-146cm--fine to medium sand; 385-432cm--several mud layers; otherwise medium to coarse shelly sand
SNL-179	8.23	3.87	4.62	84.02	11.41	1.86	0.28	1.63	numerous variable textured layers 10-50cm thick ranging from fine to medium sand to medium to very coarse sand; several gravelly and shelly zones
SNL-181	12.50	5.09	37.01	61.81	1.00	3.10	0.10	1.31	overall muddy core; 0-211cm--silty fine and very fine sand; 211-509cm--mostly muddy with thin sand lenses
SNL-182	15.24	3.78	10.59	85.07	4.23	2.59	0.17	1.27	mostly silty very fine to fine sand; 320-378cm--medium to coarse sand and gravelly sand

Table 2. Summary textural data from vibacores (continued).

CORE No.	Water Depth (m)	Length (m)	MUD (wt. %)	SAND (wt. %)	GRAVEL (wt. %)	Mean Grain Size(Ø)	Mean Grain Size(mm)	St. Dev. (Ø)	General Description
SNL-183	13.72	3.24	4.98	94.22	0.68	2.81	0.14	0.80	overall fairly uniform silty fine to silty very fine sand
SNL-184	11.28	4.80	3.52	84.30	11.57	1.79	0.29	1.61	0-152cm--silty fine and silty very fine sand; 152-160cm--mud lens; 160-480cm--medium to coarse sand with shell gravel
SNL-185	7.62	3.74	3.37	89.48	6.88	2.07	0.24	1.39	mostly fine to medium sand with several 10 to 20cm-thick layers of medium to coarse sand; mud-filled burrows throughout the core
SNL-186	11.58	5.97	41.49	57.29	1.08	3.04	0.12	1.43	interlayered sand and mud; 0-49cm--fine to very fine sand; 49-150cm--mud; 150-425cm--silty fine to medium sand with mud-filled burrows; 425-597cm--mud with thin sandy zones
SNL-187	14.33	1.96	4.70	89.15	5.97	2.35	0.20	1.39	mostly silty fine to very fine sand; several 5 to 10cm-thick lenses of medium to coarse sand within 120-150cm interval
SNL-188	16.76	2.20	6.23	86.07	7.52	2.05	0.24	1.50	0-130cm--layers of silty fine sand, silty very fine sand, mud, and medium to coarse sand; 130-220cm--clean fine sand with a few mud filled burrows at top of interval
SNL-189	15.54	2.35	2.68	88.10	9.05	1.93	0.26	1.43	sandy throughout core; fine to medium sand with lenses of medium sand with shell gravel 50-60cm and 90-100cm
SNL-190	12.50	4.24	2.38	77.30	20.27	1.24	0.65	1.78	0-150cm--very uniform fine to very fine sand; 150-425cm--coarse to very coarse sand with abundant shell clasts
SNL-191	8.23	4.80	13.53	84.67	1.52	2.17	0.22	1.39	0-95cm--very fine to fine sand; 95-180cm--mud; 180-242cm--silty fine sand; 242-480cm--medium to coarse sand
SNL-192	12.50	3.04	2.66	90.34	6.93	1.90	0.27	1.42	0-115cm--very uniform fine to very fine sand; 115-180cm--medium to coarse sand; 180-282cm--coarse to very coarse sand with abundant shell clasts; 282-304cm--medium sand

Table 2. Summary textural data from vibacores (continued).

CORE No.	Water Depth (m)	Length (m)	MUD (wt. %)	SAND (wt. %)	GRAVEL (wt. %)	Mean Grain Size(Ø)	Mean Grain Size(mm)	St. Dev. (Ø)	General Description
SNL-193	15.85	4.20	2.18	87.79	9.89	1.37	0.39	1.31	sandy throughout the core; dominantly medium to coarse sand with several gravelly layers in upper 140cm
SNL-194	18.59	2.23	10.34	68.51	21.14	1.53	0.35	1.94	sandy throughout the core; silty fine sand upper 75cm; mostly fine to medium sand below 75cm with thin lenses of shell gravel
SNL-195	15.54	2.51	1.87	56.33	41.74	0.28	0.82	1.62	coarse to very coarse sand and shell gravel; significant shell gravel content 0-50cm and 140-251cm
SNL-196	11.89	3.92	15.70	82.85	1.27	2.48	0.18	1.23	layered sand and mud; 0-82cm--silty very fine to fine sand; 82-90cm--gravelly zone; 90-243cm--mud grading down to muddy sand by 150cm; 243-392cm--dominantly medium sand with shell gravel toward base
SNL-197	5.79	3.91	2.65	96.26	0.95	2.50	0.18	0.67	relatively uniform fine sand; some mud as burrow fillings and linings; very coarse sand at 113-120cm
SNL-198	11.58	6.05	22.20	76.58	1.08	2.75	0.15	1.33	layered sand and mud; 0-85cm--silty very fine sand; 85-140cm--medium to coarse sand with shell gravel; 140-163--fine sand to silty fine sand; 163-415cm--mud with shells in lower m; 410-605cm--medium sand
SNL-199	10.36	6.11	4.42	92.90	2.29	1.86	0.28	1.07	sandy throughout the core; 0-425cm--uniform medium to coarse sand; 425-611cm--uniform silty fine sand to fine sand
SNL-200	17.68	2.85	41.12	50.51	6.51	2.67	0.14	1.86	0-130cm--mud with several layers of fine to very fine sand; 130-165cm--coarse sand and shell gravel; 165-190cm--mud; 190-285cm--coarse sand
Average	**12.85**	**3.97**	**11.07**	**78.66**	**10.05**	**1.97**	**0.29**	**1.46**	
Maximum	**18.59**	**6.11**	**41.49**	**97.14**	**41.74**	**3.10**	**0.82**	**1.94**	
Minimum	**5.79**	**1.96**	**1.87**	**50.51**	**0.39**	**0.28**	**0.10**	**0.65**	

outermost of these three cores. These cores probably sample unit S_1, and its basal seismic reflector, R_1, is likely the indurated sediment forming the hardbottom. Unit S_1 in this location does not represent an area of potential sand resources.

Elsewhere across the BSA, unit S_1 is sampled by cores 178, 181, 182, 183, 184, 187, 188, 194, and 200. Textural attributes of these cores are highly variable, though they averagemore than 10% mud and thus are unsuitable as potential sand resources.than 10% mud and thus are unsuitable as potential sand

Another group of cores consists of interbedded sand and mud. This group includes cores 186, 196, and 198. The mud content of these cores ranges from 15 percent to over 40 percent, thus rendering these deposits unsuitable as beach nourishment material as well. These cores sample unit S_8, which averages 2.9 m thick throughout the BSA. Review of the core logs for these cores indicates that sediment with coarser textural attributes (medium to coarse sand) occurs in all cores below approximately 2.5 meters. It is suggested that the lower portion of these cores is sampling unit S_7.

Cores 189, 192, 193, 195, and 199 all contain acceptable amounts of mud with all but one of these cores containing less than 5 percent mud. When the locations of these more prospective cores are considered, the cluster comprised of cores 189, 190, 192, 193, and 195 form an area that is approximately 2.5 square nautical miles. This area coincides with the area where unit S_7 is interpreted to crop out directly on the seafloor. Theses 5 cores average 2.35% mud, 79.97% sand, and 17.58% gravel. The mean grain size of 1.34 ϕ (0.395 mm; $\phi = -\log_2$ of grain diameter in millimeters, Pettijohn, 1975) falls within the medium grained sand classification.

SECTION III: SAND RESOURCE ASSESSMENT

The primary goal of this survey was to determine the potential for the BSA to serve as a source of sand for future beach nourishment of the critically eroding shoreline immediately onshore of the BSA (Figs. 1, 2). The geophysical data have aided in determining the stratigraphic architecture of the BSA (from seismic reflection data) and characteristics of the surface sediment (from side-scan sonar). Interpretations of these data have been verified to some extent through sedimentological analysis of available cores. The final step in the process of assessing the sand resource potential is to merge the geophysical interpretations and core data to determine which stratigraphic units (if any) might serve as suitable sand resources and to arrive at an estimate of the total volume of sand within suitable units. In arriving at sand volume estimates, a purposeful effort has been made to use conservative measures wherever possible. Thus, values reported in this section should be considered to be minimum estimates of the total sand volume contained within suitable units of the BSA.

Volume estimates for each stratigraphic unit can be made if the thickness and area of each unit are known. Recall that the thickness of stratigraphic units (in meters) was estimated by assuming that the speed of propagation of seismic impulses (*p*-wave velocity) through the sediments was 1800 m/sec and that this was considered to be a minimum velocity; higher velocities would yield greater thickness for each unit. To represent the final result in appropriate volume units, the thickness of each unit (in yards) was determined by dividing the estimated thickness in meters by a conversion factor (yards = meters/0.9144).

The area of each unit was determined utilizing an automatic feature of the GIS software package which will calculate the area of any contoured region in units specified by the user. For this study, it was appropriate to determine the area in square yards bound by the contours of Fig. 5.

For each contoured area, the value of thickness used is that of the lower contour. For example, a contoured region bound by the 5-m and 10-m contour ranges in thickness from 5 m to 10 m. For the purpose of estimating the volume of material bound by these contours, it was assumed that the area had the minimum thickness of 5 m throughout its areal extent. Once the total area bound by different contours was determined, the volume of sand within these contours was calculated by multiplying the area and minimum thickness. The resulting volume, expressed in millions of cubic yards (yd^3), is presented in Table 3 below.

For this study, the only stratigraphic unit considered to be a potential sand resource was unit S_7 (interpreted as a channel fill complex). While deeper stratigraphic units might also yield quality sand, their depth beneath the surface is considered to make the cost of their exploitation prohibitive versus dredging the more easily available surficial material.

As can be seen in Table 3, the estimated minimum volume of sand available within S_7 across the BSA is appreciable. The total volume of sand within unit S_7 across the BSA is at least 375 million cubic yards. However, as has been discussed previously, unit S_8 overlies unit S_7 over much of the southern portion of the BSA. Given that the average thickness of unit S_8 is 2.9 meters, it may be impractical to attempt to dredge through S_8, especially since available cores indicate that S_8 sediments are rather undesirable as beach fill material.

THICKNESS (m)	UNIT S_7 VOLUME (millions yd^3)
5	80.5
10	157.1
15	77.6
20	49.3
25	10.7
TOTAL	**375.2**

Table 2. Estimated volume of sand in stratigraphic unit S_7. Volumes were calculated by measuring the area (in yd^2) for each contour in a 5-m contour interval using GIS software. These areas were then multiplied by minimum thickness of the contoured unit (meters/0.9144 = yards) to obtain volume in cubic yards. Recall that the *p*-wave velocity used to estimate unit thickness is also conservative. Thus, results above represent minimum volume estimates of sand within the upper two stratigraphic units of the BSA.

If the area of S_7 chosen as the potential sand resource is arbitrarily restricted to that area of S_7 where the thickness of overlying S_8 is less than 0.5 m thick, a refined estimate of the quantity of available sand can be made (Fig. 12, Table 4). The area and thickness of S_7 within this box must be estimated. For the sake of this illustration, assume several scenarios for the thickness of S_7 in this box; 5 m, 10 m, and 15 m. The estimated volume of sediment in this box using these values is given in Table 4 below.

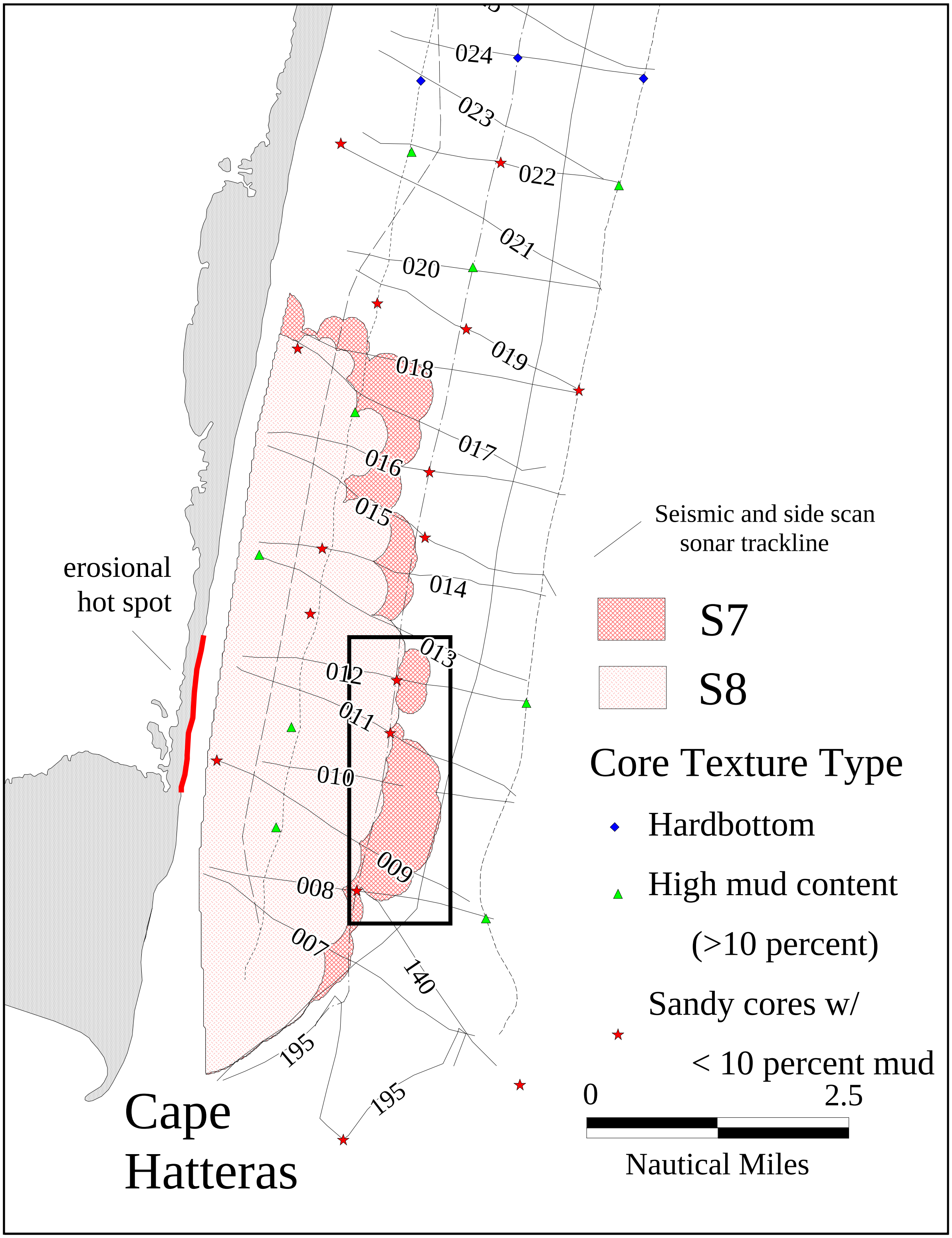

Fig. 12. Map showing hypothetical sand resource area (box) located to access sediment from unit S_7 with a minimum from unit S_8. Area of this box is 11 million yd^2. Estimates of sand resource within this box are presented in Table 4 assuming scenarios for thickness of S_7 of 5 m, 10 m, and 15 m..

ESTIMATED VOLUME OF SAND IN BOXED AREA (Fig. 12)	
Area of Box on Map = 11 million yd^2	
ASSUMED SEDIMENT THICKNESS (m)	**ESTIMATED VOLUME OF S_{7R} (million yd^3)**
5	60.1
10	120.3
15	180.4

Table 4. Estimated volume of S_7 restricted (S_{7R})to area where overlying S_8 is less than 0.5 m thick. Sand Volume calculated using same method as previous.

Obviously, not all of the sand contained within unit S_7 is economically recoverable, but this exercise illustrates that a significant amount of sand is available within the BSA that could be exploited to nourish the critically eroding shoreline immediately onshore. Whether or not a decision is made to utilize this sand will depend on factors such as technological capability (e.g. dredging methods); logistics (e.g. mobilizing and operating a dredge in this somewhat remote location); environmental considerations (e.g. potential impacts of dredging operations on fisheries); social concerns (e.g. public perception of beach nourishment or dredging in waters offshore national seashores); and economic factors (e.g. cost of transporting sand from BSA to nourishment sites). These considerations, however, were beyond the scope of this reconnaissance-level assessment.

The issue of compatibility of the offshore sand with the native beach sand will need to be addressed. To date, no systematic sampling and testing of the native beach material within the erosional hot spots has been conducted. More detailed, feasibility-oriented studies of potential nourishment projects, will likely involve this work.

REFERENCES CITED

Dresser Atlas Industries, Inc, 1982, Well logging and interpretation techniques: The course for home study: Dresser Atlas Industries, Inc., 228p.

Krumbein, W.C., 1934, Size frequency distribution of sediments: *Journal of Sedimentary Petrology*, v.4, p.65-77.

National Geophysical Data Center (NGDC), 1999, Coastal Relief Model - volume 2 - U. S. South East Atlantic coast, 1 CD-ROM.

Pettijohn, F.J., 1975, Sedimentary Rocks, 3rd Edition: New York, Harper-Row Publishers, 627p.

Stone, J., Overton, M., Fisher, J., 1991, options for North Carolina Coastal highways vulnerable to long term erosion [unpublished]: Contract Report to North Carolina Department of Transportation.