SAND RESOURCES OF THE NORTH CAROLINA OUTER BANKS

1st INTERIM REPORT: ASSESSMENT OF DIAMOND SHOALS 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 Diamond Shoals, offshore Cape Hatteras, 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 Diamond Shoals Study Area (DSSA) derived from interpretation of seismic reflection and side-scan sonar data, description of the gross textural attributes of sampled Diamond Shoals sediment, and assessment of potential sand reserves within the DSSA which might be utilized for future beach nourishment programs.

Six major seismic reflectors (designated R_0, R_1, R_2, R_3, R_4, R_5) were correlated throughout the DSSA and form the upper and lower boundaries of five principal stratigraphic units (designated S_1, S_2, S_3, S_4, S_5). Of these units, only the upper two (S_1, S_2) are considered accessible to presently available dredging technology, and thus are considered the viable sand resource units in the DSSA.

Stratigraphic unit S_1 is the only unit sampled by available cores. This unit has an average thickness of 4 m throughout the DSSA, attaining a maximum thickness in excess of 24 m near the seaward limit of the survey data. Available cores suggest that this unit is typically composed of 95% sand. The sand of unit S_1 is dominantly fine sand (0.21 mm) with lesser amounts of medium sand (0.26 mm), shell gravel (sediment coarser than 2.0 mm = 1.5%), and mud (sediment finer than 0.0625 mm = 3.3%). Sediment is typically medium sand across the shoal crest and among seaward megaripple fields.

Based on similarity of seismic reflection characteristics, stratigraphic unit S_2 is interpreted to be of similar sedimentological character to S_1. However, it is noted that no direct evidence (e.g. sediment samples) of this similarity is presently available. Unit S_2 averages 5.5 m thick throughout the DSSA and attains a maximum thickness greater than 35 m near the seaward limit of the survey data.

Side-scan sonar records throughout the DSSA indicate that the seafloor is completely covered by sediment; only one narrow band of a possible hardbottom feature was observed on a record from the southern flank of the shoals. Widespread occurrence of sand waves or megaripples on most side-scan sonar records is evidence of the mobility of surface deposits throughout the DSSA.

Estimates of the volume of sand within units S_1 and $S_1 + S_2$ of the DSSA are large. Unit S_1 is estimated to contain in excess of 1.66 billion cubic yards of sand over the surveyed area. An estimate of the combined volume of sand contained within S_1 and S_2 is at least 3.75 billion cubic yards. If these estimates are restricted to that area contained within the state 3-mile limit, unit S_1 contains 256.1 million cubic yards of sand and units S_1 and S_2 combined contain 711.5 million cubic yards of sand. Thus, it would seem that future use of Diamond deposits will not depend on sand availability, but on the interplay of technical, logistical, environmental, social, and economic factors -- which are beyond the scope of the present study.

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 subsequent sampling survey to obtain vibracores within the same area was authorized in order 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 laboratory 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 cooperative agreement between the North Carolina Department of Environment and Natural Resources and the University of Arkansas (Dr. Stephen K. Boss, Principle Investigator) was initiated for the purpose of completing analyses of existing geophysical data (single-channel seismic reflection and side-scan sonar profiles) and assessing the sand resource potential of four study areas offshore of the northern Outer Banks (Fig. 1).

The following report is the first project deliverable, and is organized into several sections to facilitate understanding of the rather complex data. Section I describes the available geophysical data base from the DSSA and presents results of interpretations of single-channel seismic reflection and side-scan sonar profiles. Section II documents textural attributes of the DSSA determined from analyses of sediment in vibracores collected during 1995. Finally, Section III provides information pertinent to assessing the DSSA as a potential resource of sand for beach nourishment in the vicinity of Cape Hatteras, NC.

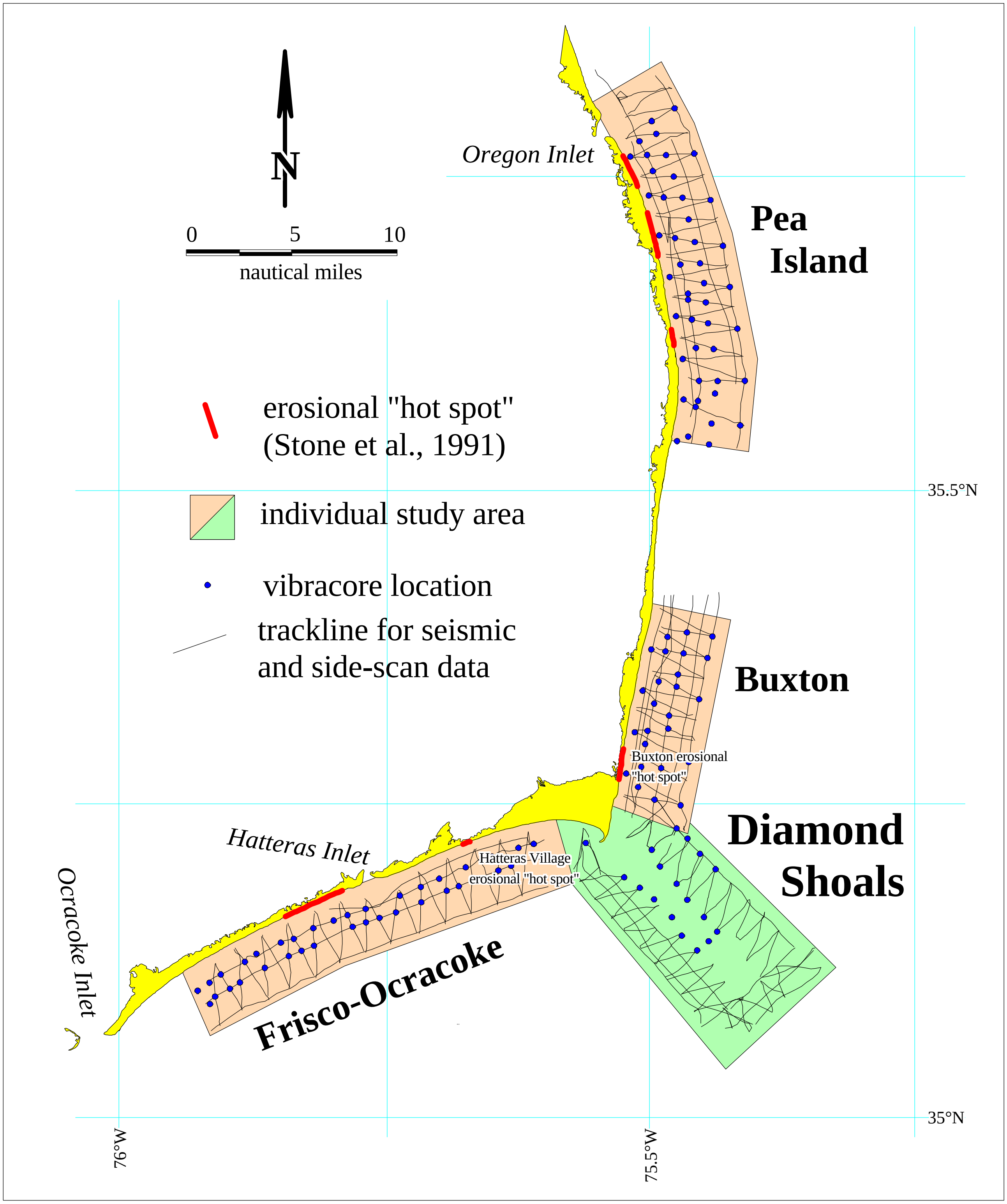


Fig. 1. Location map showing the Outer Banks Task Force sand resource project area. The four principal project areas are labeled along with locations of erosional "hot spots" (red line segments) with potential to impact NC Highway 12. Geophysical tracklines (seismic reflection and side-scan sonar profiles)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

SECTION I: GEOPHYSICAL DATA

Geophysical data consist of single-channel, high-resolution seismic reflection profiles and side-scan sonar records from the DSSA (Fig. 2). These data were collected simultaneously during the 1994 research cruise and are subdivided into 58 trackline segments constituting 278 km (150 nautical miles) around the navigable portions of Diamond Shoals.

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.

A notable limitation of existing seismic reflection data from the DSSA is that an important seismic reflection profile on the north side of Diamond Shoals (line 194, 55 km or 29.6 nm) was not archived in digital format. As a result, the only existing record for this profile was the original paper copy printed shipboard at the time of acquisition. This record was particularly poor owing to progressively deteriorating sea-state on that day. However, a photocopied version of the original profile was interpreted to the extent that it could be interpreted, and data from this interpretation are included in the analyses.

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 DSSA 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 DSSA 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 (for example, Figs. 4, 6, 8, 9) 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).

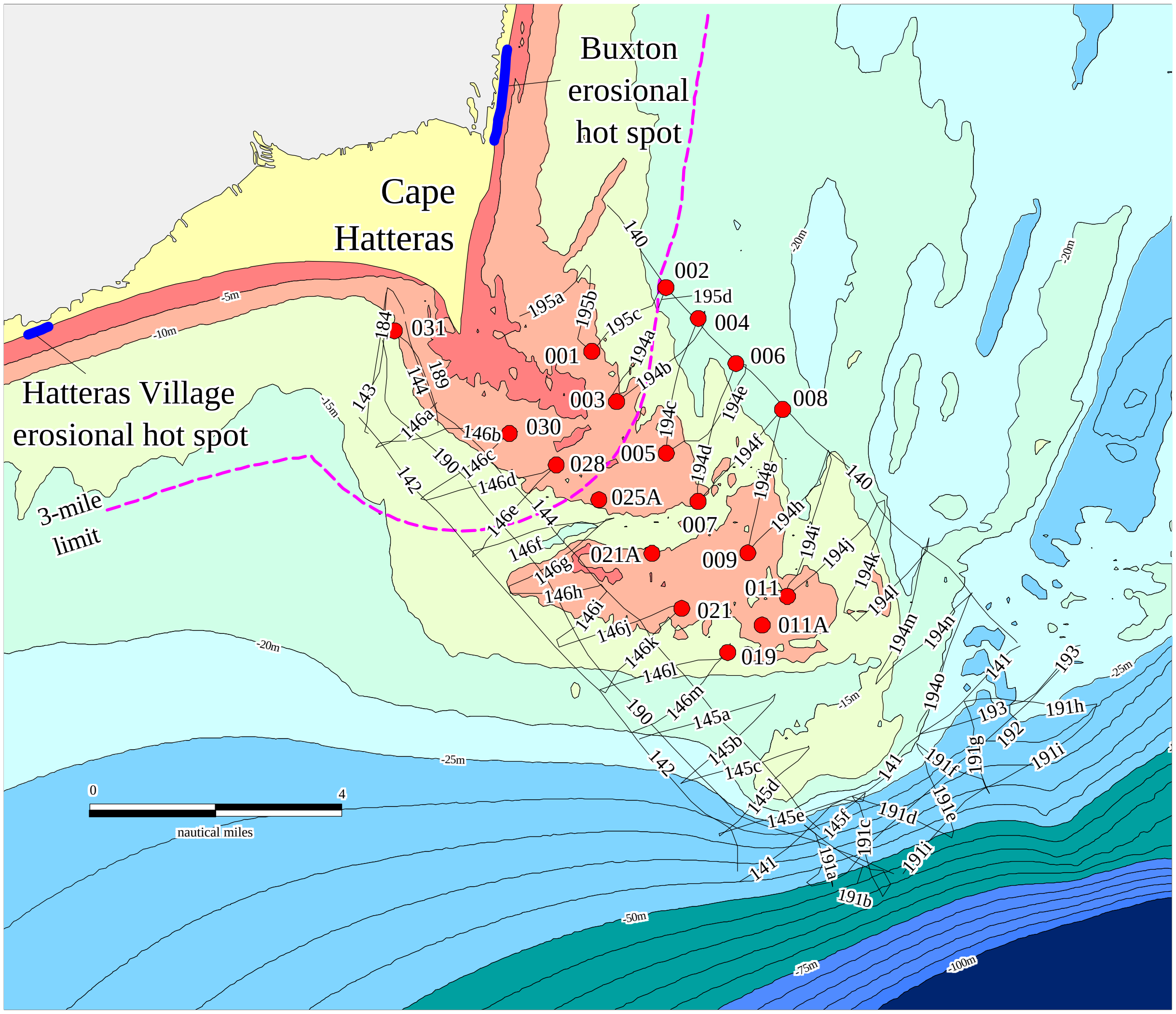


Fig. 2. Detailed location map of Diamond Shoals Study Area (DSSA) showing tracklines of seismic reflection and side-scan sonar profiles (thin lines) as well as locations of vibracores (solid cirlces) used in this sand resource assessment. Bathymetry layer created from NOAA hydrographic data (NGDC, 1999).

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" of 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 correlate individual reflectors more broadly across the survey area, cross-referencing and checking for appropriate “ties” frequently until the entire data set is interpreted with some degree of certainty. For this portion of the study, this process required two initial iterations.

Following completion of the initial interpretation cycle, all profiles were digitized at the Coastal Plain Office of the North Carolina Geological Survey. After digitization of the interpreted seismic reflection profiles, the positions of prominent reflectors were checked and two additional iterations of the entire seismic data set helped to greatly minimize uncertainty of correlations.

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

Geologic Framework of Diamond Shoals

Interpretations of seismic profile data indicate that the detailed geologic history of Diamond Shoals is remarkably complex, though seismic units can be grouped into five principal depositional units. The major reflectors separating these principal units are labeled in sequential order beginning with the seafloor reflector (R_0) and proceeding downward with R_1, R_2, R_3, R_4(?), and R_5 (Fig. 3).

Within the seismic units defined by the five major reflectors, the acoustic character of contained stratigraphic units seems somewhat distinctive, aiding in the correlation of these units around the Diamond Shoals 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 each seismic unit are provided below.

Seismic Unit S_1

The uppermost seismic unit identifiable among the DSSA seismic reflection data is bound by the present-day seafloor (R_0) and a prominent but occasionally discontinuous or difficult to identify reflector, R_1. This reflector dips gently seaward (Fig. 4) from the nearshore area where it occurs at approximately 15 ms to a maximum of 45 ms near the seaward end of the survey area. The stratigraphic unit bound by R_0 and R_1 is termed S_1, and represents the uppermost sedimentary units of Diamond Shoals, including the veneer of modern, mobile sediment.

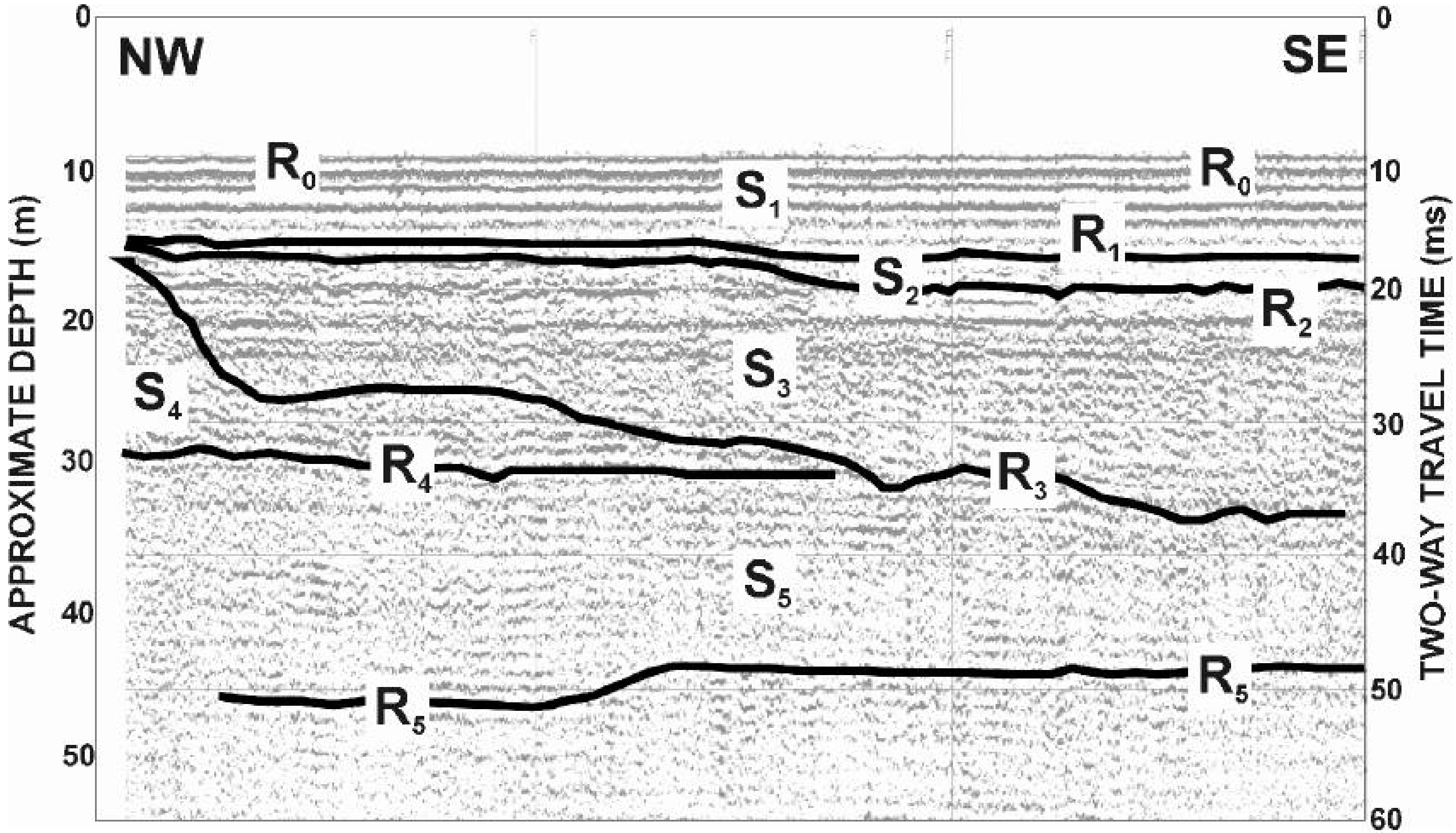


Fig. 3. Ten kilometer segment (5.5 nautical miles) of seismic reflection profile 144 between shot points 0000 (left) and 2000 (right). Segment trends parallel to axis of Diamond Shoals from near shore (left) to seaward (right). The principal reflectors (R_0 through R_5) and stratigraphic units (S_1 through S_5) correlated throughout the DSSA are indicated. Vertical scale in meters is approximate based on a sub-bottom velocity of 1,800 meters/second.

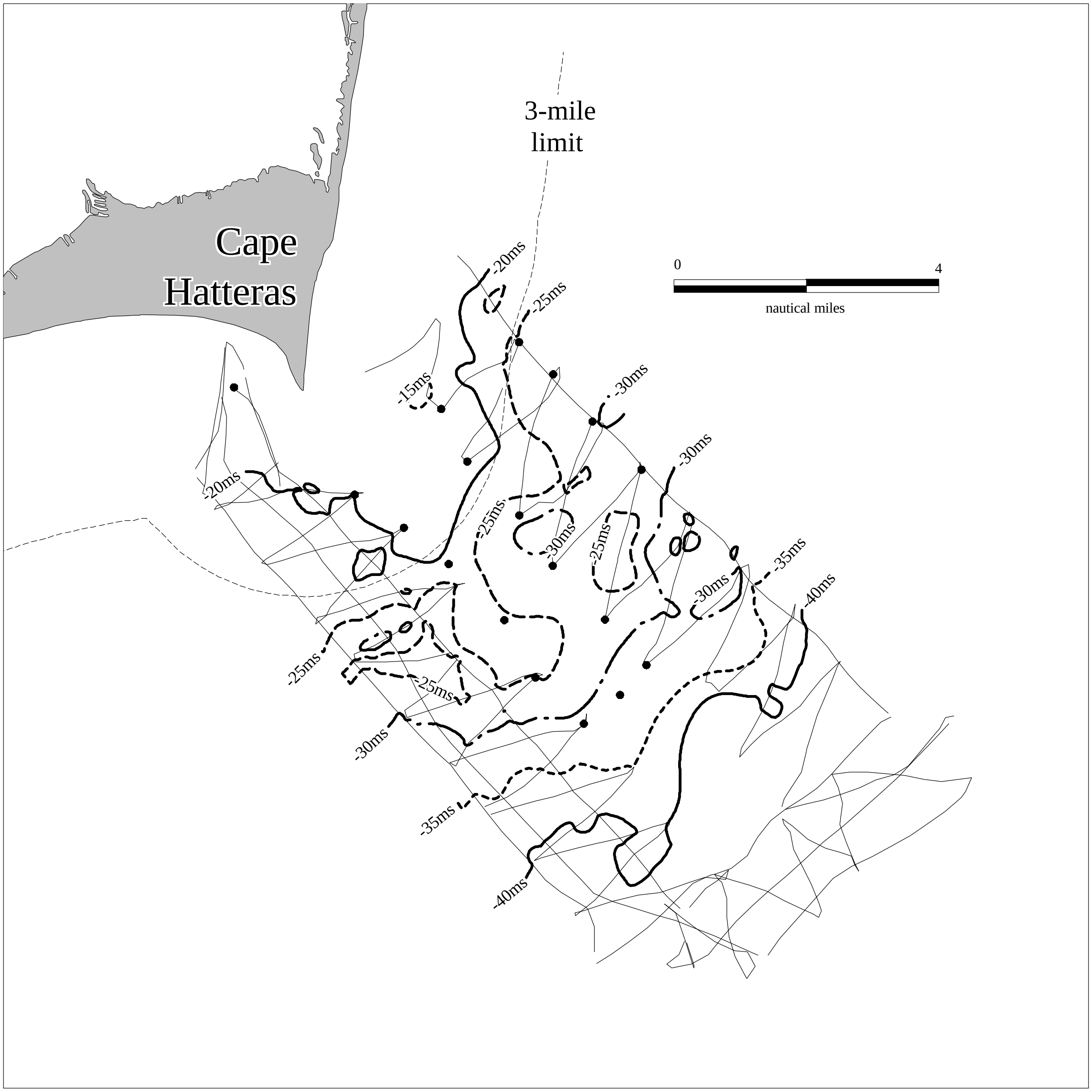


Fig. 4. Structure contour map derived from seismic reflection data showing depth (in milliseconds two-way travel time) to top of reflector R_1 within the DSSA. Contours on surface of R_1 labeled with 5 ms contour interval (approximately 4 meters). Note that R_1 slopes gently seaward from the nearshore region of the surveyed area. For reference to other maps, seismic tracklines indicated by thin lines and vibracore locations indicated with solid circles.

Unit S_1 is recognizable throughout the DSSA. An isopach map (Fig. 5) of S_1 was constructed by determining the difference in two-way travel time of the two bounding reflectors, R_0 and R_1. Thickness of S_1 was then calculated by assuming a *p*-wave velocity of 1800 m/sec and multiplying this value by the measured thickness (in milliseconds). Unit S_1 ranges in thickness from a minimum near 0 m to a maximum of >24 m (Fig. 5). Generally, the unit is thinnest nearshore and thickens as the R_1 reflector slopes gently seaward, forming a wedge of sediment. Eventually, the R_1 reflector becomes unresolvable among the thick deposits of sediment comprising the seaward nose of Diamond Shoals, making it impossible to identify the lower boundary of S_1. Unit S_1 is acoustically transparent (i.e. there are no continuous, high-amplitude seismic reflectors within the unit) over much of its area of occurrence. Toward the seaward nose of Diamond Shoals, a series of closely spaced, parallel, dipping reflectors appear in the lower portions of S_1. The change in acoustic character of the lower part of this unit toward its seaward end suggests a change in textural and depositional character of the sediments, perhaps indicative of a more variable depositional regime in deeper water. However, S_1 above these reflectors remains relatively transparent in its upper 10 – 15 ms (9 – 13.5 m) and is likely of similar sedimentological composition as that sampled by available cores.

Unit S_1 is the uppermost stratigraphic unit within the Diamond Shoals area, and it is the only 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. All of these data indicate that S_1 is of relatively uniform sandy composition throughout its distribution. Estimates of the sand volume contained within this unit throughout the DSSA are contained in Section III.

Seismic Unit S_2

The next seismic unit identifiable among the DSSA seismic reflection data is also correlated throughout the study area. Reflector R_2 is readily identifiable in all but the most seaward seismic reflection profiles within the study area. This reflector also tends to dip gently seaward (Fig. 6) from the nearshore area, beginning at approximately16 ms and disappearing offshore only because it slopes below the 60 ms record of the processed seismic profiles. In gross form, the geometry of R_2 is very similar to R_1. 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 DSSA. The isopach map (Fig. 7) of S_2 was constructed by determining the difference in two-way travel time of the two bounding reflectors, R_1 and R_2. Thickness of S_2 was then calculated by assuming a *p*-wave velocity of 1800 m/sec and multiplying this value by the measured thickness (in milliseconds). Unit S_2 ranges in thickness from a minimum of 1 m to a maximum of >35 m (Fig. 7). Generally, the unit is thinnest nearshore and thickens as the R_1 reflector slopes gently seaward, forming a wedge of sediment. However, this general pattern is somewhat uneven, being interrupted in several locations by relatively deep channels incised into lower stratigraphic units. Seaward of seismic line 191, the R_2 reflector slopes below the 60 ms cut-off of the reprocessed seismic profiles, making it impossible to identify the lower boundary of S_2 beyond this limit. Unit S_2 is generally acoustically transparent (i.e. there are few continuous, high-amplitude seismic reflectors within the unit) over much of its area of occurrence, though it is not as acoustically “clean” as S_1. The

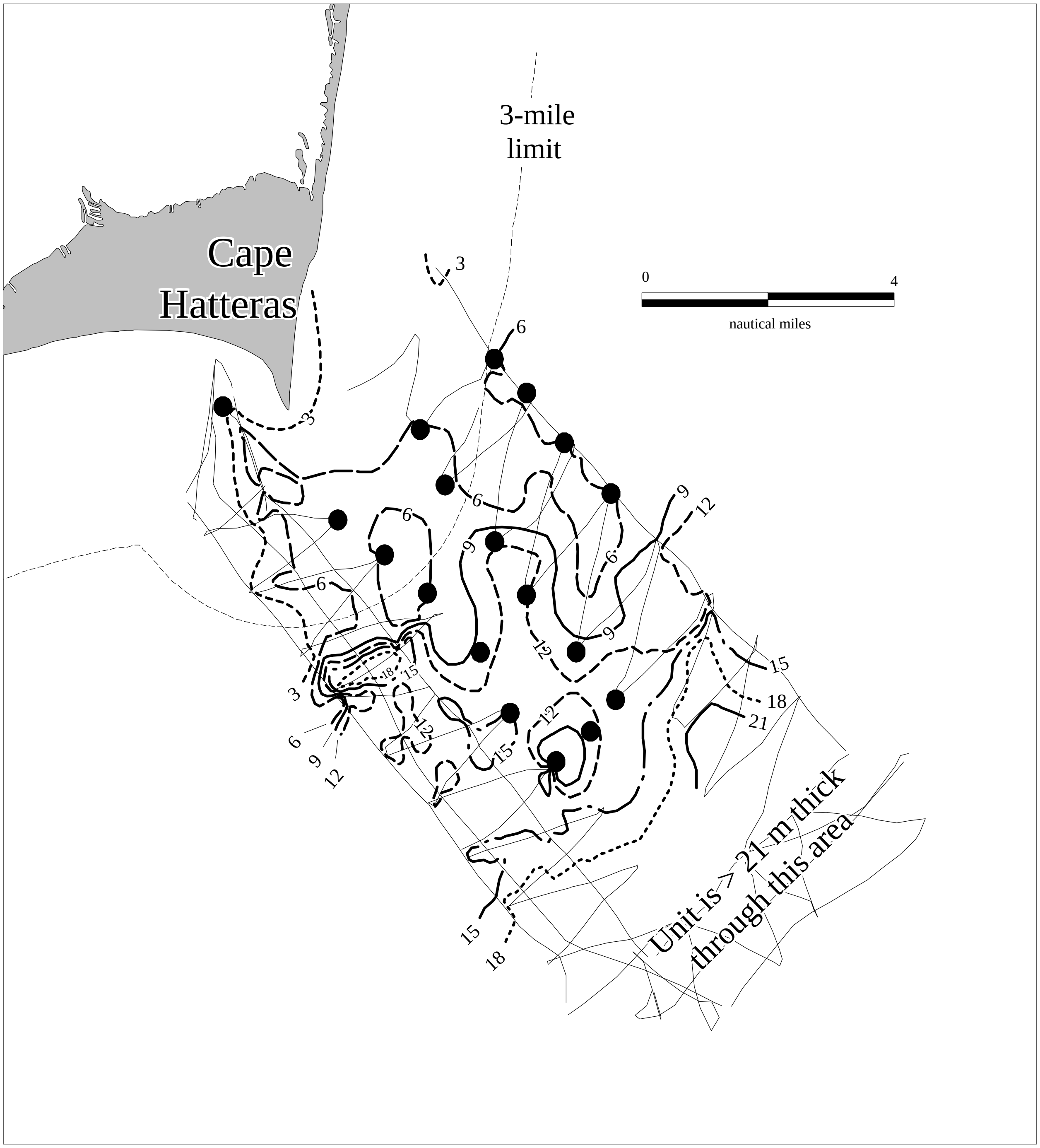


Fig. 5. Isopach map derived from seismic reflection data showing estimated thickness (in meters) of unit S_1 within the DSSA. Thickness estimated assuming uniform seismic velocity of 1800 m/sec through unit S_1. Contour interval is 3 m. Note that S_1 thickens seaward within the DSSA. For reference to other maps, seismic reflection and side-scan sonar tracklines indicated by thin lines, vibracore locations indicated with solid circles.

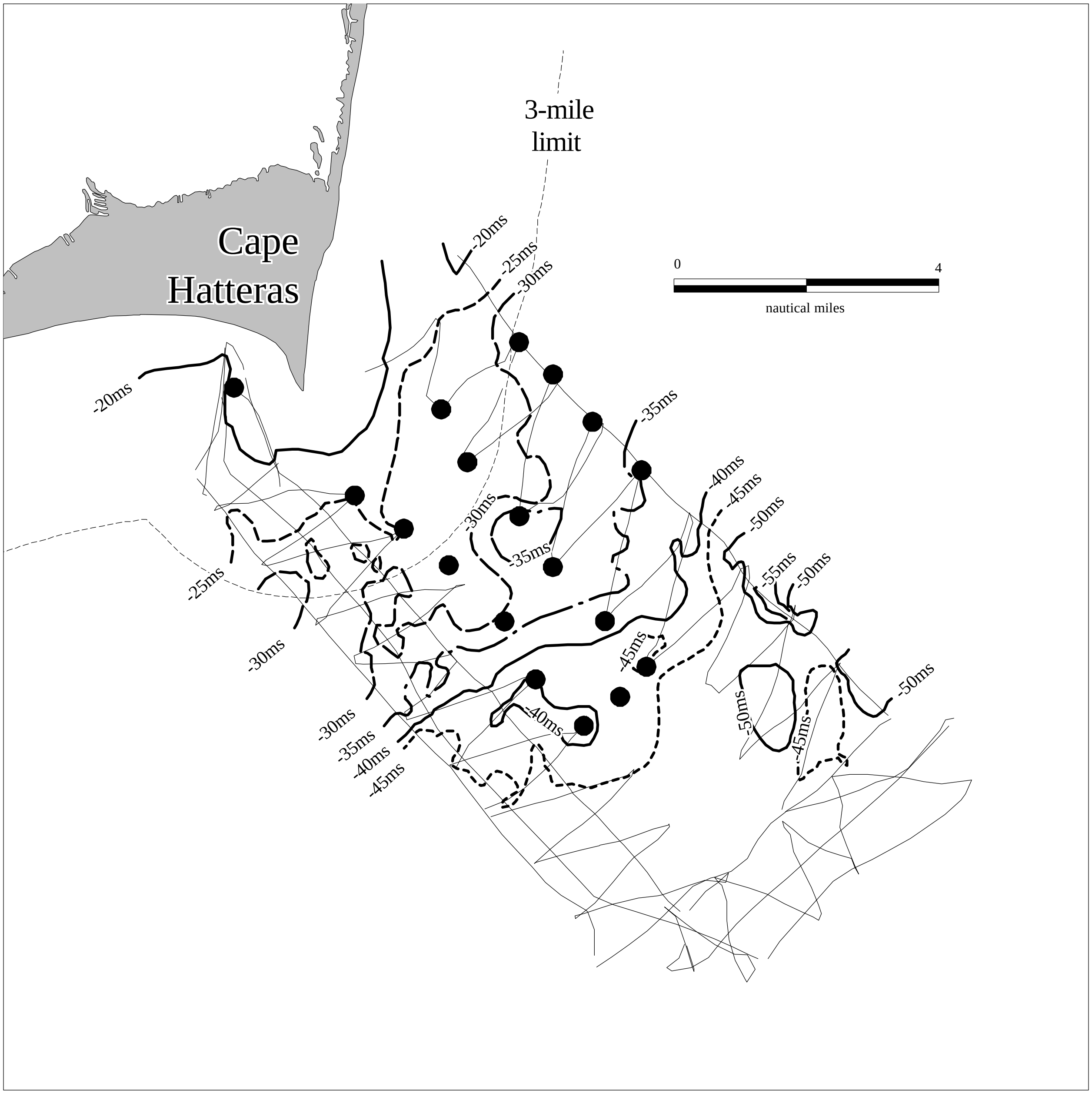


Fig. 6. Structure contour map derived from seismic reflection data showing depth (in milliseconds two-way travel time) to top of reflector R_2 within the DSSA. Contours on surface of R_2 labeled with 5 ms contour interval (approximately 4 meters). Note that R_2 is somewhat more irregular than R1, but also slopes gently seaward from the nearshore region of the surveyed area. For reference to other maps, seismic tracklines indicated by thin lines, vibracore locations indicated with solid circles.

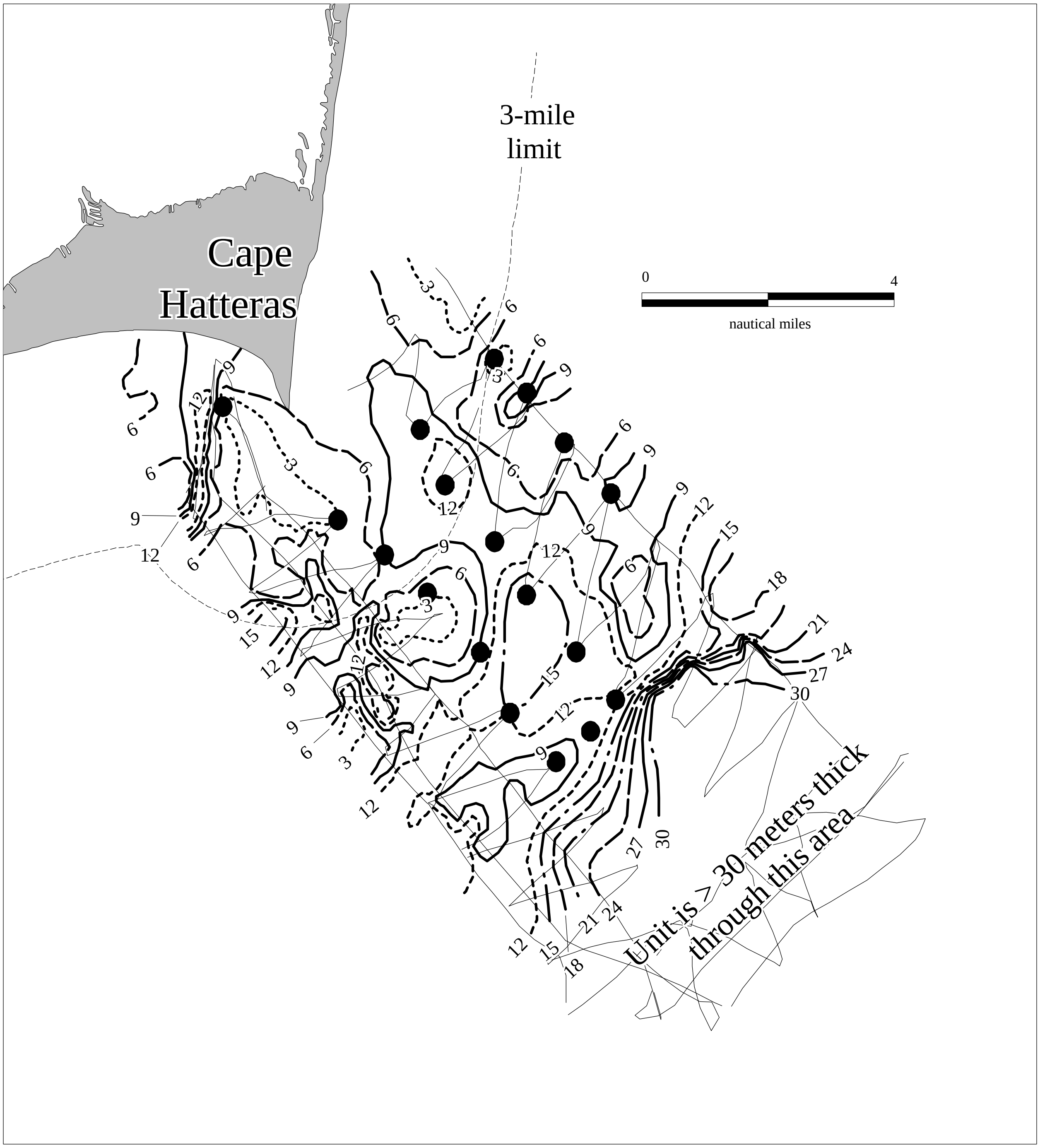


Fig. 7. Isopach map derived from seismic reflection data showing estimated thickness (in meters) of unit S_2 within the DSSA. Thickness estimated assuming uniform seismic velocity of 1800 m/sec through unit S_2. Contour interval is 3 m. Note that S_2 thickens seaward within the DSSA. For reference to other maps, seismic reflection and side-scan sonar tracklines indicated by thin lines, vibracore locations indicated with solid circles.

relatively clean acoustic character of S_2 thus suggests that it may be composed of sediments of similar character to the overlying S_1 unit, though no direct evidence of this is presently available.

Unit S_2 occurs throughout the Diamond Shoals area, and it may also constitute a substantial sand reserve. Estimates of the sand volume contained within this unit throughout the DSSA are contained in Section III.

Seismic Unit S_3

Reflector R_3 displays an intriguing geometry in that it descends relatively steeply in the nearshore region of the DSSA, suggestive of an incised channel morphology (Fig. 8). The relatively rugged relief on this reflector makes it readily traceable throughout the surveyed area. This reflector begins in the nearshore area at 18 ms, but falls rapidly to >40 ms, truncating reflectors R_4 and R_5, and remains relatively deep as it extends seaward (Fig. 8). The reflector is lost seaward of line 145k on the south side of Diamond Shoals and seaward of line 194k on the north side of Diamond Shoals as it slopes below the 60 ms lower boundary of the reprocessed seismic profiles. The stratigraphic unit bound by R_2 and R_3 is termed S_3 and displays the most intriguing depositional geometry of the units identified within the Diamond Shoals area.

Unit S_3 has a distinctive seismic geometry characterized by multiple series of faint, discontinuous but dipping seismic reflections organized into discrete wedge-shaped “packages” stacked horizontally in the offshore direction. This distinctive “seismic facies” allows for recognition and correlation of S_3 throughout the study area. An isopach map of S_3 was not constructed because its relatively great depth beneath the sea surface (-16 m to -56 m) precludes its exploitation as a potential sand resource in this area. No direct evidence of the sedimentological constitution of S_3 is available, but the seismic character of S_3 units suggests that it may be sedimentologically diverse, perhaps being composed of thin interbeds of sediment with varying textural attributes.

Seismic Unit S_4

Reflector R_4 is observed in only a few of the most shoreward seismic profiles on the southern flank of Diamond Shoals (lines 182, 183, 184, 189, 190, 143). The reflector ranges in depth from 31 ms to 50 ms in the area where it can be identified.

The limited occurrence of this reflector makes an assessment of its stratigraphic significance uncertain. The reflector does not persist into the offshore region of the DSSA. If it was more widespread at one time, it has been truncated (eroded) by development of R_3. Reflector R_4 may be a significant stratigraphic marker shoreward in the shoreface region of the DSSA, and within the Frisco-Ocracoke study area. However, since this area has not yet been analyzed, little information on R_4 is available.

Seismic Unit S_5

Reflector R_5 is the deepest of the major reflecting horizons above 60 ms two-way travel time in the study area. R_5 is relatively widespread, and is readily correlated within the DSSA. It disappears seaward within the DSSA as it is truncated by R_3 in the vicinity of lines 146g-146i

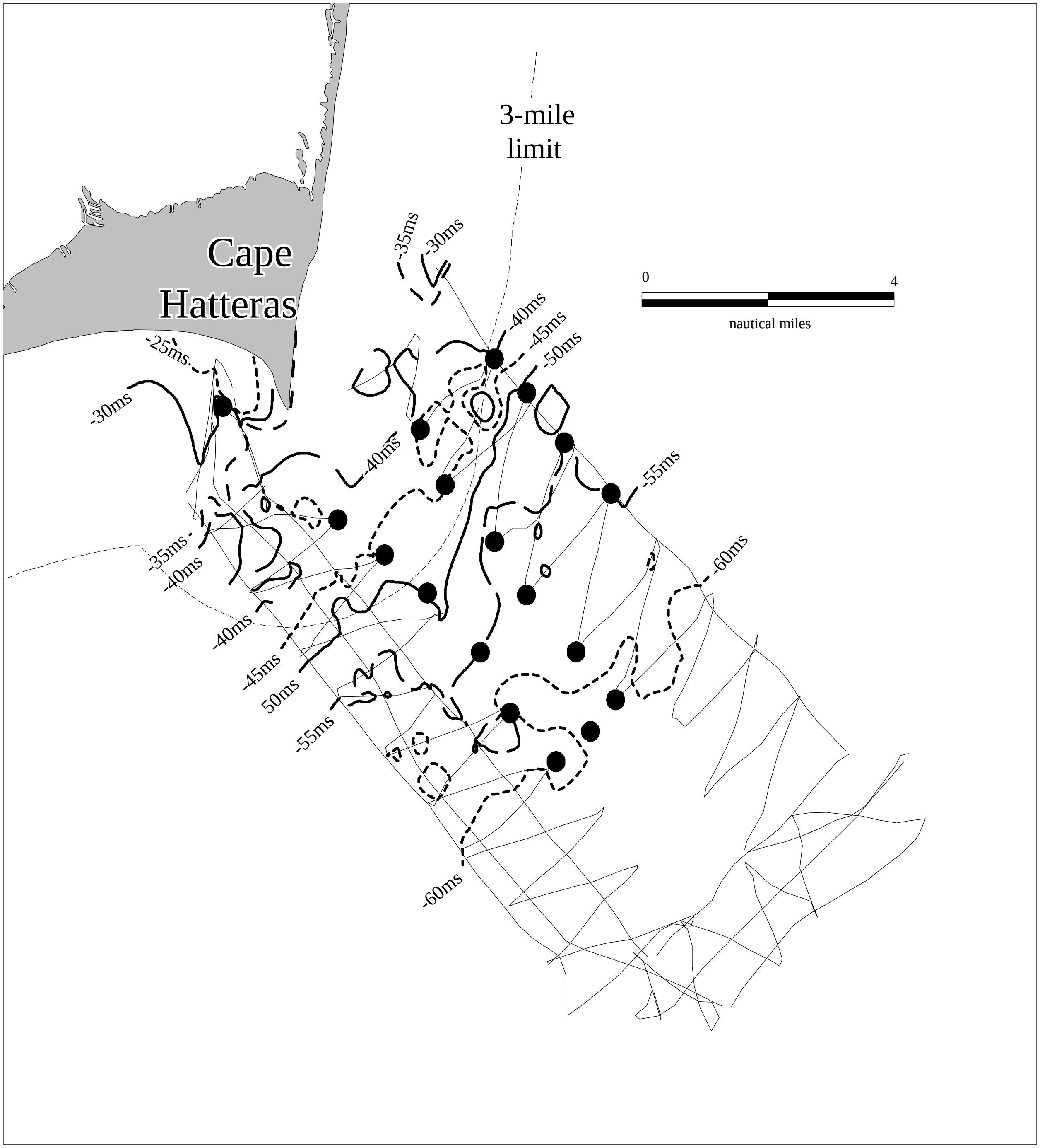


Fig. 8. Structure contour map derived from seismic reflection data showing depth (in milliseconds two-way travel time) to top of reflector R_3 within the DSSA. Contours on surface of R_3 labeled with 5 ms contour interval (approximately 4 meters). Note that R_3 descends relatively steeply in the nearshore region of the surveyed area, then slopes gently seaward. For reference to other maps, seismic tracklines indicated by thin lines, vibracore locations indicated with solid circles.

and 194g. The geometry of R_5 is relatively flat, and reflectors beneath R_5 are typically sub-parallel, suggestive of a different stratigraphic architecture than the overlying Diamond Shoals stratigraphy (Fig. 9). No direct evidence is presently available regarding the age or stratigraphic position of this reflector.

The sedimentological composition of the depositional unit overlying R_5, S_5, is unknown. However, regardless of its sedimentological properties, the unit is too deep to be considered a viable candidate for exploitation as part of a sand resource or beach nourishment program in this area.

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 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, at a 400-meter setting, the towfish should "fly" approximately 36 meters above the bottom and be continually adjusted to that level. However, throughout the majority of Diamond Shoals survey area, water depth is <36 m, so it was not possible to adhere to this procedure. The consequences of operating in shallow water were 1) the imaged seafloor swath typically was less than 400 m, 2) there were significant portions of sonograms where acoustic returns from the sea surface obscured seafloor data (especially in rough weather), 3) it was 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, 4) occasionally the towfish hit the seafloor.

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 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.

The Diamond Shoals area side-scan record is characterized by a weak to moderate acoustic return. This acoustic character of seafloor sediment suggests a predominance of very fine- or fine- to medium-grained sand as the surface sediment type within the DSSA. In addition, the general uniformity of seafloor determined from side-scan sonograms supports the conclusion drawn from seismic reflection data that a single stratigraphic unit of uniform textural/sedimentological character occurs at the seafloor throughout the study area.

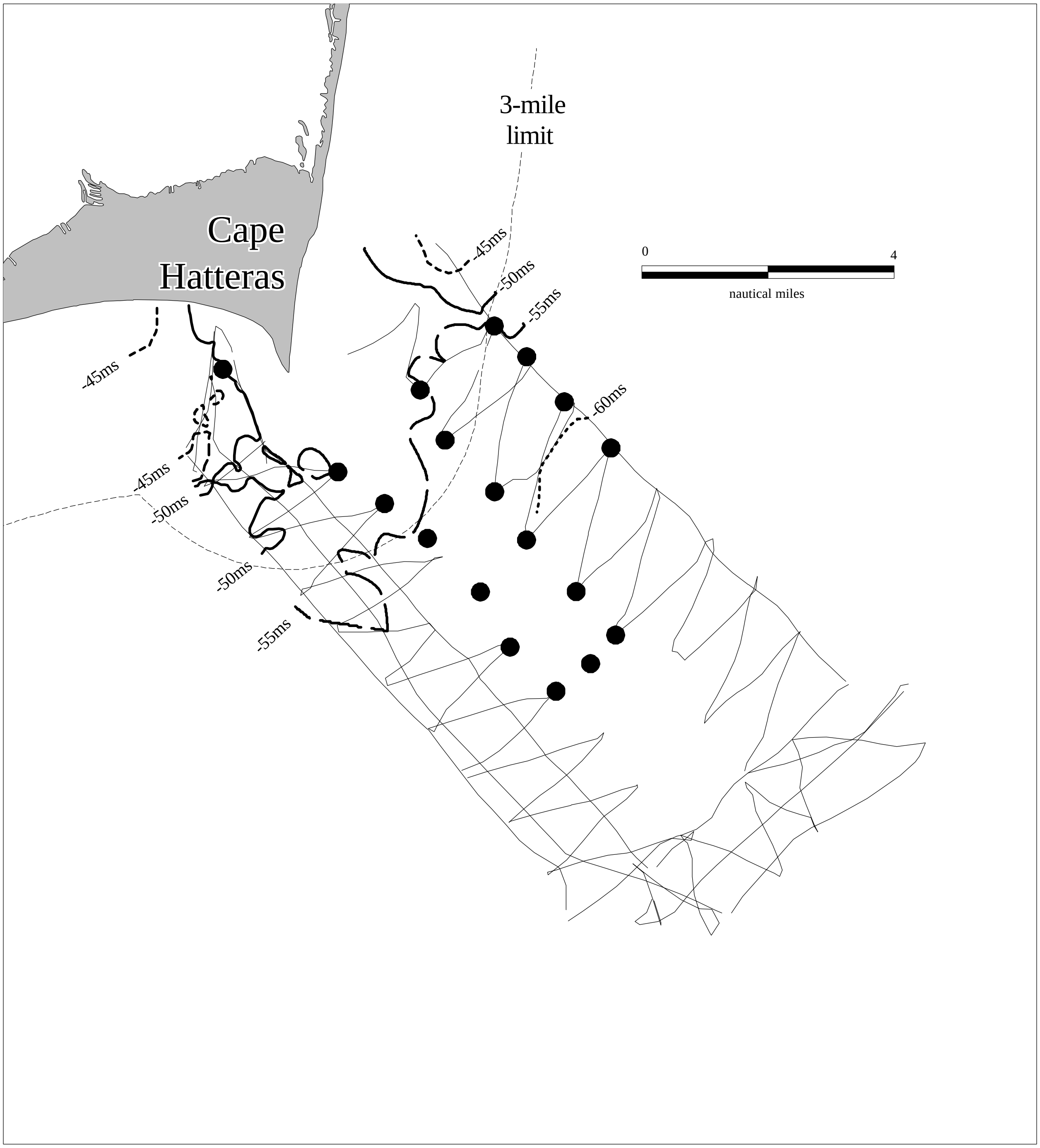


Fig. 9. Structure contour map derived from seismic reflection data showing depth (in milliseconds two-way travel time) to top of reflector R_5 within the DSSA. Contours on surface of R_5 labeled with 5 ms contour interval (approximately 4 meters). Note that R_5 becomes truncated by R_3 approximately midway along the axis of Diamond Shoals. For reference to other maps, seismic tracklines indicated by thin lines, vibracore locations indicated with solid circles.

Recognizable bedforms are widespread among the side-scan sonar data for this study. Relatively well-developed bedforms, termed megaripples or dunes (Fig. 10) are particularly common. These features range in size from less than 1-meter amplitude and 1- to 2-meter wavelength (typically 8 – 12 meter wavelength) to 2- to 4-meters amplitude and up to 250-meter wavelength (observed for submarine dunes). Megaripples and dunes result from active currents working on unconsolidated sand, with megaripple and dune crests aligned perpendicular to the direction of the current. Depending on the size and shape of the bedforms, and their orientation to the towfish, such features may be distinctly imaged or not imaged at all.

In the northeastern part of the study area, the seismic profiles show very large-scale bedforms (for example submarine dunes 2- to 6-meters high with 250-meter wavelength) that are evident on the side-scan record as wide-spaced lighter bands crossing the sonogram at a high angle to the trackline (Fig.11). The megaripple pattern overprints the dune pattern in this area.

The common occurrence of megarippled sediment evident on side-scan sonograms throughout the survey area attests to the abundance and mobility of surficial sediment across Diamond Shoals, and suggests that this sediment is dominantly sand. There is little evidence for the development or occurrence of hardbottom areas within the studied area. Only a single possible hardbottom "scarp" of very localized extent and minimal relief was observed on a side-scan sonogram from the southern flank of the shoals (Fig. 12).

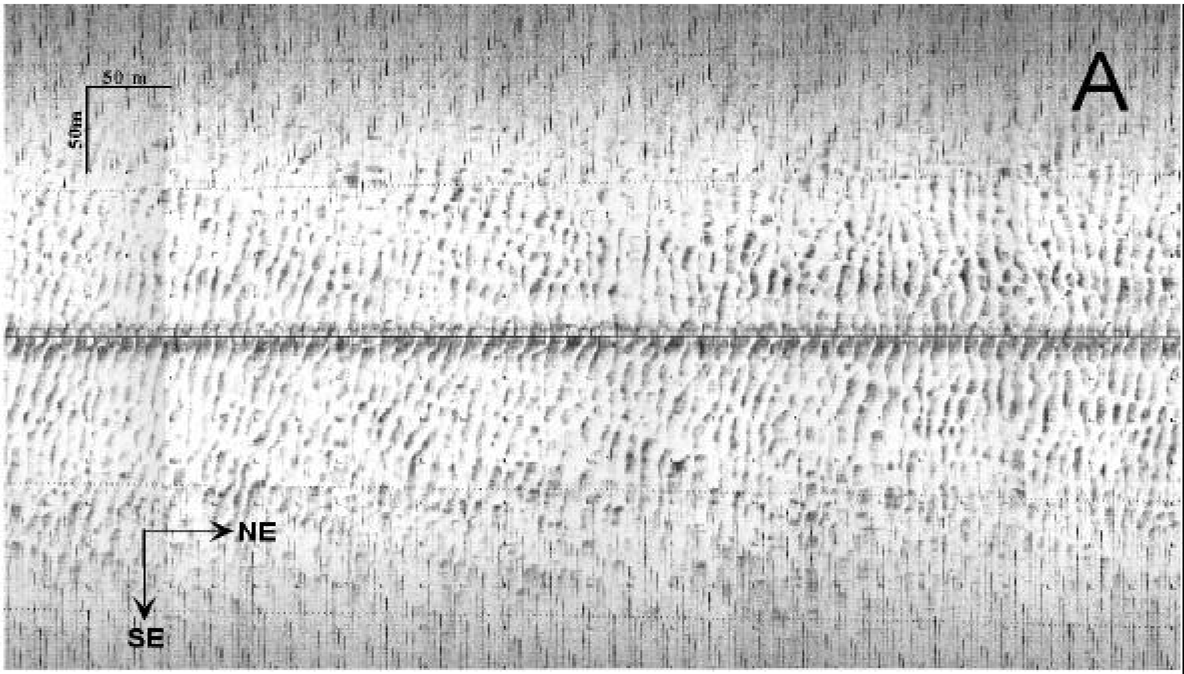
Overall, the side-scan records from the DSSA indicate the presence of a mobile sand veneer across the entire survey area. This sand constitutes the surface of stratigraphic unit S_1. The uniform, seismically transparent character of unit S_1 observed on seismic reflection profiles suggests that subsurface sediment within S_1 is of similar character to that exposed and imaged at the surface.

SECTION II: SEDIMENT TEXTURAL CHARACTERISTICS FROM CORES

Eighteen vibracores were collected around the margins and across the axis of Diamond Shoals during the summer of 1995 aboard the U.S. Army Vessel *Snell* (Fig. 2; Table 2). Core lengths range from 1.75 m to 6.04 m, with an average length of 3.87 m. Most cores are located along the north and south flanks of Diamond Shoals, though several were obtained from near the crest of the shoals. These locations were constrained to some degree by navigability of the shoals area.

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 4.3 ms two-way travel time, with a range of 2 ms to 7 ms. Thus, it is clear that cores penetrate to very shallow depths within the Diamond Shoals sediment package. By posting calculated core lengths in milliseconds on corresponding seismic reflection profiles, it is possible to determine which stratigraphic unit was sampled by each core. It appears that all 18 cores sampled unit S_1, and no core penetrated into even the uppermost portion of S_2. Therefore, all sediment data recorded in this report are exclusively from unit S_1.

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



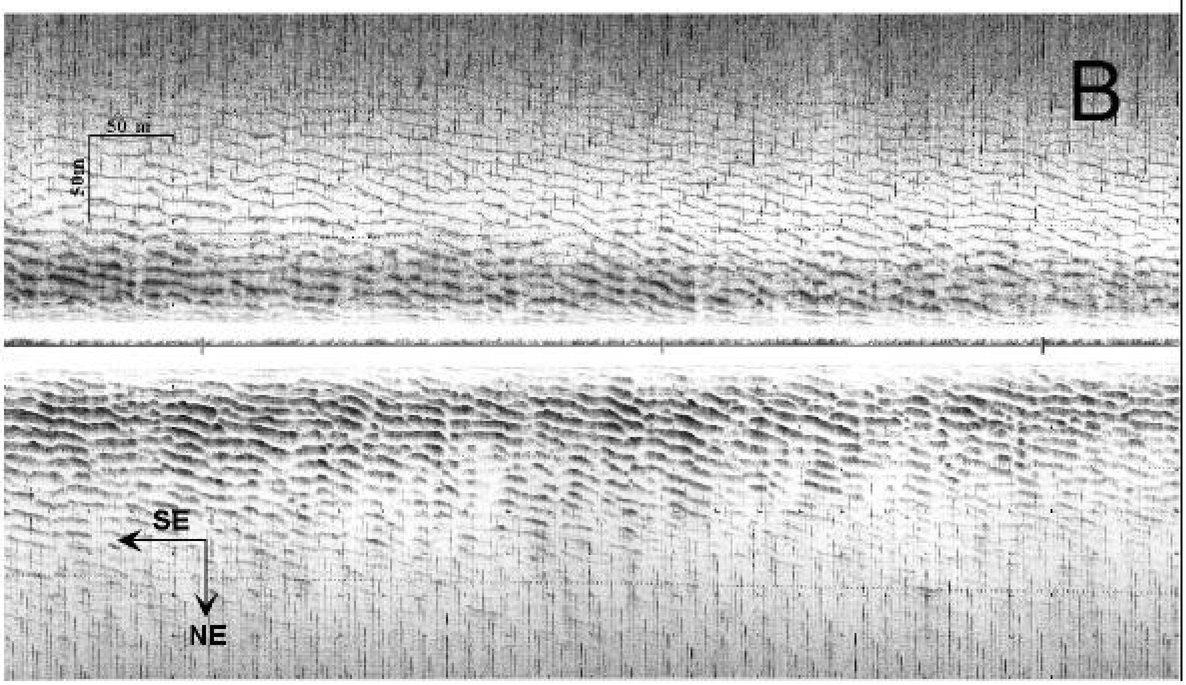


Fig. 10. Examples showing acoustic signature of megaripples observed on side-scan sonograms from the DSSA. A) Megaripples oriented with crests nearly perpendicular to southwestward ship track along line 141 near crossing with line 145e southwest of Diamond Shoals axis. B) Megaripples oriented with crests approximately parallel to southeastward ship track along line 144 near crossing with line 141 in southeastern part of study area. Note that in each image, the azimuthal orientation of megaripple crests is southeast-northwest, suggesting current flow to the northeast.

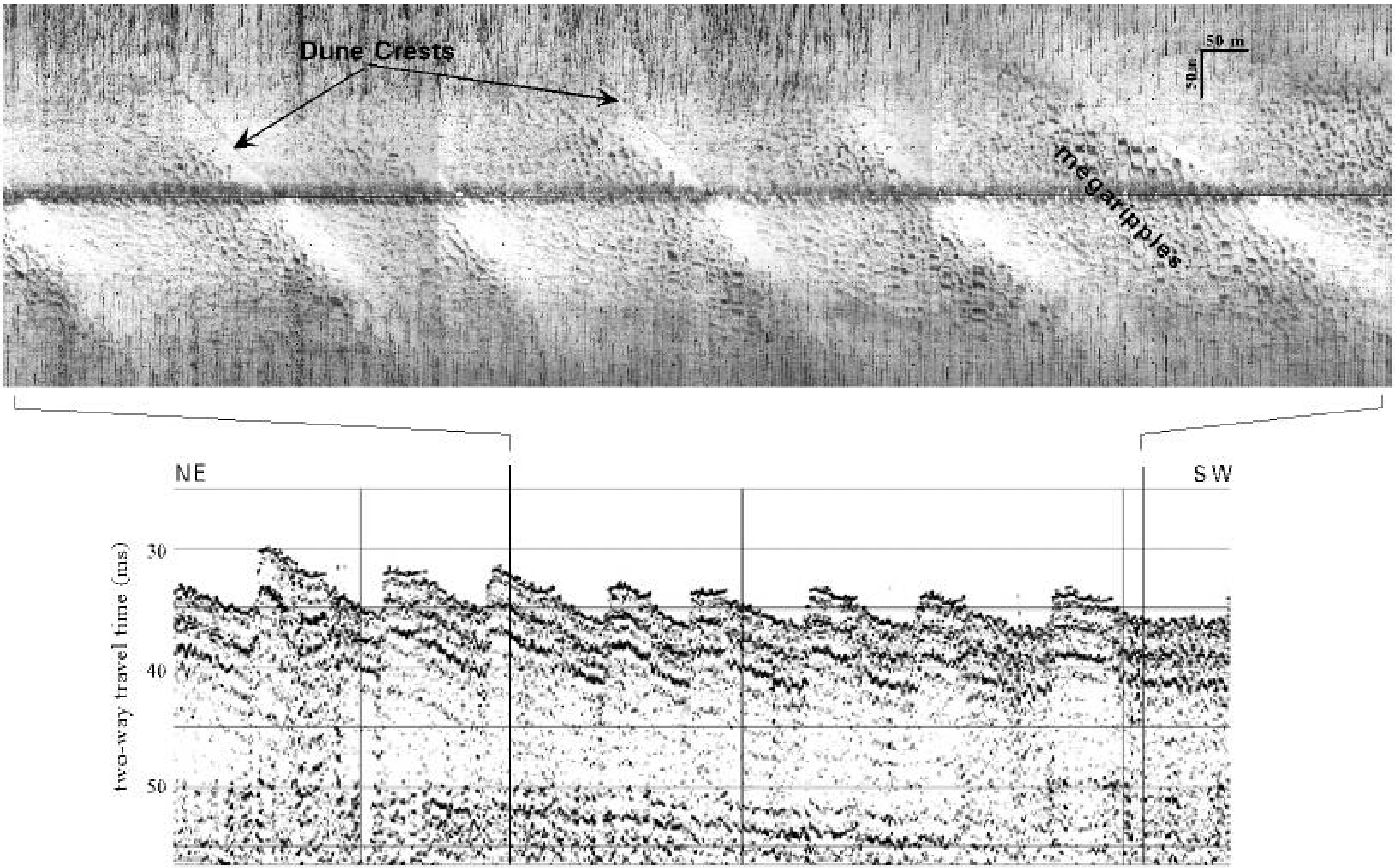


Fig. 11. Comparison of side-scan sonogram (top) and seismic reflection profile (bottom) over submarine dunes with superimposed megaripples near the seaward nose of Diamond Shoals (trackline 192 between lines 191g and 191h). In the upper image, presence of dunes is indicated by light streaks crossing the sonogram diagonally. Note that gently sloping stoss surface of dune facing towfish direction (ship is traveling southwest to northeast; i.e. right to left in the figure) displays megaripples while the lee is in acoustic shadow (white on sonogram). Individual dune crests can be correlated from the side-scan to the seismic record. Seismic reflection profile indicates dunes have ca. 2 - 4 m amplitude and 250 m wavelength.

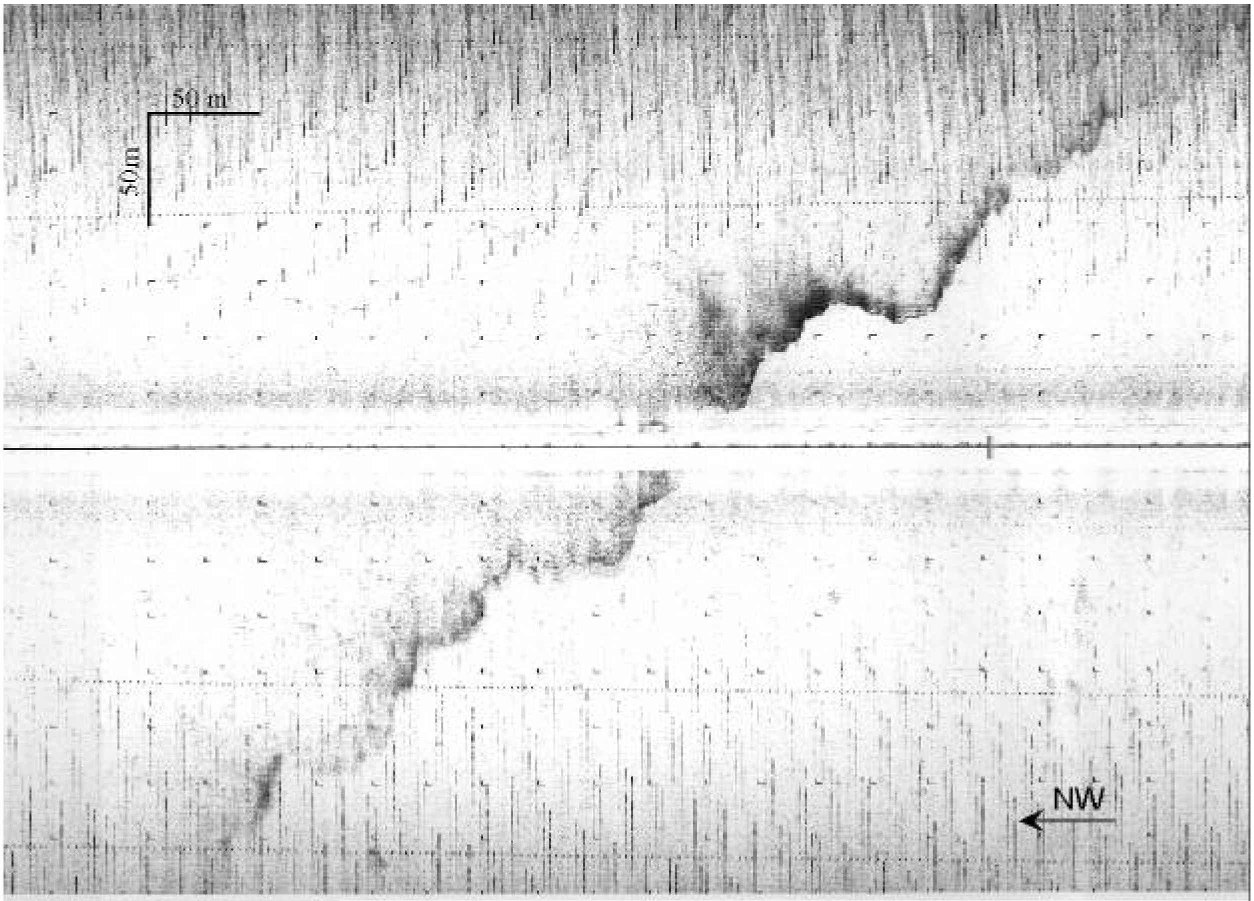


Fig. 12. Side scan sonar sonogram showing anomalous seafloor feature with relatively strong acoustic return and irregular boundary. Feature trends approximately east-west across line 142 near junction with line 146d. This is possibly a small scarp and hardbottom caused by a stratigraphic discontinuity, though there is no expression of this feature on corresponding seismic reflection profile. This is the only occurrence of such a feature within the DSSA, and available data are insufficient to make a positive identification.

such as weight percent size fractions, mean grain size, sorting, etc.) 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.

Throughout the Diamond Shoals area, sediment texture within individual cores is relatively uniform. Given this uniformity of texture, the mean grain size of sediment expressed in ϕ-units (where $\phi = -\log_2$ of grain diameter in millimeters; Pettijohn, 1975) provides a reasonable parameter for describing the textural character of S_1 sediment. Mean grain size varies in cores from 1.40 ϕ (0.38 mm, medium sand; Krumbein, 1934) to 3.16 ϕ (0.11 mm, very fine

Table 2. Summary of vibracore data.

CORE	Water Depth (m)	Length (m)	MUD (wt. %)	SAND (wt. %)	GRAVEL (wt. %)	Mean Grain Size (Ø)	St. Dev. (Ø)	General Description
SNL-001	7.3	2.82	2.23%	97.14%	0.39%	2.49	0.65	uniform fine-grained sand; laminae of very coarse skeletal sand 80-120 cm
SNL-002	17.37	2.60	7.21%	92.16%	0.26%	3.03	0.78	uniform fine-very fine-grained sand; slightly coarser grained in upper 1 meter
SNL-003	6.4	5.10	1.08%	98.21%	0.59%	1.96	0.83	overall fine- to medium-grained sand; abundant laminae of corarse to very coarse grained skeletal sand
SNL-004	17.4	2.18	6.86%	84.75%	8.08%	2.10	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-005	8.8	5.16	1.16%	98.15%	0.33%	2.40	0.56	very uniform fine-grained sand through entire core
SNL-006	16.8	4.62	9.65%	80.25%	9.80%	2.39	1.71	uniform fine-grained sand in upper 2.5 meters; beds of and lenses of very coarse sand and gravel; also minor amount of mud below 2.5 meters as thin beds
SNL-007	7.3	3.69	1.98%	97.75%	0.70%	1.40	0.79	overall medium-grained sand with abundant zones of coarse-grained skeletal sand
SNL-008	18.0	1.75	3.67%	96.11%	0.10%	2.68	0.61	very uniform fine-grained sand through entire core
SNL-009	10.7	3.89	1.31%	97.40%	1.16%	1.71	0.87	overall medium-grained sand; fine-grained sand dominants several zones up to .75 meters thick
SNL-011	10.7	3.63	1.00%	96.74%	2.65%	1.48	0.96	overall medium-grained sand; zones of coarse-grained, skeletal sand abundant
SNL-011A	10.4	3.22	1.36%	97.69%	0.56%	2.13	0.75	overall fine-grained sand; zones of medium to corase sand at approximateley .5 meters and 1.5 meters
SNL-019	13.1	2.81	2.28%	96.96%	0.65%	2.30	0.79	overall fine-grained sand; zone of medium to corase sand at 1.7-2 meters; thin mud layer at 1.3 meters
SNL-021	8.2	5.22	1.27%	98.31%	0.15%	2.00	0.69	uniform medium- to fine-grained sand throughout the core
SNL-021A	8.5	4.29	1.46%	98.22%	0.13%	2.25	0.59	uniform fine-grained sand throughout core; thin mud layer at 3.6 meters
SNL-025A	7.0	6.04	1.07%	98.18%	0.57%	1.86	0.78	layered medium- and fine-grained sand; some coarse grained-sand mixed into layers of medium-grained sand
SNL-028	10.7	3.89	3.96%	95.87%	0.11%	2.52	0.62	uniform fine-grained sand throughout core; thin mud layers at 1.2 and 1.6 meters
SNL-030	5.8	6.02	0.97%	98.42%	0.41%	2.26	0.61	mostly uniform fine-grained sand; laminae and thin beds of medium-coarse skeletal sand in upper 1.25 meters
SNL-031	11.3	2.64	11.50%	88.28%	0.05%	3.16	0.71	overall silty very fine-grained sand; silty with mud lens at 1.6 meters
		All Cores --->	**3.33%**	**95.03%**	**1.48%**	**2.23**	**0.83**	

sand; Krumbein, 1934), with an average for all cores of 2.23 ϕ (0.21 mm, fine sand; Krumbein, 1934). Sediment in cores from the shoal crest or seaward sand waves (SNL-011, 011a, 020, 021, 021a, 025) are the coarsest; mean grain size ranges from 1.48 ϕ (0.36 mm, medium sand) to 2.25 ϕ (0.21 mm, fine sand) with an average mean grain size of 1.94 ϕ (0.26 mm, medium sand; Krumbein, 1934). Coarser sediment in these locations probably results from winnowing of finer grained material by waves and strong currents crossing the shoal crest and seaward nose.

Generally, all cores are quite sand-rich. Sand content within cores averages 95%, with a range from 88.3% to 98.4%. Mud (sediment grains smaller than 4 ϕ or 0.0625 mm) is typically a minor component, averaging 3.3% (range = 1.0% to 11.5%) along with gravel (sediment grains larger than 1 ϕ or 2.0 mm) which averages 1.48% (range = 0.05% to 9.8%). With the exception of a few thin (up to several cm thick) lenses in a several of the cores, the mud is generally disemminated throughout the cores. Gravel-sized particles occur primarily as coarse shell debris in all cores.

SECTION III: SAND RESOURCE ASSESSMENT

The primary goal of this survey was to determine the potential for Diamond Shoals to serve as a source of sand for future beach nourishment programs in the vicinity of Cape Hatteras. The geophysical data have aided in determining the stratigraphic architecture of the DSSA (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 arrive at an estimate of the total volume of sand within the DSSA.

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 Diamond Shoals.

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 multiplying the estimated thickness in meters by a conversion factor (yards = meters x 0.9144).

For this study, only the two uppermost stratigraphic units (S_1 and S_2) were considered as potential sand resources given presently available dredging technologies. 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 easily available surficial material. The thickness of the combined S_1 and S_2 units (S_{1+2}) is shown in Fig. 13.

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 Table 3, the area in square yards bounded by 3-meter contours of S_1 and S_{1+2} isopach maps was determined.

For each contoured area, the value of thickness used is that of the lower contour. For example, a contoured region bound by the 3-m and 6-m contour ranges in thickness from 3 m to 6 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 3 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.

MINIMUM	MINIMUM VOLUME (million yd^3)	
THICKNESS (m)	**S_1**	**S_{1+2}**
3	152.4	31.0
6	270.9	241.4
9	221.9	369.3
12	556.7	426.2
15	214.8	357.0
18	197.4	318.9
21	49.3	565.3
24	NA	586.4
27	NA	267.3
30	NA	193.7
33	NA	396.0
TOTAL	**1,663.3**	**3,752.5**

Table 3. Estimated volume of sand in stratigraphic units S_1 and S_{1+2} in the entire DSSA. Volumes were calculated by measuring the area (in yd^2) for each contour in a 3-m contour interval using GIS software (note that the contour interval (CI) displayed in Fig. 13 is 5 m--this was done for clarity of the graphic. A 3-m CI map of S_{1+2} was used to construct the right-hand column of this table). These areas were then multiplied by minimum thickness of the contoured unit (meters x 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 DSSA.

As can be seen in Table 3, the estimated minimum volumes of sand available within S_1 and S_{1+2} across the DSSA are appreciable. The total volume of sand within unit S_1 across the DSSA is at least 1.66 billion cubic yards. When this S_1 volume is combined with the volume of S_2 (i.e. S_{1+2}), this total increases to at least 3.75 billion cubic yards. When these estimates are restricted to that area contained within the state/federal 3-mile limit, unit S_1 contains 256.1 million cubic yards of sand and unit S_{1+2} contains 711.5 million cubic yards or sand. If only 20 percent of this potential resource is practical to recover, then the available sand would still exceed 140 million cubic yards.

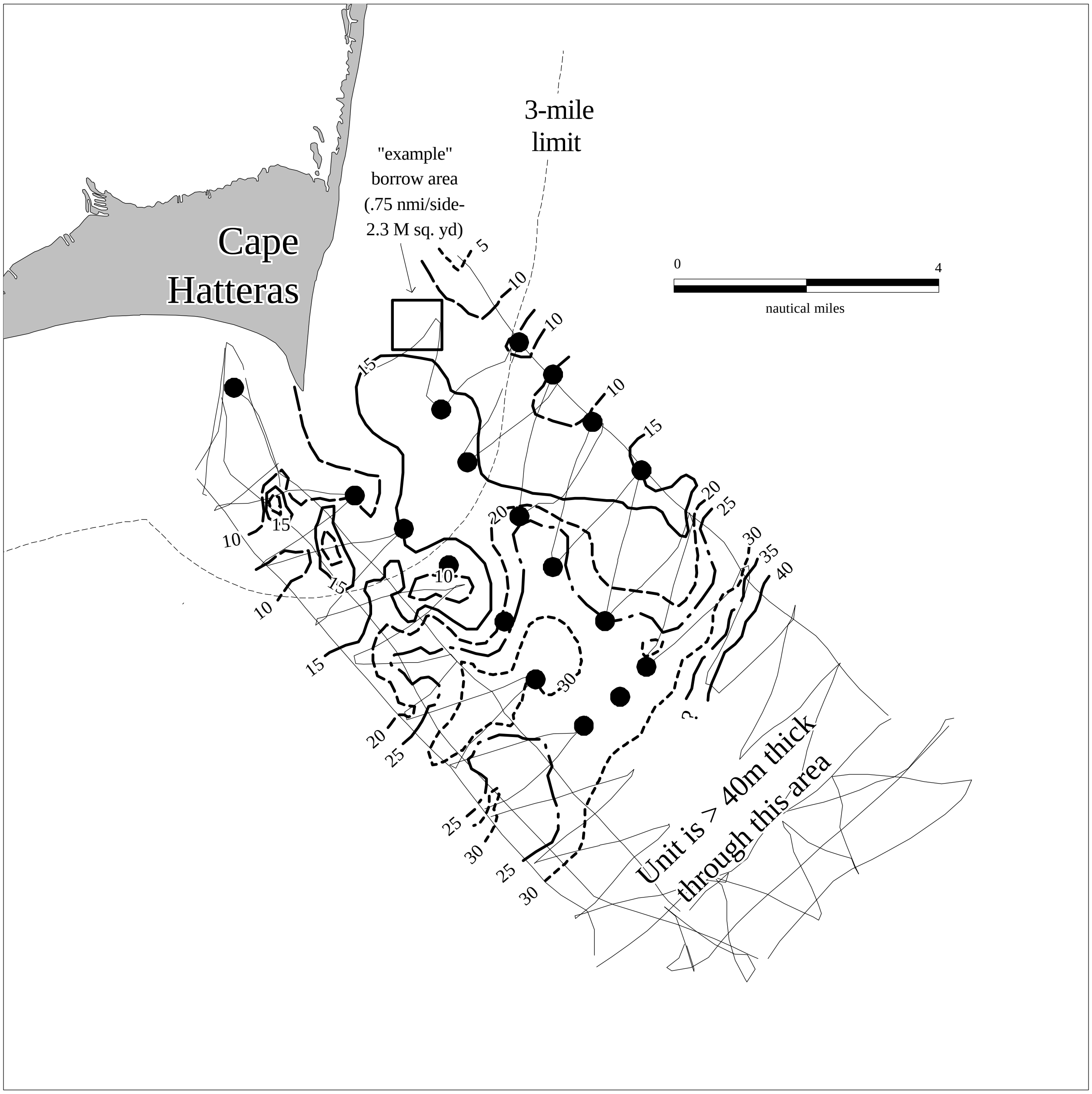


Fig. 13. Isopach map derived from seismic reflection data showing estimated thickness (in meters) of combined unit S_{1+2} within the DSSA. Thickness estimated assuming uniform seismic velocity of 1800 m/sec through units. Contour interval is 5 m. Shaded box indicates location of hypothetical borrow area occupying 2.3 million yd^2. Assuming that dredging operations removed the upper 6 feet of sediment, this borrow area would yield 4.6 million yd^3 of sand. For reference to other maps, seismic reflection and side-scan sonar tracklines indicated by thin lines, vibracore locations indicated with solid circles.

In order to place these values in perspective, a beach fill 1,760 yards long (1 statute mile) x 200 yards wide x 10 yards thick would require 3.52 million cubic yards of sand. This hypothetical project would consume approximately 2.5 percent of the available sand.

Given the great volume of sediment estimated for the DSSA, it is perhaps instructive to consider how much sand might be extracted from a given area. A hypothetical borrow area has been drawn on Fig. 13. This area occupies 2.3 million square yards (.75 nautical miles per side). Table 4 presents calculations of the total volume of sediment available within this box if dredging excavated to the indicated depths. Again, the volume of sediment available across the DSSA is significantly greater than these volumes.

DREDGING DEPTH(feet)	VOLUME (million cubic yds)
6	4.6
15	11.5
30	23.1

Table 4. Example calculations showing the volume of sand which available within the hypothetical borrow area illustrated in Fig. 13. Estimated volume determined by multiplying the area of the hypothetical borrow area by the indicated dredging depth above.

Obviously, not all of the sand contained within units S_1 and S_2 is accessible or economically recoverable, but this exercise illustrates that sand availability across the DSSA is unlikely to be a limiting factor in decisions to utilize those sand resources for future beach nourishment programs. Factors that are more likely to limit utilization of Diamond Shoals sand for future beach nourishment programs are technological (e.g. dredging methods), logistical (e.g. operations within the rigorous marine environment of Diamond Shoals), environmental (e.g. potential impacts of dredging operations on fisheries), social (e.g. public perception of beach nourishment or dredging of waters offshore national seashores), and economic (e.g. cost of transporting sand from DSSA to desired beach 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.

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