SAND RESOURCES OF THE NORTH CAROLINA OUTER BANKS

4th INTERIM REPORT: ASSESSMENT OF PEA ISLAND 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 Pea Island, 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 are presented as an outline of the stratigraphic architecture of the Pea Island Study Area (PISA) derived from interpretation of bathymetric, seismic reflection, and side-scan sonar data; description of the gross textural attributes of sediment in cores; and assessment of potential sand resources that might be utilized for future beach nourishment programs.

Six principal seismic reflectors (designated R_0 through R_5) were correlated throughout the PISA and form the upper and lower boundaries of five principal stratigraphic units (designated S_1 through S_5) extending from the seafloor to approximately 50 m sub-sea. Individual seismic units vary in thickness from 1 to 20 m (0 to 66 ft), but average 6 to 8 m thick. The seismic signatures of units within the PISA are 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 variable geologic or sedimentologic units.

Side-scan sonar records indicate a variety of sea-floor types, although the quality of side-scan sonar records suffer from the unique and variable bathymetry of the seafloor within the PISA. As a result, side-scan sonar data from this study area are of limited value in characterizing the seafloor within the PISA.

Forty-four vibracores were collected. Vibracore lengths range from 0.73 m to 6.08 m (average 3.83 m). Cores within the PISA contain variable sediment types, but average 78 percent sand (mean grain size of 2 ϕ = 0.2 mm), 16 percent fine-grained material (<0.062 mm), and 5percent gravel (mostly shell debris > 2 mm). A significant number of the cores (24) contain >10 percent mud (maximum = 89 percent mud) and may be considered unsuitable for beach fill. All percentages are given as weight percent.

The uppermost stratigraphic unit (Unit S_1) may be a potential sand resource in the northeastern (seaward) portion of the study area and in the southern portion of the study area. Throughout much of the PISA, a bathymetric trough truncates Unit S_1. Unit S_1 ranges from 1 m to 18 m thick and averages of 7 m thick. Several cores penetrate this unit, and show that S_1 is predominantly fine to very fine sand, with lesser quantities of shell gravel, medium to coarse sand, and mud .

In the northeastern corner of the PISA, Unit S_1 is estimated to contain in excess of 69 million cubic yards of sand. The other potential sand resource target within S_1 is in the southern portion of the PISA. This second target area is estimated to contain 56 million cubic yards of sand. In addition, sand may be derived from bypass operations at Oregon Inlet, or pumped/trucked from behind the terminal groin at Oregon Inlet according to what is feasible and allowable by economic factors and resource agency requirements.

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 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 and August 1995) aboard the United States Army Vessel *D/B 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 fourth project deliverable, and is organized into several sections to facilitate understanding of the rather complex data within the Pea Island Study Area (PISA). Section I describes the available geophysical data and presents results of interpretations of PISA bathymetry and stratigraphy derived from seismic reflection profiles and side-scan sonar. Section II documents textural attributes of sediment in vibracores collected within the PISA during 1995. Finally, Section III provides information pertinent to assessing the PISA as a potential resource of sand for beach nourishment along critically eroding beaches within the PISA.

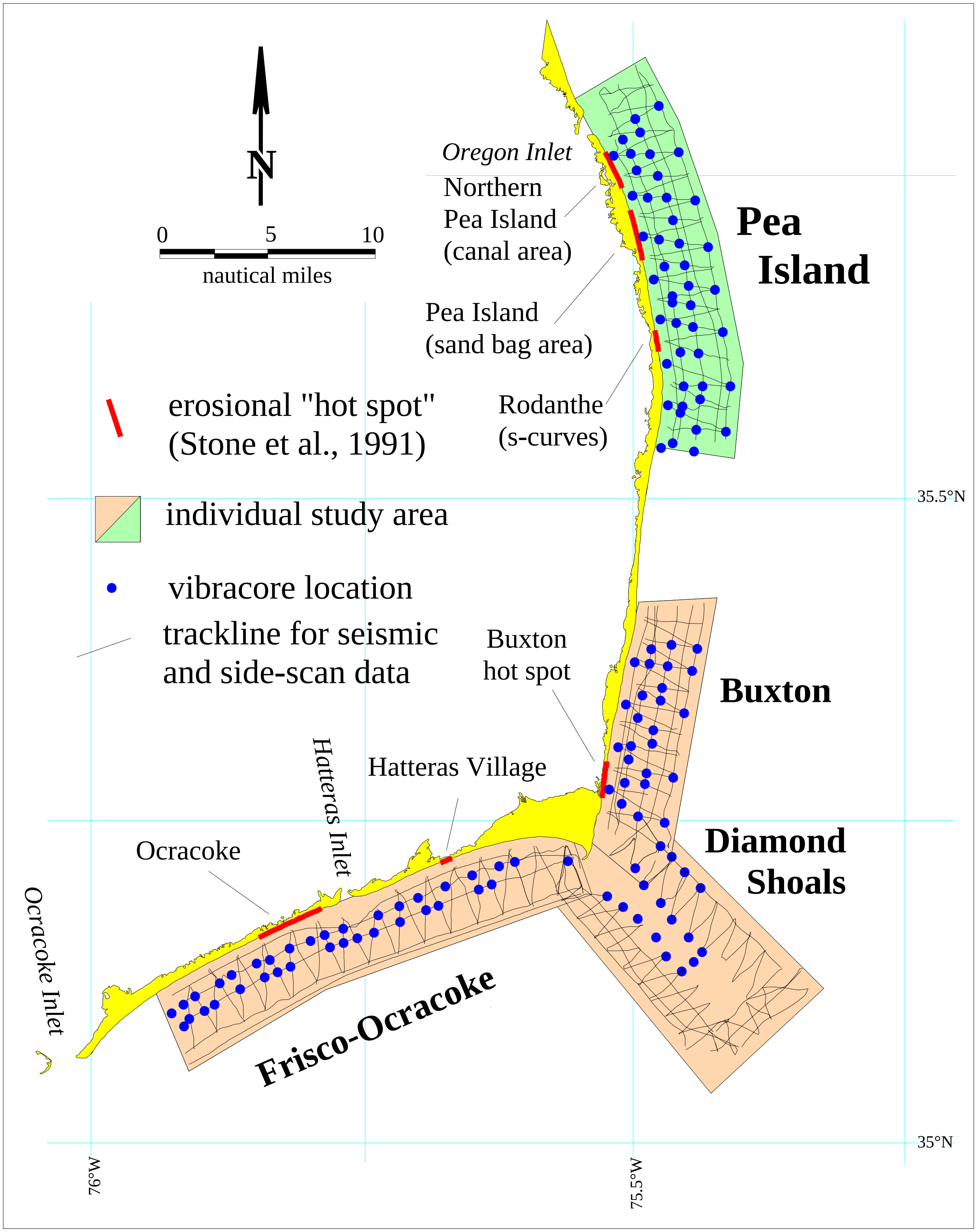

Fig. 1. Location map showing the Outer Banks Task Force sand resource project area. The four project areas are labeled along with locations of erosional "hot spots" (red line segments) with potential to impact NC Highway 12. Geophysical tracklines (seismic reflection and side-scan sonar profiles) are 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 Pea Island Study Area (PISA) is approximately rectangular, measuring about 33 km by 6 km (18 nautical miles by 3.2 nautical miles) and occupying an area of 198 km^2 (58 nm^2). Geophysical data consist of single-channel, high-resolution seismic reflection profiles and side-scan sonar records from the PISA (Fig. 2). These data were collected simultaneously during the 1994 research cruise and are subdivided into 38 trackline segments constituting 341 km (184 nautical miles). Tracklines are oriented with 5 lines parallel to the coast from 0.5 to 3.0 nautical miles offshore and 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 of state jurisdiction.

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 PISA 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 PISA 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. 4, and 5 through 8) 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).

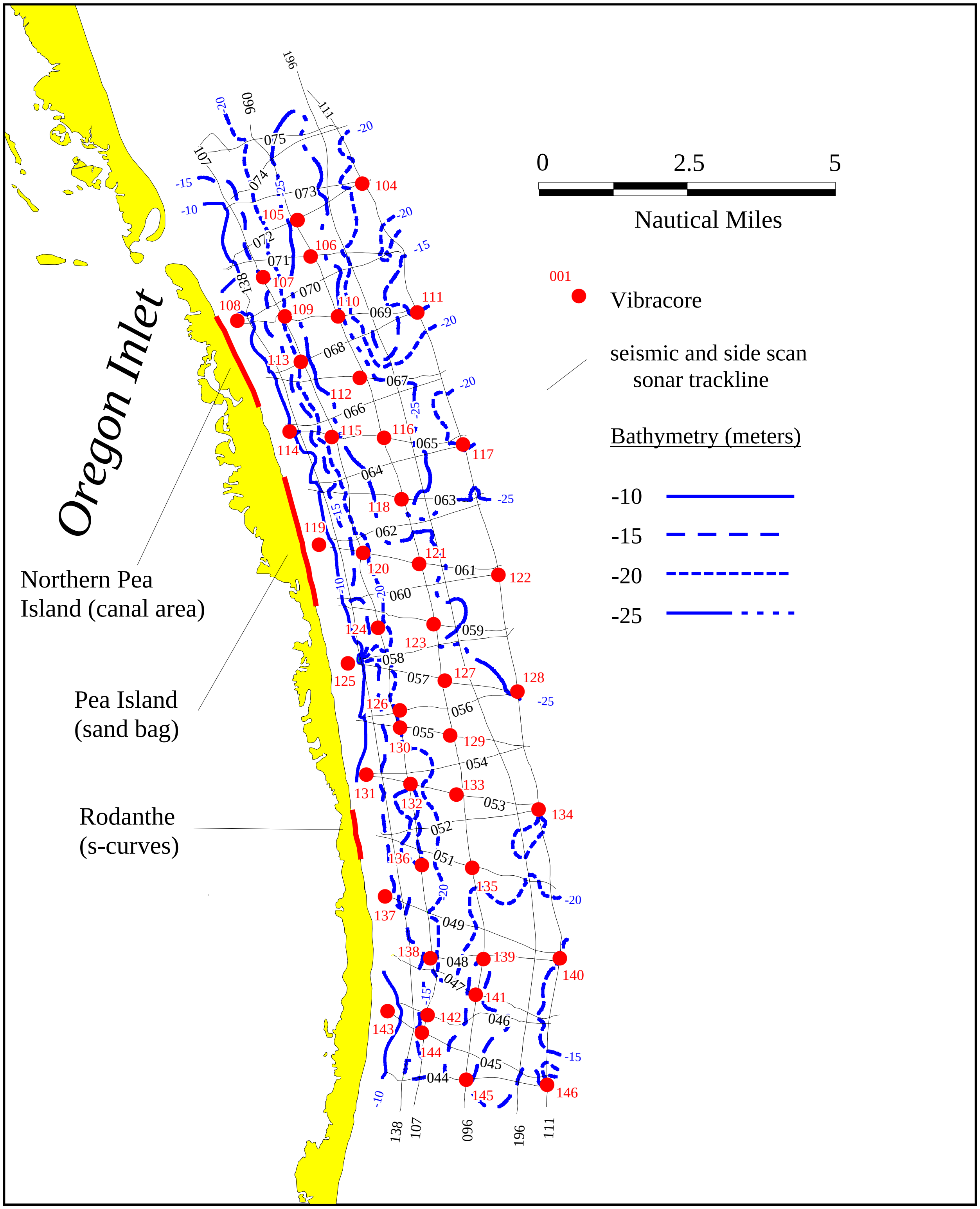

Fig. 2. Detailed location map of Pea Island Study Area (PISA) showing tracklines of seismic reflection and side-scan sonar profiles (thin lines) as well as locations of vibracores (solid cirlces) used in this sand resource assessment. Bathymetry from this study.

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.

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

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 PISA. Mapping of reflector surfaces in three-dimensions made it possible to estimate the volume of material contained within the major depositional sequences throughout the PISA.

Bathymetry of the Pea Island Study Area

Within the PISA, a broad bathymetric trough is developed on the seafloor (Fig. 3). This feature occurs approximately 2 km (1.1 nm) from shore as an arcuate depression ranging in width from 3 to 6 km (1.6 to 3.2 nm), and attains a depth in excess of 20 m (66 ft) in the northern portion of the PISA. The occurrence of this trough offshore of Pea Island results is a relatively steep shoreface and divides the shoreface from shoal areas near the seaward limit of the PISA (Fig. 3). The geologic origin of this trough is not known. However, this trough clearly

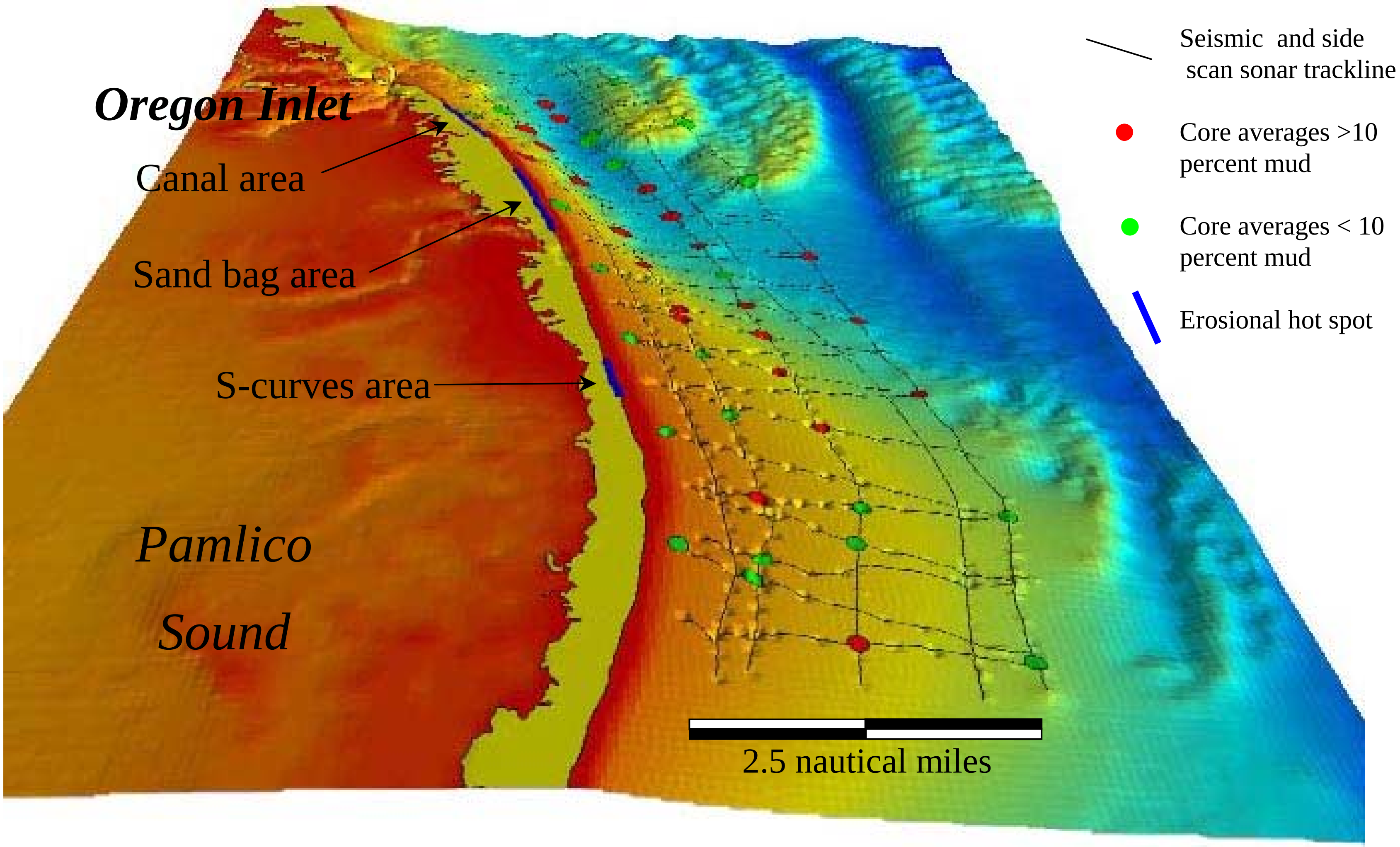

Fig. 3. Three-dimensional perspective view of the seafloor within the PISA. This view is from the south (azimuth = 180^{o}) toward the north at an inclination angle of 35^{o}. The bathymetric trough that dominates the geomorphology of the seafloor within the PISA is evident (vertical exaggeration approximately 30x). Map of Pea Island with erosional hot spots, seismic/side-scan sonar tracklines, and core locations has been draped over bathymetry to show relation of trough to survey data. Colors on core symbols indicate bulk sediment textural attributes (see legend). Note high degree of correspondence of mud-rich cores within boundaries of trough.

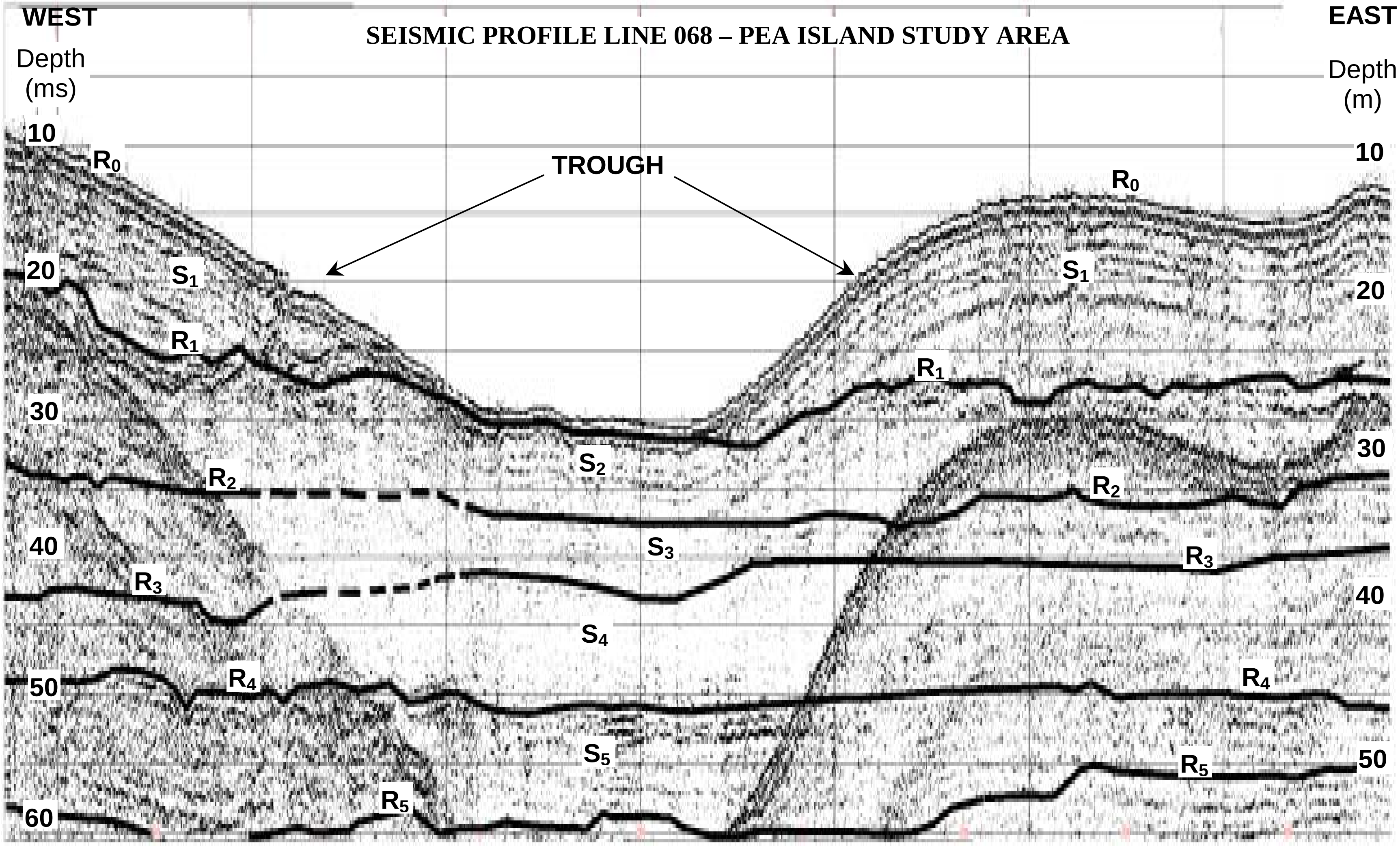

Fig. 4. Seismic reflection profile 068 in PISA. Offshore is to the right. The principal reflectors (R_0 through R_5) and stratigraphic units (S_1 through S_5) correlated throughout the PISA are indicated. Vertical scale on left is two-way travel time (in milliseconds). Vertical scale on right is in meters approximated on a sub-bottom velocity of 1,800 meters/second. Line length is 2.6 nautical miles (4.9 km); vertical exaggeration is approximately 180X.

truncates the uppermost seismic unit (Unit S_1) within the study area such that a deeper unit (Unit S_2) is exposed along the sides and bottom of the trough. The presence of this trough immediately offshore of Pea Island has a dramatic impact on coastal erosion and the availability of sand resources within the PISA.

Geologic Framework of the Pea Island Study Area

Seismic units can be grouped into five 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, and R_5 (Fig. 3).

Within the seismic units defined by the six major reflectors, the acoustic character of contained stratigraphic units is somewhat distinctive, aiding in the correlation of these units around the PISA.

Six primary seismic reflectors (designated R_0 through R_5) were identified within the PISA. 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, and R_5 (Fig. 4). These surfaces form the boundaries of 5 depositional units, term S_1 through S_5. By convention, each unit (or sequence) is named according to the label of its basal reflector. 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.

Within the seismic units defined by the six major reflectors, the acoustic character of contained stratigraphic units is somewhat distinctive, aiding in the correlation of these units around the PISA. Brief descriptions of some of these seismic units are provided below.

Seismic Unit S_1

Unit S_1 (Fig. 4) is the uppermost stratigraphic unit and is recognizable throughout the PISA. Unit S_1 appears to have a tabular geometry, though it is truncated by the bathymetric trough that bisects the PISA (Fig. 5). As such, it is not possible to determine with certainty whether the unit designated S_1 near shore is the same unit observed to form the shoal features offshore in the northeastern portion of the PISA. However, cores from the nearshore areas and offshore shoal features are texturally similar and thus suggest original stratigraphic continuity of these units. Unit S_1 ranges in thickness from 1 m to 18 m (being thinnest where it is truncated by the offshore trough) and averages 7 m thick (Fig. 6) throughout the PISA. The basal reflector of Unit S_1 may crop out on the sides of the trough, suggesting that Unit S_2 is exposed on the floor of the trough throughout the PISA.

Direct sedimentological data is available for Unit S_1 from vibracores that penetrate this deposit in the nearshore and offshore shoal areas of the study area. In addition to core sediment data, the surface expression of S_1 is represented on the side-scan sonar records of the PISA. These data indicate that S_1 is of somewhat variable composition throughout its area of occurrence, though it is dominantly fine to very fine sand with lesser quantities of shell gravel, coarse to medium sand, and fine-grained sediments (silt and clay). Overall Unit S_1 appears to be dominantly sandy.

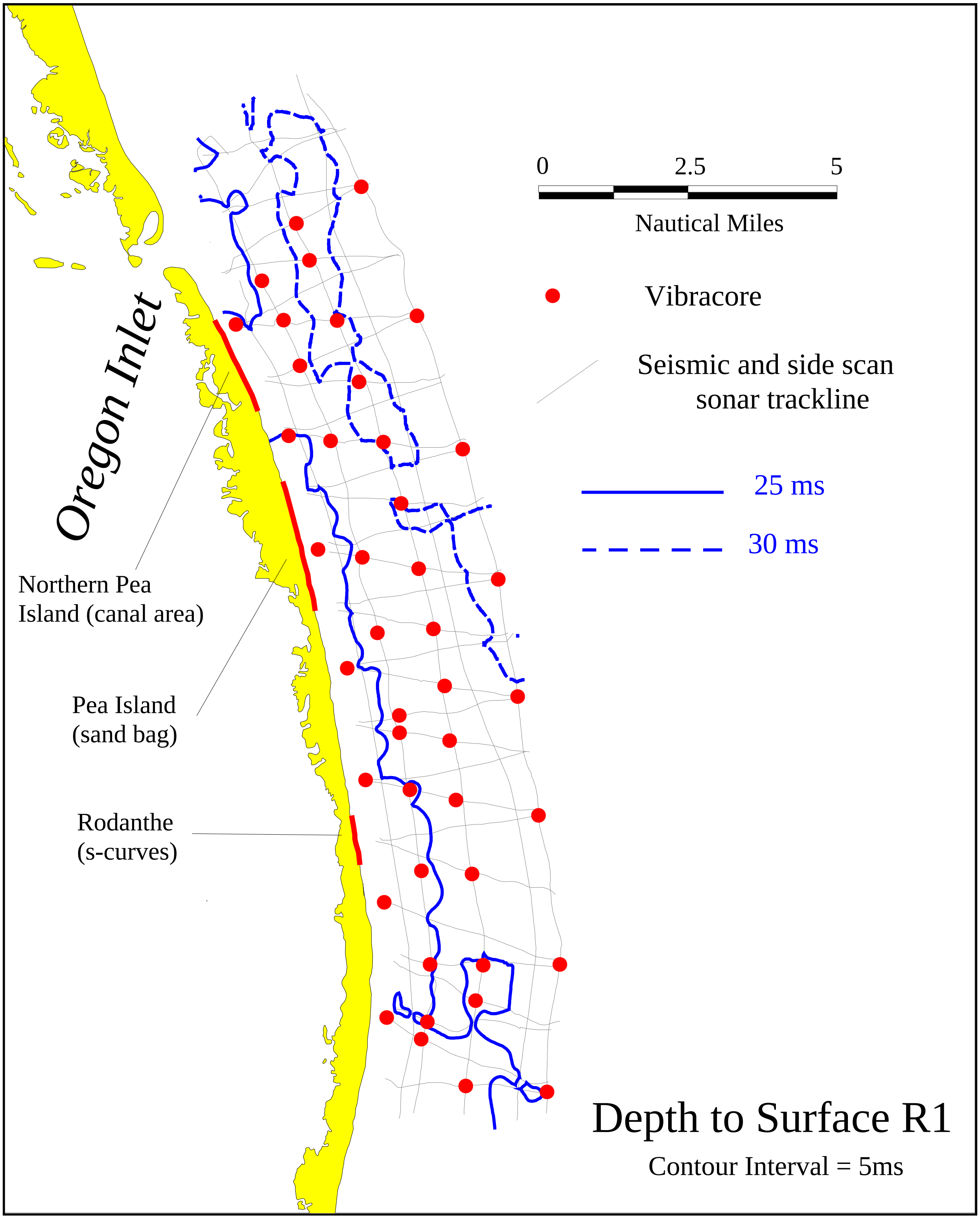

Fig. 5. Structure contour map derived from seismic reflection data showing depth below sea level (in milliseconds two-way travel time) to reflector R_1 within the PISA. Contour interval of 5 ms is approximately 4 meters.

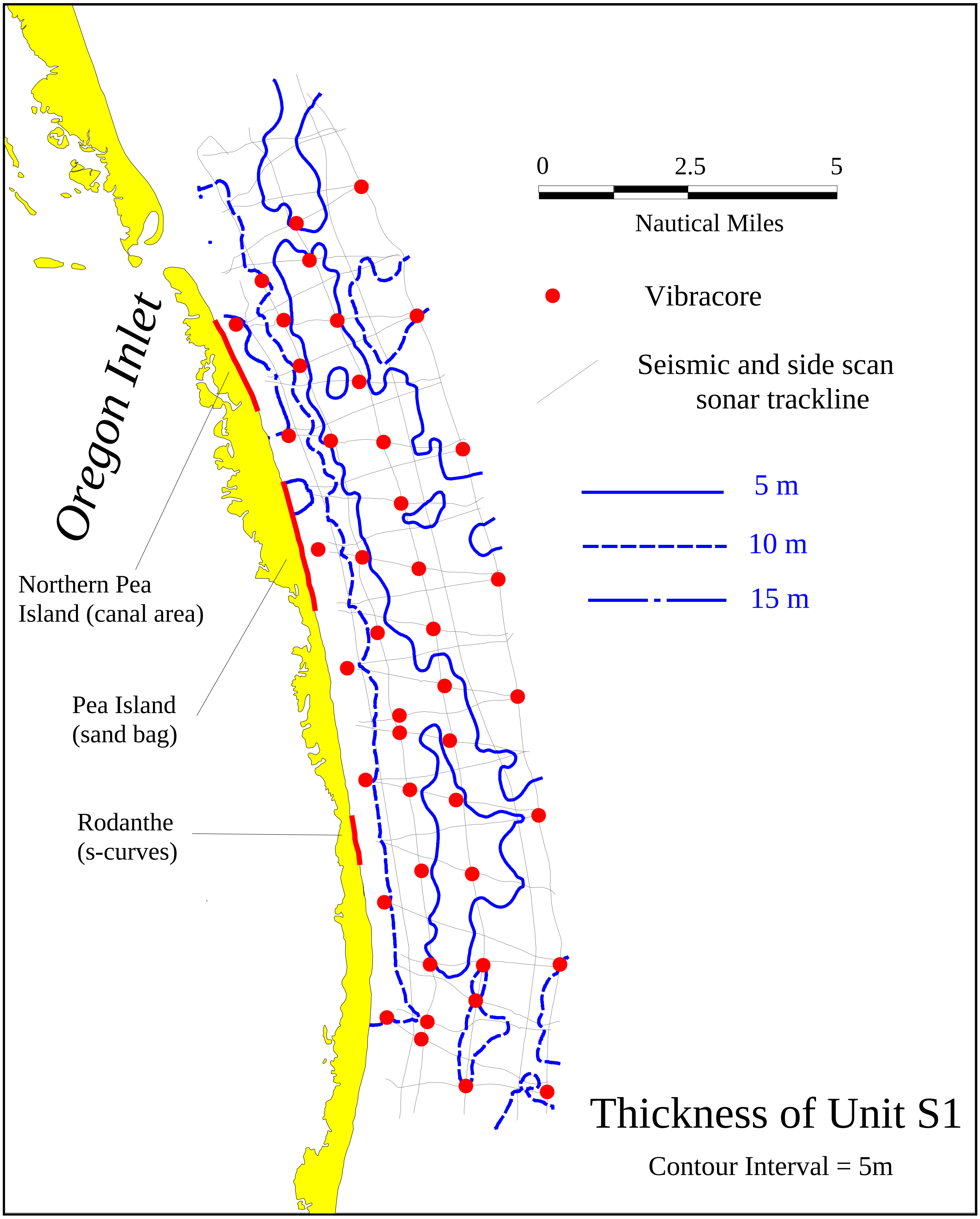

Fig. 6. Isopach map of unit S_1 in the PISA. The average thickness of S_1 is 7 m.

Seismic Unit S_2

The next seismic unit identifiable among the PISA seismic reflection data is also recognizable throughout the entire study area (Fig. 7). The R_2 reflector occurs between 28 and 46 milliseconds two-way travel time across the PISA.

Unit S_2 also displays a generally tabular geometry, averaging 8 m thick (range 1 to 20 m) throughout the study area. The unit was sampled by a large number of cores located within the bathymetric trough of the PISA (Figs. 2 and 3; Table 2). Seismically, unit S_2 is characterized by a series of closely-spaced parallel reflectors indicative of interbedded sediment types. Cores indicate that Unit S_2 is texturally very different from unit S_1, being composed dominantly of mud, shell gravel and very fine sand to silt interlayered within each core. The quantity of mud within unit S_2 clearly determines that this unit is unsuitable as a sand resource for possible beach nourishment along PISA hot spots.

Seismic Unit S_3

Reflector R_3 occurs throughout the PISA. This reflector occurs at depths ranging from 35 ms to 52 ms two-way travel time, and averages 42 ms two-way travel time. The unit has a tabular geometry with range of thickness estimated to be 1 m to 14 m (average = 6 m). No cores penetrate unit S_3, so its sedimentary constitution is not presently known. However, its depth beneath the surface is sufficiently great to preclude its consideration as a potential sand resource.

Seismic Units S_4 and S_5

Reflectors R_4 and R_5 form the basal reflectors of units S_4 and S_5. 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 toward the southeast across the PISA (Figs. 8, 9). R_4 is recognized throughout most of the study area, occurring 44 to 58 milliseconds two-way travel time beneath the sea surface. Unit S_4 attains a maximum thickness of 15 m and averages 8 m across the PISA. R_5 occurs consistently between 52 to 63 milliseconds two-way travel time (averaging 53 ms) throughout the PISA. Reflector R_5 is very consistent in character and appears to correlate with reflector R_6 in the Buxton Study Area and Reflector R_5 in the Diamond Shoals Study Area). The widespread extent of this reflector and its consistent depth of occurrence suggests that it represents a major stratigraphic boundary, perhaps the Pliocene-Pleistocene boundary.

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

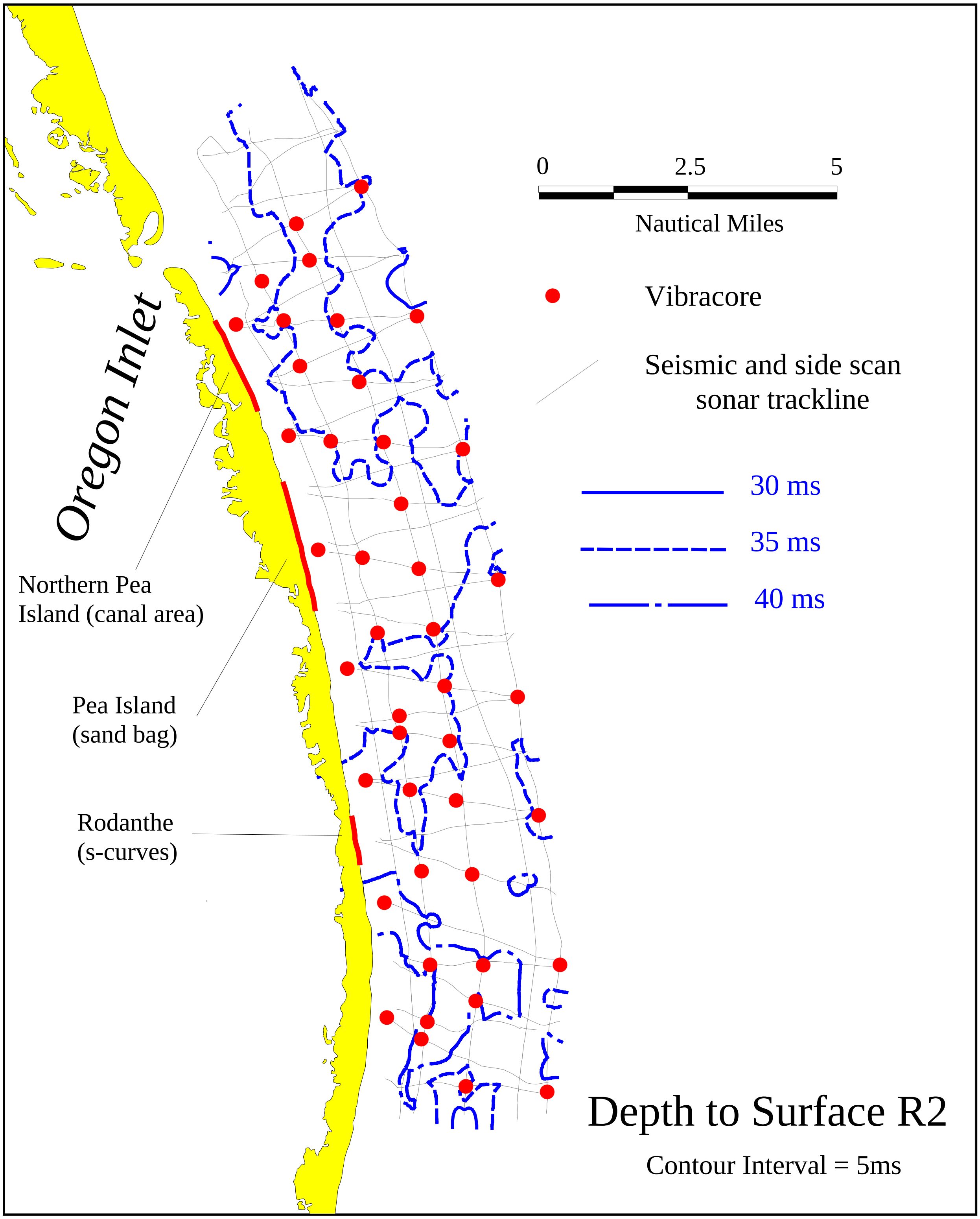

Fig. 7. Structure contour map derived from seismic reflection data showing depth below sea level (in milliseconds two-way travel time) to reflector R_2 within the PISA. Contour interval of 5 ms is approximately 4 meters.

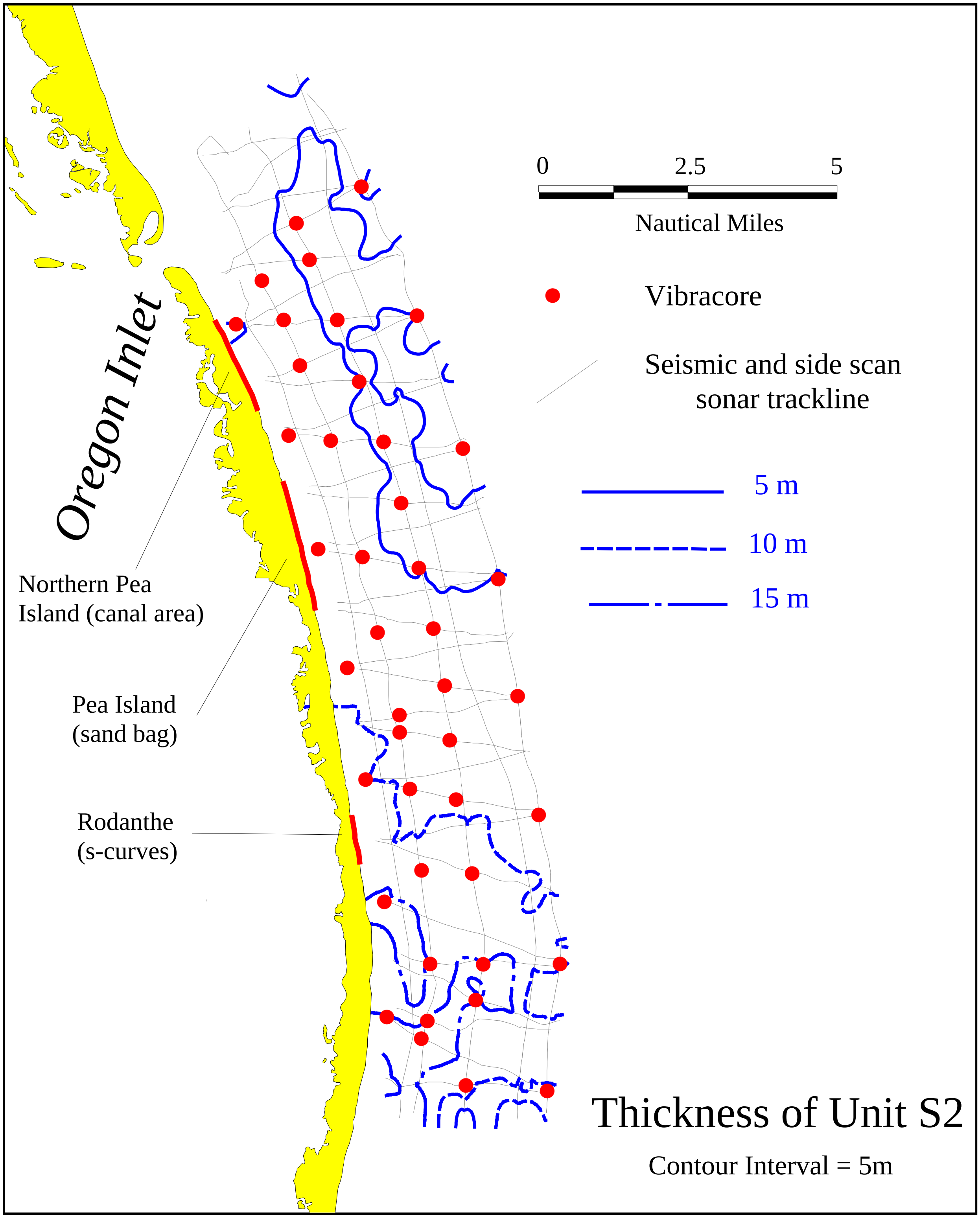

Fig. 8. Isopach map of unit S_2 in the PISA. The average thickness of S_2 is 8 m.

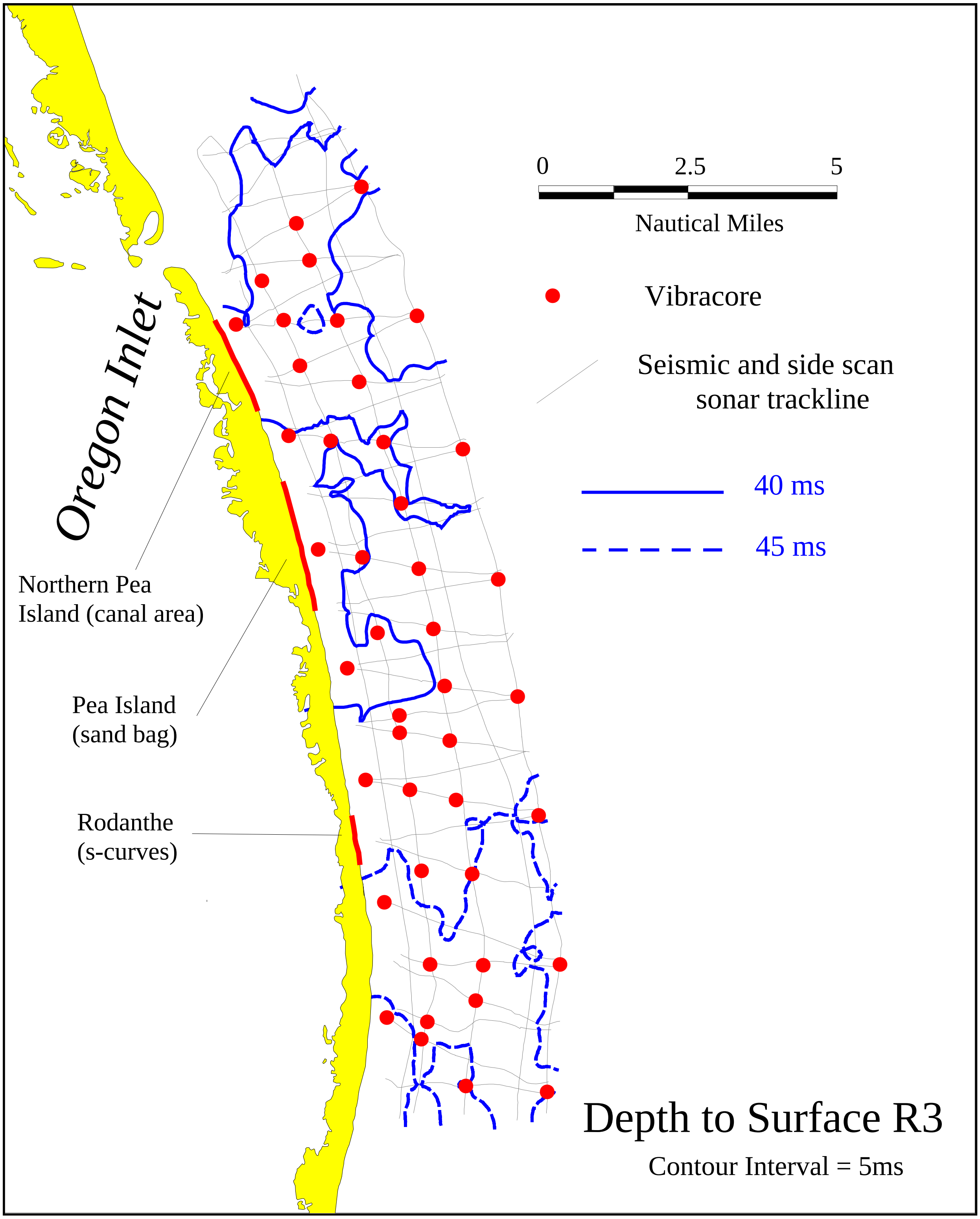

Fig. 9. Structure contour map derived from seismic reflection data showing depth below sea level (in milliseconds two-way travel time) to reflector R_3 within the PISA. Contour interval of 5 ms is approximately 4 meters.

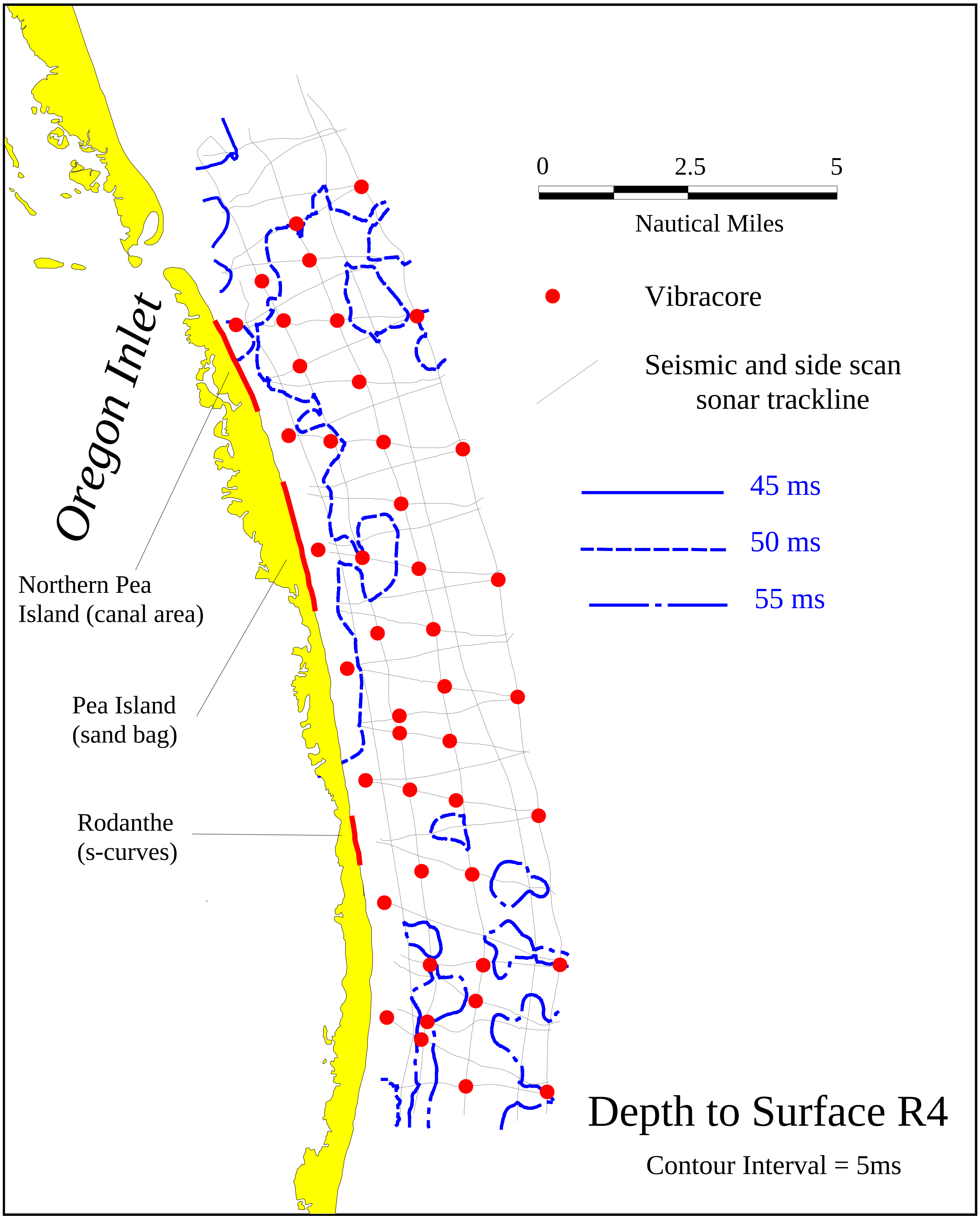

Fig. 10. Structure contour map derived from seismic reflection data showing depth below sea level (in milliseconds two-way travel time) to reflector R_4 within the PISA. Contour interval of 5 ms is approximately 4 meters.

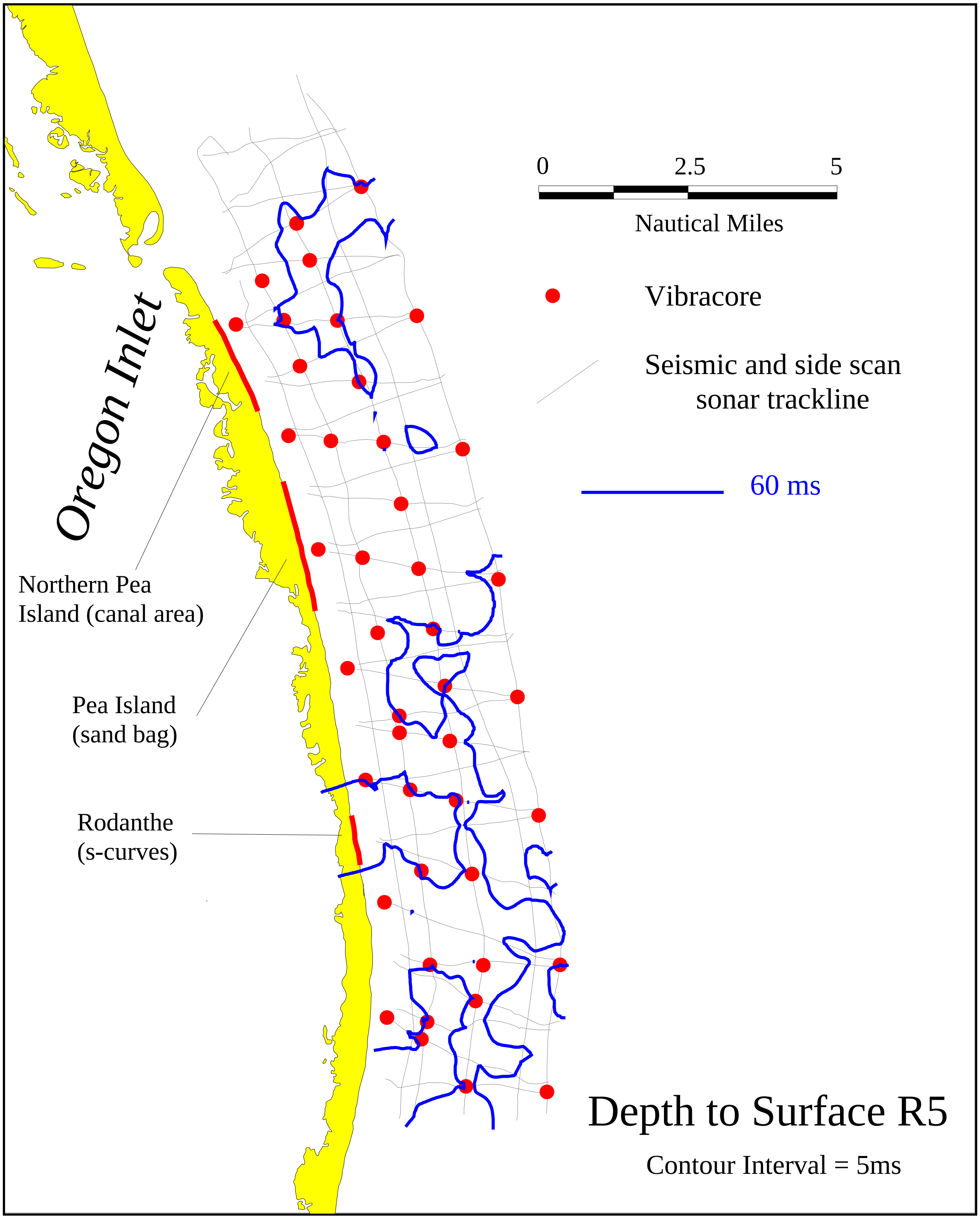

Fig. 11. Structure contour map derived from seismic reflection data showing depth below sea level (in milliseconds two-way travel time) to reflector R_5 within the PISA. Contour interval of 5 ms is approximately 4 meters.

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, the towfish should "fly" at a relatively constant and recorded height above the seafloor. In the PISA, an area with considerable bathymetric variability, the fish would need continuous monitoring and adjustment. 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 will be less than 400 m, 2) acoustic returns from the sea surface can obscure seafloor data (especially in rough weather), or 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. An additional consequence of operating the side-scan towfish at improper height above the bottom in an area of highly variable bathymetry such as the PISA is that it is not possible to determine whether changes in acoustic character of the side-scan sonograms are related to actual variability of seafloor physical properties or to variability of the fish height off the bottom. Thus, the side-scan sonar data are of limited utility for characterizing sea-floor types within the PISA. Side-scan sonar data are described below, however, for purposes of comparison with other study areas.

In general, the side-scan sonograms show a weak or low reflectivity in the northeastern shoal area, the area shoreward of the trough, and over the southern bathymetric high. Most of the shore-perpendicular lines show a low to moderate reflectivity associated with the western portion of the trough area. Limited areas, usually within the trough, show a moderate to high reflectivity. The bathymetric high in the southern portion of the PISA and the central area of the trough where it extends seaward within the PISA (Figs. 2, 3) show a mixed low and moderate reflectance with a “blocky” pattern suggestive of possible hard bottom.

Ordinarily, low reflectivity on side-scan sonar records is interpreted to indicate fine-grained sediments (mud to very fine sand), moderate reflectivity indicates fine to medium or coarse sand, and high reflectivity suggests very coarse sand and gravel. However, within the PISA, interpretation of seafloor types based on side-scan sonar reflectivity shows poor correspondence to seafloor type determined from observation of surficial deposits in cores. For example, low reflectivity seafloor within the PISA invariably corresponded to mud to medium sand. Moderately reflective seafloor, however, corresponded to sediment types ranging from mud to gravel. Finally, side-scan sonar signatures typically associated with hard bottom shows no evidence of hard bottom lithology in cores. Thus, it appears that observed patterns of seafloor reflectivity are more probably related to variations in the orientation of the seafloor relative to the sonar towfish and provide unreliable records. As a result of low confidence in the reliability of side-scan sonar records, a map of seafloor types derived from interpretation of sonograms is not presented.

SECTION II: SEDIMENT TEXTURAL CHARACTERISTICS FROM CORES

Forty-four vibracores were collected within the PISA during the summer of 1995 aboard the U.S. Army Vessel *D/B Snell* (Fig. 2; Table 2). Core lengths range from 0.73 m to 6.08 m, with an average length of 3.83 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 3.5 ms two-way travel time. Minimum and maximum length cores would penetrate to 0.7 ms to 5.5 ms two-way travel time on seismic profiles. Thus, it is clear that cores penetrate to very shallow depths within the PISA sediment package. Despite the fact that cores penetrate to relatively shallow depths, it was possible to sample different stratigraphic units within the PISA because cores were located in areas underlain by different stratigraphic units. Figure 12 shows the distribution of cores coded by greater than (red symbol) or less than (green symbol) 10 weight percent mud content along with the generalized outline of the bathymetric low that trends approximately parallel to shore through the northern two-thirds of the study area. There is a high coincidence of muddy cores within this bathymetrically and stratigraphically lower area. Cores within the trough area primarily sample Unit S_2 and the lower portions of Unit S_1. Nearshore cores and cores from the bathymetric highs in the northeastern at and southwestern portions of the PISA sample primarily 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 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.

Overall, cores within the PISA contain an appreciable amount of mud with an average of 16.31 weight percent (range = 1.05 to 89.17 percent). Sand content averages 78.33 weight percent (range = 10.38 to 98.24percent) and gravel content averages 5.22 weight percent (range = 0.18 to 35.57 percent). Ten weight percent mud content is the generally accepted limit for beach fill material. Thus, it would appear that sand resources suitable for beach nourishment are somewhat limited within the PISA.

The best quality cores (i.e. those with higher sand and low mud content) occur in several general areas of the PISA: a shoal area in the northeast portion of the study area (cores 104, 110, 111, 112, and 117), along the nearshore regions of the PISA west of of the offshore trough (cores 119, 125, 131, 132, 136, and 137), and on the broad bathymetric high in the southern part of the study area (cores 139, 140, 141, 142, 143, and 144). The average mud, sand and gravel of the cores in these three areas is: 3.82, 87.84, and 8.11 weight percent for the northeastern shoal area; 3.21, 91.89, and 4.76 weight percent for the nearshore area; and 2.61, 91.91, and 5.39 weight percent southern broad bathymetric high.

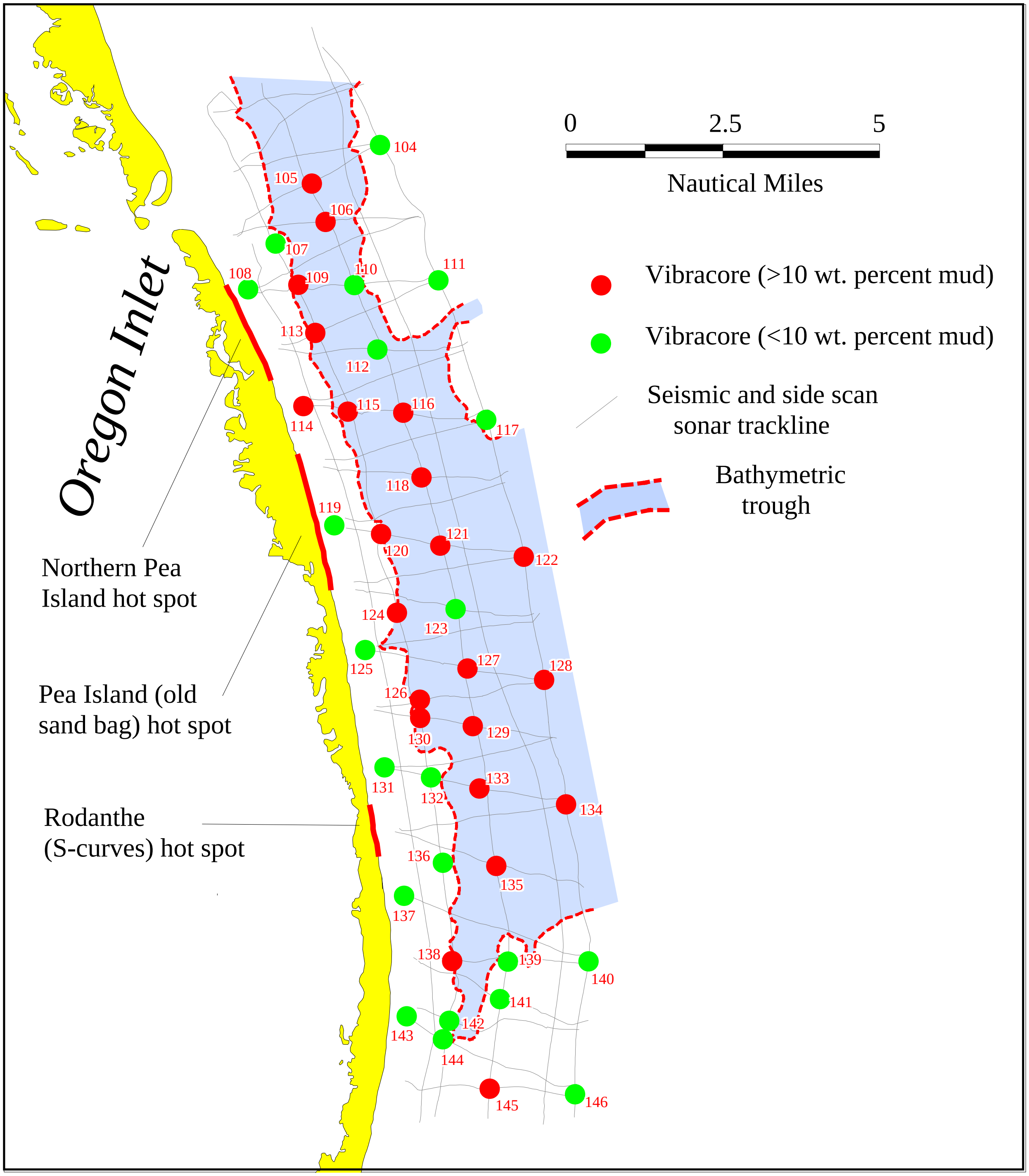

Fig. 12. Map showing distribution of cores coded to indicate mud content above or below 10 weight percent –a commonly accepted limit for suitability as beach nourishment material. The general outline of the bathymetric trough is outlined. Note the high degree of correlation of high mud content cores with this feature.

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-104	16.16	5.07	2.68	95.34	1.67	2.07	0.24	0.91	uniform medium to fine sand throughout with coarse shelly sand zone at 0-68cm.
SNL-105A	21.95	1.07	45.12	54.56	0.32	3.66	0.08	1.06	muddy very fine sand throughout.
SNL-105B	21.95	0.73	26.50	72.23	1.23	3.14	0.11	1.35	uniform muddy very fine sand throughout.
SNL-106	23.16	4.82	15.53	78.98	5.36	2.29	0.20	1.56	mostly medium to fine sand throughout; 0-200cm-- very fine sand and mud; 200-482cm; medium to fine sand with zones of muddy medium sand with shelly fragments at 366-385cm and 400-437cm.
SNL-107	13.11	4.05	5.84	93.25	0.73	2.52	0.17	0.96	0-100cm--fine to very fine sand; 100-205cm--silty fine to very fine sand layers; 205-405cm--finely laminated very fine sand.
SNL-108	6.40	5.10	4.16	94.13	1.55	2.31	0.20	0.96	fine sand throughout with numerous very fine sand lenses.
SNL-109	16.46	4.34	10.10	88.57	1.22	2.10	0.23	1.36	0-217cm--fine to very fine sand with mud lump at 108-118cm; 217-325cm--coarse to medium sand with faint layering; 325-403cm--interlayered mud and shelly fine sand; 403-434cm--mud.
SNL-110	21.34	1.94	3.72	60.53	35.57	0.16	0.90	1.54	gravelly coarse sand throughout with fine sand zone at 166-194cm.
SNL-111	11.28	2.85	1.24	98.24	0.36	1.83	0.28	0.69	laminated fine to medium sand throughout.
SNL-112	22.56	5.34	8.78	88.12	2.77	1.90	0.27	1.25	0-467cm--burrowed fine to medium sand with scattered small shell fragments; 467-534cm--shelly medium sand with mud.

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-113	16.77	3.50	89.17	10.38	0.34	4.26	0.05	0.80	uniform mud throughout core.
SNL-114	9.45	4.29	13.90	80.08	5.94	1.73	0.30	1.69	0-65cm--medium to fine sand; 65-186cm--gravelly coarse to medium sand; 186-232cm--muddy fine sand; 232-327cm--mud; 327-443cm--medium to fine sand.
SNL-115	18.29	6.06	48.04	47.49	4.4	3.50	0.09	1.48	0-100cm--muddy very fine sand; 100-370cm--mud;370-450cm--muddy coarse to medium sand with shell debris;450-606cm--muddy very fine sand.
SNL-116	21.64	6.08	21.14	74.37	4.37	2.64	0.16	1.52	0-250cm--muddy very fine sand with scattered very small shell fragments;250-400cm--fine sand with mud; 400-447cm--shelly fine sand with mud;447-608cm--fine sand with mud.
SNL-117	16.77	2.68	2.70	96.97	0.18	2.04	0.24	0.78	mixture of medium to fine sand throughout;0-45cm—medium sand;45-100cm--laminated medium to fine sand;100-268cm--fine sand.
SNL-118	21.34	5.82	26. 23	71.85	1.52	2.95	0.13	1.44	0-37cm--mud with medium sand layers;37-450cm--mottled, muddy very fine sand; 450-582cm-- muddy medium sand.
SNL-119	7.93	1.87	1.57	95.07	3.11	1.87	0.27	0.94	0-24cm-- silty very fine sand;24-36cm-- medium to coarse sand with shell fragments;36-187cm--medium to fine sand with thin heavy mineral laminae.
SNL-120	14.94	4.08	21.57	69.4	8.92	2.74	0.15	1.67	0-200cm--very fine to fine sand with two medium sand layers at 60-80cm; 200-242cm-- muddy very fine sand;242-300cm--medium sand with mud;300-408cm--interlayered mud and very fine sand.
SNL-121	21.03	6.07	22.37	73.04	4.19	2.91	0.13	1.40	0-200cm-- silty very fine sand with pebble gravel mix and mud lump at 44cm; 200-400cm--very fine sand with mud; 400-550cm--muddy fine sand; 550-607cm--medium to fine sand with numerous shell fragments.

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-122	22.86	6.06	16.25	82.38	1.07	2.66	0.16	1.23	0-500cm--muddy very fine to fine sand;500-606cm--coarse to medium sand.
SNL-123	19.21	1.84	1.22	87.74	10.95	1.22	0.43	1.14	0-55cm--coarse sand with large shell fragments; 55-184cm--medium sand.
SNL-124	16.16	6.08	38.32	54.18	7.42	3.05	0.12	1.76	0-100cm--very fine to fine sand;100-120cm--very coarse sand and gravel;120-200cm--muddy very fine to fine sand;200-608cm--mud with shelly coarse sand zone at 369-447cm.
SNL-125	7.32	2.23	2.29	93.19	4.4	1.96	0.26	1.18	0-56cm--fine to very fine sand; 56-70cm--coarse sand and gravel; 70-136cm--medium to fine sand;136-193cm-- fine sand with medium to coarse sand lenses;193-223cm-- fine sand.
SNL-126	16.77	5.34	40.08	57.3	2.54	3.35	0.10	1.37	0-46cm--very fine sand; 46-475cm-- muddy very fine sand; 475-534cm-- shelly coarse sand.
SNL-127	19.20	5.67	46.11	44.42	9.38	2.85	0.14	1.97	0-50cm-- coarse sand and gravel; 50-400cm--mud with fine sand; 400-567cm-- fine sand.
SNL-128	21.95	6.08	15.89	79.26	4.74	2.69	0.15	1.38	0-40cm--coarse to very coarse sand with shell fragments and gravel;40-376cm--muddy fine sand; 376-608cm--muddy fine to very fine sand with zone of muddy coarse sand with shell fragments at 376-400cm.
SNL-129	17.98	6.07	40.47	57.92	1.47	3.37	0.10	1.21	0-20cm-- mud;20-607cm--muddy fine to very fine sand with zone of coarse sandy mud with shell debris at 300-337cm.
SNL-130	16.77	1.26	15.32	61.45	23.18	1.68	0.31	2.20	0-71cm--very coarse sand and shelly gravel;71-126cm--muddy fine to very fine sand.
SNL-131	8.84	1.40	4.92	89.4	5.62	2.34	0.20	1.29	0-101cm--fine to very fine sand;101-140cm--medium to fne 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-132	14.63	2.43	3.66	94.06	2.12	2.10	0.23	1.19	0-69cm--fine sand; 69-126cm--medium to coarse sand with fine shell debris; 126-243cm-- fine to very fine sand with several medium to coarse sand lenses between 145-180cm.
SNL-133	17.68	5.80	24.13	72.66	3.16	2.88	0.14	1.28	0-25cm--shelly fine sand;25-100cm--fine sand with mud stringers;100-243cm--mud;243-580cm--fine sand with scattered shell fragments.
SNL-134	17.07	6.05	29.56	61.42	8.88	2.24	0.21	1.87	0-255cm--medium to fine sand with mud zones at 176-193cm and 247-255cm; 255-281cm--gravelly very coarse sand;281-313cm--mud with fine sand layer at 290-292cm;313-331cm--shelly gravelly coarse sand;331-471cm--mud with very fine sand stringers;471-523cm--muddy shelly very coarse sand;523-565cm-- mud; 565-605cm--muddy shelly coarse sand and gravel.
SNL-135	17.37	6.08	24.62	66.02	9.3	2.41	0.19	1.75	0-200cm--mud with shelly gravelly zone at 160-200cm;200-300cm--shelly medium to coarse sand;300-382cm--fine sand with scattered shells;382-393cm--gravelly medium to coarse sand;393-608cm--shelly fine to very fine sand.
SNL-136	14.02	2.04	4.06	94.05	1.8	2.73	0.15	0.90	fine sand throughout; 0-204cm--fine to very fine sand with zone of very coarse sand at 145-151cm.
SNL-137	8.84	3.80	2.77	85.59	11.53	1.69	0.31	1.50	0-157cm--fine to very fine sand with coarse sand zones at 124-142cm;157-249cm--coarse to very coarse sand with shelly debris;249-303cm--fine to very fine sand with coarse sand zone at 290-297cm; 303-380cm--shelly coarse sand.
SNL-138	15.85	1.48	13.94	82.14	3.86	2.71	0.15	1.48	0-15cm-- shelly coarse sand;15-148cm--muddy very fine sand.
SNL-139	13.41	1.04	1.05	94.12	4.7	1.35	0.39	1.00	0-104cm--shelly medium to fine sand throughout core.
SNL-140	13.41	1.75	2.59	96.39	0.95	1.85	0.28	0.90	0-38cm--fine to medium sand;38-175cm--fine sand with coarse sand lens at 100-107cm.

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-141	10.67	4.79	1.41	92.61	5.76	1.53	0.35	1.15	0-70cm--shelly medium to coarse sand;70-200cm--medium sand with zone of fine to medium sand at 170-190cm; 200-316cm-- burrow mottled fine sand;316-353cm--gravelly coarse sand; 353-479cm--slightly laminated very fine to fine sand.
SNL-142	15.24	3.50	5.18	81.65	13.14	2.24	0.21	1.69	0-132cm--very fine sand with several muddy lenses;132-210cm--shelly gravelly fine sand;210-365cm--shelly fine sand.
SNL-143	7.01	3.67	1.82	96.34	1.83	2.05	0.24	1.05	0-84cm--fine sand;84-113cm--medium sand;113-177cm--fine sand with small mud lumps;177-260cm--medium sand;260-367cm--fine to medium sand.
SNL-144	14.33	1.73	3.62	90.35	5.94	2.31	0.20	1.40	0-100cm--very fine to fine sand with coarse sand lens at 70-74cm; 100-119cm--gravelly fine to medium sand;119-145cm--fine sand;145-173cm--medium to coarse sand.
SNL-145	10.97	1.32	1.48	97.63	0.87	2.14	0.27	0.80	fine sand throughout core.
SNL-146	15.85	5.33	6.73	91.69	1.48	2.41	0.19	1.13	0-40cm-- medium sand;40-62cm--fine sand with thin mud layers at 51-54cm and 60-62cm; 62-111cm--shelly medium to coarse sand;111-533cm--very fine to fine sand with coarse shell bed at 381-389cm.
Average	**15.82**	**3.83**	**16.31**	**78.33**	**5.22**	**2.37**	**0.22**	**1.30**	
Maximum	**23.16**	**6.08**	**89.17**	**98.24**	**35.57**	**4.26**	**0.90**	**2.20**	
Minimum	**6.40**	**0.73**	**1.05**	**10.38**	**0.18**	**0.16**	**0.05**	**0.69**	

Note on Phi (Ø) scale:
>4 Ø (.0625 mm) -- mud (silt + clay)
3 - 4 Ø (.125-.0625 mm) -- very fine sand
2 - 3 Ø (.25-.125 mm) -- fine sand
1 - 2 Ø (.50-.25 mm) -- medium sand
0 - 1 Ø (1.0-.50 mm) -- coarse sand
-1 - 0 Ø (2.0-1.0 mm) -- very coarse sand
<-1 Ø (2 mm) -- gravel

SECTION III: SAND RESOURCE ASSESSMENT

The primary goal of this survey was to determine the potential for the Pea Island Study Area to serve as a source of sand for future beach nourishment of the critically eroding shoreline at several locations (Figs. 1, 2). The geophysical data have aided in determining the stratigraphic architecture of the PISA (from seismic reflection data) and characteristics of the surface sediment (from core samples). 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 PISA.

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). To determine the unit thickness for volume estimates, that part of the unit which is more than 20 meters below sea level was eliminated. This cut-off keeps the volumetric estimates within conventionally accepted dredging limits.

The area of each unit was determined utilizing an automatic feature of the GIS software that 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. Note that the accuracy of this measure was validated by Boss and Brown (1999) in a study of Lake Alma, Arkansas.

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 a 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 volumes, expressed in millions of cubic yards (yd^3), are presented in Tables 3 and 4 below.

For this study, the only stratigraphic unit considered to be a potential sand resource was unit S_1. 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. Unit S_1 is truncated by the prominent bathymetric trough observed within the PISA. However, two targets associated with shoal areas in the northeastern and southwestern portion of the study area appear to provide sufficient quantities of sand to be considered as potential sand resources (Fig. 13).

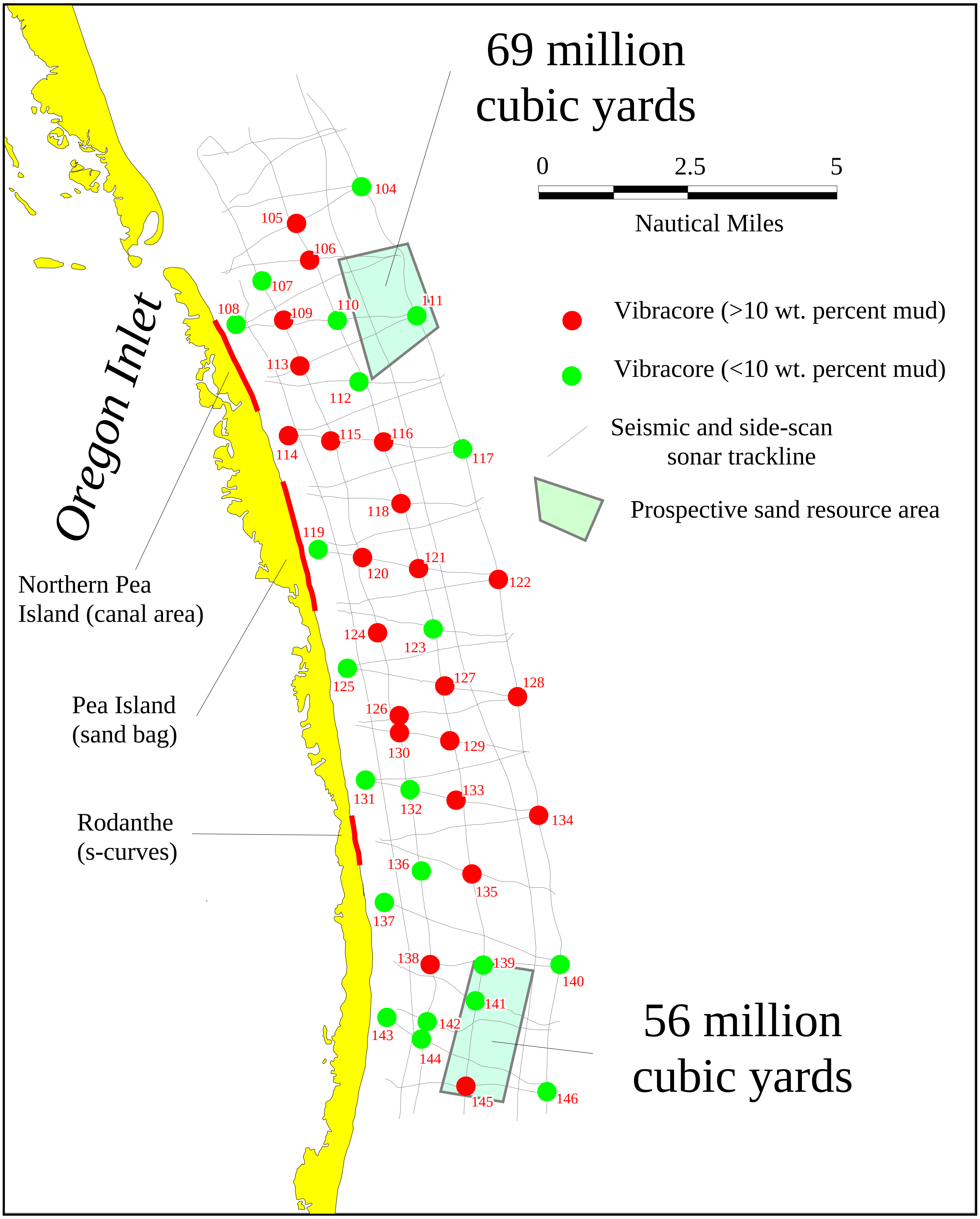

Fig 13. Map showing potential sand resource areas (shaded boxes) located to access sand from unit S_1 offshore of the Pea Island Study Area. Estimates of sand resources within these areas are given in Tables 3 and 4.

The area of the northern box offshore of Pea Island is about 8.97 million square yards. The volume of S_1 within this box is 69 million cubic yards (Table 3). The water depth for this box ranges from 12 to 14 m (39 to 46 feet).

Table 3. Estimated volume of S_1 within northern boxed area offshore Pea Island. Sand Volume estimated using method described in text.

ESTIMATED VOLUME OF SAND IN NORTHERN BOX OFFSHORE PEA ISLAND (Fig. 12)	
Area of Box on Map = 8,967,000 yd^2	
ASSUMED SEDIMENT THICKNESS (m)	**ESTIMATED VOLUME OF S_1 (million yd^3)**
5	26
10	23
TOTAL	69

The area of the southern box offshore of Pea Island is about 9.35 million square yards. The volume of S_1 within this box is 56 million cubic yards (Table 4). The water depth for this box ranges from 8 to 12 m (26 to 39 feet).

Table 4. Estimated volume of S_1 within southern boxed area offshore Pea Island. Sand Volume estimated using method described in text.

ESTIMATED VOLUME OF SAND IN SOUTHERN BOX OFFSHORE PEA ISLAND (Fig. 12)	
Area of Box on Map = 9,346,000 yd^2	
ASSUMED SEDIMENT THICKNESS (m)	**ESTIMATED VOLUME OF S_1 (million yd^3)**
5	42
10	14
TOTAL	56

Obviously, not all of the sand contained within unit S_1 is economically recoverable, but this exercise illustrates that there is sand available within the PISA that could be exploited to nourish the critically eroding shoreline immediately onshore. A decision whether or not to use this sand will depend of 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 (e.g. public perception of beach nourishment or dredging of waters offshore national seashores), and economic (e.g. cost of transporting sand from PISA to nourishment sites) factors. These considerations, however, were beyond the scope of this reconnaissance-level assessment.

An alternative sand resource that has not been considered in this study could be obtained from a sand bypass project at Oregon Inlet or removal of sand from the beach south of the terminal groin at Oregon Inlet. An appreciable quantity of sand might be available from either of these sources, and this would greatly enhance the quantity of sand available for potential beach nourishment along Pea Island.

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.

ACKNOWLEDGMENTS

The authors acknowledge the assistance and support of Aaron Ingold, Walter Haven, and Derek Bryant, geologic technicians with the North Carolina Geological Survey Coastal Plain Office.

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APPENDIX A Histograms showing grain size distribution for whole vibracores.

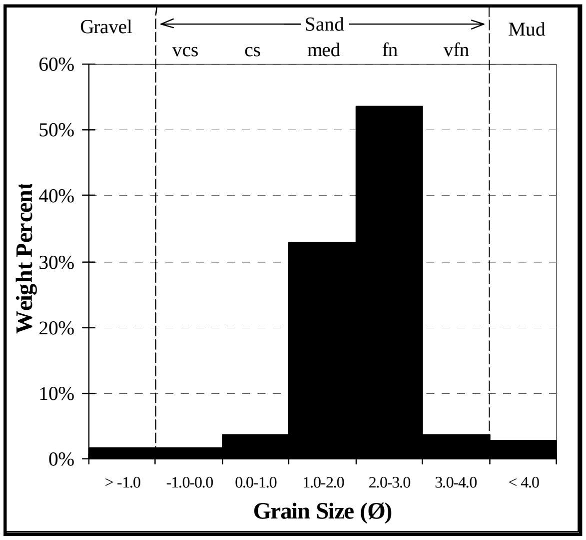
Note on Phi (Ø) scale:

>4 Ø (.0625 mm)	mud (silt + clay)
3 - 4 Ø (.125-.0625 mm)	very fine sand
2 - 3 Ø (.25-.125 mm)	fine sand
1 - 2 Ø (.50-.25 mm)	medium sand
0 - 1 Ø (1.0-.50 mm)	coarse sand
-1 - 0 Ø (2.0-1.0 mm)	very coarse sand
<-1 Ø (2 mm)	gravel

$\phi = -\log_2$ of grain diameter in millimeters (Pettijohn, 1975)

Appendix A (continued).

SNL-104



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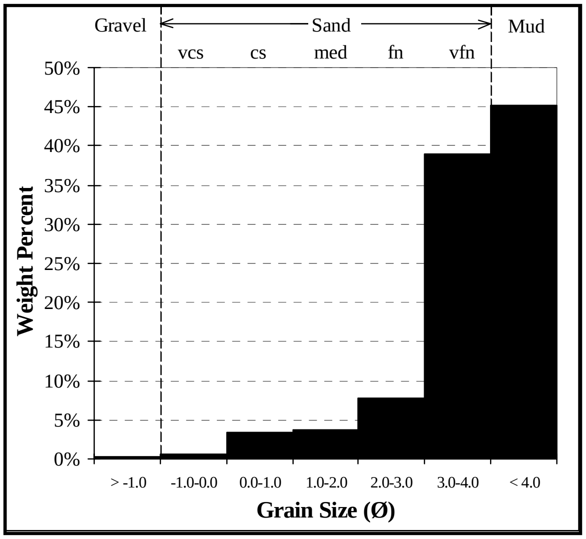

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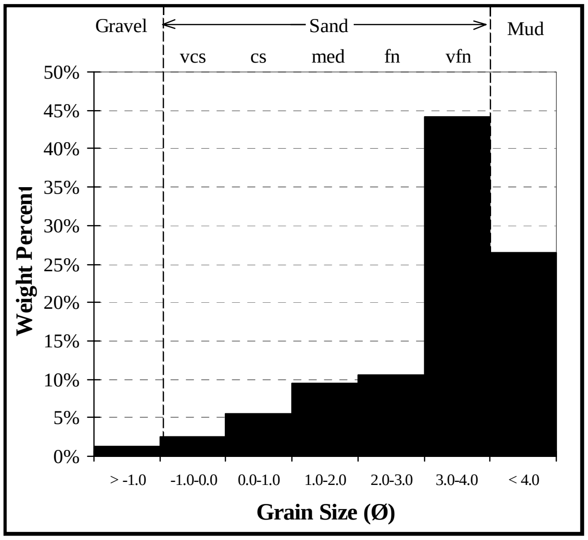

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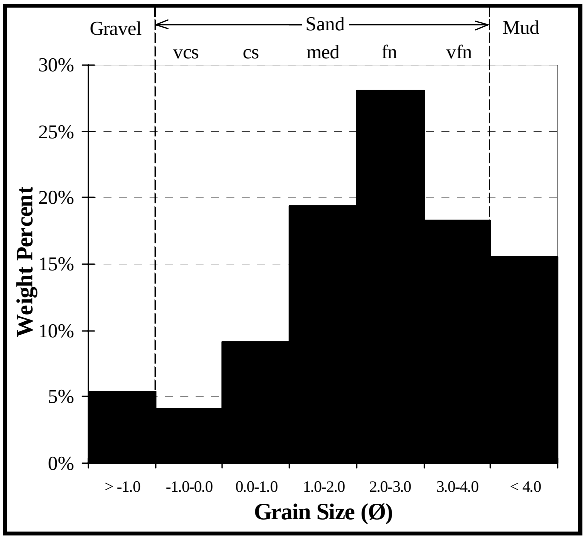

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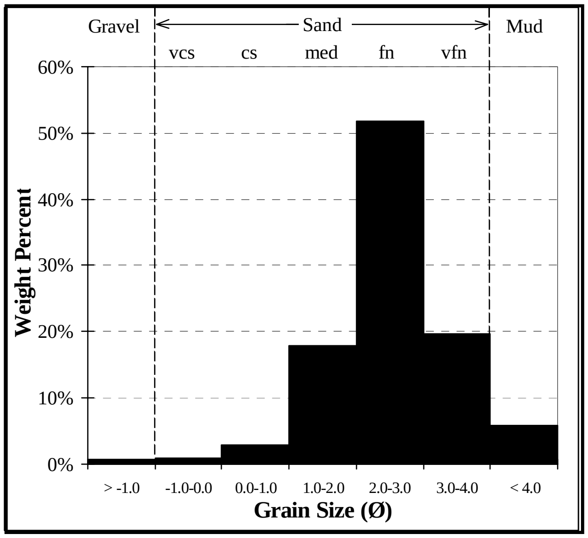

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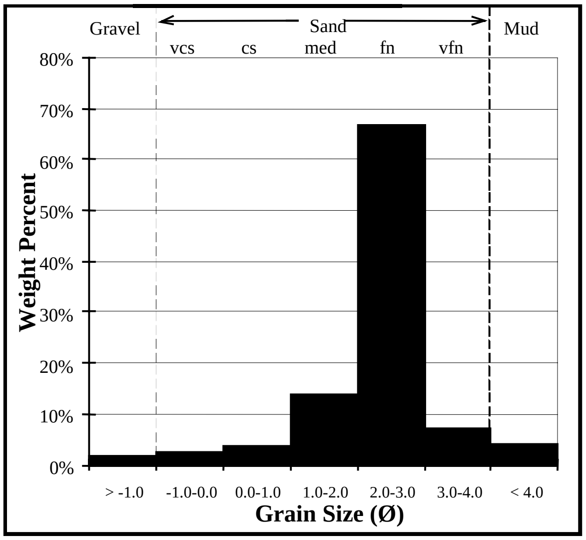

Appendix A (continued).

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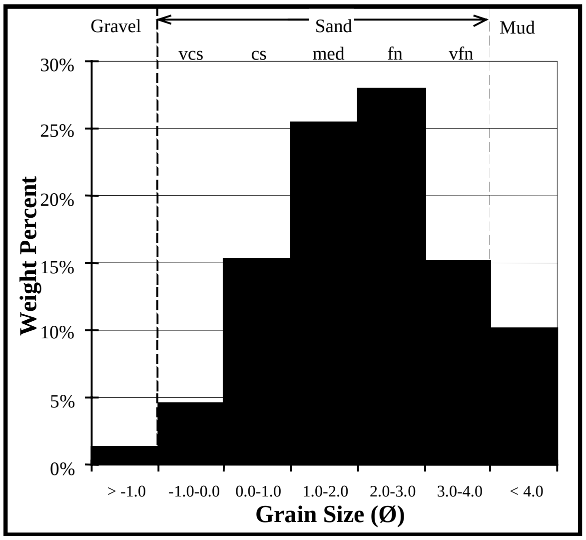

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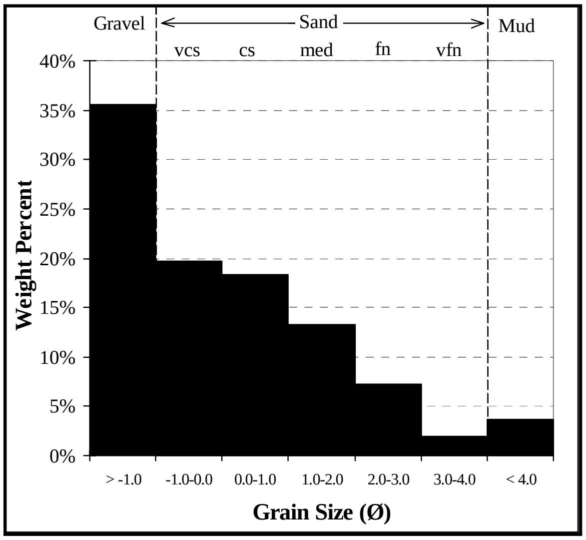

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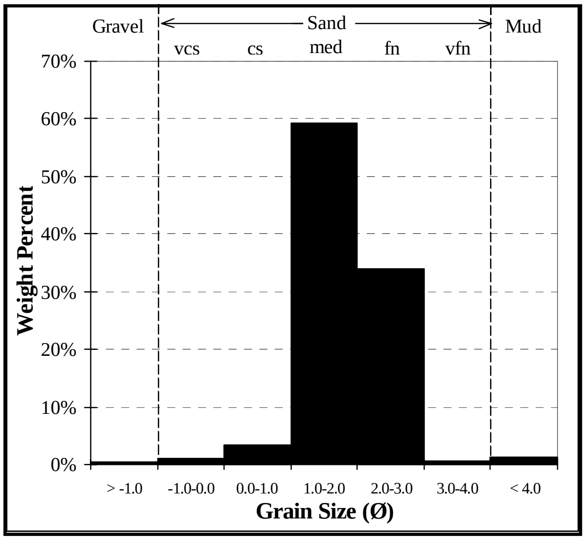

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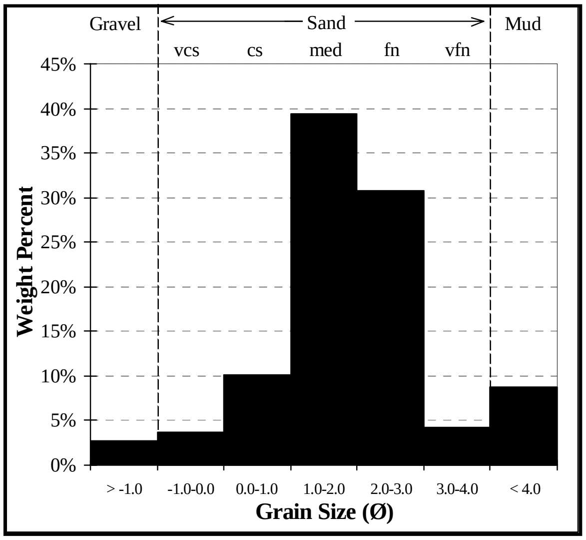

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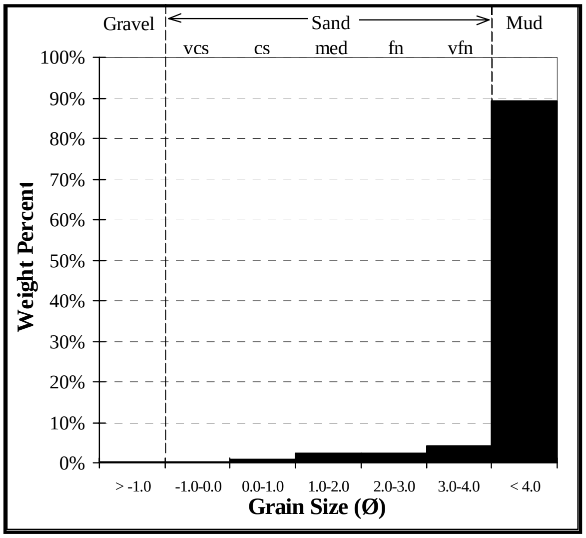

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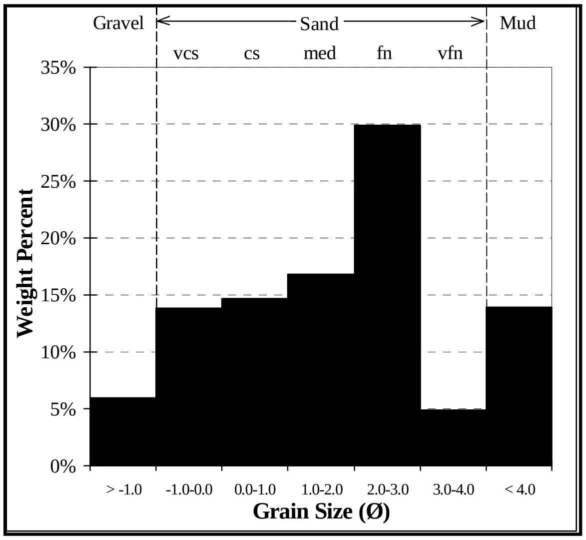

Appendix A (continued).

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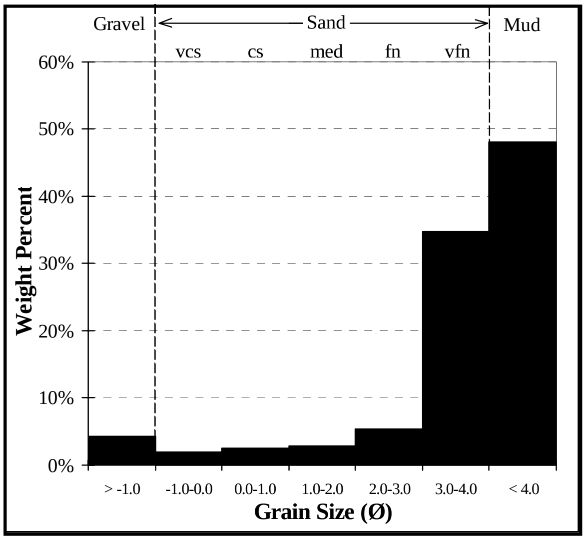

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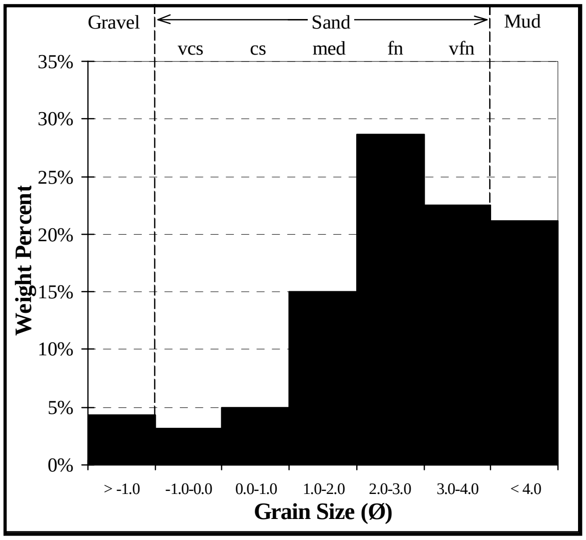

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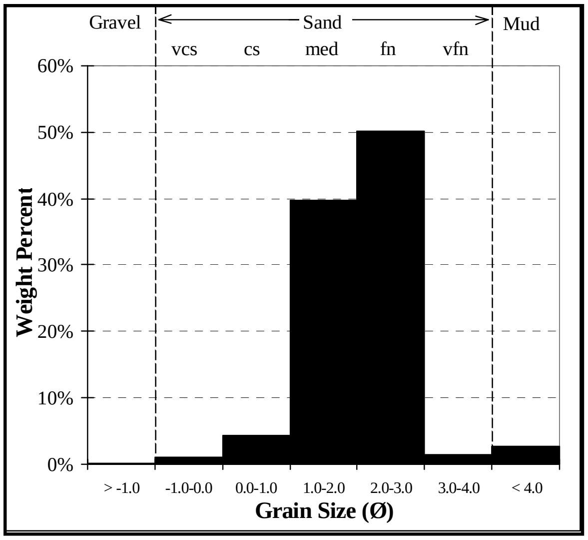

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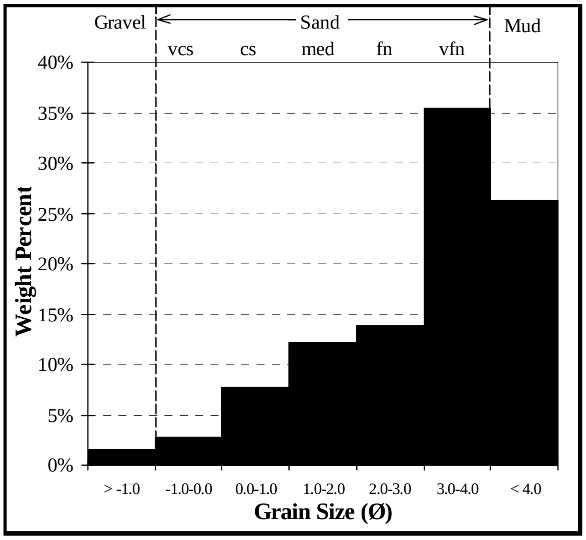

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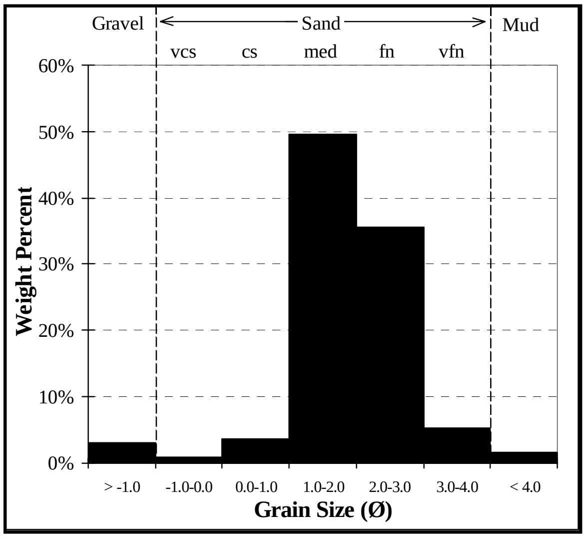

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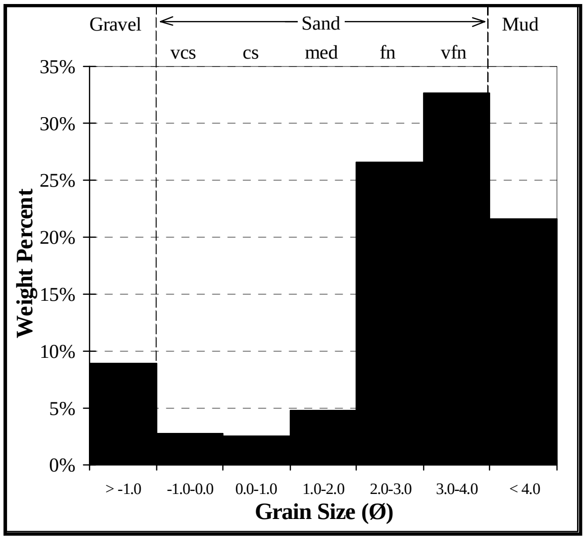

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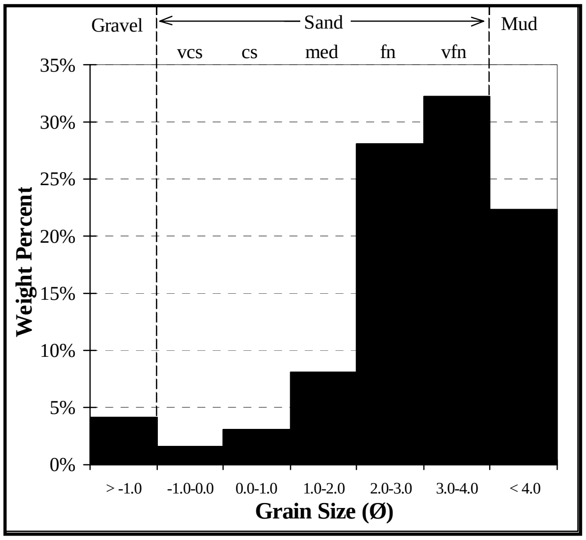
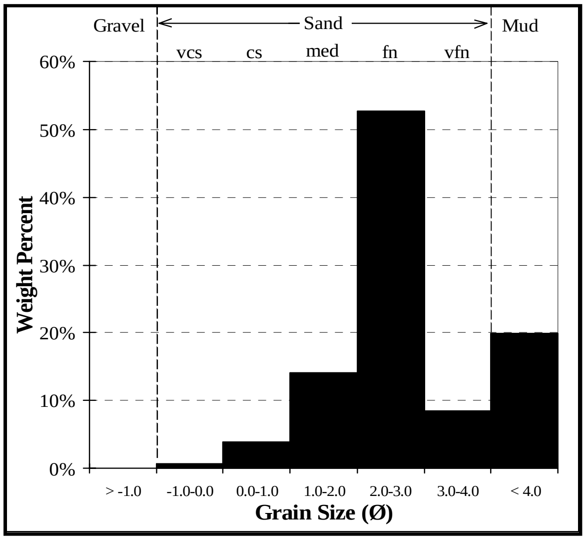
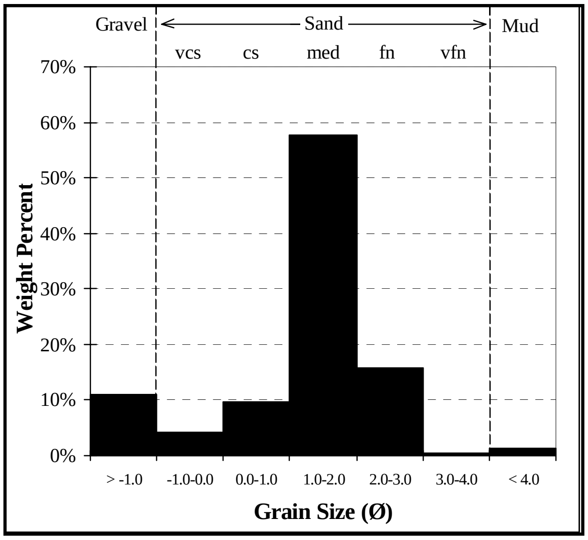
SNL-121



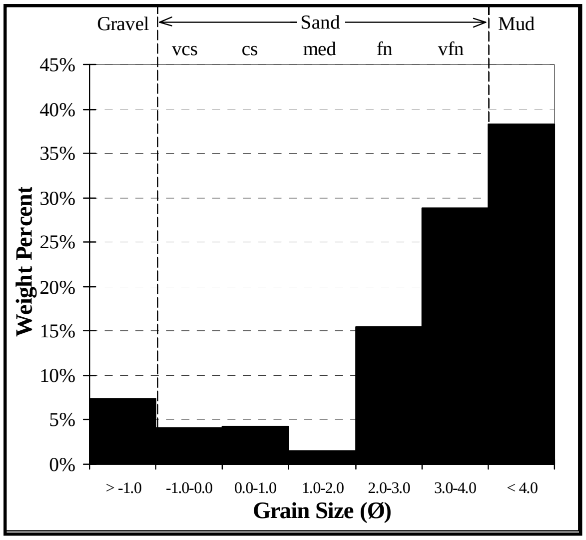
SNL-122



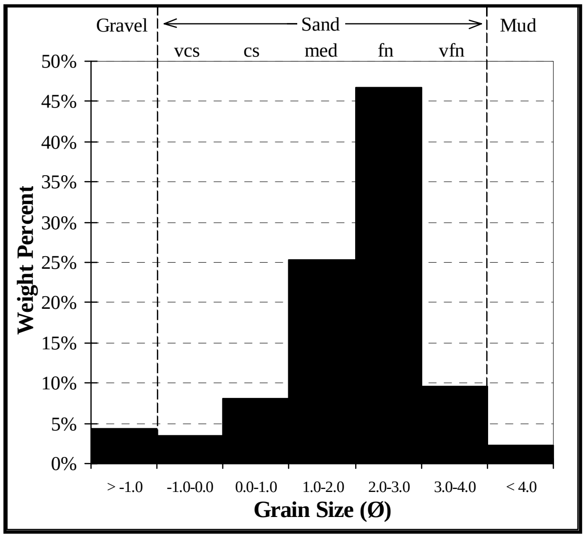
SNL-123



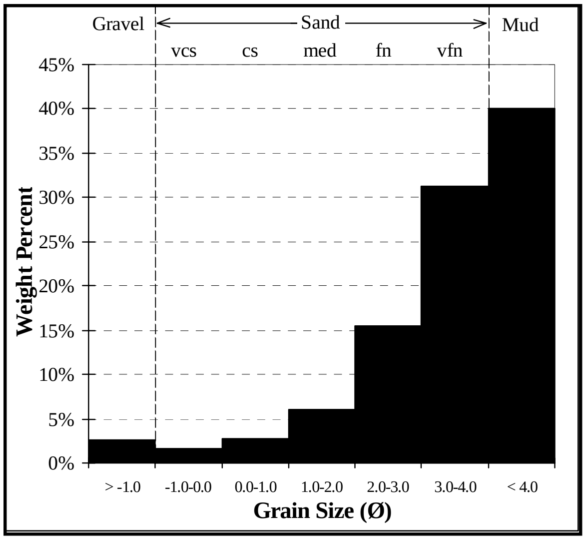
SNL-124



SNL-125

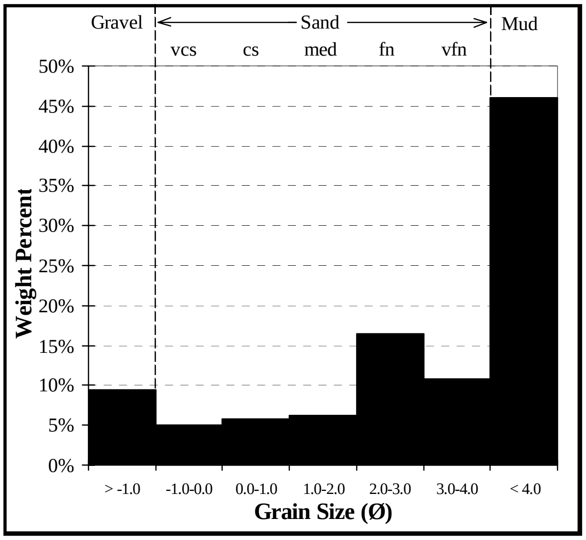


SNL-126

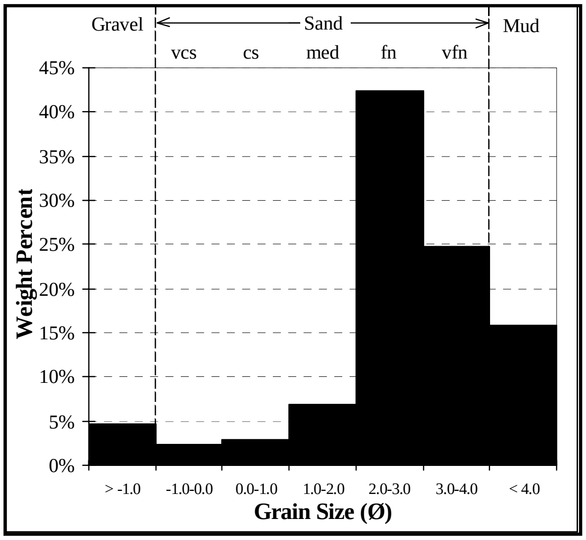


Appendix A (continued).

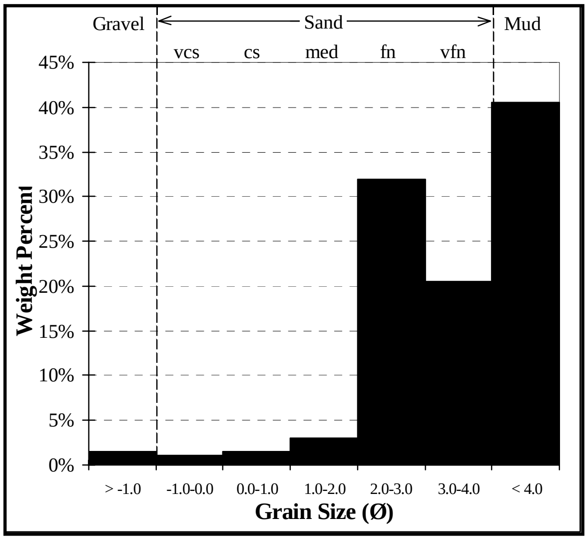
SNL-127



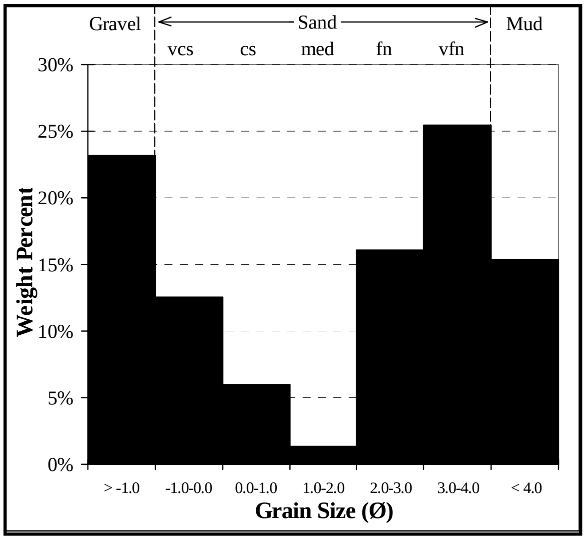
SNL-128



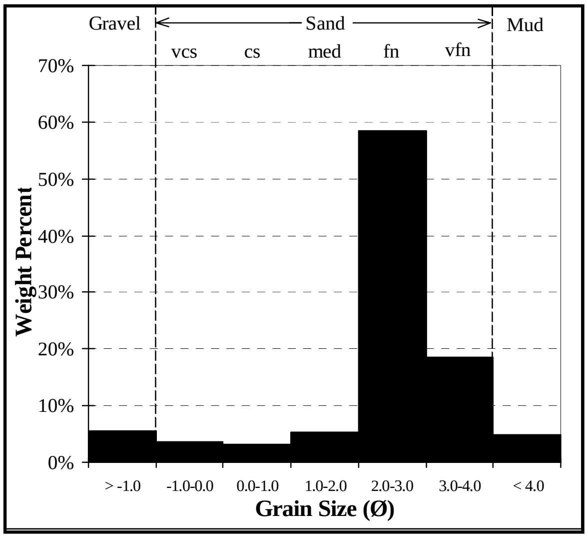
SNL-129



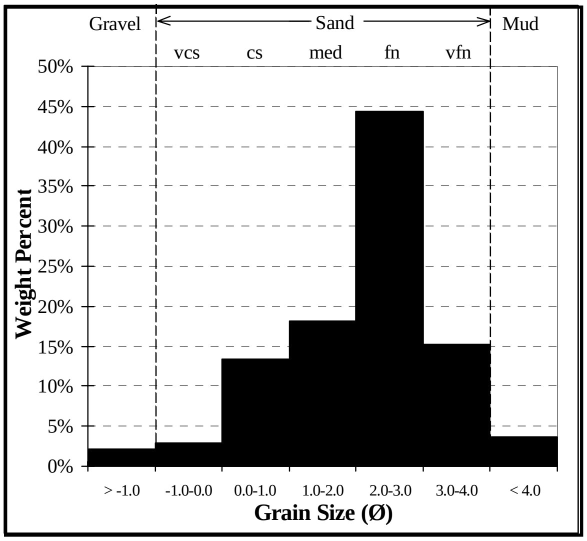
SNL-130



SNL-131

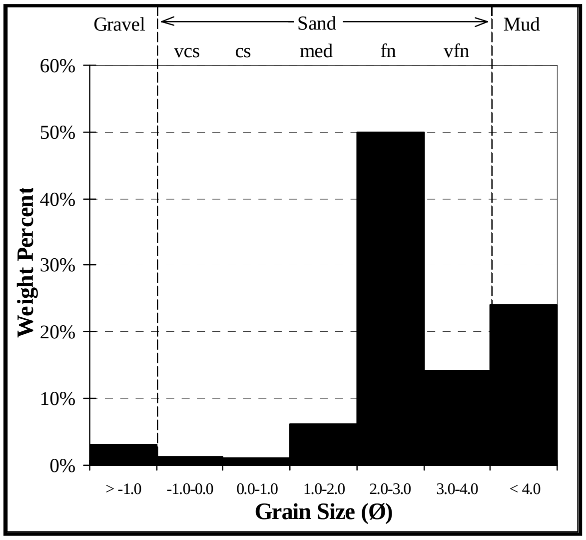


SNL-132

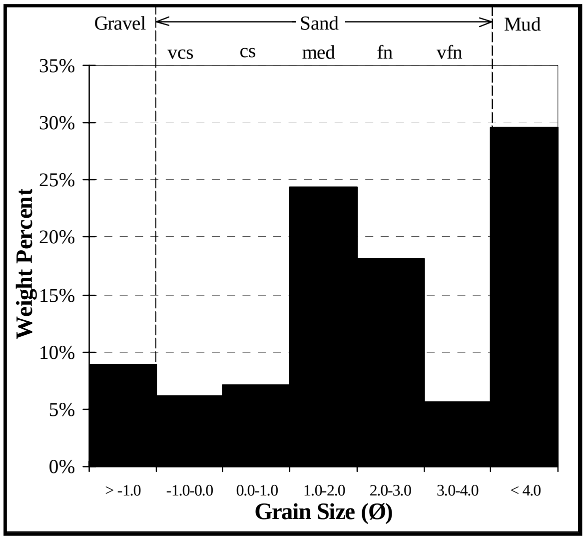


Appendix A (continued).

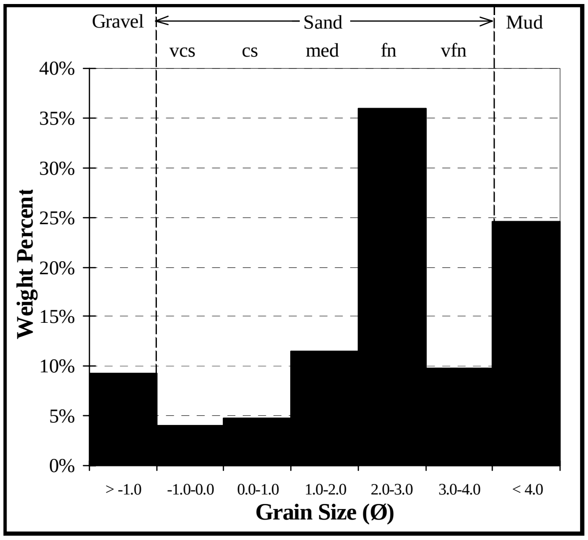
SNL-133



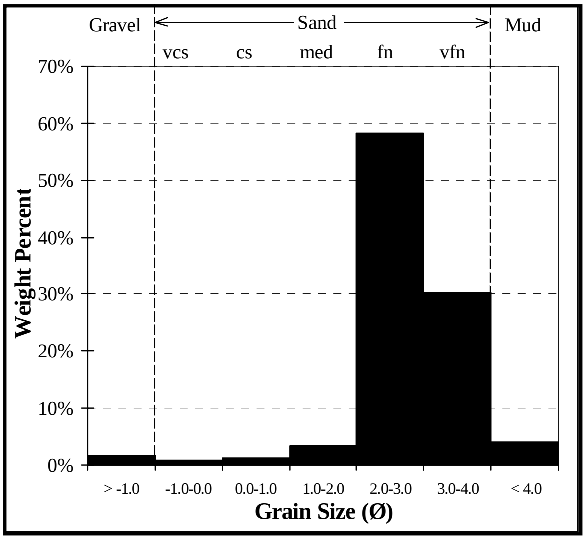
SNL-134



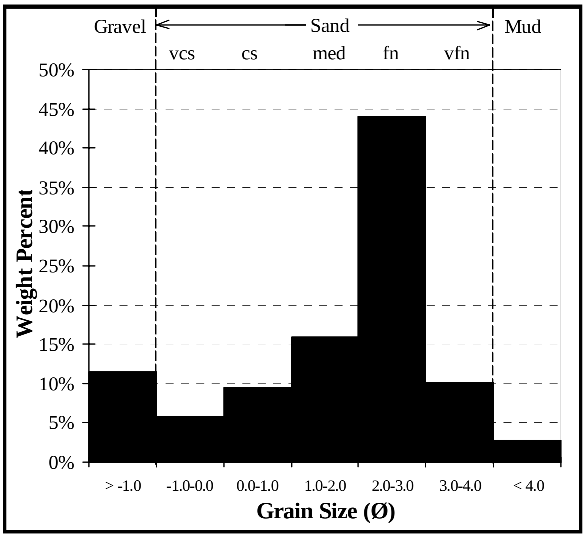
SNL-135



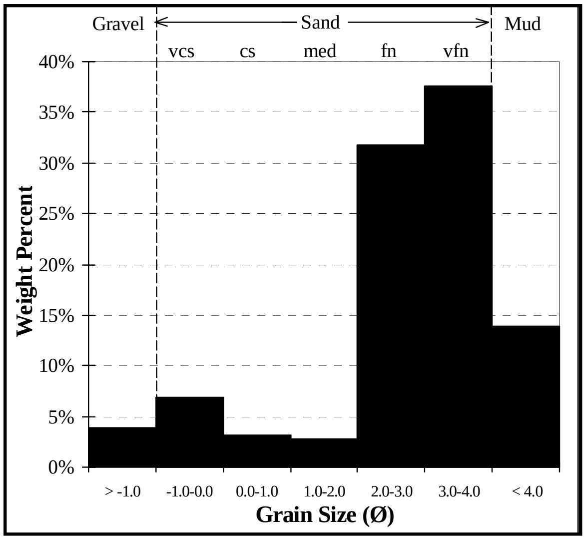
SNL-136



SNL-137

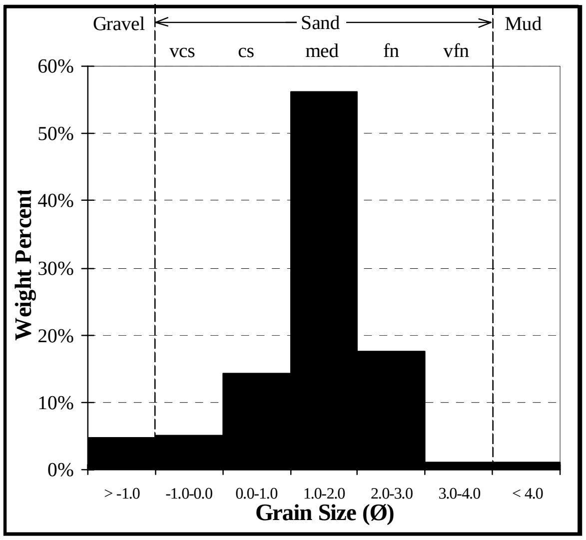


SNL-138

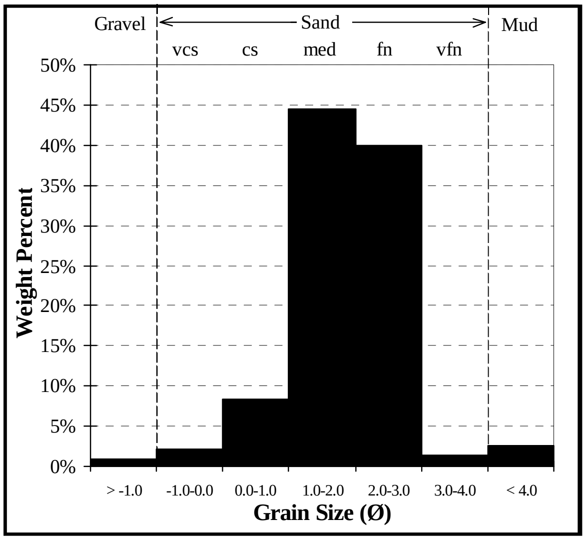


Appendix A (continued).

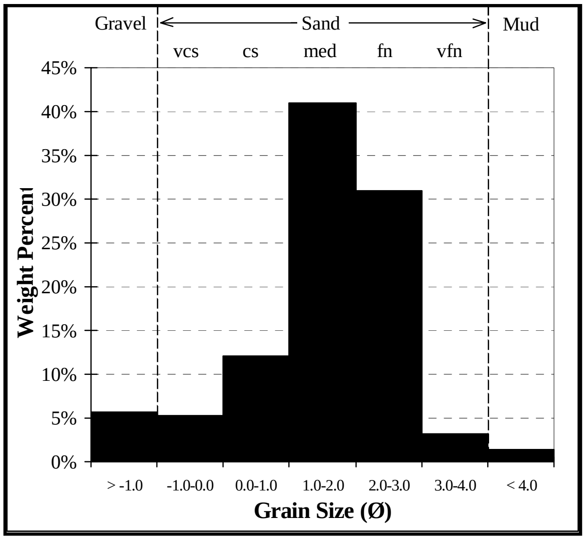
SNL-139



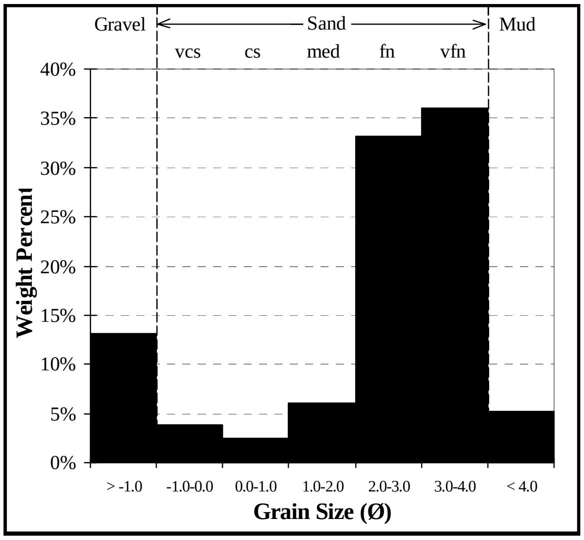
SNL-140



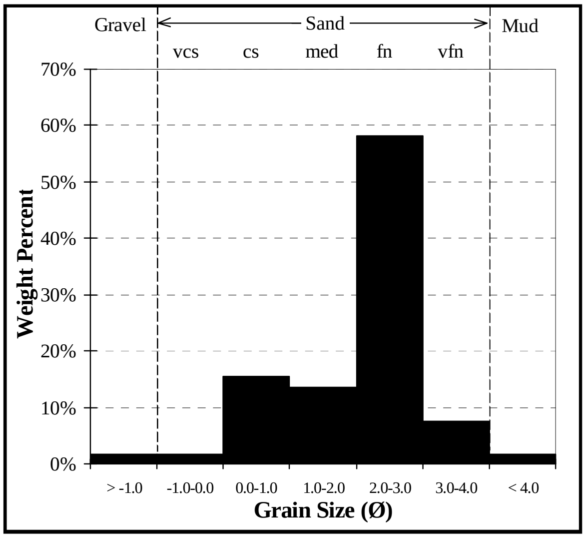
SNL-141



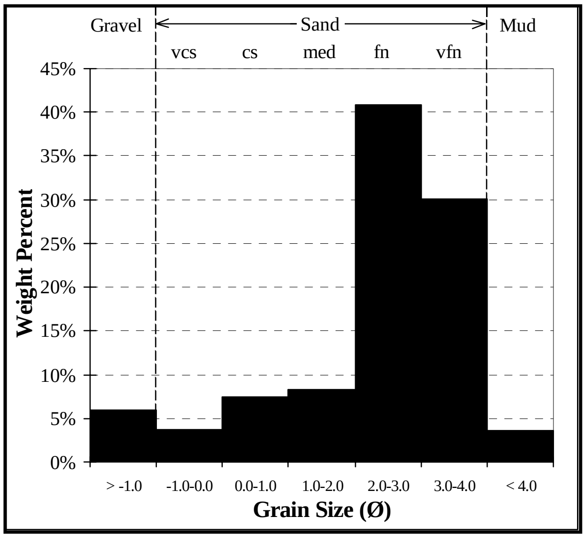
SNL-142



SNL-143

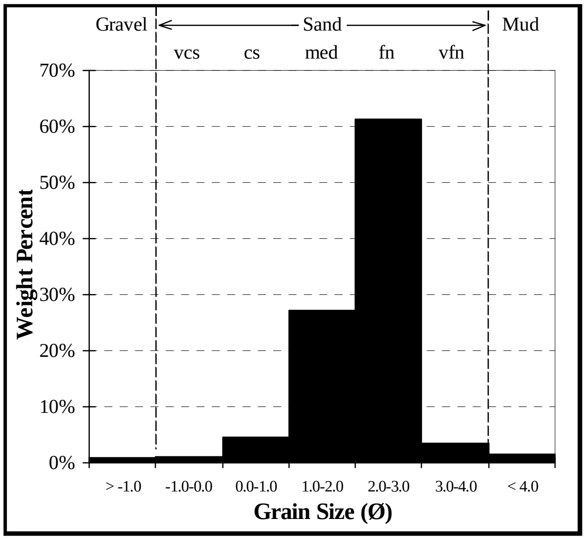


SNL-144



Appendix A (continued).

SNL-145



SNL-146