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High-Resolution Geologic Mapping of the Inner Continental Shelf: Nahant to Gloucester, Massachusetts

By Walter Barnhardt, Brian Andrews, and Brad Butman

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Introduction

This report presents high-resolution maps of the seafloor offshore of Massachusetts, from Nahant to Gloucester. Approximately 134 km² of the inner shelf were mapped with a focus on the nearshore region in water depths less than 40 m (fig. 1.1). The maps were prepared as part of a cooperative mapping program between the U.S. Geological Survey (USGS) and the Massachusetts Office of Coastal Zone Management (CZM). They are based on marine geophysical data, sediment sampling, and bottom photography obtained on two research cruises carried out in 2003 and 2004. The primary objective of this program is to develop a suite of seafloor maps that provide geologic information for management of coastal and marine resources. Accurate maps of seafloor geology are important first steps toward protecting fish habitat, delineating marine reserves, and assessing environmental changes due to natural or human impacts. The maps also provide a geologic framework for scientific research, industry and the public.

The organization of this report is outlined in the navigation bar along the left-hand margin of the page. This is section 1, the introduction. Section 2 briefly describes the mapping products contained in this report and has links to large-format map sheets that can be viewed on line or downloaded. Section 3 is a description of the data collection, processing, and analysis procedures used to create the map products. Section 4 examines the geologic framework and late Quaternary evolution of the region, and presents two different strategies for mapping the complex seafloor. This report also contains four appendices that include GIS layers of all data collected in this study, and copies of the sample and photographic data used to validate the interpretations.

Maps

Five map sheets have been compiled showing the seafloor offshore of Massachusetts from Nahant to Gloucester. Text on each map sheet introduces the map, briefly describes the data and methods, and summarizes key features. Section 3 (Data Collection and Processing) and Section 4 (Geologic Interpretation) in this report provide more detailed information than presented on the map sheets. Links to the maps at full scale, the map text, and a page-size map are provided on the USGS website: http://woodshole.er.usgs.gov/project-pages/coastal_mass/

Map Sheet 1: Shaded-relief topography of seafloor (colored)

Map Sheet 2: Shaded-relief topography of seafloor (gray scale)

Map Sheet 3: Backscatter intensity of seafloor (gray scale)

Map Sheet 4: Shaded-relief topography of seafloor, colored by backscatter intensity

Map Sheet 5: Geologic maps of the seafloor

Data Collection and Processing

Field program

Approximately 134 km² of the inner shelf were mapped using acoustic data from interferometric sonar (bathymetry and backscatter), sidescan sonar (backscatter), and chirp seismic-reflection profiling (stratigraphy and structure). The three systems were simultaneously deployed from the R/V *Rafael*, a 7.6-m (25-ft) USGS research vessel that is specially outfitted for mapping in nearshore marine, estuarine, and lacustrine, environments (fig. 3.1). Seafloor mapping focused on the nearshore region between the 5 and 40 meter isobaths.

Mapping of the area was conducted in two separate research cruises in Fall 2003 and Spring 2004. The first, USGS cruise RAFA03007, began 24 September and ended 14 October 2003, for a total of 18 survey days. The second, USGS cruise RAFA04002, consisted of two legs; Leg 1 (17 April and 4 May), and Leg 2 (5-8 May) 2004, with 8 days for geophysical surveys and 3 days for the ground validation portion of the project. The methods used in the collection, processing and analysis of the different data sets are detailed below.

Navigation for the research vessel and all data collection used Real-Time Kinematic Global Positioning System (RTK-GPS). The RTK corrected GPS signal was sent to the R/V *Rafael* from a base station established by the USGS that occupied a Defense Mapping Agency geodetic monument near the Eastern Point Lighthouse in Gloucester. Prior to the initial mapping the x and y positions were calculated for that location using a 3-day average of 12-hour data sets using the Online Positioning User Service (OPUS, National Geodetic Survey) solution. Mean

Sea Level (MSL) elevations were calculated from NOAA Tidal Station #8441841 using the same OPUS solution and then applied to the corrected elevations for the base station at Eastern Point Lighthouse. Depths were originally recorded using MSL, and were later reduced to mean lower low water (MLLW) for the final bathymetric grid and for easier comparison to NOAA nautical charts. The difference between MSL and MLLW was 1.441 m (NOS CO-OPS, 2005). All survey data were collected in Universal Transverse Mercator (UTM) coordinate system, Zone 19 using the WGS84 Geodetic Model.

Interferometric Sonar

Bathymetry data (water depth) were collected with a SEA Submetrix 2000 series interferometric sonar that operates at a frequency of 234 kHz and configured in a rigid pole-mount on the starboard side of the R/V *Rafael*. The GPS antenna was mounted on the top of the pole over the sonar head. The system has two channels that collect depth data in a continuous swath on either side of the vessel. The width of the swath is generally 7-10 times the water depth. Under optimal conditions in water depths of 15 m, for example, the interferometric sonar can achieve a 75 m range to each side of the ship's track, or 150 m total swath width.

A total of 1,175 km of survey lines were occupied during the two surveys. Survey lines were spaced 100 m apart to ensure overlap of adjacent swaths, and obtain 100% coverage of the seafloor (fig. 3.2). Data were processed and gridded using Linux-based SwathEd software (UNB, 2005). The bathymetric data have a vertical resolution of approximately 1% of water depth. The final bathymetric grid was mapped at a resolution of 5 m/pixel. Although interferometric sonar backscatter intensity was also collected, it was not used for geologic interpretations because the towed sidescan-sonar data (towed closer to the seafloor) has a lower grazing angle and provides a better image of the seafloor morphology.

Sidescan Sonar

Acoustic backscatter data were collected using an Edgetech DF1000 dual frequency (100/500 kHz) sidescan sonar that was towed approximately 25 m astern, of the R/V *Rafael*, and approximately 10 m off the bottom. Backscatter intensity, as recorded with sidescan sonar, is an acoustic measure of roughness of the seafloor (fig. 3.3). Additionally, due to the low angle of incidence of towed systems, topographic highs and lows can be interpreted based on acoustic shadows identified in the imagery. All sonar data were acquired with Triton-Elics ISIS topside acquisition software and later processed for beam angle and slant range correction using LINUX based Xsonar/Showimage as described in Danforth (1997). Sonar data from each survey line were mapped in geographic space in Xsonar and then imported as raw image files to Geomatics GPC works (PCI Geomatica ver 8.2) and mosaiced. The mosaic was exported as a georeferenced tiff image for further analysis in ArcGIS (ESRI Inc). The positional accuracy of the final mosaic is dependant on the estimated towfish layback during acquisition that estimates the horizontal and vertical distance between the GPS receiver and the towfish. Using the Georeferencing toolbar in ArcGIS, the final towed sidescan mosaic was "rubber sheeted" to match the position of the mosaic from the pole-mounted interferometric sonar, which has higher order positional accuracy. Although both the 100 kHz and 500 kHz data were collected, the 100 kHz data were used for the final 1-m mosaic because there was less acoustic noise in the lower frequency data.

Seismic-Reflection Profiling

Approximately 1,175 km of high-resolution seismic-reflection profiles (fig. 3.4) were collected using a Knudsen 320b chirp system (3.5-12 kHz). Data were processed using SIOSEIS (Scripps Institute of Oceanography) and Seismic Unix (Colorado School of Mines) to produce segy files and jpg images of the seismic profiles. The segy data were then imported into SeisWorks (Landmark Graphics Inc), an integrated seismic interpretation software package, where selected horizons were digitized to calculate depth to reflections below the seafloor. A constant velocity of 1500 m/s was applied through both water and sediment. Interpreted depth to bedrock (every 5 shots) was exported into ArcGIS for interpolation into a 50-m grid. Interpreted depth to reflections were calculated, exported every 5 shots, and then imported to ArcGIS for interpolation into a continuous raster with a resolution of 50m/pixel. These data were used to generate a sediment isopach map, which shows the total thickness of sediment between the seafloor and bedrock (fig. 3.5).

Ground Validation

The remotely-sensed data were validated with direct sampling of the surficial sediments and photographs of the seafloor. The ground validation portion of the project commenced immediately following the conclusion of the geophysical surveys in May 2004. One hundred target stations were identified prior to the survey for sampling and photography with the USGS Mini SEABed Observation and Sampling System (Mini SEABOSS; Valentine and others, 2000) (fig. 3.6). Stations were selected based primarily on the previously collected acoustic backscatter data, with the objective of characterizing broad areas of different backscatter intensity (fig. 3.7). In addition, the sampling design included investigation of both gradual and sharp transitions in backscatter values, inferred to be differences in substrates. The research vessel occupied the target location (+/- 10 m), deployed the Mini SEABOSS and drifted with the current over the bottom at approximately 1-3 knots. Continuous video was collected while the camera was within sight of the bottom and photographs were obtained from a still camera at user-selected locations along the transect. Samples of the surficial sediment were usually collected at the end of the drift transect. The upper 2 cm of sediment were scraped from the surface of the grab for textural analysis. At each station about 5 minutes of video and about 5 bottom photographs were obtained.

Sediment samples were collected at locations with relatively soft sediment (sand or mud) where the Mini SEABOSS would not be damaged. Samples were not collected in cobble or rocky regions. Samples were analyzed for grain size at the USGS Sediment Laboratory. Poppe and Polloni (2000) describe the standard procedure for grain size textural analysis (fig. 3.8).

Geologic Interpretation

Setting

The Nahant-Gloucester study area lies in the western Gulf of Maine, where the coast and inner continental shelf are bedrock framed with numerous rocky islands and rugged headlands. Bedrock in the region consists of complexly faulted and deformed intrusive rocks that range in age from Precambrian (> 540 million years) to Paleozoic (250-540 million years) (Zen and others, 1983). Bedrock is widely exposed along the shoreline and is a primary control on the shape of the coast. Rocky headlands provide shelter for small harbors and pocket beaches. The rugged topography of the seafloor is presumably due to these same rocks cropping out offshore.

The coastal landscape has been sculpted by multiple glaciations. During the last Ice Age, glaciers reached their maximum extent south of Cape Cod about 21,000 calendar years ago. As climate warmed, the glaciers retreated northward across the study area, passing the present coast about 14,500 years ago (Kaye and Barghoorn, 1964). Numerous moraines, outwash plains, drumlins, kettle lakes, and other features record the glacial history of the region. Glacial-marine sediment was deposited contemporaneously with ice retreat, blanketing wide areas of the coast and inner shelf from northeastern Massachusetts (the "Boston blue clay" - Kaye and Barghoorn, 1964) to eastern Maine (the Presumpscot Formation - Bloom, 1963). This sediment unconformably overlies older glacial deposits and bedrock, and typically consists of well stratified sand and mud with scattered dropstones of ice-rafted material. Thick sequences of glacial-marine sediment are best preserved in bedrock valleys and deep basins in the western Gulf of Maine (Belknap and Shipp, 1991). The relatively thin glacial deposits in the Cape Ann region are discontinuous and only partly mantle the underlying bedrock (Shaler, 1889).

Relative sea-level change has also influenced the geologic evolution of the coast and inner continental shelf. Following the retreat of the ice sheets, the study area has experienced a marine transgression, a regression, and a second transgression due to changes in relative sea level (fig. 4.1) (Crosby and Lougee, 1934; Stone and Peper, 1981; Oldale and others, 1993). These shoreline migrations have repeatedly impacted a wide zone ranging from elevations of +33 m to depths of about -50 m, where a submerged delta of the Merrimack River and other coastal features are preserved on the inner continental shelf offshore of Cape Ann (Oldale, 1985a; Oldale and others, 1983, 1993). In the general absence of modern river-sediment input, marine processes have reworked older sediment, leaving behind relatively thin, discontinuous glacial deposits on top of bedrock. Erosion has removed an unknown amount of sediment and etched a prominent unconformity on the surface of older deposits. The eroded material was redistributed across the inner shelf and at least some of it was transported landward, where it has accumulated in beach deposits.

Mean tidal range at Salem, Massachusetts is 2.7 m, with a spring tidal range of 3.1 m. Wind directions vary seasonally with dominant winds from the southwest in summer and from the northwest in fall and winter. Summer wave conditions are generally low energy with southerly swells. Tropical cyclones or hurricanes are rare, but strong winter storms (Nor'easters) strike the coast every year. The position of a particular site within an embayment, and its orientation and fetch, strongly affects the resultant wave energy.

Mapping Seafloor Geology

The seafloor topography and surficial geology of the western Gulf of Maine are complex and difficult to map (Trumbull, 1972; Poppe and Polloni, 2000; Barnhardt and others, 1996). Earlier maps characterized the texture of seafloor sediments at regional scales based on widely spaced bottom samples (Schlee, 1973; Folger et al., 1975; Poppe et al, 1989). Traditional methods of mapping in more homogenous, non-glaciated regions of seafloor have relied on contouring changes in grain-size properties (Hollister, 1973), but those methods are impractical on this part of the Massachusetts shelf. The substrate variations that exist cannot be accurately shown given the density of samples in the area.

Two characteristics of the study area complicate attempts to map it: 1) the rugged, high-relief seafloor exhibits abrupt changes in water depth (fig. 3.2), and 2) different substrates form a distinct "patchiness" on the seafloor that changes over distances of only a few meters (fig. 3.3). For example, high-relief bedrock and bouldery glacial deposits (till) are commonly exposed on the seafloor in close proximity to flat-lying deposits of finer sediment (sand, mud). Rocky areas also contain isolated accumulations of shelly sediment that are ponded in small cracks and other low-lying areas between rock outcrops. These variations occur over small spatial scales that are smaller than a sampling grid can resolve. Although backscatter intensity from sidescan sonar provides information on substrate type at a previously unobtainable level of detail, only laboratory analyses of physical samples can provide percentages of mud/sand/gravel in bottom sediment. An extraordinarily large number of closely-spaced samples would be required to fully characterize sediment texture in the Nahant-Gloucester area.

The challenge for mapping in this region is to represent, in a cartographically correct map, the heterogeneity of geologic environments that exist on the shelf. Our goal in this report is to produce interpretative maps that synthesize the complex geology at a regional scale and in readily useable formats for both scientific and non-technical audiences. We use two different approaches to depict seafloor geology: 1) multivariate analysis and 2) physiographic zones, which are described in the following sections. The interpretative geologic maps are presented at a scale of 1:60,000 (map sheet 5, panels E and F) to provide a big-picture, regional view of seafloor geology and, in the future, to facilitate systematic mapping across the entire Gulf of Maine.

Multivariate Analysis

Quantitative, computer-generated mapping methods are being developed in this study to delineate the characteristics of geologic materials on the seafloor and test the validity of statistical approaches to mapping. Preliminary results of this research show potential for semi-automated classification of bottom types in the nearshore environment of this study. Visual inspection of the bathymetric and acoustic backscatter maps (figs. 3.2 and 3.3) show a loose correlation between water depth, backscatter intensity, and the slope of the seafloor. In general, areas of low slope tend to have low backscatter values, and areas of higher slope have higher backscatter values.

The main objective is to create a statistical method that can be applied to quantify the distribution of substrates on a regional scale. The inputs for this unsupervised classification were 5-m resolution grids of seafloor topography (water depth), backscatter intensity (substrate

reflectance) and seafloor slope (derived from seafloor topography). This method uses a two-step unsupervised classification of the seafloor. First, an Iterative Self Organizing (ISO) clustering function (also known as migrating means technique) was applied to the three input grids. The ISO function groups overlapping cells from the grids into 4 user-defined classes and creates an ASCII signature file of the results. The second part of the process uses this signature file as an input to a Maximum Likelihood Classification routine that outputs a classified raster. These two steps were combined in a custom model using ArcGIS Model Builder (fig 4.2). The output grid from this analysis groups surficial materials on the seafloor in three general classes: ledge, cobble/boulders, and sand/silt (fig. 4.3). The fourth class “no data” is used to identify areas around the edges of the input data where all three input grids did not overlap and thus did not meet the criteria for classification.

Although this type of unsupervised classification technique is commonly used in aerial remote sensing of terrestrial environments, it has not been widely applied to marine remote sensing data primarily because survey costs and survey time are usually greater. Marine acoustic data is also difficult to classify because of external noise (e.g., boat wakes, breaking waves, and propeller wash) and refraction effects in the water column (e.g., thermocline). The signal-to-noise ratio in marine surveys is relatively low compared to terrestrial surveys that use data from airplanes or satellites. In this study, the four generalized groupings of bottom types were selected to compliment the primary objective which is to provide geologic data maps of the seafloor on a *regional scale*. A rigorous quantitative error analysis of the final bottom classification was not run as part of this study because of time constraints. Future work on these data will include comparison of supervised and unsupervised classification of these data.

Physiographic Zones

The seafloor in the study area can be divided into five environments, or physiographic zones, which are delineated based on seafloor morphology and the dominant characteristics of surficial materials (fig. 4.4). Physiographic mapping allows efficient mapping of large areas and presents geologic information in a readily useable format. It is a more qualitative method than the multivariate approach described above, and relies heavily on geologic interpretation. Delineation of physiographic zones does not require full coverage with bathymetric and backscatter data, which can be difficult to collect in shallow water environments. Other data, such as single-beam depth soundings, can also be used to characterize the seafloor physiography where full coverage does not exist. In Figure 4.4, for example, information from air photographs, nautical charts, and site visits was used to map physiographic zones in the narrow band of shallow water adjacent to the coast, where water depths were less than about 5 m.

The five physiographic zones are *Nearshore Basins*, *Rocky Zones*, *Nearshore Ramps*, *Shelf Valleys*, and *Bay-Mouth Shoals*. Geologic maps using these zones have been produced at regional scales for other areas in the Gulf of Maine where seafloor topography and substrates are similar to the inner shelf offshore of northeastern Massachusetts (Kelley and others, 1989; Kelley and Belknap, 1991; Barnhardt and Kelley, 1995). The zones are described below in terms of their size, morphology, physical setting, and substrate properties.

Nearshore Basins (NB) are areas of shallow, low-relief seafloor adjacent to the mainland and separated from offshore areas by islands and shoals. Along its landward margin, the basin sediment merges with the intertidal zone in a gradational contact. One large Nearshore Basin is recognized in the study area, located inside Salem Sound and Marblehead Harbor. It is sheltered from the open ocean by small islands and shoals. The basin is bordered by the mainland coast on its landward side and terminates against Rocky Zone, Shelf Valley, and Bay-Mouth Shoal on its seaward side. The inner-most part of the basin is the Danvers River estuary. Although exposures of bedrock and coarse-grained sediment locally occur within the basins, the generally smooth seafloor primarily consists of sandy and muddy sediment. Nearshore Basins comprise 22.4 km² or 13.1% of the mapped area (table 4.1). Water depths range from 0 to 19 m.

Seismic-reflection profiles indicate that sediment up to 33 m thick fills the basin, deeply burying high-relief bedrock in many areas of Nearshore Basins (fig. 4.5). Based on geophysical characteristics and previously published research (Oldale and Edwards, 1990; Oldale and others, 1983, 1993), we infer a Holocene age (less than 10,000 years) for the sandy/muddy surficial deposits. Long cores are needed to validate geophysical interpretations and to confirm age estimates on subsurface deposits by collecting and dating organic materials. In most areas of the Nearshore Basin, a pronounced acoustic reflector marks the base of the Holocene deposits (fig. 4.5). Previous studies have recognized this reflective surface as the transgressive unconformity that was eroded into the top of older deposits due to sea-level rise and shoreline transgression that occurred over the last 12,000 years (Oldale and others, 1983, 1993). Sediment below the transgressive unconformity is inferred as Pleistocene in age. It was originally deposited in contact with, or in close proximity to large ice sheets that once covered the region. Till, which is a poorly sorted, sandy sediment containing large clasts (pebbles, cobbles, boulders), forms numerous drumlins and moraines along the coast of northeastern Massachusetts and in offshore regions (Oldale, 1985b; Oldale and others, 1994). Glacial-marine sediment is the most abundant basin fill, especially in deeper parts of the basin where the thickest deposits of interbedded mud and sand accumulated. The highly stratified material characteristically drapes over bedrock pinnacles and has been designated the Presumpscot Formation throughout the western Gulf of Maine (Belknap and Shipp, 1991).

Table 4.1. Area of physiographic zones in the survey region.

| ZONE | AREA (km ²) | AREA (%) |
|------------------------|-------------------------|------------|
| Nearshore Basins (NB) | 22.4 | 13.1 |
| Rocky Zones (RZ) | 63.4 | 37.0 |
| Nearshore Ramps (NR) | 68.6 | 40.0 |
| Shelf Valleys (SV) | 12.5 | 7.3 |
| Bay-Mouth Shoals (BMS) | <u>4.4</u> | <u>2.6</u> |
| Total | 171.4* | 100.0 |

*In addition to areas completely imaged with sonar (134 km²), the geologic map in figure 4.4

includes adjacent shallow-water areas along the coast and surrounding islands (37.4 km²)

Rocky Zones (RZ) are rugged areas of extreme bathymetric relief ranging from nearly vertical rock cliffs to relatively flat, gravel-covered plains littered with boulders up to 4 m in diameter. Although ledge and coarse-grained sediment locally occur in all physiographic zones, they dominate the seafloor in Rocky Zones. Large expanses of Rocky Zone surround many of the islands and extend several kilometers seaward from the coast as hazardous shoals. Sandy sediment with abundant shell fragments locally accumulates in sediment ponds that fill low-lying troughs (fig. 4.6D). Shells of benthic-dwelling bivalves and other encrusting organisms are commonly observed around the base of elevated rocky outcrops (fig. 4.6F). Rocky Zones are the 2nd largest physiographic element, comprising 63.4 km² or 37.0% of the study area (table 4.1). Water depths range from 0 to 48 m.

The defining characteristics of Rocky Zones are high relief and hard bottom. Rocky Zones occur from the intertidal zone to water depths of > 40 m, and are common in relatively shallow water throughout the western Gulf of Maine (Kelley et al, 1989; Kelley and Belknap, 1991; Barnhardt and Kelley, 1995). Rocky Zones are expressed as series of bathymetrically complex, rock- and boulder-covered ridges and mounds that extend from the coast out to the seaward margin of the study area. These rugged areas of seafloor correspond loosely to zones of erosion/non-deposition mapped by Knebel and Circe (1995). Seismic-reflection profiles suggest that bedrock forms the core of the ridges and mounds, which are covered by a thin layer of bouldery sediment (Fig. 4.7). The most prominent of these bouldery features is a series of lobate-shaped, convex-seaward ridges that we interpret as end moraines (red arrows in fig. 4.6). The submarine moraines have steep margins and consist of acoustically incoherent material, probably till, on seismic-reflection profiles. A series of bottom photographs, taken across one of the submerged moraines, shows cobbles and boulders at the crest of the moraine (fig. 4.6A) and a narrow apron of sandy gravel at the base (fig. 4.6B). Seaward of the gravelly apron, the smooth seafloor is covered with muddy sand (fig. 4.6C). Relatively sharp boundaries define the textural transitions between these different materials. In general, sediment thickness in Rocky Zones is 1 m or less, although seismic-reflection profiles show that ponded sediment is up to 10 m thick in a few locations. An acoustically transparent unit, inferred to be muddy glacial-marine sediment, underlies a thin surficial layer of gravelly sediment in these larger sediment ponds. Ponded sediment is often covered with bedforms and gravelly scour surfaces that are evidence of active reworking by waves and bottom currents, probably during large storms. The bedforms have wavelengths of 15-20 m, with crests 10-30 cm high that generally trend in a NE-SW direction and locally bend around bathymetrically high areas of seafloor. The sandy bedforms are variously classified as megaripples or subaqueous dunes (Ashley, 1990).

Nearshore Ramps (NR) are areas of gently-sloping seafloor with generally shore-parallel bathymetric contours. This zone is primarily covered with sand-rich sediment, although small exposures of ledge, cobbles and boulders locally crop out on the seafloor. Nearshore Ramp terminates on the landward side against the mainland shoreline, Rocky Zone, and/or Shelf Valley. On the seaward side, it extends out to the depth of the sea-level lowstand at approximately 50 m, where it merges with deeper basin sediment outside the limit of the study area. The smooth, generally sandy seafloor of Nearshore Ramps are the most prominent

physiographic element in the study area, comprising 68.6 km² or 40.0% of the study area (table 4.1). Water depths range from 0 to 48 m.

Nearshore Ramps abut sandy beaches in the southwestern part of the study area between Nahant and Marblehead Neck, and in the northeastern part near Manchester (fig. 4.4). Large areas of Nearshore Ramp are covered with uniform, relatively featureless, low backscatter material. In limited areas, however, a mosaic of different bottom types occurs on the seafloor. These areas exhibit complex distributions of high and low backscatter intensity, forming light and dark patches that are irregular in size and shape (Fig. 4.8). Textural transitions between the different patches of sediment are marked by sharp boundaries. The seafloor has a mottled appearance due to high backscatter, gravelly material that lies in slight depressions (Fig. 4.8A,B), surrounded by slightly elevated deposits of low backscatter, silty/sandy sediment (Fig. 4.8C). Topographic changes at the margins of the depressions typically range from 5 to 50 cm, but locally can exceed 1 m. These irregular patches of high/low backscatter resemble "sorted bedforms" or "rippled scour depressions" that have been observed on continental shelves around the world (Cacchione and others, 1984; Murray and Thielor, 2004; Guitierrez and others, 2005; Ferrini and Flood, 2005; Green and others, 2004). The enigmatic features are common on other parts of the Massachusetts inner shelf (Aubrey and others, 1982; Goff and others, 2005). Numerous theories for their origin have been proposed, but generally the distinct morphology and texture of these features result from the interaction of waves and currents (i.e., along- and cross-shelf transport of sediment) with the existing substrate materials on the seafloor (i.e., geologic framework).

Seismic-reflection profiles show that thick sediment deposits underlie the smoothly sloping surface of Nearshore Ramps in the study area. The thick deposits conceal the high-relief bedrock that lies below the seafloor (fig. 3.5). The surficial deposits, however, have different ages and origins. These are determined based on the stratigraphic setting, primarily whether they lie above or below the transgressive unconformity, which separates the Pleistocene and Holocene sedimentary sequences.

In the southwestern part of the study area, the transgressive unconformity lies at or very near the seafloor offshore of Nahant. The unconformity truncates material that is highly stratified with closely spaced internal reflections draping over bedrock, the diagnostic properties of Pleistocene glacial-marine sediment (Fig. 4.7). Bottom photographs confirm that bluish gray deposits of glacial-marine silty clay are exposed on this part of the Nearshore Ramp (fig. 4.7A). Where the stiff, cohesive deposits of silty clay crop out on the seafloor, backscatter intensity is high. Where the seafloor is covered with sandy Holocene material, backscatter intensity is low. The thin, discontinuous nature of sandy surficial sediment in this area creates alternating patches of low backscatter (Holocene) and high backscatter (Pleistocene).

In the northeastern part of the study area, surficial sediment covering the Nearshore Ramp is Holocene in age, thousands of years younger than the glacial-marine clay that crops out offshore of Nahant. The Nearshore Ramp offshore of Manchester is covered with a relatively thick layer of Holocene sediment that completely buries the transgressive unconformity beneath up to 15 m of muddy sand (fig. 4.9). No glacial-marine deposits were observed on the seafloor in this part of the mapped area.

Shelf Valleys (SV) are elongate depressions that extend offshore more or less perpendicular to the trend of the coastline, and slope gently seaward. They are bordered by rocky, bouldery walls where they cut through areas of Rocky Zone (fig. 4.4). The channels form a pattern of tributaries and main channels, which locally bifurcate into multiple branches and pass around isolated patches of Rocky Zone. The type of sediment in Shelf Valleys is highly variable, ranging from gravel to muddy sand (fig. 4.6B,C). Bedrock commonly crops out within the walls and floors of the channels. Shelf Valleys comprise 12.5 km² or 7.3% of the study area (table 4.1). Water depths range from 7 to 45 m.

Four Shelf Valleys of different sizes cross the study area, generally trending from NW to SE. The largest valley, located in the northeastern part of the study area, measures 8 km long and up to 1 km wide (fig. 4.4). In plan view, it has a branching geometry that is analogous to terrestrial river valleys, and a smooth, gently sloping bottom. The large valley extends from the Nearshore Basin at its head in Salem Sound, passes between rocky islands (Misery, Bakers Islands), and gradually terminates seaward where it merges with a Nearshore Ramp in water about 40 m deep. This valley is the only one that can be traced directly to a modern river (Danvers River). It probably was formed by fluvial erosion during times of lower sea level.

The three smaller valleys, clustered in the center of the study area offshore of Marblehead Neck, measure 1.5 to 5 km long and 0.1 to 1 km wide. They also exhibit an overall branching geometry but, compared to the larger valley, the tributaries are more lobate in plan form and the main channel is poorly defined. The valley bottoms have an irregular, not smooth, morphology that consists of a series of small, interconnected depressions. In addition, they have no obvious terrestrial source; the heads of the small valleys do not correlate with modern stream valleys onshore. All three valleys terminate on their seaward end against Nearshore Ramps in 30-40 m water depth. This class of small Shelf Valleys probably represent a series of kettles that originally formed in glacial drift, and have been modified by erosion.

The hardness and roughness of the seafloor, as recorded with sidescan sonar (i.e., backscatter intensity in fig. 3.3), varies along the length of the Shelf Valleys. High backscatter areas within the valleys are floored with coarse sand, gravel (including pebbles, cobbles and boulders), and bedrock exposures, indicating areas of erosion or non-deposition. Highly reflective aprons of coarse material typically lie adjacent to channel margins and surround the base of rocky outcrops. Bottom photographs show that submarine talus piles contain abundant carbonate (fig. 4.6B). The thalweg, or deepest part of the valleys, is a relatively featureless region floored with low backscatter material such as sand and muddy sand (fig. 4.9A). Seismic-reflection profiles show that Shelf Valleys locally contain deposits up to 31 m thick (fig. 3.5).

Bay-Mouth Shoals (BMS) are areas of shallow, generally smooth seafloor at the entrance to Salem Sound. Relatively steep slopes define the margins of the shoals, which are elevated above the surrounding shelf and locally emerge above sea level as small islands. The tops of the shoals are uniformly covered with high backscatter, sandy, gravelly material (figs. 4.5C, 4.6E). Seismic-reflection systems achieved only shallow penetration through these deposits (fig. 4.5), and their structure is largely unknown. Fields of bedforms typically occur on top and around the margins of the shoals, indicating contemporary reworking of the seafloor by waves and currents.

The sandy bedforms have linear to slightly sinuous crests, amplitudes of 10-30 cm, and wavelengths of 15-20 m. They are variously classified as megaripples or subaqueous dunes (Ashley, 1990). Bay-Mouth Shoals are the least abundant zone, covering 4.4 km², or 2.6% of the study area. Water depths range from 0 to 17 m.

Bottom Sediment Texture

Bottom samples from the study area contained nearly all components of the particle size spectrum (fig. 4.10). Sediment texture ranged from sandy silt in Nearshore Basins to pebbles, cobbles, and boulders in Rocky Zones (table 4.2). No meaningful correlation exists between mean grain size and water depth; both coarse- and fine-grained sediment were collected in all water depths (fig. 4.11). In general, the sediment was poorly sorted with respect to grain size.

Sand is the most common bottom sediment in this study. All samples contained significant quantities of sand, with particles 0.062 - 2 mm in diameter comprising an average of 72.2% by weight. Values ranged from a minimum of 19% to a maximum of 99.8%. Samples with the highest sand content were collected from Nearshore Ramps (31 samples, average 79.9%). Sand-rich sediment was also collected from Nearshore Basins (11 samples, average 62.1%) and Shelf Valleys (11 samples, average 69.9%). The lowest values were from Rocky Zones (3 samples, average 38.1%). No samples were collected from Bay-Mouth Shoals, but bottom photos show a mix of sand and gravel on the bottom (figs. 4.5C, 4.6E).

Gravel is the least common bottom sediment sampled. Large particles greater than 2 mm in diameter comprise an average of 6.5% of all samples by weight. Only two samples contained more than 50% gravel, but at least some gravel-size material was collected from 48% of the sample sites. Gravel most commonly occurs in Rocky Zones (average 55.9%), where it comprises a major component of glacial deposits and surrounds the base of rock outcrops. Samples from other zones average less than 5% gravel. Gravel is probably underrepresented in these grab samples due to problems collecting large diameter particles and the need for large samples to perform statistically valid analyses. Sidescan sonar observations suggest that gravel is probably more abundant than indicated by sampling alone.

Muddy sediment, which includes silt and clay size particles less than 0.062 mm in diameter, comprises an average of 21.3% of all sediment samples. Although moderately abundant overall, half of all samples contain less than 10% mud by weight. Samples with the highest values were collected from Nearshore Basins (average 33.3%) and Shelf Valleys (average 27.5%). Sediment from Nearshore Ramps were highly variable in terms of mud content, ranging from 0.1% to 49.3%. Samples from Rocky Zones averaged only 6.0% mud.

Table 4.2. Location, depth, and textural properties for stations where sediment samples were collected. See Map Sheet 5, panel C for the textural data overlain on backscatter intensity. See Appendix I for a GIS database with links to texture data and bottom photographs, and for locations of all stations where no samples were collected. Detailed sediment texture data are available in Appendix II and links to bottom photographs at each station in Appendix III.

| STATION # | ZONE | DEPTH (m) | LAT. | LON. | SAND % | SILT % | CLAY % | GRAVEL % | DESCRIPTION (Folk, 1974) |
|-----------|------|-----------|---------|----------|--------|--------|--------|----------|--------------------------|
| 1 | NR | 28.0 | 42.4118 | -70.8884 | 58.5 | 33.5 | 8.1 | 0.0 | mS |
| 3 | NR | 31.3 | 42.4235 | -70.8633 | 50.8 | 37.5 | 11.2 | 0.5 | (g)mS |
| 8 | NR | 11.6 | 42.4522 | -70.9097 | 93.0 | 6.3 | 0.7 | 0.0 | S |
| 9 | NR | 22.1 | 42.4482 | -70.8915 | 80.0 | 12.9 | 7.1 | 0.0 | mS |
| 10 | NR | 27.2 | 42.4421 | -70.8712 | 79.4 | 8.3 | 1.7 | 10.6 | gmS |
| 13 | NR | 30.6 | 42.4381 | -70.8600 | 86.5 | 7.8 | 1.3 | 4.5 | (g)mS |
| 14 | NR | 32.7 | 42.4403 | -70.8457 | 54.1 | 3.0 | 1.1 | 41.8 | sG |
| 15 | NR | 31.9 | 42.4517 | -70.8433 | 84.5 | 2.9 | 0.8 | 11.8 | gS |
| 16 | NR | 25.6 | 42.4510 | -70.8631 | 97.2 | 1.9 | 0.5 | 0.4 | (g)S |
| 19 | NR | 14.3 | 42.4715 | -70.8746 | 89.8 | 6.8 | 1.5 | 1.9 | (g)S |
| 21 | SV | 17.2 | 42.4780 | -70.8484 | 73.3 | 17.2 | 3.3 | 6.3 | gmS |
| 23 | SV | 26.9 | 42.4696 | -70.8364 | 22.6 | 57.8 | 19.4 | 0.2 | (g)sM |
| 24 | NR | 38.3 | 42.4536 | -70.8228 | 60.4 | 26.6 | 12.9 | 0.1 | (g)mS |
| 25 | NR | 40.9 | 42.4507 | -70.8162 | 67.3 | 16.9 | 13.6 | 2.3 | (g)mS |
| 28 | SV | 37.7 | 42.4708 | -70.8063 | 54.2 | 35.6 | 9.8 | 0.5 | (g)mS |
| 30 | NR | 40.0 | 42.4799 | -70.7786 | 96.8 | 2.2 | 1.0 | 0.1 | (g)S |
| 31 | NR | 36.0 | 42.4820 | -70.7923 | 43.6 | 43.6 | 12.9 | 0.0 | sM |
| 41 | NB | 16.3 | 42.5175 | -70.8283 | 61.5 | 30.4 | 8.1 | 0.0 | mS |
| 42 | NB | 14.4 | 42.5281 | -70.8239 | 78.6 | 17.4 | 3.9 | 0.1 | (g)mS |
| 43 | NB | 12.9 | 42.5347 | -70.8313 | 23.8 | 65.6 | 10.6 | 0.0 | sM |
| 44 | NB | 9.0 | 42.5383 | -70.8364 | 76.9 | 2.2 | 0.8 | 20.2 | gS |
| 45 | NB | 11.4 | 42.5407 | -70.8316 | 81.1 | 8.0 | 1.3 | 9.7 | gmS |
| 46 | NB | 10.1 | 42.5427 | -70.8407 | 60.3 | 17.1 | 2.2 | 20.5 | gmS |
| 47 | NB | 11.3 | 42.5435 | -70.8337 | 29.5 | 64.1 | 6.4 | 0.0 | sM |
| 48 | NB | 13.1 | 42.5383 | -70.8208 | 32.3 | 59.8 | 8.0 | 0.0 | sM |
| 50 | SV | 12.9 | 42.5438 | -70.8073 | 40.7 | 51.1 | 8.2 | 0.0 | sM |

| | | | | | | | | | |
|------|----|------|---------|----------|------|------|-----|------|-------|
| 54 | NB | 15.8 | 42.5342 | -70.8143 | 63.3 | 34.2 | 2.5 | 0.0 | mS |
| 55 | NB | 14.6 | 42.5328 | -70.8126 | 96.2 | 3.0 | 0.8 | 0.0 | S |
| 57 | SV | 16.1 | 42.5319 | -70.8006 | 95.6 | 3.3 | 1.1 | 0.0 | S |
| 61 | NR | 27.5 | 42.5055 | -70.7869 | 82.5 | 1.4 | 0.5 | 15.7 | gS |
| 62 | NR | 14.2 | 42.5170 | -70.7904 | 99.8 | 0.1 | 0.1 | 0.0 | S |
| 64 | NR | 32.2 | 42.5067 | -70.7684 | 63.9 | 31.7 | 4.4 | 0.0 | mS |
| 67 | RZ | 39.1 | 42.5213 | -70.7395 | 19.0 | 1.3 | 0.3 | 79.4 | sG |
| 70 | SV | 25.3 | 42.5360 | -70.7673 | 94.4 | 4.2 | 1.3 | 0.1 | (g)S |
| 73 | SV | 19.8 | 42.5457 | -70.7902 | 95.3 | 4.0 | 0.7 | 0.0 | S |
| 74 | SV | 13.6 | 42.5515 | -70.7878 | 93.2 | 6.1 | 0.7 | 0.0 | S |
| 75 | NB | 11.3 | 42.5554 | -70.7912 | 79.8 | 17.8 | 2.3 | 0.0 | mS |
| 77 | SV | 23.5 | 42.5452 | -70.7757 | 80 | 16.0 | 4.0 | 0.0 | mS |
| 80 | SV | 35.9 | 42.5323 | -70.7495 | 68.2 | 29.9 | 1.6 | 0.3 | mS |
| 82 | RZ | 33.6 | 42.5384 | -70.7443 | 42.8 | 3.0 | 0.9 | 53.4 | sG |
| 84 | NR | 32.6 | 42.5476 | -70.7359 | 66.1 | 31.8 | 2.0 | 0.0 | mS |
| 85 | NR | 25.0 | 42.5555 | -70.7495 | 50.8 | 47.5 | 1.7 | 0.0 | mS |
| 86 | NR | 15.5 | 42.5659 | -70.7516 | 92.3 | 7.1 | 0.7 | 0.0 | S |
| 87 | NR | 37.3 | 42.5451 | -70.719 | 90.3 | 8.6 | 1.1 | 0.0 | S |
| 88 | NR | 38.8 | 42.5410 | -70.7108 | 96.3 | 3.4 | 0.3 | 0.0 | S |
| 89 | RZ | 41.5 | 42.5378 | -70.7069 | 52.6 | 9.4 | 3.2 | 34.8 | msG |
| 92 | NR | 32.3 | 42.5553 | -70.7204 | 90.8 | 8.6 | 0.6 | 0.0 | S |
| 93 | NR | 29.6 | 42.5576 | -70.7248 | 80.1 | 18.5 | 1.4 | 0.1 | (g)mS |
| 94 | NR | 19.7 | 42.5642 | -70.7338 | 92.3 | 7.0 | 0.7 | 0.0 | S |
| 95 | NR | 11.9 | 42.5692 | -70.7339 | 99.7 | 0.2 | 0.1 | 0.0 | S |
| 98 | NR | 27.0 | 42.5625 | -70.7083 | 99.2 | 0.2 | 0.1 | 0.6 | (g)S |
| 99 | NR | 28.0 | 42.5568 | -70.7346 | 77.0 | 21.7 | 1.3 | 0.0 | mS |
| 007B | NR | 15.4 | 42.4442 | -70.9087 | 75.3 | 0.1 | 0.0 | 24.6 | gS |
| 056B | SV | 16.9 | 42.5357 | -70.8077 | 51.6 | 23.1 | 3.7 | 21.6 | gmS |
| 096B | NR | 26.5 | 42.5618 | -70.7227 | 99.5 | 0.3 | 0.2 | 0.0 | S |
| 100 | NR | 23.1 | 42.5674 | -70.7068 | 80.4 | 17.1 | 2.5 | 0.0 | mS |

Key to sediment descriptions (Folk, 1974):

G = gravel S = sand M = mud
g = gravelly s = sandy m = muddy
(g) = slightly gravelly

Geologic Framework and Late Quaternary Evolution

The physiography and surficial sediment of the inner continental shelf offshore of northeastern Massachusetts reflect the region's underlying geologic framework and complex late Quaternary history. Bedrock controls the overall geometry of the coast and inner shelf, where resistant intrusive rocks form rugged coastal headlands and submarine shoals and ridges. No major rivers deliver significant sediment to the area, so reworking of existing deposits (mostly glacial in origin) determines the observed distribution of bottom sediment. Modern processes interact with bedrock and glacial sediment to create the sandy beaches and other coastal landforms extant along the present shoreline. Glaciation and relative sea-level change are the most important processes to act on the region, and have produced a heterogeneous mix of bottom types on the inner continental shelf.

The entire study area has experienced erosion and deposition by glaciers, which laid down extensive deposits of till and, in many locations near the study area, locally molded the till into small hills called drumlins. The long axes of these oval, streamlined hills have a preferred orientation of approximately NW-SE, parallel to the regional ice-flow direction. Drumlins occur throughout the region from Boston (Bunker Hill, harbor islands) to north of Cape Ann (Castle Hill, Steep Hill). Erosional remnants of drumlins were also recognized just seaward of this study in central Massachusetts Bay, about 10 km southeast of Nahant (Oldale and others, 1994). These bouldery submarine hills average about 1200 m long, 600 m wide, and 12 m high and have the same NE-SW orientation as their counterparts on land. No drumlins have been mapped in the coastal areas between Salem and Gloucester (B. Stone, personal communication, 2005). Due to limited penetration by seismic-reflection profiles, it is unclear if the rugged, boulder-covered shoals in the study area are true drumlins, rather than rock-cored features covered by a thin layer of reworked till.

A series of moraines, which are arcuate ridges of till that form along the margins of ice sheets, record the retreat of glaciers across the mouth of Salem Sound (fig. 4.6). The closely spaced ridges outline former positions of the lobate ice margin and indicate that it retreated northward in a step-wise fashion, with each small moraine representing a temporary pause or slight re-advance of the ice. As ice retreated across the region, the sea advanced inland in contact with the ice front, and the coast migrated landward (transgression). At the maximum highstand elevation of about +33 m, marine waters covered low-lying areas northeast of Salem, isolating the rugged Cape Ann peninsula as a rocky island. During this transgression, which accompanied deglaciation, sediment-laden meltwater discharged from the glaciers in great quantities. Sediment from the meltwater plumes settled to the seafloor, filling sedimentary basins with thick deposits of well stratified glacial-marine material (figs. 4.5, 4.7 and 4.9). The draping nature of glacial-marine deposits, which are traceable up and over bedrock highs and across basins for long distances in the Gulf of Maine (Belknap and Shipp, 1991), indicate rapid deposition in an ice-marginal ocean.

Following deglaciation, relative sea level fell rapidly across the landscape due to isostatic uplift of the coast (fig. 4.1). In response, the shoreline migrated seaward (regression), exposing shelf areas down to depths of about 50 m below the present shoreline (Oldale and others, 1993). Rivers and streams flowed to the seas across the emergent landscape and incised the former

seafloor. The largest drainage, the ancestral Danvers River, carved a prominent valley across present shelf the northern part of the study area (fig. 4.4). Several smaller shelf valleys were also incised by streams that originated near the coast and flowed through a series of interconnected depressions, probably kettles. Fluvial and marine processes acted to remove glacial and glacial-marine material from the emergent shelf and transport it seaward to the lowstand shoreline. No ancient shorelines were observed in this study.

The second transgression, which continues today, began about 12,000 years ago as rates of isostatic uplift decreased (fig. 4.1; Oldale and others, 1993). Sea level rose rapidly during the early Holocene, flooding formerly emergent areas of the inner shelf for a second time. Waves and currents again acted on sediment that was not removed during the prior regression. The passage of the surf zone further eroded deposits of glacial and glacial-marine sediment, and exhumed underlying bedrock. Transgressive erosion also planed off till outcrops, leaving boulder-covered bathymetric highs on the seafloor. Migration of the shoreface across the shelf produced the strong reflector on the surface of glacial-marine deposits that is seen in seismic-reflection profiles and interpreted as the transgressive unconformity. The unconformity is buried beneath surficial sand and silt deposits that range in thickness up to 15 m (figs. 4.5, 4.9). The transgressive unconformity is actively forming at the seafloor in shallow areas of Rocky Zone, where fine-grained sediment has been winnowed, and in parts of the Nearshore Ramp in Nahant Bay, where glacial-marine mud is exposed on the seafloor (fig. 4.7). No unconformity was observed beneath the flat-topped surface of Bay-Mouth Shoals, indicating that they represent eroded Pleistocene deposits, not accumulations of younger sediment. Fields of bedforms in rocky Zones, Bay-Mouth Shoals, Nearshore Ramps and Shelf Valleys are evidence that erosion is continuing on those parts of the seafloor due to contemporary wave and current action. The primary site of sediment accumulation is the Nearshore Basin in Salem Sound, where thick deposits of estuarine mud were mapped.

Summary

The inner continental shelf between Nahant and Gloucester, Massachusetts is a bedrock-framed, glaciated seafloor. The area possesses sedimentary deposits whose distribution and characteristics are largely dictated by the inherited geologic framework, glaciation, and changes in relative sea level. The shape of the pre-glacial bedrock surface controls the overall geometry of the coast and shelf. Changes in relative sea level have allowed terrestrial and marine processes to repeatedly operate over the inner shelf and coast, exerting great influence on the stratigraphy and surficial geology of the region. The initial transgression, which accompanied deglaciation, and regression were times of major sediment introduction to the shelf. The ongoing transgression is largely a period of sediment reworking, in which sand and silt derived from glacial deposits has been redistributed across the shelf and coarser material left behind as mounds of pebbles, cobbles, and boulders. These shoreline migrations, driven by changing sea level, have repeatedly winnowed older deposits between the present coast and the lowstand shoreline, largely removing sediment cover from bedrock highs and etching a distinct unconformity that separates Pleistocene and Holocene sedimentary sequences. Bathymetrically high areas, covered with coarse material up to boulder size, are probably eroded remnants of morainal ridges and other glacial deposits.

This report defines five shelf environments on the basis of bathymetry and surficial sediment. The largest of these physiographic zones are *Nearshore Ramps*, which are smoothly sloping, sandy regions that extend offshore from the coast to depths of about 40 m. They contain the thickest deposits of sandy Holocene sediment in the region, but locally are floored with eroding glacial-marine sediment that is exposed at the seabed. Significant deposits of muddy sediment are limited to the sheltered environment of the *Nearshore Basin* occupying Salem Sound. *Rocky Zones* are high relief areas of rock outcrops and glacial gravels. Abundant shelly material occurs near the exposures of rock and gravel, and probably results from high productivity of calcareous epifauna on the extensive areas of hard substrate. Dendritic systems of *Shelf Valleys* cross the seafloor perpendicular to the coast, and probably originated as stream channels or kettles. Finally, *Bay-Mouth Shoals* are generally flat-topped, erosional features covered with sand and gravel that occur at the entrance to Salem Sound, where they are reworked by waves and currents.

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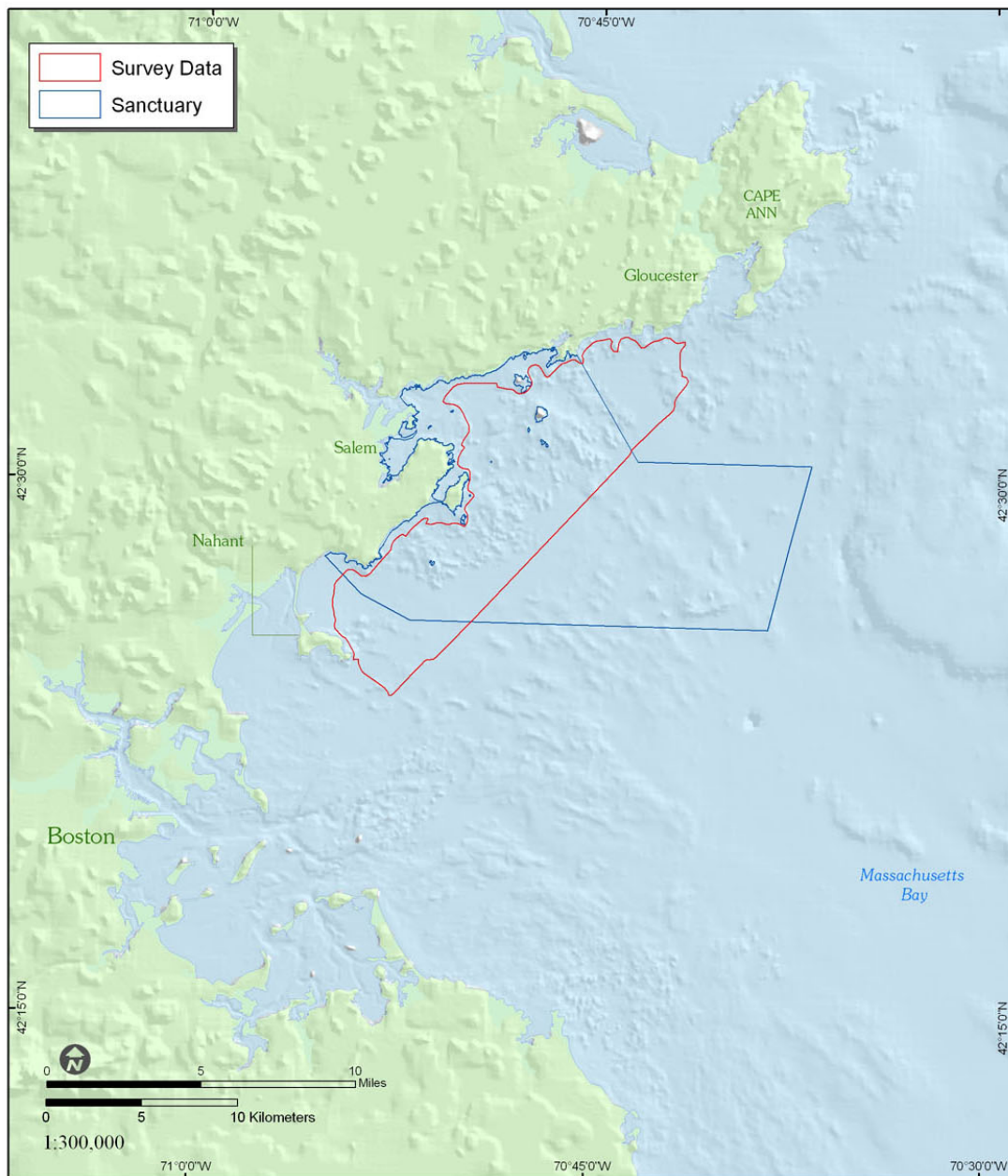


Figure 1.1. Map showing the location of the survey area (outlined in red) offshore of northeastern Massachusetts between Nahant and Gloucester, including part of the South Essex Ocean Sanctuary (blue line).



Figure 3.1. Photograph of the USGS research vessel Rafael.

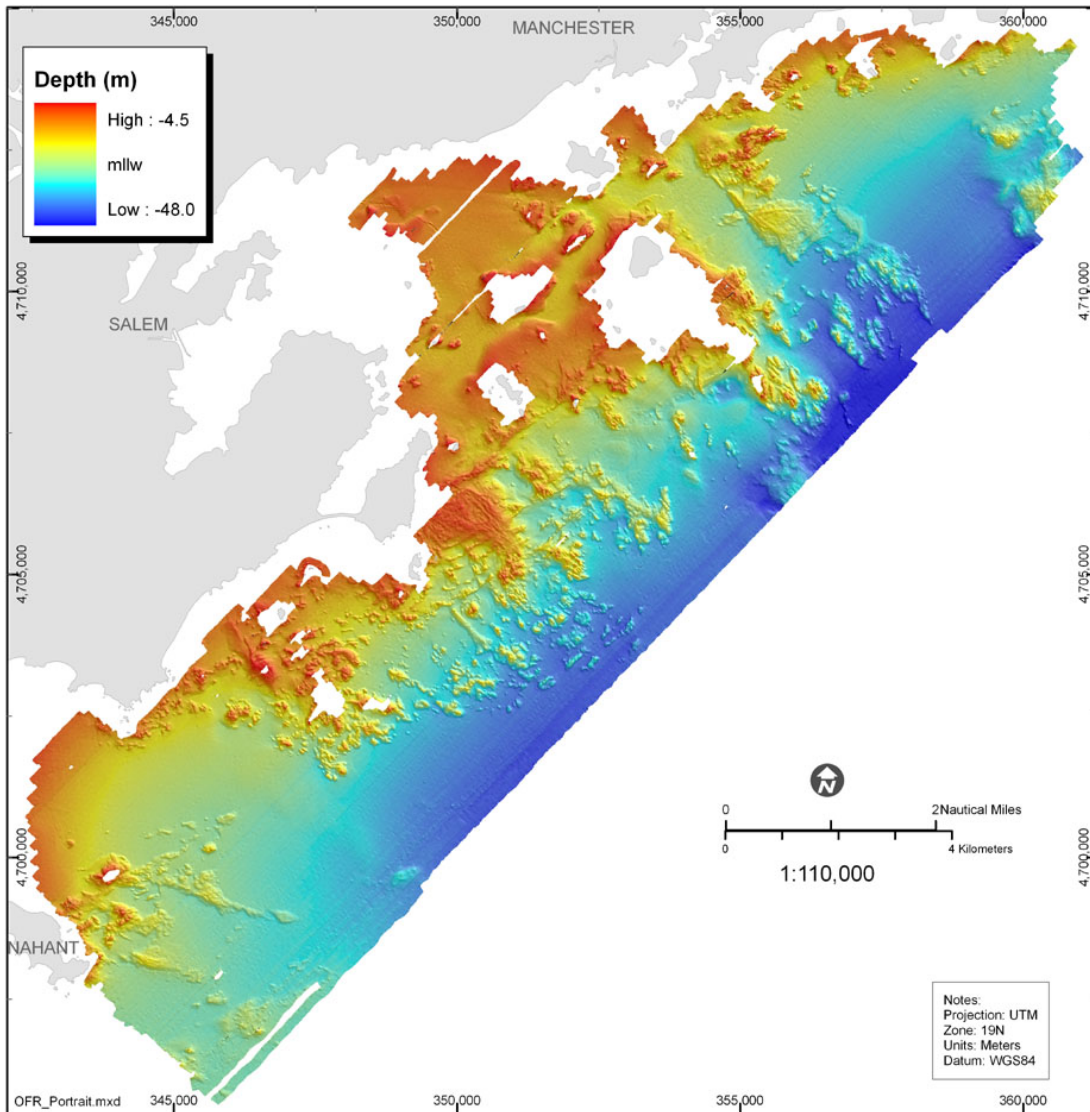


Figure 3.2. Shaded-relief map of seafloor topography offshore of northeastern Massachusetts between Nahant and Gloucester.

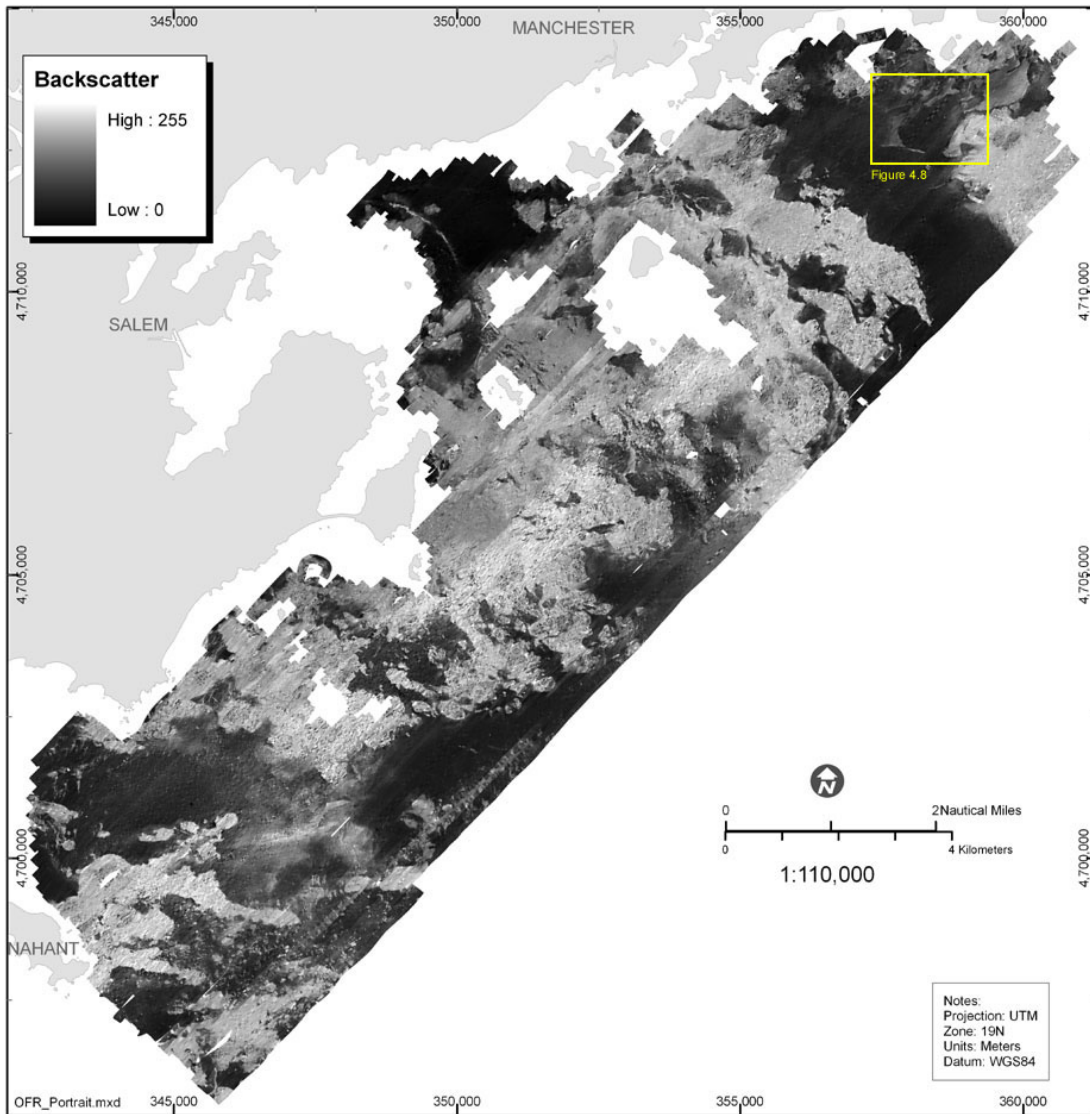


Figure 3.3. Map showing acoustic backscatter intensity offshore of northeastern Massachusetts between Nahant and Gloucester. Backscatter intensity, as recorded with sidescan sonar, is an acoustic measure of the hardness and roughness of the seafloor. In general, higher values (light tones) represent rock, gravel and coarse sand. Lower values (dark tones) generally represent fine sand and muddy sediment. Yellow box (upper right) indicates the location of Figure 4.8.

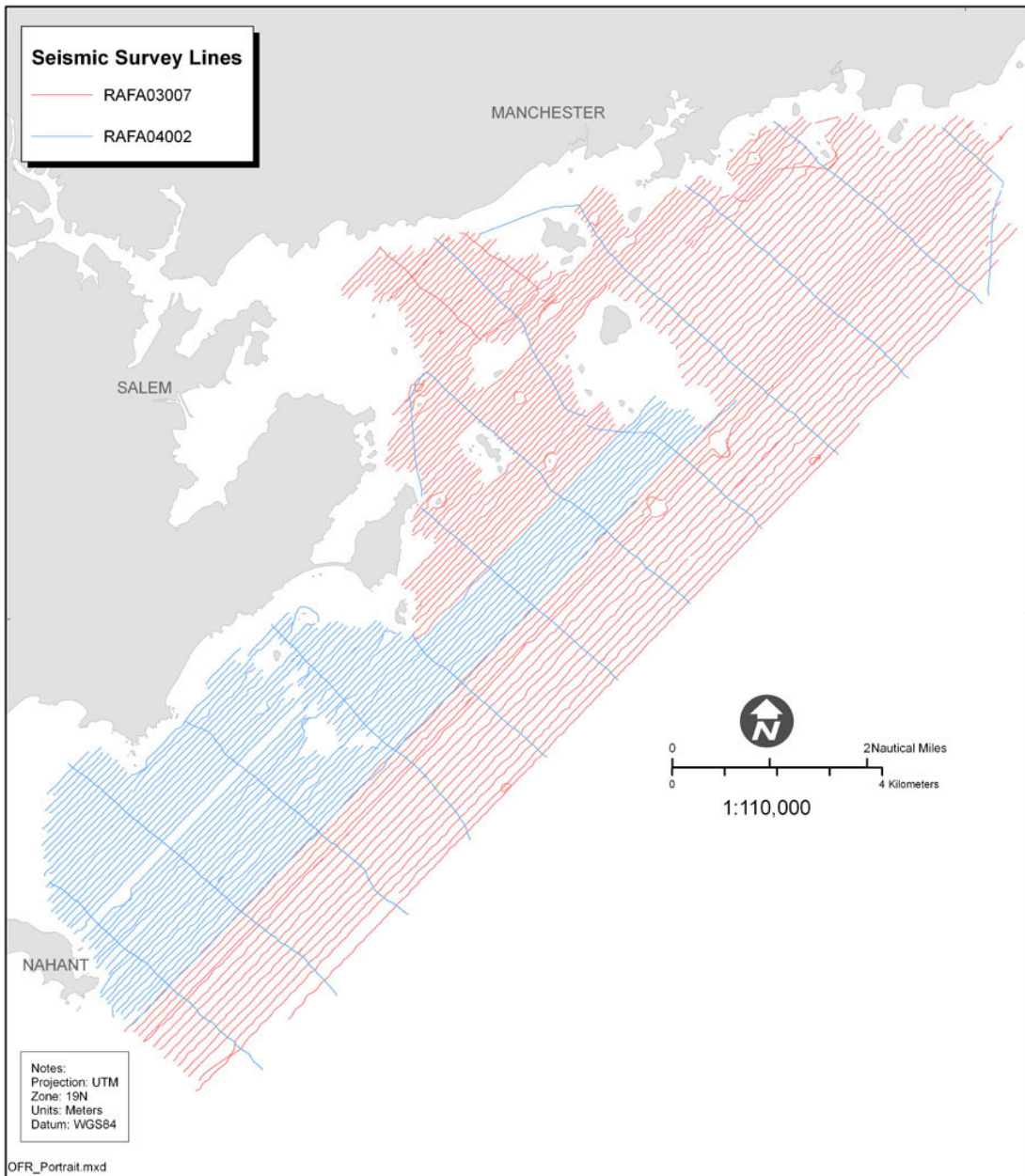


Figure 3.4. Map showing tracklines of seismic-reflection profiles in the survey area.

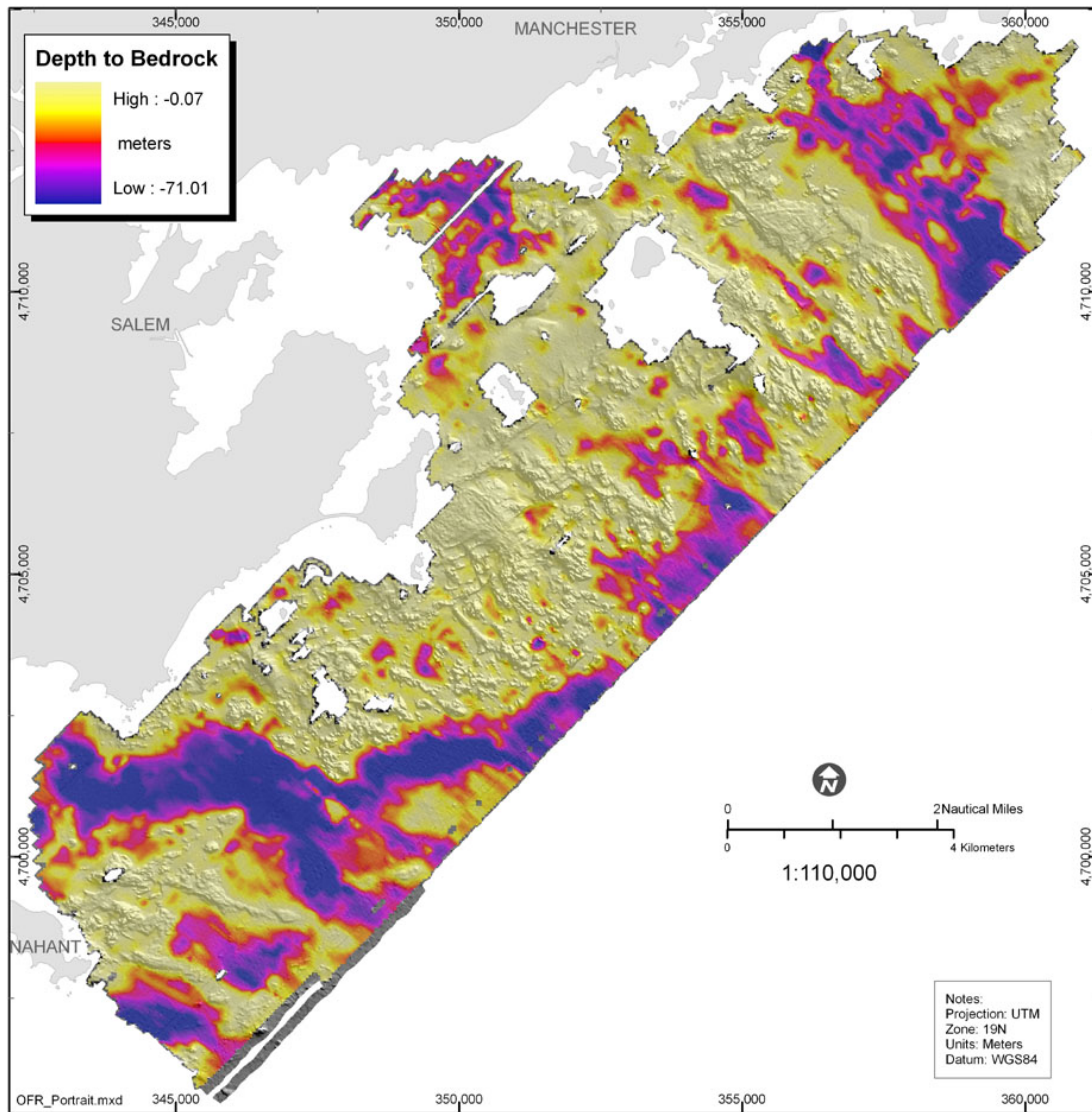


Figure 3.5. Isopach map of total sediment thickness in the survey area. Gridded values were interpolated from closely spaced seismic-reflection profiles shown in Figure 3.4.

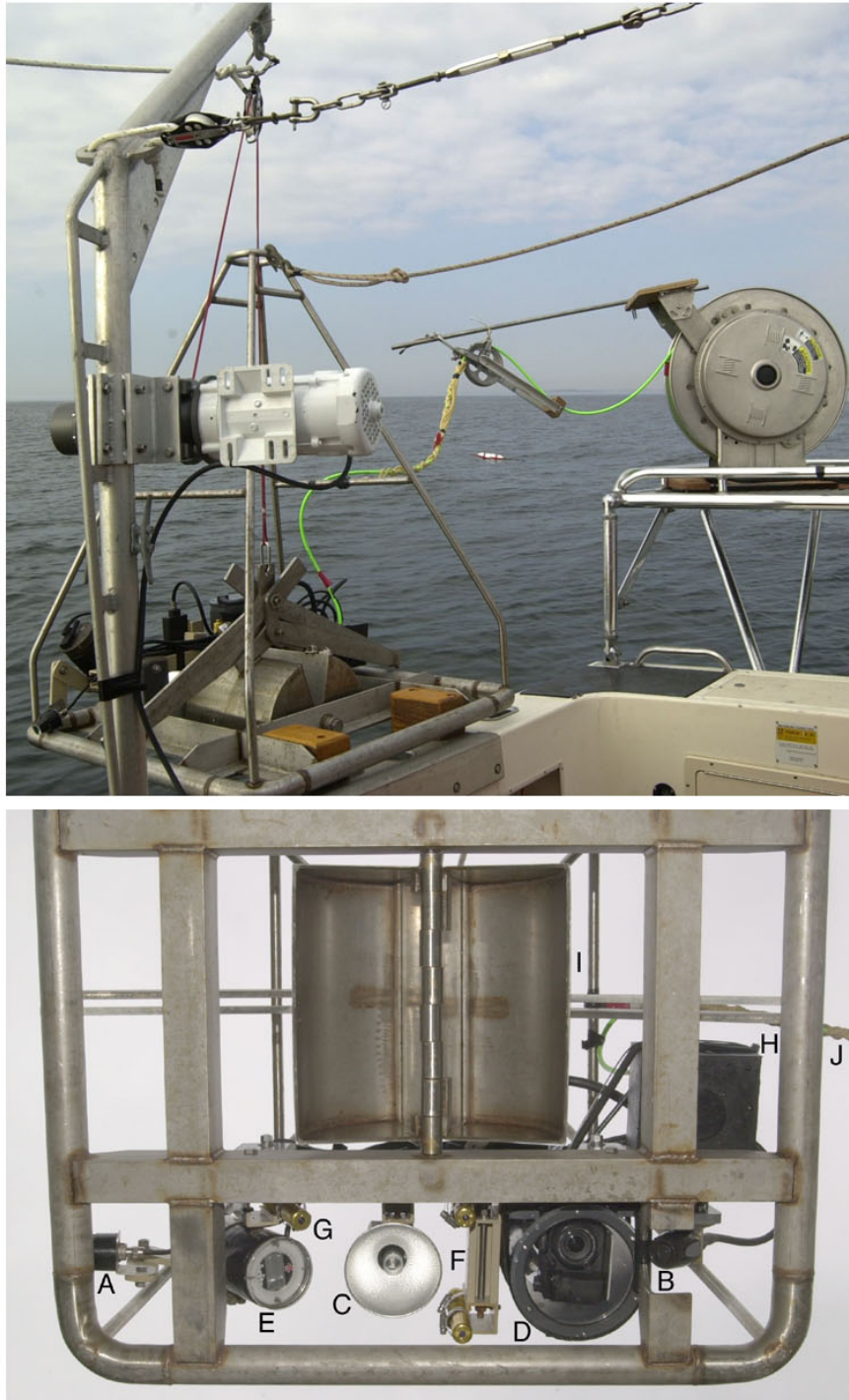


Figure 3.6. TOP: Photograph of Mini SEABOSS and winch on the deck of the RV Rafael. BOTTOM: Components of Mini SEABOSS viewed from below: A) forward video camera, B) downward video camera, C) video light, D) digital still camera and housing, E) strobe light, F) parallel laser for scale, G) laser for ranging, H) junction block, I) van Veen grab sampler, and J) multi-conducting cable.

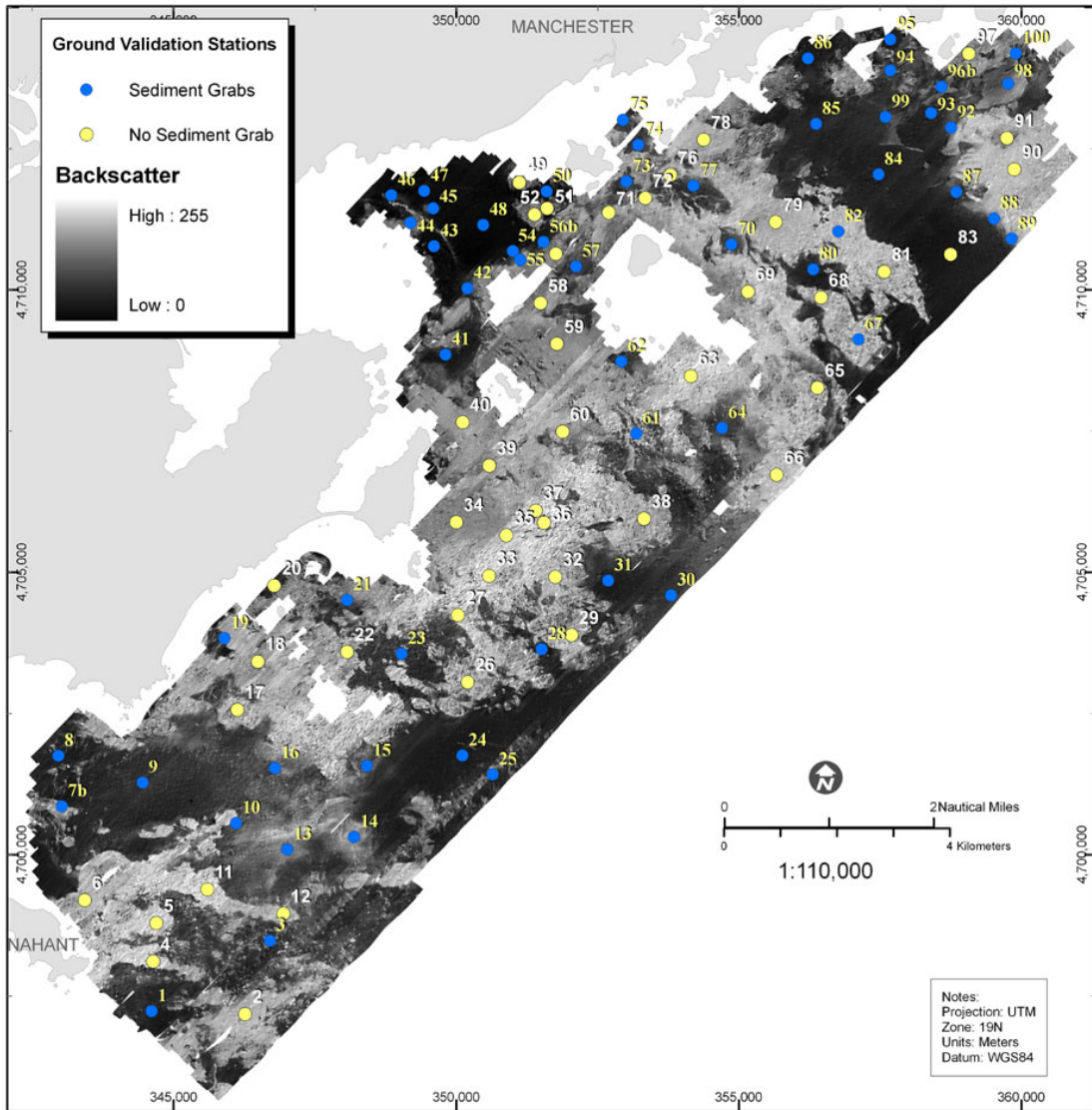


Figure 3.7. Map showing bottom sample locations and video transects overlain on a map of acoustic backscatter from sidescan sonar. Each numbered circle indicates a station where multiple photographs, video, and/or samples were collected.

SEDIMENT LABORATORY

GRAIN-SIZE ANALYSIS FLOW DIAGRAM

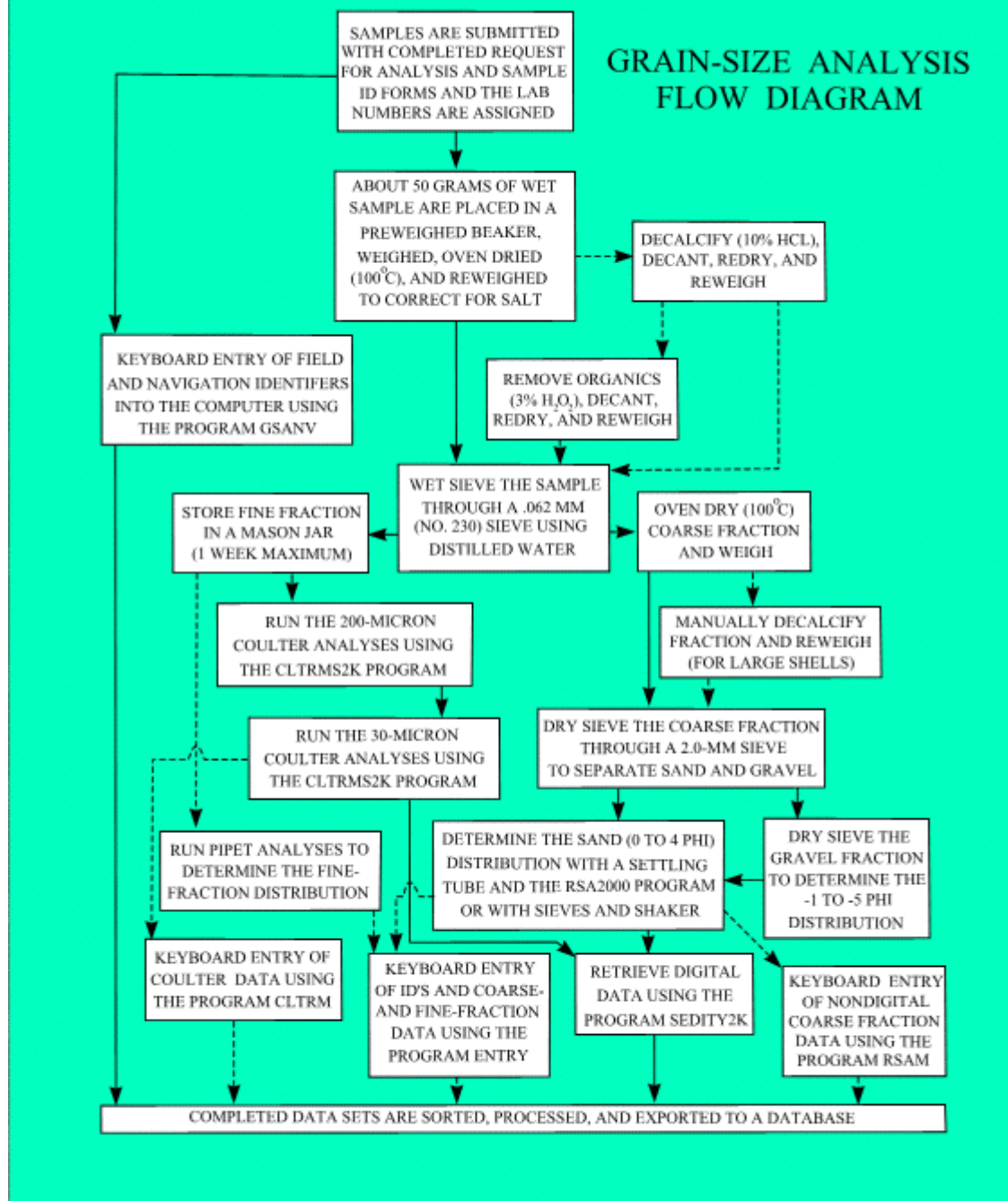


Figure 3.8. Flow diagram showing steps in laboratory analysis of sediment samples (Poppe and Polloni, 2000).

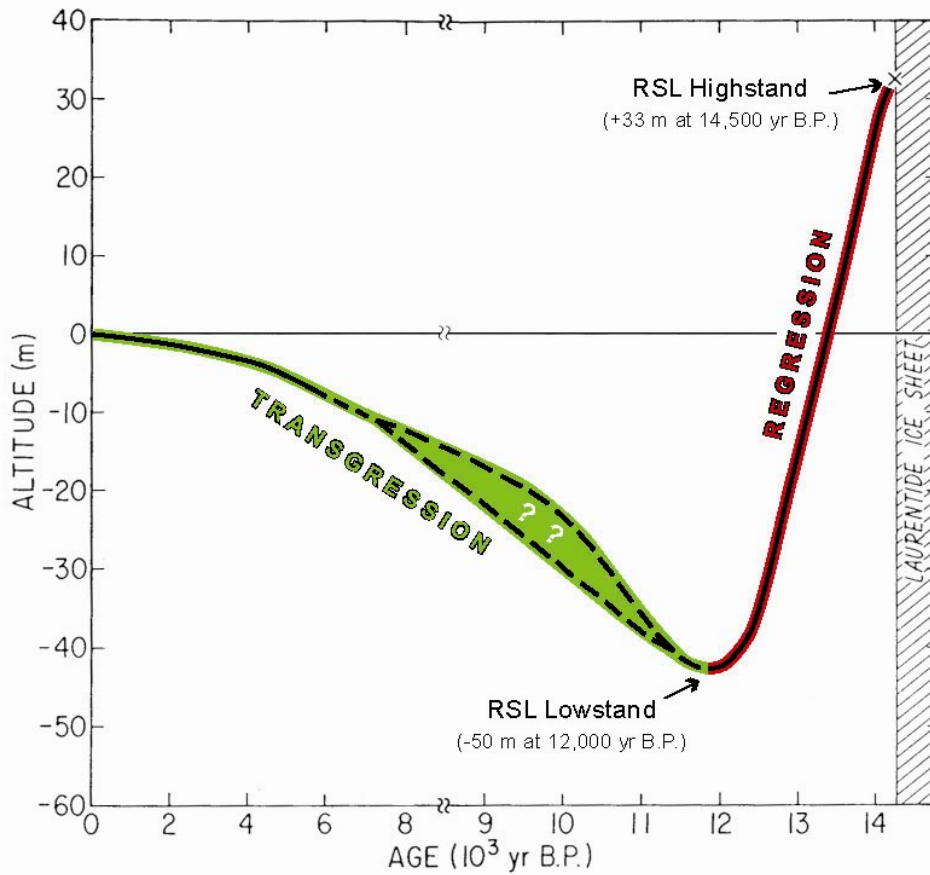


Figure 4.1. Late Quaternary relative sea-level curve for northeastern Massachusetts (modified from Oldale and others, 1993). Over the last 14,500 years, relative sea level fell from a highstand of about +33 m to a lowstand of about -50 m, and then rose at varying rates to the present. These large fluctuations in relative sea level drove regression (red shading) and transgression (green shading) of the shoreline across the inner continental shelf. The dashed lines indicate uncertainty in the sea-level data. Note that the age scale changes at 8,000 years B.P.

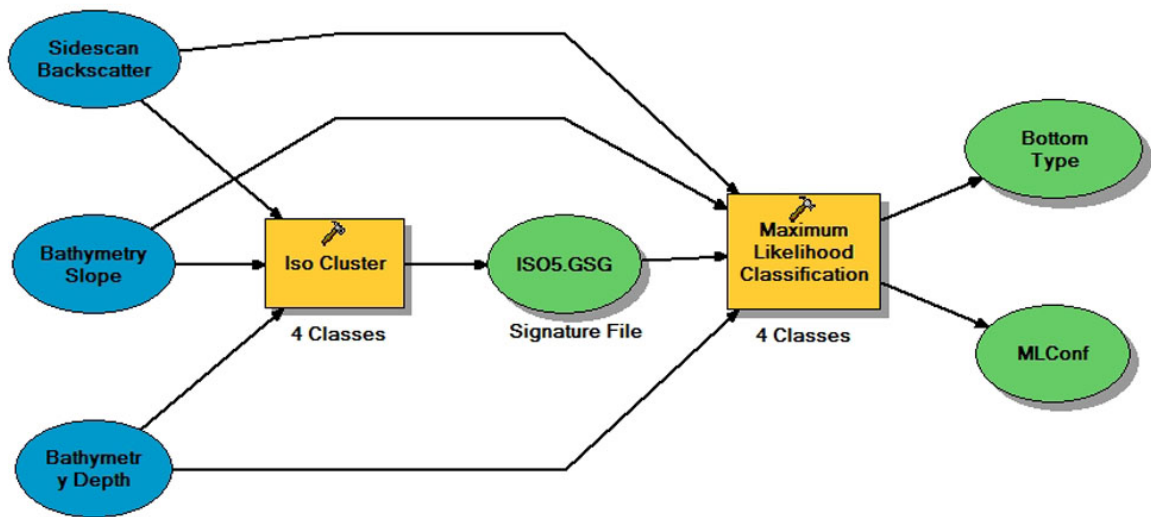


Figure 4.2. Model builder schematic of multivariate analysis, showing input data (depth, slope, acoustic backscatter) and processing steps used to create map in Figure 4.3.

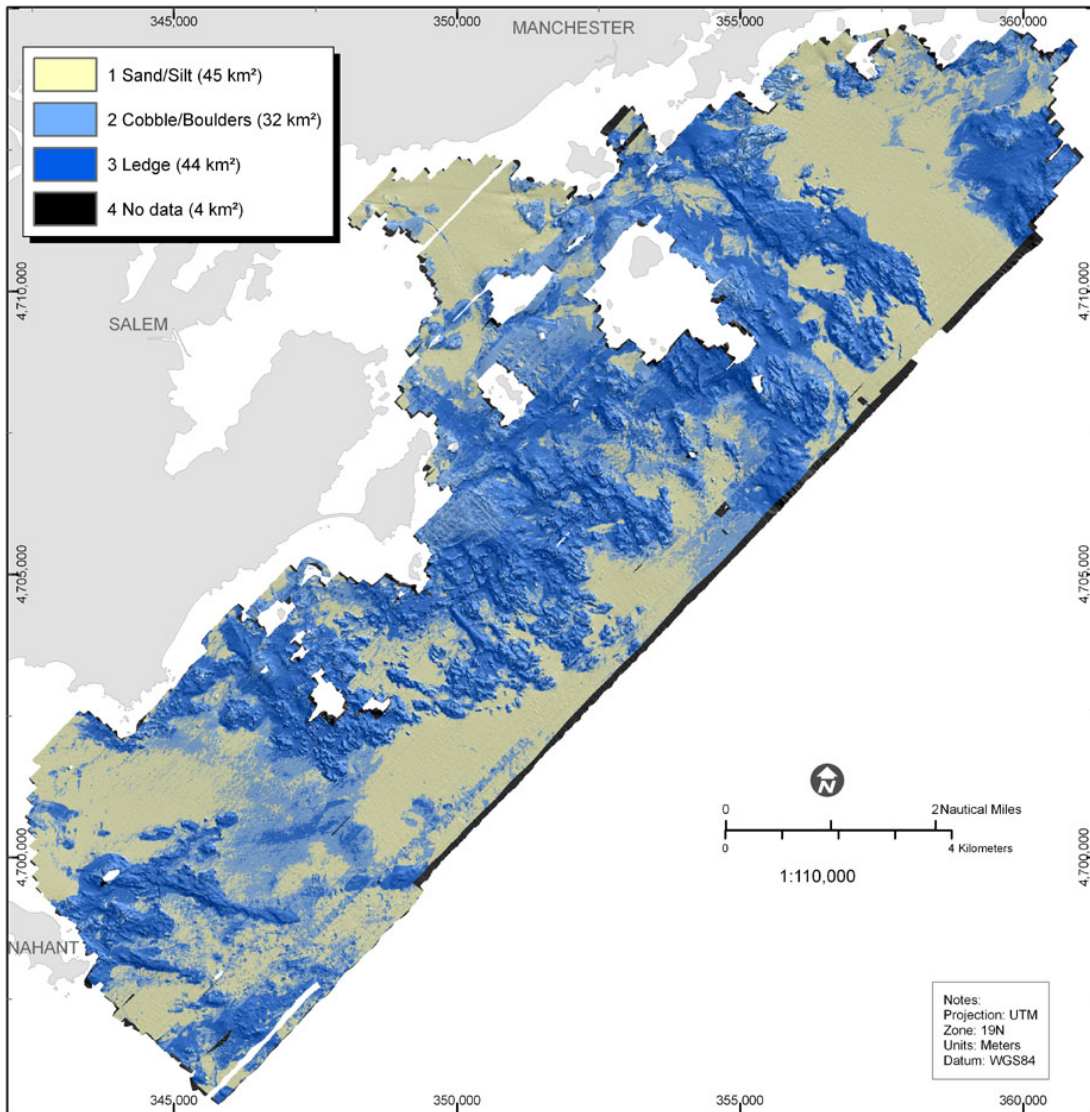


Figure 4.3. Map of generalized bottom type generated by multivariate analysis of seafloor properties.

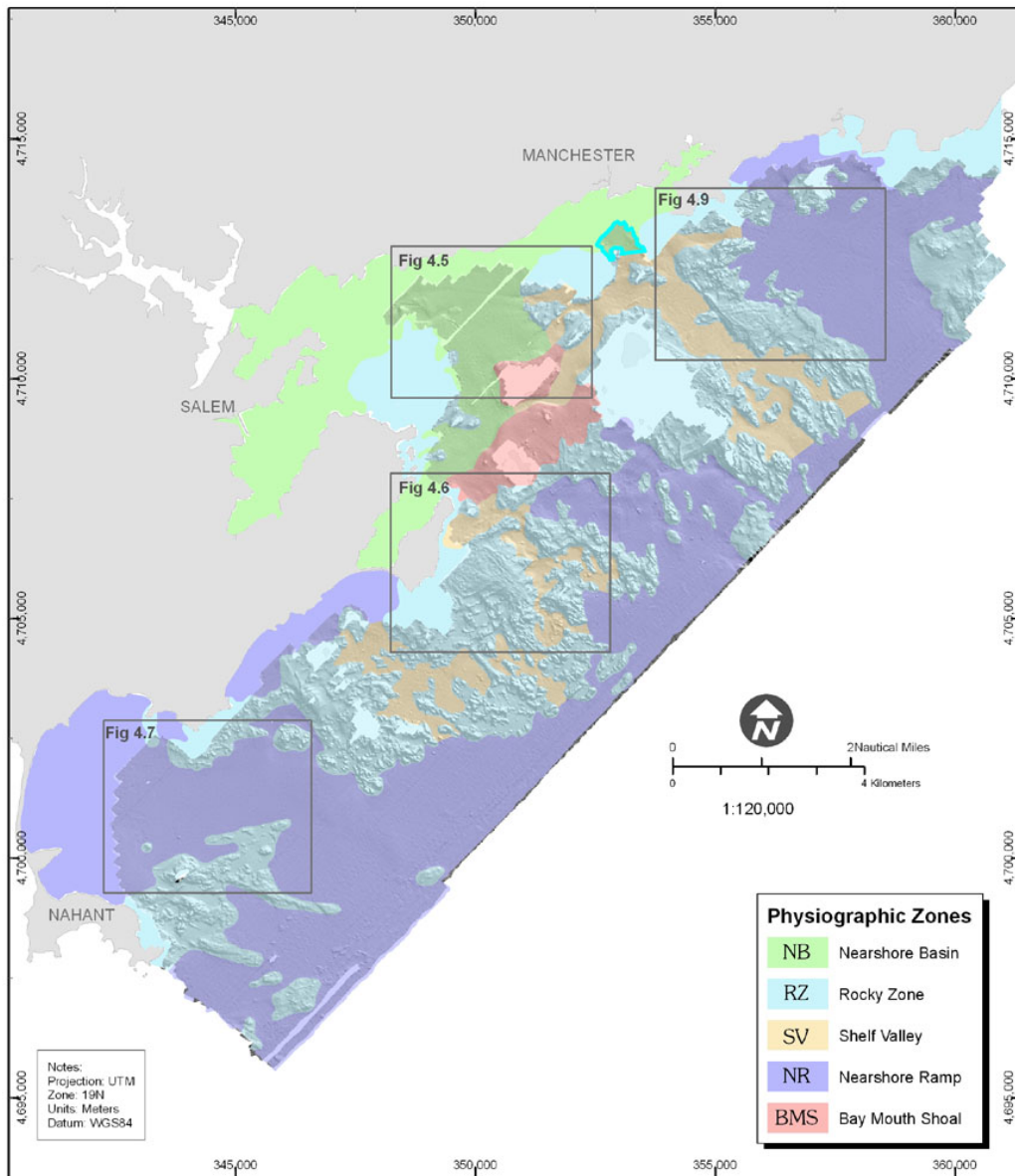


Figure 4.4. Map depicting the physiographic zones of the inner continental shelf. See text for description of zones. Index boxes show locations of inset maps in Figures 4.5, 4.6, 4.7, and 4.9.

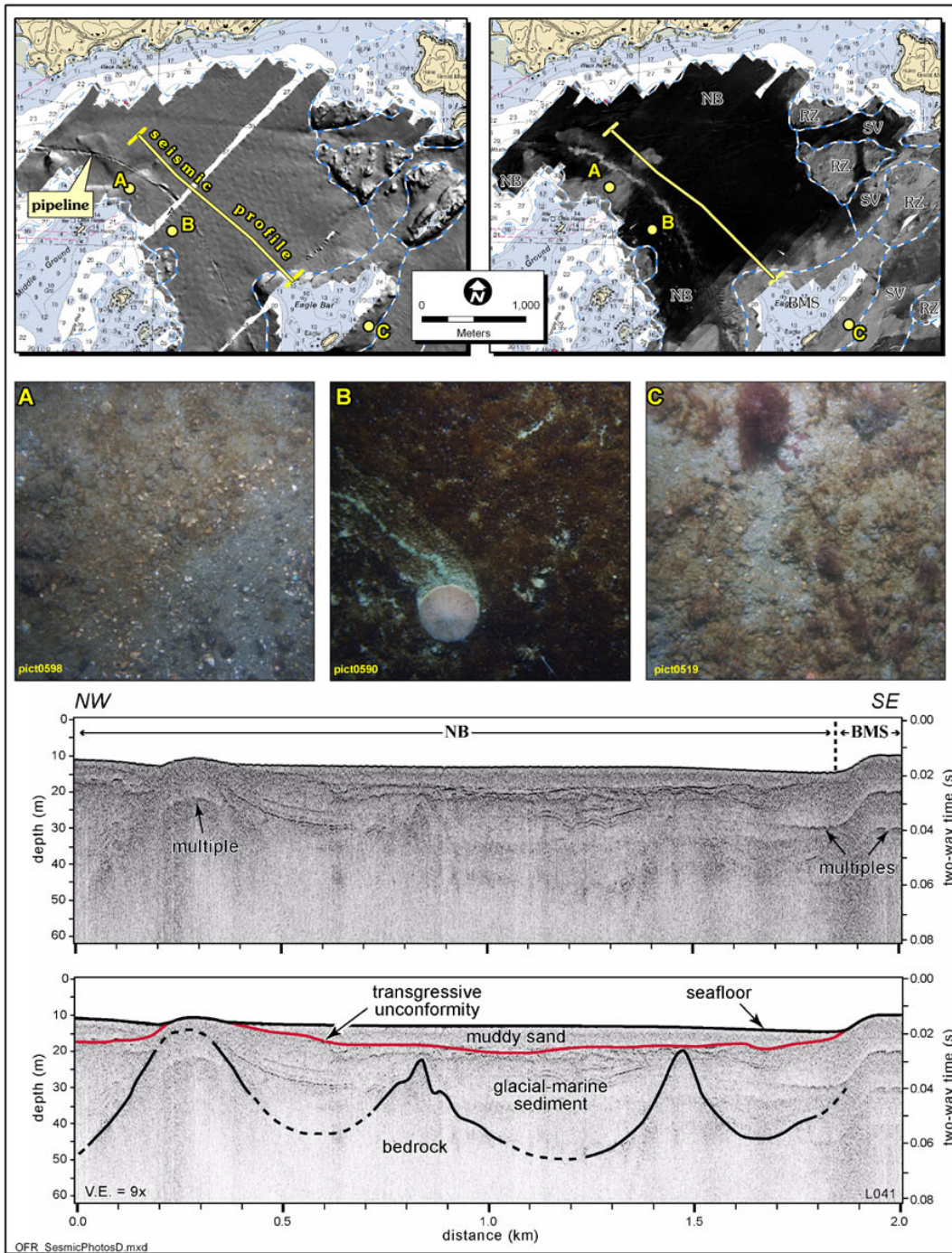


Figure 4.5. Maps of seafloor topography (upper left) and backscatter intensity (upper right) in Salem Sound. Both maps are overlain on NOAA-NOS nautical chart #13275. Dashed lines show boundaries of physiographic zones, which are based on seafloor topography and dominant substrate properties. See Figure 4.4 for location of maps. Bottom photographs A-C (middle) and seismic-reflection profile (bottom) are indicated by yellow circles and line, respectively. The distance across the bottom of the photographs is approximately 50 cm.

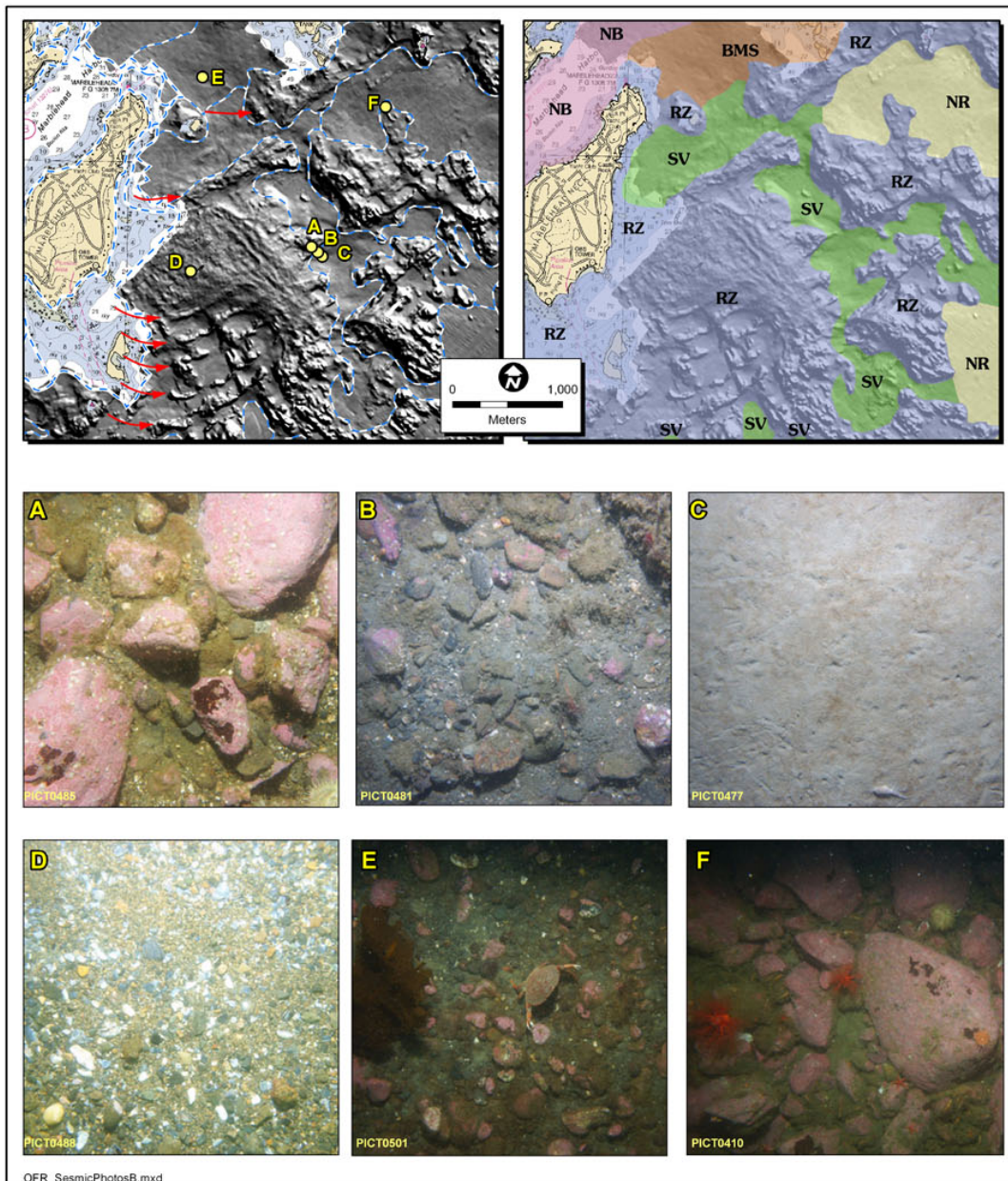


Figure 4.6. Shaded-relief map of seafloor topography (upper left) east of Marblehead Neck with red arrows indicating moraine segments. Map of physiographic zones in this area (upper right) is based on seafloor topography and dominant substrate properties. Both maps are overlain on NOAA-NOS nautical chart #13275. See Figure 4.4 for location of maps. Yellow circles indicate bottom photographs A-F (bottom). The distance across the bottom of the photographs is approximately 50 cm.

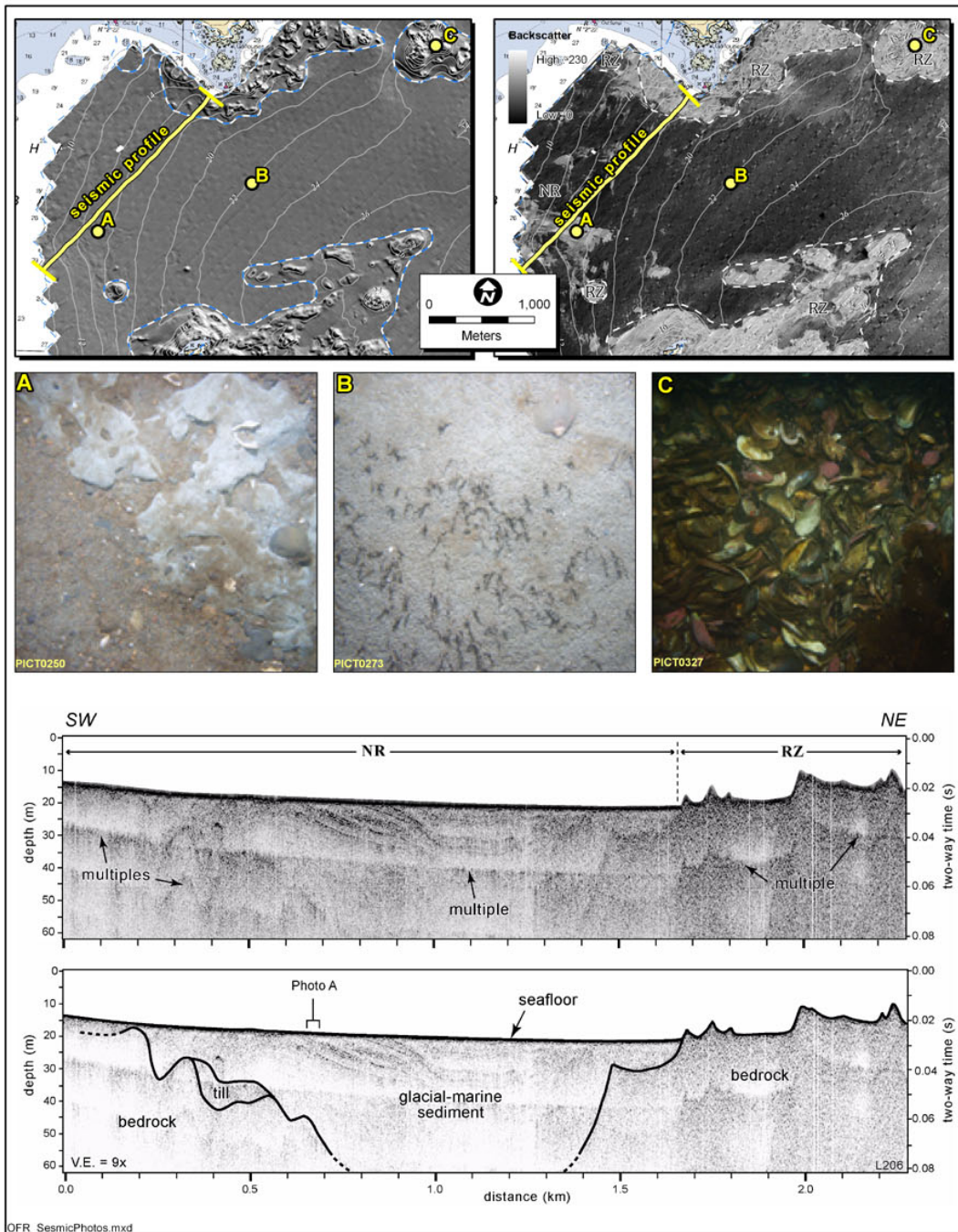


Figure 4.7. Maps of seafloor topography (upper left) and backscatter intensity (upper right) in Nahant Bay and approaches. Both maps are overlain on NOAA-NOS nautical chart #13275. Contour interval is 2 m. See Figure 4.4 for location of maps. Dashed lines show boundaries of physiographic zones, which are based on seafloor topography and dominant substrate properties. Bottom photographs A-C (middle) and seismic-reflection profile (bottom) are indicated by yellow circles and line, respectively. The distance across the bottom of the photographs is approximately 50 cm.

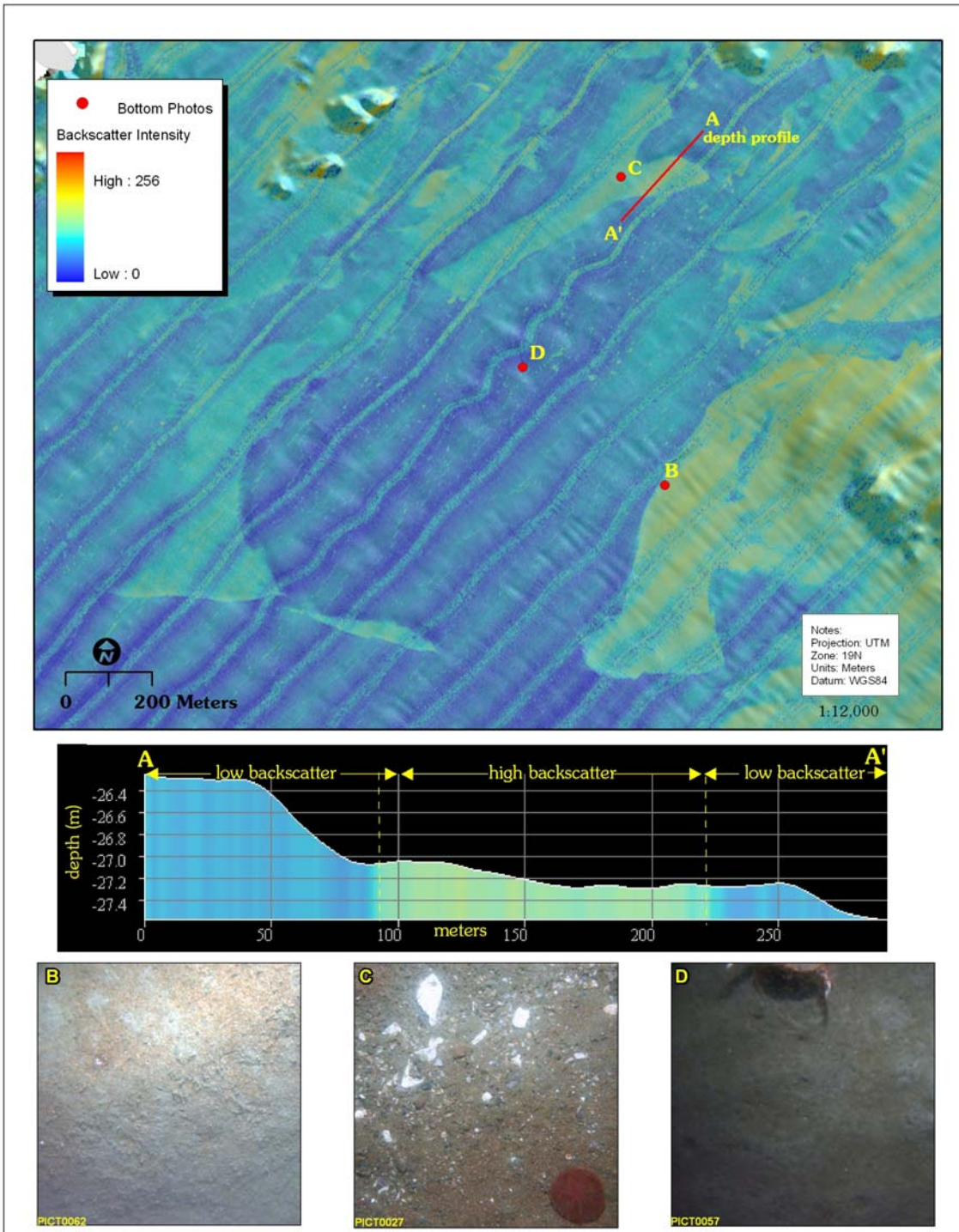


Figure 4.8. Map of seafloor topography colored by backscatter intensity in the northeastern part of the study area. Depth and backscatter data in this map were collected simultaneously by the pole-mounted interferometric sonar, ensuring precise navigation. The depth profile (A - A') crosses a sorted bedform in the upper part of the map; color coding on the profile shows high backscatter material on the floor of a shallow depression and high backscatter on adjacent, slightly elevated areas of the seafloor. Parallel stripes that trend SW-NE are artifacts of data collection. Bottom photographs B-D are indicated by red dots on the map. See figure 3.3 for location.

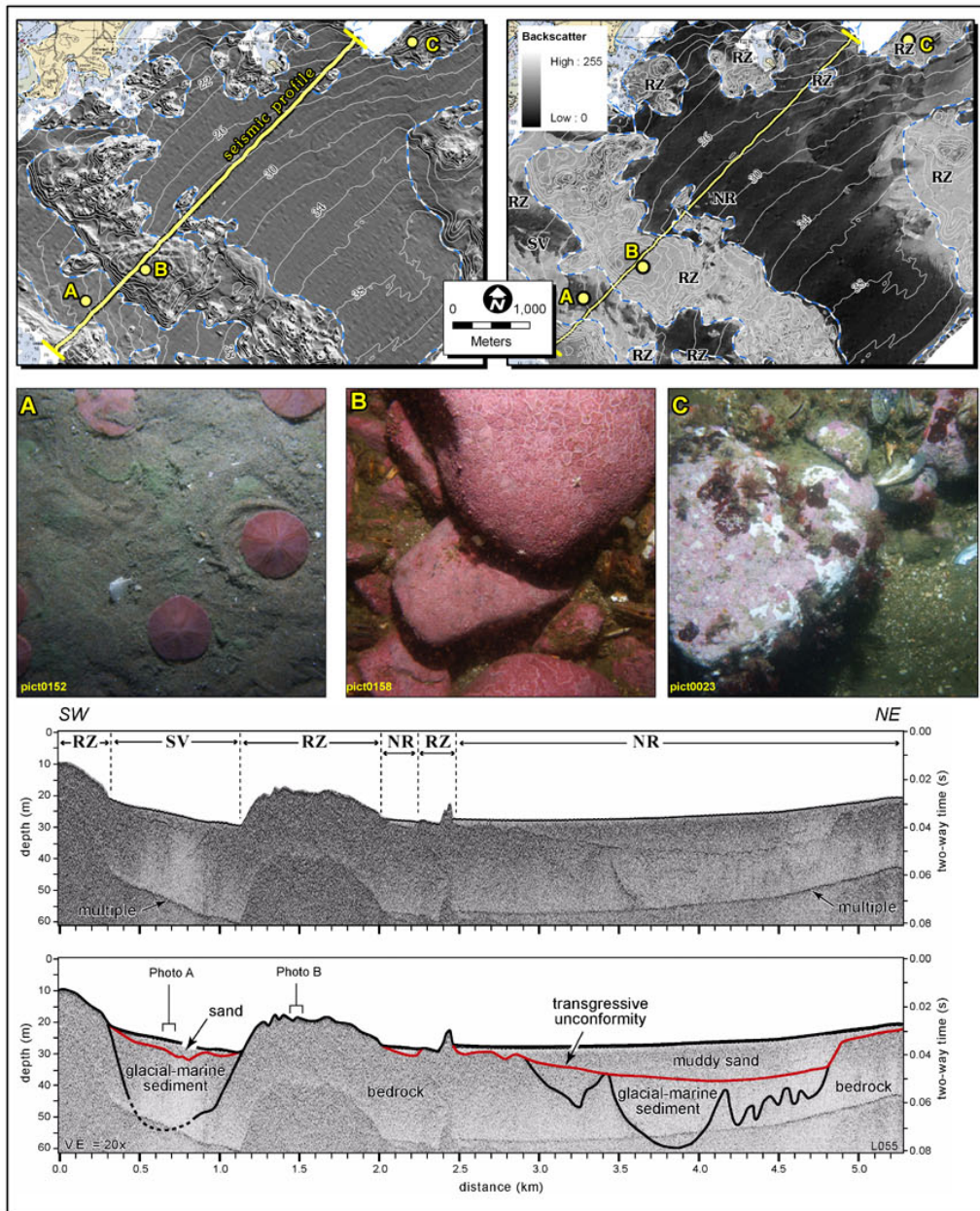


Figure 4.9. Maps of seafloor topography (upper left) and backscatter intensity (upper right) in the eastern part of the study area. Both maps are overlain on NOAA-NOS nautical chart #13275. Contour interval is 2 m. See Figure 4.4 for location of maps. Dashed lines show boundaries of physiographic zones, which are based on seafloor topography and dominant substrate properties. Bottom photographs A-C (middle) and seismic-reflection profile (bottom) are indicated by yellow circles and line, respectively. The distance across the bottom of the photographs is approximately 50 cm.

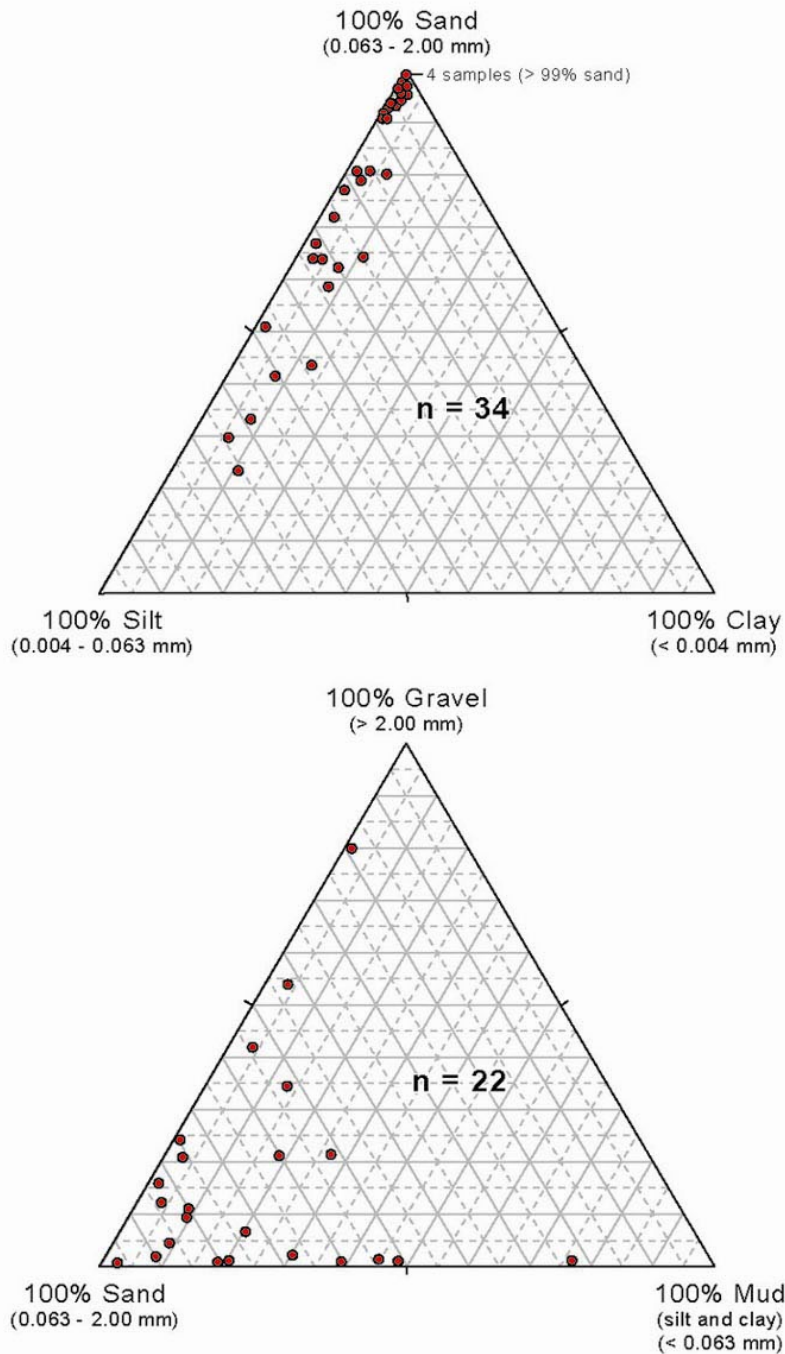


Figure 4.10. Ternary diagrams depicting the texture of surficial sediment collected in grab samples. The apexes of the diagrams represent 100% of the labeled textural component (i.e., gravel, sand, silt, and/or clay). The upper diagram depicts 34 samples that lack gravel; the lower diagram depicts 22 samples that contain at least 0.5% gravel. See table 4.2 for additional information on these samples.

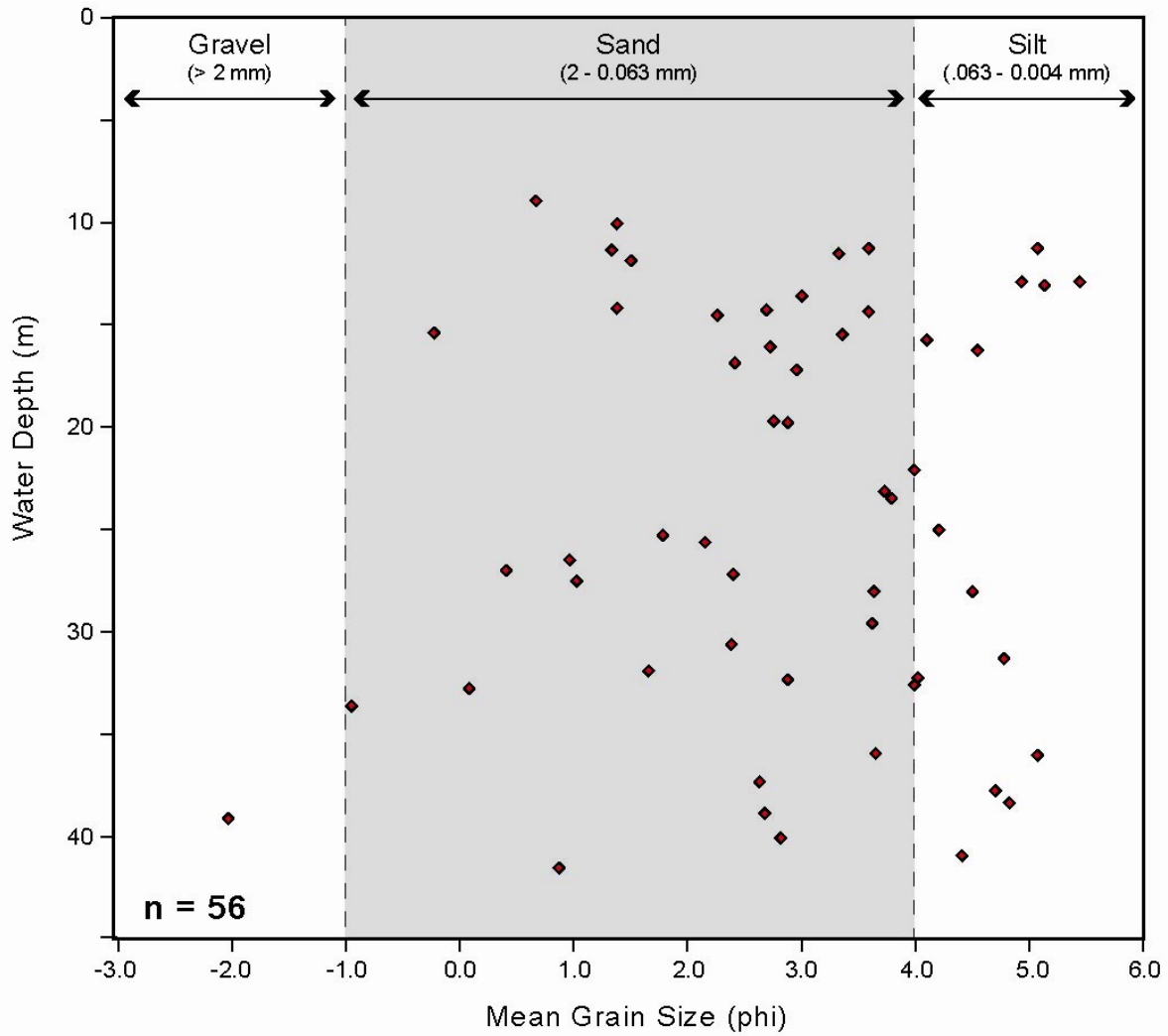


Figure 4.11. Graph depicting the mean grain size versus water depth of sediment samples collected at 56 stations in the survey area.