



Prepared in cooperation with the Massachusetts Office of Coastal Zone Management

High-Resolution Geologic Mapping of the Inner Continental Shelf: Cape Ann to Salisbury Beach, Massachusetts

By Walter A. Barnhardt, Brian D. Andrews, Seth D. Ackerman, Wayne E. Baldwin, and Christopher J. Hein

Open-File Report 2007-1373

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Suggested citation:
Barnhardt, W.A., Andrews, B.D., Ackerman, S.D., Baldwin, W.E., and Hein, C.J., 2009, High-resolution
geologic mapping of the inner continental shelf; Cape Ann to Salisbury Beach, Massachusetts: U.S.
Geological Survey Open-File Report 2007-1373, variously paged, DVD-ROM and available online at
<http://pubs.usgs.gov/of/2007/1373/>.

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Abstract

The geologic framework of the Massachusetts inner continental shelf between Cape Ann and Salisbury Beach has been shaped by a complicated history of glaciation, deglaciation, and changes in relative sea level. New geophysical data (swath bathymetry, sidescan sonar and seismic-reflection profiling), sediment samples, and seafloor photography provide insight into the geomorphic and stratigraphic record generated by these processes. High-resolution spatial data and geologic maps in this report support coastal research and efforts to understand the type, distribution, and quality of subtidal marine habitats in the Massachusetts coastal ocean.

Section 1 - Introduction

This report presents high-resolution maps and spatial data for the seafloor offshore of Massachusetts, between Cape Ann and Salisbury Beach. Approximately 325 km² of the inner continental shelf was mapped with a focus on water depths less than 100 m (fig. 1.1). The maps are the third in a series (Barnhardt and others, 2006; Ackerman and others, 2006) produced by a cooperative mapping program of the U.S. Geological Survey (USGS) and the Massachusetts Office of Coastal Zone Management (CZM). The maps are based on marine geophysical data, sediment samples, and bottom photography obtained on two research cruises in 2004 and 2005. The primary objective of this cooperative program is to develop 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 caused by natural or human impacts. The maps also provide a geologic framework for scientific research, industry, and the public.

The outline of this report is shown in the navigation bar along the left-hand margin. This is section 1, the introduction. Section 2 briefly describes the mapping products in this report and has links to large-format map sheets that can be viewed on line or downloaded. Section 3 fully describes 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. Appendices 1-4 contain all geophysical and sample data collected in the study.

Setting

The Cape Ann-Salisbury Beach study area lies in the western Gulf of Maine offshore of the northeastern Massachusetts coast (fig. 1.1). The general configuration of the shoreline and

inner shelf is controlled by the structure and composition of the regional bedrock framework. Late Quaternary glaciation and relative sea-level change have been the major processes shaping the coast and inner shelf in the region. Isostatic rebound following retreat of the Laurentide Ice Sheet has dominated the history of relative sea level and caused profound changes in the position of the coastline. A 10-km wide zone of the inner shelf has been extensively reworked by a transgression, a regression, and a second transgression over the last 14,500 years (fig. 1.2).

The Merrimack River, which drains approximately 12,900 km² in northeastern Massachusetts and south-central New Hampshire, discharges into the Gulf of Maine north of Cape Ann (fig. 1.1). The river catchment is dominated by granitic plutons in the White Mountains. The plutons have weathered to produce extensive sandy glacial deposits. Sandy sediment has been transported by the river to the coast at Plum Island and subsequently reworked in a southeasterly alongshore direction as a result of strong waves out of the northeast (FitzGerald and others, 2002). Sediment supplied by the river and derived from erosion of coastal and inner shelf deposits has built the longest chain of sandy barriers in the Gulf of Maine (FitzGerald and others, 1994). The barrier islands and spits stretch approximately 34 km from Ipswich Bay to the New Hampshire border and are pinned to bedrock or glacial promontories (fig. 1.3). Backbarrier environments consist primarily of marsh and tidal creeks that commonly open to small bays near the inlet openings (Smith and FitzGerald, 1994).

Mean tidal range is 2.5 m, with a spring tidal range of about 2.9 m. Wind directions vary seasonally with dominant winds from the southwest during spring and summer and from the northwest during fall and winter. Summer wave conditions are generally low energy with southerly swells. Tropical cyclones or hurricanes are rare, but extratropical storms that blow hard out of the northeast, locally known as Northeasters, strike the coast every year during the fall and winter. The storms produce strong winds and large waves that cause extensive erosion along the east-facing shorelines of Massachusetts. Storm winds blowing out of the southeast and southwest are less common and have less impact on the coast because of the sheltering effect of Cape Ann.

Section 2 - Maps

Five map sheets have been compiled showing the seafloor offshore of Massachusetts from Cape Ann to Salisbury Beach. The 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) 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 : 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 map of the seafloor

Section 3 - Data Collection and Processing

Field Program

Acoustic data from interferometric and multibeam echo sounders (bathymetry and backscatter), a sidescan sonar (backscatter), and a chirp seismic-reflection profiler (subsurface stratigraphy and structure) were used to map approximately 325 km² of the inner continental shelf. The mapping was conducted during two research cruises in 2004 and 2005, which respectively encompassed offshore and nearshore parts of the study area (fig. 1.1). The convention of referring to the relatively deep offshore and shallow nearshore areas is used throughout this report because data in each area were acquired using different technologies and survey designs. Methods used in the collection, processing, and analysis of the data are detailed in the following sections. A full description of the data-acquisition and processing steps is available in the metadata that accompany this report.

The first cruise was conducted in the offshore part of the study area (water depths 25–92 m) by Science Applications International Corporation (SAIC) aboard the RV *Ocean Explorer* (fig. 3.1) between February 23 and March 23, 2004. A multibeam echo sounder (MBES) was used to collect bathymetry and backscatter data, providing detailed imagery of 257 km² of the seafloor.

The second cruise was conducted in the nearshore part of the study area (water depths 2–30 m) by the USGS aboard the RV *Connecticut* (fig. 3.1) between September 8 and 20, 2005. The survey included 9 days of geophysical data acquisition and 3 days of sampling. Three acoustic systems (interferometric sonar, sidescan sonar, and chirp seismic-reflection profiler) were deployed simultaneously to collect bathymetry, backscatter, and subbottom data covering 68 km² of the seafloor. After the geophysical survey was completed, the ship was equipped to collect sediment samples, bottom photographs, and video of the seafloor.

Bathymetry

In the offshore area, a RESON 8101 MBES operating at a frequency of 240 kHz was used to acquire bathymetric and backscatter data (SAIC, 2004). The MBES was mounted on the keel of the ship. A Position and Orientation System for Marine Vessels (POS/MV) was mounted on the vessel centerline just forward and above the MBES transducer and recorded vessel position and attitude data. A Brooke Ocean Technology profiler measured sound velocity in the water column while the ship was underway. Survey lines were run at an average speed of 9 knots in a NW–SE orientation (fig. 3.2). Depending on water depth, tracklines were spaced 50, 75, 100, and 125 m apart to achieve 100 percent coverage of the seafloor. Data were processed by using Survey Analysis and Area Based Editor (SABER) software. Tidal offsets, calculated using a discrete tidal zoning model and observations from the National Oceanic and Atmospheric Administration (NOAA) Tidal Station #8418150 at Portland, Maine (NOS CO-OPS, 2005), were used to reference the soundings to the local mean lower low water (MLLW) datum. The bathymetric data have a vertical resolution of approximately 0.5 percent of water depth (SAIC, 2004). The final bathymetric grid (fig. 3.3) was mapped at a resolution of 5 m/pixel. Navigation for the offshore area utilized the signal from the U.S. Coast Guard Differential Global Positioning System.

In the nearshore area, bathymetry and backscatter data were collected with a SEA SwathPlus 234 kHz bathymetric system. The interferometric sonar was mounted on a rigid pole

on the starboard side of the ship with the transducers 3 m below the waterline. A TSS DMS 2-05 inertial-motion unit was mounted directly above the sonar transducers and recorded vessel position and attitude data. Sound-velocity profiles were collected approximately every 2 hours by a hand-casted Applied MicroSystems SV Plus Sound Velocimeter. Survey lines were run at an average speed of 5 knots in a NW-SE orientation (fig. 3.2). The lines were spaced 100 m apart to obtain 100 percent coverage of the seafloor. Data were processed and gridded by using the CARIS Hydrographic Information Processing System (HIPS ver. 6.1). The bathymetric data have a vertical resolution of approximately 1 percent of water depth. The final bathymetric grid (fig. 3.3) was mapped at a resolution of 5 m/pixel. Navigation for the nearshore area was based on a Real-Time Kinematic Global Positioning System (RTK-GPS). The RTK-corrected GPS signal was sent to the ship once every second from a base station established by the USGS on land. During post-processing, soundings were referenced to local MLLW by using orthometric to chart datum offsets obtained from NOAA Tidal Station #8440452 at the Parker River National Wildlife Refuge.

Acoustic Backscatter

In the offshore area, acoustic-backscatter and bathymetric data were collected simultaneously with the SAIC RESON MBES operating at a frequency of 240 kHz (SAIC, 2004; see Appendix V). The system has a 101-beam transducer that collects data in a continuous swath on either side of the vessel. Depending on water depth, survey tracklines were spaced 50, 75, 100, and 125 m apart to achieve 100 percent coverage of the area. The acquisition parameters for the MBES were maximized for collecting high-quality bathymetry instead of backscatter. These acquisition parameters included power and gain changes that produced a striping effect in the backscatter mosaic. The USGS reprocessed the raw MBES backscatter files in Generic Sensor Format (GSF) to minimize the power and gain artifacts by using a radiometric-correction technique developed by the Ocean Mapping Group and the University of New Brunswick (Beaudoin and others, 2002).

In the nearshore area, acoustic backscatter data were collected by using a Klein 3000 dual-frequency sidescan sonar (132/445 kHz) that was towed approximately 10 m off the bottom. Backscatter intensity is an acoustic measure of relative hardness and roughness of the seafloor (fig. 3.4). Data were acquired with Sonar Pro acquisition software and later corrected for beam angle and slant-range distortions by using Xsonar/Showimage as described in Danforth (1997). The 132-kHz data from each survey line were mapped at 1 m/pixel resolution in geographic space in Xsonar, imported as raw image files to Geomatica GPC works (PCI Geomatica ver 8.2), and combined into a mosaic. To correct for navigational uncertainties caused by towfish layback, the final mosaic was adjusted to match the bathymetry grid from the pole-mounted interferometric sonar. The mosaic was exported out of PCI as a georeferenced Tagged Image File Format (TIFF) image for further analysis in ArcGIS.

Seismic-Reflection Profiling

Seismic-reflection profiles reveal the subsurface stratigraphy and geologic structure of the inner shelf. Approximately 1100 km of high-resolution chirp seismic-reflection profiles (fig. 3.2) were collected by using an EdgeTech Geo-Star FSSB system and an SB-0512i towfish (0.5–12 kHz). Delph Seismic+Plus acquisition software (Triton Elics International, Inc.) was used to control the topside unit and digitally log data in the SEG-Y rev. 1 standard format. Data were acquired at a 0.25-s shot rate, a 9-ms pulse length, and a 0.5–6.0 kHz frequency sweep. Trace

lengths were adjusted between 100–200 ms to account for changes in water depth. The SB-0512i was towed approximately 10 m astern and 3 m below the sea surface. Navigation was obtained from the GPS receiver mounted above the interferometric sonar head. On the basis of horizontal offsets between the towfish and GPS receiver, the positional accuracy was estimated to be ± 20 m.

Raw SEG-Y data were postprocessed with two Unix-based programs. SIOSEIS (Scripps Institution of Oceanography) was used for amplitude-based seafloor picking and heave filtering, and Seismic Unix (Colorado School of Mines) was used to generate ASCII-formatted navigation files and JPEG compressed images of the profiles. Navigation and processed SEG-Y data were imported into SeisWorks (Landmark Graphics, Inc.) for digital interpretation. Reflections representing the tops of geologic units and unconformities were digitized to produce two-way travel time horizons. A constant seismic velocity of 1500 m/s through water and sediment was used to convert travel time to distance. Isopachs of total sediment thickness (i.e., sediment between bedrock and the seafloor) and Holocene sediment thickness (i.e., sediment overlying the transgressive unconformity) were exported at 30-shot intervals to produce ASCII point files containing shot position and associated thickness (figs. 3.5 and 3.6).

Triangulated Irregular Network (TIN) surfaces were created from the ASCII point files and converted to regular grid (50 m/pixel) by using natural neighbors within ArcGIS 9.2. An additional grid representing the transgressive unconformity (fig. 3.7) was generated by subtracting the isopach of Holocene sediment thickness from the gridded bathymetry. Values from the gridded bathymetry were extracted at locations coincident to the points defining the Holocene sediment thickness. Positive thickness values were then subtracted from the negative bathymetric values at each point, resulting in points representing the approximate elevation of the Holocene transgressive unconformity (relative to MLLW). This point file was then used to generate a continuous, interpolated 50 m/pixel raster grid. Utilization of isopach surfaces to generate these grids effectively removes the inherent static and time-varying vertical offsets associated with tidal fluctuations and deep towing of the SB-0512i towfish.

Ground Validation

In both the offshore and nearshore areas, geophysical data were validated with samples of surficial sediments and photographs of the seafloor. A total of 87 locations were occupied for sampling and photography with the USGS SEABed Observation and Sampling System (SEABOSS; Valentine and others, 2000) (fig. 3.8). Stations were selected to characterize backscatter transitions and broad areas of uniform backscatter intensity (fig. 3.9). At each station, the SEABOSS was towed, or drifted with the current, over the bottom at speeds of 1 to 3 knots. The recorded positions are actually the positions of the RTK-GPS antenna on the survey vessel, not the SEABOSS sampler, which was deployed from the stern of the vessel. Because no layback or offset was applied to the recorded position, the estimated horizontal accuracy of the SEABOSS location is ± 40 m. Continuous video was collected, usually for 5 to 15 minutes, and photographs were obtained from a still camera at all locations. Sediment samples were usually collected at the end of each tow. To prevent damage to sampling gear, no samples were collected in rocky, hardbottom areas. The upper 2 cm of sediment were taken from the surface of the sediment sample for textural analysis. All samples were analyzed for grain size by using standard procedures described in Poppe and others (2005). Additional sediment-texture data are available for the region (Reid and others, 2005). Although not included in this report, those data closely corroborated the bottom-type characterization in this study.

Section 4 - Geologic Interpretation

Mapping Seafloor Geology

The seafloor in the Gulf of Maine is geologically complex because of its late Quaternary history of glaciation and sea-level change. In rocky areas, the rugged seafloor exhibits abrupt changes in water depth (fig. 3.3), and different substrates create a distinct patchiness that changes over distances of only a few meters (fig. 3.4). For example, high-relief bouldery glacial deposits (till) are locally 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 ponded in small cracks and other low-lying areas between rock outcrops. These variations occur over spatial scales that are smaller than a typical sampling grid can resolve. Early efforts to characterize the texture of seafloor sediments at regional scales were based on bottom samples collected at widely spaced locations (Trumbull, 1972; Hollister, 1973; Schlee, 1973; Folger and others, 1975; Poppe and others, 1989), but this sampling scheme would be impractical on most parts of the Massachusetts inner continental shelf. An extraordinarily large number of closely spaced samples would be required to fully characterize the variations in bottom type that exist in the region.

This study integrates remotely sensed geophysical data with bottom samples and underwater photography to characterize seafloor geology at a broad, regional scale. Two different approaches are used to depict the nature and distribution of rocks and sediment deposits on the inner shelf: a qualitative classification based on geologic interpretation and a more quantitative bottom classification based on statistical methods.

1. Interpretive geologic mapping readily incorporates a wide range of different data. For example, air photographs and field observations can be used to extrapolate mapped units into shallow-water areas along the coast where survey ships cannot reach. An experienced marine geologist can also interpret data that are acquired with different sonar systems and data that contain noise or artifacts. In addition, the interpretive maps can be constructed on the basis of unevenly distributed or relatively sparse data, such as the sediment samples, seafloor photographs, and seismic-reflection data in the offshore part of this study.
2. The quantitative bottom classification is currently being developed, and only preliminary results are presented here. This approach works best where uniformly high-quality data completely cover the seafloor. In this study, therefore, the classification was limited to the nearshore area where high-quality backscatter data from a towed sidescan sonar were available. The classification was not extended to the offshore area where backscatter data were collected with a MBES.

Interpretive Geologic Mapping

The geology of the study area is characterized on the basis of seafloor morphology, sediment thickness, and the type of surficial materials. This description results in a classification scheme with five environments or physiographic zones: Rocky Zones, Nearshore Ramps, Ebb-Tidal Deltas, Shelf Valleys, and Outer Basins (fig. 4.1). Maps using these zones provide a broad regional view of seafloor geology and have been produced for other areas in the Gulf of Maine that are similar to the Massachusetts inner shelf (Kelley and others, 1989; Kelley and Belknap, 1991; Barnhardt and Kelley, 1995; Barnhardt and others, 1996). The zones are described below in terms of their size, morphology, physical setting, and substrate properties.

Rocky Zone

Rocky Zones (RZ) are rugged areas of high relief and hard bottom. Ledge and coarse-grained sediment in these areas produce extreme bathymetric relief ranging from nearly vertical rock cliffs to relatively flat, gravel-covered plains littered with large boulders (fig. 4.2).

Although local areas of ledge and coarse-grained sediment are in all physiographic zones, they dominate the seafloor in Rocky Zones. In general, sediment thickness is 1 m or less. Abundant shell fragments locally accumulate in sediment ponds that fill low-lying troughs. The ponded sediment is covered with bedforms and gravelly scour surfaces that are evidence of active reworking by waves and bottom currents. The sandy bedforms are variously classified as megaripples or subaqueous dunes (Ashley, 1990) with wavelengths of 15 to 20 m.

Areas of Rocky Zone were found in four general locations (fig. 4.1). The largest expanses were in the northern and southern parts of the study area, representing the offshore extensions of hard granitic rocks that underlie the adjacent coast (Zen and others, 1983). Rocky Zones primarily consist of ledge and coarse-grained talus with shells of benthic-dwelling organisms around the base of outcrops. These high-relief areas are offshore of Salisbury Beach as part of a prominent series of rock outcrops that trend northeastward towards the Isles of Shoals and surround the northern coast of Cape Ann as a narrow band.

Relatively small, separate patches of Rocky Zone are unevenly distributed throughout the central part of the study area. They range from 2500 m² (approximately 50 m by 50 m, the smallest mappable unit) to 2 km² in area and from elongate to circular in plan view, commonly with a highly irregular outline. These moderate-relief, acoustically reflective features are seaward of the Merrimack River mouth in a broad, widely spaced series that extends in a generally SW-NE direction and seaward of the entrance to Plum Island Sound in an isolated group about 5 km offshore.

Rocky Zones are the third largest physiographic element, composing 18.3 km² or 5.1 percent of the study area (table 4.1). Water depths above Rocky zones range from 0 to 90 m.

Table 4.1. Description of physiographic zones.

ZONE	DESCRIPTION	AREA (km ²)	AREA (percent)
Rocky Zone (RZ)	rugged, high-relief outcrops; bedrock, boulders and gravel; water depths 0–90 m	18.3	5.1
Nearshore Ramp (NR)	gently seaward sloping; sand and gravel; complex bedforms; water depths 0–50 m	228.4	63.9
Ebb-Tidal Delta (ETD)	broad platforms seaward of inlets; sandy; lobate in plan view; water depths < 8 m	10.6	3.0
Shelf Valley (SV)	elongate depressions with rocky walls; sand and gravel in thalwegs; water depths 12–25 m	1.1	0.3
Outer Basin (OB)	expansive, smooth seafloor; muddy; thick sediment deposits; water depths > 50 m	99.1	27.7
Total		357.5*	100.0

*In addition to areas completely imaged with sonar, the geologic map in figure 4.3 includes adjacent shallow-water areas along the coast.

Nearshore Ramp

Nearshore Ramps (NR) are gently sloping areas of sandy or gravelly seafloor that lie offshore of sandy beaches. This zone exhibits generally shore-parallel bathymetric contours and is primarily covered with sand-rich sediment, although locally small exposures of ledge, cobbles, and boulders are also on the seafloor. Nearshore Ramp terminates on the landward side against the mainland shoreline. On the seaward side, it extends about 10 km offshore to a depth of 50 m, where it merges with muddy sediment in the deeper Outer Basin (fig. 4.3).

The extensive Nearshore Ramp abuts sandy beaches from Salisbury Beach in the north to Coffins Beach in the south (fig. 4.1). The generally smooth, seaward-dipping seafloor is underlain by Holocene fluvial, deltaic, and littoral sediments that have accumulated above Pleistocene glacial and glacial-marine deposits. Relative ages of these deposits are determined from stratigraphic superposition, primarily whether they lie above or below the transgressive unconformity that separates the Pleistocene and Holocene sedimentary sequences. The transgressive unconformity lies at or very near the seafloor beneath a relatively thin, discontinuous cover of sandy Holocene sediment (fig. 4.4). This mobile Holocene sediment is up to 9 m thick (fig. 3.6). Analysis of the sediment-thickness map indicates that the sandy surficial deposit contains an estimated volume of 121 million m³. The deposit mainly consists of fine-grained sand with a gravelly lag at the base that coincides with the transgressive unconformity. It is important to note, however, that the seismic-reflection system is not able to resolve sediment thicknesses less than 0.5 m. Therefore, the volume is a conservative estimate because it is based on the assumption that Holocene sediment is absent over relatively large areas of the inner shelf. The actual volume would increase if those areas, shown by the dark gray shading in figure 3.6, were covered with a layer of Holocene sediment that is 0.5 m thick. In the offshore area, the volume of Holocene sediment was not calculated because the spacing between seismic-reflection profiles was too wide.

A complex mosaic of surficial sediment covers the Nearshore Ramp, which is characterized by numerous, irregularly shaped patches of high- and low-backscatter intensity (fig. 3.4). The different patches of sediment are distinguished by sharp boundaries, giving the seafloor an overall mottled appearance. Sediment texture differs significantly across the backscatter transitions. High-backscatter patches represent coarse sand to fine gravel (mean is 0.6 phi) and are characterized by small two-dimensional dunes (Ashley, 1990) with wavelengths of about 1 m. Low-backscatter patches represent fine to medium sand (mean is 2.4 phi) that are characterized by long-wavelength (100–800 m), asymmetrical bedforms. The amplitudes of these broad, low-relief bedforms typically range from 10 to 50 cm but locally can exceed 1 m. The slightly elevated crests exhibit low backscatter, whereas adjacent, shallow troughs (topographic depressions) exhibit high backscatter (fig. 4.5). The bedforms exhibit variable orientations, which indicates that different processes are acting to move sediment in different directions (Hein and others, 2007).

The smooth, generally sandy seafloor of the Nearshore Ramp is the most prominent physiographic element, composing 228.4 km² or 63.9 percent of the study area (table 4.1). Water depths range from 0 to 50 m.

Ebb-Tidal Delta

Ebb-Tidal Deltas (ETD) are sandy shoals and tidal channels located on the seaward sides of inlets. These broad, shallow platforms are lobate in plan view, have relatively steep slopes along their seaward-facing margins, and extend about 1.5 km offshore from the coast. In the

study area, ebb-tidal deltas are characterized by fine to medium sand that was deposited where tidal currents exit an inlet and interact with waves and currents of the open ocean (FitzGerald and others, 2002). The sandy shoals are dynamic features that evolve over time in response to changes in the magnitude and direction of local sediment-transport processes.

Ebb-tidal deltas have formed seaward of three inlets along the barrier-island chain north of Cape Ann: (1) the Merrimack River mouth, (2) the entrance to Plum Island Sound, and (3) the entrance to Essex Bay (fig. 4.1). Only small areas along the terminal lobes of these shoal features were imaged in this survey because of shallow water. The lobes were delineated largely based on interpretations of air photographs and NOAA nautical charts 1378, 1379, and 1382. Large jetties built at the mouth of the Merrimack River and extensive dredging of the navigation channel have greatly altered the natural system. The ebb-tidal deltas associated with Plum Island Sound and Essex Bay merge into a single broad platform that extends offshore of Castle Neck and Coffins Beach. No jetties have been built at these inlets.

Ebb-tidal deltas compose 10.6 km² or 3.0 percent of the study area (table 4.1). Water depths are less than about 8 m.

Shelf Valley

Shelf Valleys (SV) are elongate depressions that cut through areas of Rocky Zone (fig. 4.4). Sediment in Shelf Valleys is highly variable, ranging from gravel to muddy sand. Highly reflective aprons of coarse material with abundant shell fragments typically lie adjacent to rocky, bouldery walls that form the valley margins. The single sediment sample that was collected from a Shelf Valley contained 50 percent gravel and 47 percent sand, with a mean grain size of -0.99 phi, one of the coarsest sediment textures found in this study (table 4.2).

Shelf Valleys were formed only in the northern part of the study area, where they generally trend from NE to SW (fig. 4.1). The valleys are small, measuring less than 0.5 km wide and up to 2 km long, but clearly extend beyond the mapped area. They have a gently sloping bottom and, in plan view, exhibit a branching geometry that is analogous to dendritic river valleys on land. The valleys probably formed by fluvial erosion during times of lower sea level, although they have no obvious terrestrial source; the heads of the small valleys do not correlate with modern stream valleys onshore. They terminate on their seaward end against Nearshore Ramps in water depths of 20 to 25 m.

Of all the physiographic elements mapped in this study, Shelf Valley is the smallest, composing only 1.1 km² or 0.3 percent of the study area (table 4.1). Water depths range from about 12 to 25 m.

Outer Basin

Outer Basins (OB) are extensive areas of muddy seafloor that generally form the seaward border of the inner continental shelf of New England. The basins lie in water deeper than 50 m, below the depth of the postglacial lowstand of sea level, and might reach depths of over 300 m in the outer Gulf of Maine (Kelley and others, 1989). The generally flat seafloor exhibits low backscatter in sidescan-sonar imagery but also includes isolated deposits of coarse-grained sediment and bedrock outcrops (fig. 4.6). The 20 sediment samples collected from the Outer Basin (Table 4.2) range in texture from fine sand (mean is 2.4 phi) to clayey silt (mean is 7.5 phi).

Table 4.2. Location, depth, and textural properties for bottom samples collected as part of this study. Additional sediment data are available in appendix I (GIS database) and appendix II (Excel spreadsheet). Links to bottom photographs at each station are in appendix III.

Station	Zone	Depth (m)	Latitude	Longitude	Sand %	Silt %	Clay %	Gravel %	Description (Folk, 1974)
01	NR	17	42.7766	-70.7812	NoGrab				
02	NR	27	42.7760	-70.7418	99.3	0.5	0.2	0.0	S
03	NR	29	42.7772	-70.7397	38.5	0.1	0.0	61.3	sG
04	NR	32	42.8002	-70.7373	98.7	0.8	0.4	0.1	S
05	NR	34	42.8003	-70.7219	62.0	0.5	0.3	37.3	sG
06	NR	38	42.7932	-70.7014	84.7	0.2	0.1	15.1	gS
07	NR	39	42.7940	-70.6958	98.8	0.7	0.5	0.0	S
08	NR	40	42.8148	-70.7055	51.2	0.5	0.3	48.0	sG
09	OB	52	42.8172	-70.6758	92.8	3.5	3.4	0.4	S
10	RZ	76	42.8172	-70.6280	29.3	27.2	17.7	25.8	gsM
11	OB	85	42.8302	-70.6157	2.2	59.0	38.8	0.0	M
12	RZ	71	42.8475	-70.6236	No Grab				
13	RZ	70	42.8448	-70.6385	No Grab				
14A	RZ	67	42.8583	-70.6588	38.1	25.2	11.0	25.7	gmS
15	OB	56	42.8695	-70.6856	33.7	42.0	24.3	0.0	sM
16A	NR	40	42.8628	-70.7247	91.8	4.4	2.9	0.8	(g)S
16B	NR	39	42.8636	-70.7276	55.8	0.2	0.1	43.9	sG
17	NR	38	42.8547	-70.7372	90.0	6.5	2.4	1.1	(g)S
18	NR	32	42.8628	-70.7571	89.2	0.8	0.3	9.8	gS
19	NR	31	42.8598	-70.7625	93.6	0.6	0.3	5.6	gS
20	NR	31	42.8631	-70.7656	97.6	1.7	0.6	0.0	S
21	SV	30	42.8677	-70.7742	46.5	2.5	1.0	50.0	sG
23	NR	26	42.8515	-70.7776	99.0	0.5	0.3	0.2	S
24	NR	26	42.8422	-70.7803	99.1	0.6	0.3	0.0	S
25	NR	30	42.8300	-70.7556	81.0	0.3	0.1	18.6	gS
26	RZ	27	42.8109	-70.7517	98.9	0.9	0.3	0.0	S
27	NR	27	42.8093	-70.7630	97.2	0.2	0.1	2.5	(g)S
28	NR	23	42.7757	-70.7652	99.2	0.5	0.2	0.2	S
29	NR	20	42.7614	-70.7669	97.8	2.0	0.3	0.0	S
30	NR	19	42.7503	-70.7631	88.6	1.2	0.1	10.1	gS
31	NR	19	42.7488	-70.7581	84.9	0.8	0.2	14.1	gS
32	NR	26	42.7406	-70.7294	89.8	5.8	0.7	3.7	(g)S
33	NR	29	42.7361	-70.7174	59.0	33.5	7.5	0.0	mS
34	RZ	18	42.7285	-70.7041	No Grab				
35	NR	27	42.7145	-70.7001	94.1	1.6	0.5	3.8	(g)S
36	NR	32	42.7235	-70.6849	81.2	1.0	0.3	17.5	gS
37	NR	36	42.7191	-70.6582	97.9	1.5	0.6	0.1	S
38	NR	36	42.7414	-70.6742	99.1	0.7	0.3	0.0	S
39	NR	47	42.7428	-70.6492	95.2	3.4	1.4	0.0	S
40	OB	62	42.7500	-70.6392	81.6	12.5	6.0	0.0	mS
41	OB	74	42.7548	-70.6101	39.0	33.0	28.0	0.0	sM
42	NR	42	42.7152	-70.6122	97.0	1.9	0.9	0.1	S
43	NR	29	42.6973	-70.6050	96.5	2.5	1.0	0.0	S
45	NR	29	42.6984	-70.6152	96.7	3.0	0.4	0.0	S
46	NR	37	42.7093	-70.6409	93.2	4.7	2.0	0.0	S

47	RZ	31	42.7323	-70.6909	No Grab				
48	NR	33	42.7395	-70.6935	98.3	1.2	0.5	0.0	S
49	NR	32	42.7456	-70.6996	99.0	0.5	0.3	0.2	S
50	NR	34	42.7517	-70.6899	98.8	0.8	0.4	0.0	S
51	NR	36	42.7534	-70.6835	98.3	1.0	0.7	0.1	S
52	NR	35	42.7598	-70.6867	96.5	0.4	0.3	2.8	(g)S
53	NR	28	42.7541	-70.7227	98.4	1.0	0.3	0.4	S
54	NR	25	42.7597	-70.7265	82.1	0.8	0.3	16.9	gS
55	NR	25	42.7615	-70.7238	77.7	0.4	0.2	21.8	gS
56	NR	25	42.7628	-70.7190	99.5	0.4	0.1	0.0	S
57	NR	27	42.7639	-70.7151	96.5	1.2	0.5	1.8	(g)S
58	NR	29	42.7646	-70.7107	99.3	0.4	0.2	0.1	S
59	NR	38	42.7694	-70.6921	97.8	0.4	0.4	1.5	(g)S
60	OB	61	42.7777	-70.6651	80.2	14.9	4.9	0.0	mS
61	OB	76	42.7861	-70.6354	21.4	51.6	27.1	0.0	sM
63	OB	87	42.7954	-70.6039	4.2	56.8	39.0	0.0	M
64	OB	62	42.7992	-70.6685	79.7	14.3	5.9	0.0	mS
65	NR	50	42.7951	-70.6751	95.2	2.9	1.6	0.3	S
66	NR	41	42.7828	-70.6881	97.1	1.9	0.7	0.3	S
67	NR	33	42.7817	-70.7130	98.7	0.5	0.3	0.5	(g)S
68	NR	39	42.8187	-70.7261	93.3	4.4	1.6	0.8	(g)S
69	RZ	36	42.8312	-70.7156	No Grab				
70	NR	47	42.8271	-70.6949	94.8	3.3	1.9	0.0	S
71	OB	56	42.8338	-70.6747	89.3	6.7	2.8	1.2	(g)S
72	NR	42	42.8421	-70.7094	96.9	2.0	0.9	0.2	S
73	RZ	31	42.8426	-70.7275	99.8	0.1	0.1	0.1	S
74	NR	40	42.8368	-70.7300	80.9	9.1	5.2	4.8	(g)mS
75	NR	30	42.8491	-70.7588	No Grab				
76	RZ	21	42.8162	-70.7609	No Grab				
77	NR	19	42.8374	-70.7935	96.1	0.9	0.3	2.7	(g)S
78	NR	10	42.8303	-70.8012	99.0	0.3	0.0	0.7	(g)S
79	NR	24	42.8279	-70.7823	86.5	1.8	0.4	11.4	gS
81	NR	26	42.7833	-70.7572	82.6	0.5	0.1	16.8	gS
82	NR	14	42.7677	-70.7832	95.4	1.8	0.3	2.5	(g)S
83	NR	10	42.7413	-70.7747	96.9	0.3	0.1	2.7	(g)S
84	NR	7	42.7271	-70.7688	98.7	1.2	0.1	0.0	S
85	RZ	24	42.7278	-70.7259	No Grab				
86	NR	22	42.7212	-70.7248	98.8	0.9	0.3	0.0	S
87	NR	22	42.7085	-70.7142	84.5	14.0	1.5	0.0	mS
88	NR	23	42.7046	-70.7014	97.8	1.9	0.4	0.0	S
89	NR	19	42.6916	-70.6780	95.5	4.0	0.6	0.0	S
90	NR	8	42.6713	-70.6885	98.5	1.2	0.3	0.0	S
91	NR	7	42.6888	-70.7247	98.7	1.2	0.1	0.0	S

Key to sediment descriptions (Folk, 1974):

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

A single, large Outer Basin lies adjacent to the seaward margin of the sandy Nearshore Ramp about 10 km seaward of the mainland coast (fig. 4.1). It stretches from the 50-m isobath to the eastern extent of the survey. The sedimentary sequence in Outer Basins consists of relatively thick deposits of Holocene mud and sand that conformably overlie Pleistocene sediment and bedrock (fig. 4.3).

The Outer Basin is the second largest physiographic element, composing 99.1 km² or 27.7 percent of the study area (table 4.1). Water depths range from 50 m to more than 90 m.

Quantitative Bottom Classification

Quantitative methods have long been used to classify terrestrial environments through analysis of satellite data. Success in that field indicates that similar methods can be used to classify seafloor environments through analysis of marine acoustic data. The classification method in this study uses a two-part unsupervised classification algorithm based on established statistical methods typically applied to terrestrial remote-sensing data (Jensen, 2005) and available in most GIS and remote-sensing software packages (ESRI, 2008; ERDAS, 2008). The goal is to predict the sediment texture in the nearshore area by modeling the relationship between the mean grain size, water depth, bathymetric slope, and acoustic-backscatter intensity. Additional details of the classification method are contained in appendix IV of this report.

The shallow seafloor (less than 25 m deep) in the study area is characterized by distinct patterns of high and low acoustic backscatter that correlate with differences in sediment texture and seafloor morphology (fig. 4.5). In general, high backscatter represents coarse sandy sediment, and low backscatter represents fine sandy sediment. Figure 4.7 illustrates the relation between mean sediment-grain size and acoustic backscatter values at 14 sampling locations in the nearshore area. The plotted points of these samples occupy two discrete groups: (1) very fine to fine sand (3.4 to 2.1 phi) and (2) coarse sand (0.7 to 0.0 phi). Fine sand generates relatively low backscatter (mean values less than 45), and coarse sand generates relatively high backscatter (mean values greater 45). No samples of medium sand (2.0 to 1.0 phi) were collected in the mapped area. The backscatter trends are so apparent in a visual (qualitative) assessment that we explored using more quantitative analyses to investigate the relation between acoustic-backscatter data and the distribution of surficial sediment on the seafloor.

Preliminary results of the classification indicate that two grain-size classes dominate the seafloor in the nearshore area (fig. 4.8). Approximately two thirds (43 km²) of the area is covered with fine to very fine sandy sediment, and the remaining one third (24 km²) is covered with coarse sandy sediment. The area predicted to be fine to very fine sand correlates well with the area where Holocene sediment thickness is greater than 0.5 m (fig. 3.5). These finer sediments generate low backscatter intensity and form a broad, relatively continuous deposit that lies in shallow water adjacent to the beach. The area predicted to be coarse sand correlates well with areas of high backscatter intensity and areas where Holocene sediment thickness is less than 0.5 m. These coarser sediments generate high backscatter intensity and form localized patches exposed in troughs between large bedforms of fine sand and a more extensive sheet that lies offshore of the central coast of Plum Island.

Accurate bottom classification using statistical analyses is difficult, particularly along continental shelves with a broad range of different sediment types. We feel that the bottom-classification method performed adequately in this preliminary trial, largely because of the relatively simple geology of the nearshore area. The two main classes of sediment have distinct acoustic signatures, thus providing an opportunity to determine a first-order approximation of

surficial geology. However, small outcrops of rock, which cover an estimated 2 km² or 3 percent of the nearshore area, were not delineated. Continued development of this classification method will focus on distinguishing bedrock and additional classes of sediment.

Bottom-Sediment Texture

Sediment samples in the study area contain all components of the particle-size spectrum (fig. 4.9). Sediment texture ranges from clayey silt in the Outer Basin to pebbles, cobbles, and boulders in Rocky Zones (table 4.2). No samples were collected from Ebb-Tidal Deltas.

Sand is the most common bottom sediment in this study, with 95 percent of samples containing more than 20 percent sand. Sand-sized particles (4 to -1 phi, or 0.062 to 2 mm in diameter) compose an average of 82 percent by weight in all samples, with values ranging from a minimum of 2 percent to a maximum of 100 percent. Samples with the highest sand content were collected from Nearshore Ramps (81 samples, average of 92 percent sand). Sand-rich sediment was also collected from Rocky Zones (7 samples, average of 67 percent sand) and Shelf Valleys (1 sample, 84 percent sand). The lowest values were from the Outer Basin (20 samples, average of 49 percent sand).

Gravel, a textural class that ranges between coarse sand (-1 phi, or 2 mm in diameter) and large boulders (more than 4 m in diameter), is the least common bottom sediment sampled in this study. Gravel-sized particles compose an average of 5 percent by weight of all samples. Only 9 samples contain more than 20 percent gravel, but at least some gravel-size material was collected from 39 percent of the sampling locations. Gravel is the most common sediment texture in Rocky Zones (average of 9 percent gravel), where it composes a major component of glacial deposits and surrounds the base of rock outcrops. Samples from other zones average less than 5 percent gravel. Gravel is probably underrepresented in grab samples because of problems collecting large-diameter particles and the need for large samples to perform statistically valid analyses. Sidescan-sonar and camera observations suggest that gravel is probably more abundant than the weight percentages indicated by sampling alone.

Muddy sediment, which includes both silt- and clay-sized particles (less than 4 phi, or 0.062 mm in diameter), is primarily in the deeper parts of the study area. Mud composes an average of 13 percent by weight of all sediment samples, but two-thirds of the samples contain less than 5 percent. Samples with the highest values were collected from the Outer Basin (average of 51 percent). Sediment from Rocky Zones is highly variable in terms of mud content, ranging from 0 percent to 51 percent with the higher values from deeper areas where a thin layer of mud drapes sand and gravel. The lowest values are in samples from Nearshore Ramps (average of 3 percent mud) and Shelf Valley (1 sample, 4 percent mud).

Geologic Framework and Late Quaternary Evolution

The framework geology and complex late Quaternary history of northeastern Massachusetts have strongly influenced the geologic evolution of the inner continental shelf. Bedrock controls the overall geometry of the coast and inner shelf. Complexly faulted and deformed rocks range in age from Precambrian (older than 540 million years) to Paleozoic (250–540 million years) (Zen and others, 1983). Erosion-resistant granites form the high cliffs, rocky islands, and shoals that characterize the shoreline of Cape Ann (Dennen, 1992). The reentrant of Ipswich Bay and adjacent lowlands are underlain by relatively weak metasedimentary and volcanic rocks of the Newbury Basin (Dennen, 1991). Coastal plain strata of Cretaceous and

Tertiary age underlie Jeffrey's Ledge, a relatively shallow, glacially modified platform that trends northeast from Cape Ann (Oldale, 1985b).

The inner continental shelf and adjacent terrestrial areas share a common history of glaciation and relative sea-level change. Late Pleistocene glaciers reached their maximum extent south of Cape Cod about 23,000 yrs B.P. (Balco and others, 2002) and retreated northward as climate warmed, passing the present coast of Cape Ann about 14,500 yrs B.P. (Kaye and Barghoorn, 1964). The glaciers smoothly eroded the granite hills and left behind a relatively thin, discontinuous cover of till and glacial-marine sediment overlying bedrock. A succession of different sedimentary environments formed in the region following deglaciation, as recorded by a sequence of fluvial, marine, and littoral deposits that accumulated in areas of the inner shelf submerged by the ongoing rise in sea level. These older deposits have been extensively reworked by marine transgression to produce the complex patterns of surficial sediment that exist today.

Geologic mapping on land by Stone and others (2006) delineated glacial deposits in northeastern Massachusetts and grouped them into two main categories: glacial till and glacial stratified deposits. Glacial till is poorly sorted, unconsolidated sediment deposited directly by a glacier. The heterogeneous mixture is generally unstratified and includes particle sizes that range from clay to boulders. Deposits of till thicker than about 3 m generally take the form of moraines and drumlins. Moraines are hummocky, ridge-like features with locally dense accumulations of boulders that reflect the shape of the ice sheet's margin. Terminal moraine deposits on Cape Ann were first described by Shaler (1889) and later shown by Oldale (1985b) to extend offshore onto Jeffrey's Ledge. Drumlins are small streamlined hills that have long axes oriented approximately NW-SE, parallel to the regional ice-flow direction. They occur among the salt marshes of Plum Island Sound (Great Neck) and Essex Bay (Hog Island). The southern terminus of Plum Island, a sandy barrier, is pinned against an eroding drumlin at the entrance to Plum Island Sound (fig. 1.3). Another drumlin (Steep Hill) lies on the opposite bank of the inlet, behind the sandy beach of Castle Neck. On the inner shelf seaward of Plum Island, rugged mounds of coarse-grained sediment rise up from the generally low-relief seafloor (fig. 4.3). The irregularly shaped areas of Rocky Zone largely consist of gravel-sized particles with numerous large boulders more than 1 m in diameter. Seismic-reflection profiles suggest that bedrock forms the cores of the features, which are covered by a layer of bouldery sediment that is acoustically incoherent, probably till. These deposits probably mark the locations of drumlins or other ice-contact deposits that were eroded during the Holocene marine transgression. Similar features in Massachusetts Bay about 25 km southwest of Cape Ann were described as eroded drumlins by Oldale and others (1994). Abundant shelly material from rock-dwelling, calcareous organisms has accumulated in low-lying depressions within Rocky Zones and along the margins of rock-walled Shelf Valleys.

Glacial stratified deposits consist of unconsolidated sediment that was sorted and deposited in layers by meltwater discharged from a glacier (Stone and others, 2006). They include coarse-grained deposits of sand and gravel that accumulated in the coastal zone, relatively close to the glaciers, forming glacial-marine deltas along the ice margin. The topset/foreset contacts on these deltas mark the highstand marine limit, which ranges in elevation from approximately +15 m along the north shore of Cape Ann to +33 m in the lower Merrimack River Valley (Crosby and Lougee, 1934; Stone and Peper, 1982; Stone and others, 2004). More distal deposits of finer-grained, glacial-marine sediment cover wide areas of the coast and inner shelf from northeastern Massachusetts (Boston blue clay; Kaye and Barghoorn, 1964) to eastern

Maine (Presumpscot Formation; Bloom, 1963). This sediment was deposited contemporaneously with ice retreat and typically consists of well stratified sand and mud with scattered dropstones of ice-rafted material that blanketed older glacial deposits and bedrock (fig. 4.5). Thick sequences of glacial-marine sediment in the western Gulf of Maine are best preserved in bedrock valleys and deep basins (Belknap and Shipp, 1991) and at the mouths of major rivers beneath thick sequences of Holocene material (Oldale and Edwards, 1990; Barnhardt and others, 1997).

Isostatic rebound of the crust caused relative sea level to fall to a lowstand depth of about –50 m at 12,000 yr B.P. (fig. 1.2; Oldale and others, 1993). Evidence for the depth of the sea-level lowstand primarily consists of an ancient river delta and other coastal features that are preserved on the inner continental shelf offshore of Plum Island and Cape Ann (Oldale, 1985a; Oldale and others, 1983). The age of the lowstand is poorly constrained by a small number of cores that have been collected from submerged shoreline features (Oldale and Edwards, 1990). During regression and lowstand, rivers and coastal streams eroded the emergent landscape, carving channels into older glacial sequences (figs. 4.10 and 4.11) and transporting sediment to the lowstand shoreline. Sediment supplied by the Merrimack River produced a large delta with dipping clinoforms, inferred to be foreset beds, that prograded into the deeper Gulf of Maine (fig. 4.5). The submerged paleodelta is located 6 to 7 km offshore, and measures 20 km long, 4 to 7 km wide, and up to 20 m thick (Oldale and others, 1983, 1993; Edwards, 1988).

As isostatic rebound decreased, relative sea level rose from the lowstand at different rates to its present elevation, submerging the paleodelta. Landward migration of the shoreline across the delta's upper surface, driven by submergence, caused extensive erosion and redistribution of sediment in areas above the lowstand (0–50 m depth). Seismic-reflection profiles show that seaward-dipping delta foresets were truncated, forming a prominent unconformity that separates fluvial/deltaic deposits of latest Pleistocene age from the overlying marine/coastal deposits of Holocene age (fig. 4.11). This transgressive surface of erosion, also referred to as the ravinement unconformity (Swift, 1968), is generally flat and slopes gently seaward, extending from the depth of the lowstand to the modern shoreface (fig. 3.7). The transgressive unconformity is exposed at the seafloor in many areas and is locally overlain by thin, discontinuous Holocene deposits of sandy sediment. These deposits, where present, are generally less than 2 m thick but are up to 9 m thick in the vicinity of Ipswich Bay. The large volume of Holocene sediment in the southern part of the study area adjacent to Cape Ann indicates a long-term net transport of sediment towards the south.

Asymmetric bedforms and distinct grain-size differences on the surface of the Nearshore Ramp (fig. 4.7) indicate that the seafloor is actively being reworked by inner-shelf processes (Hein and others, 2007). These irregular patches of high and low backscatter are examples of sorted bedforms or rippled scour depressions that have been observed on continental shelves around the world (Cacchione and others, 1984; Murray and Thiel, 2004; Guitierrez and others, 2005; Ferrini and Flood, 2005; Green and others, 2004). The enigmatic features are also common on other parts of the Massachusetts inner shelf (Aubrey and others, 1982; Goff and others, 2005; Barnhardt and others, 2006). 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.

Unlike shallower parts of the inner shelf, the Outer Basin did not undergo emergence and erosion during times of lower sea level. Erosional unconformities that formed during regression and transgression do not extend below depths of about –50 m. As a result, sediment

accumulation has been uninterrupted since deglaciation, preserving the relatively thick deposits of marine and glacial-marine mud that largely bury the high-relief bedrock in offshore areas. Isolated areas of Rocky Zone stand higher in elevation relative to the adjacent seafloor in the Outer Basin, and thus represent island-like patches of hard substrate surrounded by expanses of muddy sediment.

Summary

The inner continental shelf between Cape Ann and Salisbury Beach, Massachusetts, exhibits a complex assemblage of sediment textures related to the inherited geologic framework and reworking during postglacial sea-level changes. Rapidly changing environments associated with glaciation and deglaciation of the region have exposed the inner shelf to a variety of marine and terrestrial processes (fig. 4.12). High-relief bedrock is locally exposed on the seafloor (Rocky Zone, Shelf Valley) but otherwise is buried beneath relatively thick deposits of glacial and non-glacial sediment. The glacial deposits consist of till and glacial-marine sediment, which are overlain by deposits of fluvial, estuarine, deltaic, and marine sediment. The Merrimack River, one of the largest rivers in New England, delivered abundant sediment to construct a large sandy delta graded to a lowstand of sea level at a depth of about -50 m. Ongoing transgression across the paleodelta's upper surface (Nearshore Ramp) has removed significant material from shallow areas above the lowstand depth and eroded a distinct unconformity on top of the Pleistocene sedimentary sequence. Surficial deposits of Holocene sediment, which overlie the regional transgressive unconformity, are relatively thin and unevenly distributed. The mobile sandy sediments range in thickness from less than 0.5 m in the northern and central parts of the study area to 9 m in the south near Cape Ann. This distribution indicates long-term net transport of sediment in a southerly direction. These deposits contain approximately 121 million m^3 of fine sandy sediment in the nearshore area alone, where we have sufficient seismic-reflection data to accurately map its thickness. Along with sediment derived from reworking of older deposits along the coast and inner shelf, sandy sediment supplied by the river has constructed a large barrier system. Modern processes interact with bedrock and glacial sediment to create the sandy beaches, tidal-inlet complexes (Ebb-Tidal Deltas), and other present-day landforms along the present shoreline. In depths below about -50 m, the seafloor was not exposed during the postglacial sea-level lowstand. A complete stratigraphic section is preserved in these deeper areas (Outer Basins) where fine-grained sediment is accumulating, presumably derived from erosion of shallow, formerly emergent areas of the shelf. These different sedimentary environments provide habitat for a variety of benthic-dwelling marine organisms. Geologic mapping at this scale is the first step toward determining the distribution, type, and quality of subtidal marine habitats in the Massachusetts coastal ocean.

Acknowledgments

Susan Snow-Cotter (1961–2006) and Anthony Wilbur of the Massachusetts Office of Coastal Zone Management were instrumental in establishing and maintaining the cooperative seafloor-mapping program, which is funded by the Coastal and Marine Geology Program of the USGS and the Commonwealth of Massachusetts. Assistance in the field was provided by Emile Bergeron, William Danforth, Barry Irwin, and Charles Worley of the USGS. We thank Jane Denny, William Danforth, and David Foster of USGS for their help in processing the large amounts of acoustic data. Jennifer Martin arranged this document in HTML. This manuscript,

maps, and GIS data benefited from reviews by Jane Denny, S. Jeffress Williams, Matthew Arsenault, Vee Ann Cross, Anthony Wilbur, and Daniel Sampson.

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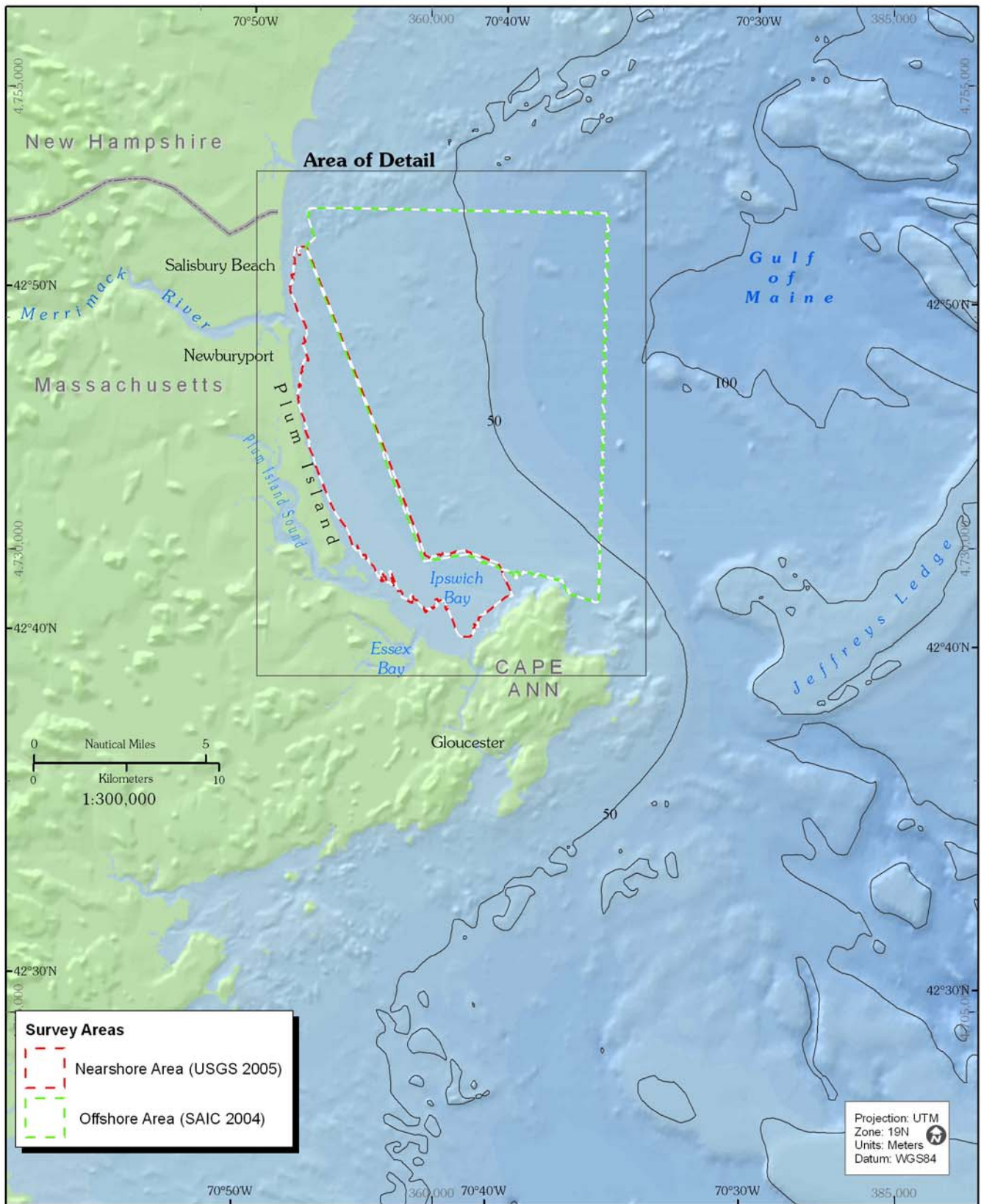


Figure 1.1. Map showing the location of the survey areas offshore of northeastern Massachusetts between Cape Ann and Salisbury Beach. The offshore area (green dashed outline) and nearshore area (red dashed outline) were mapped in two separate cruises in 2004 and 2005, respectively. USGS, U.S. Geological Survey; SAIC, Science Applications International Corporation.

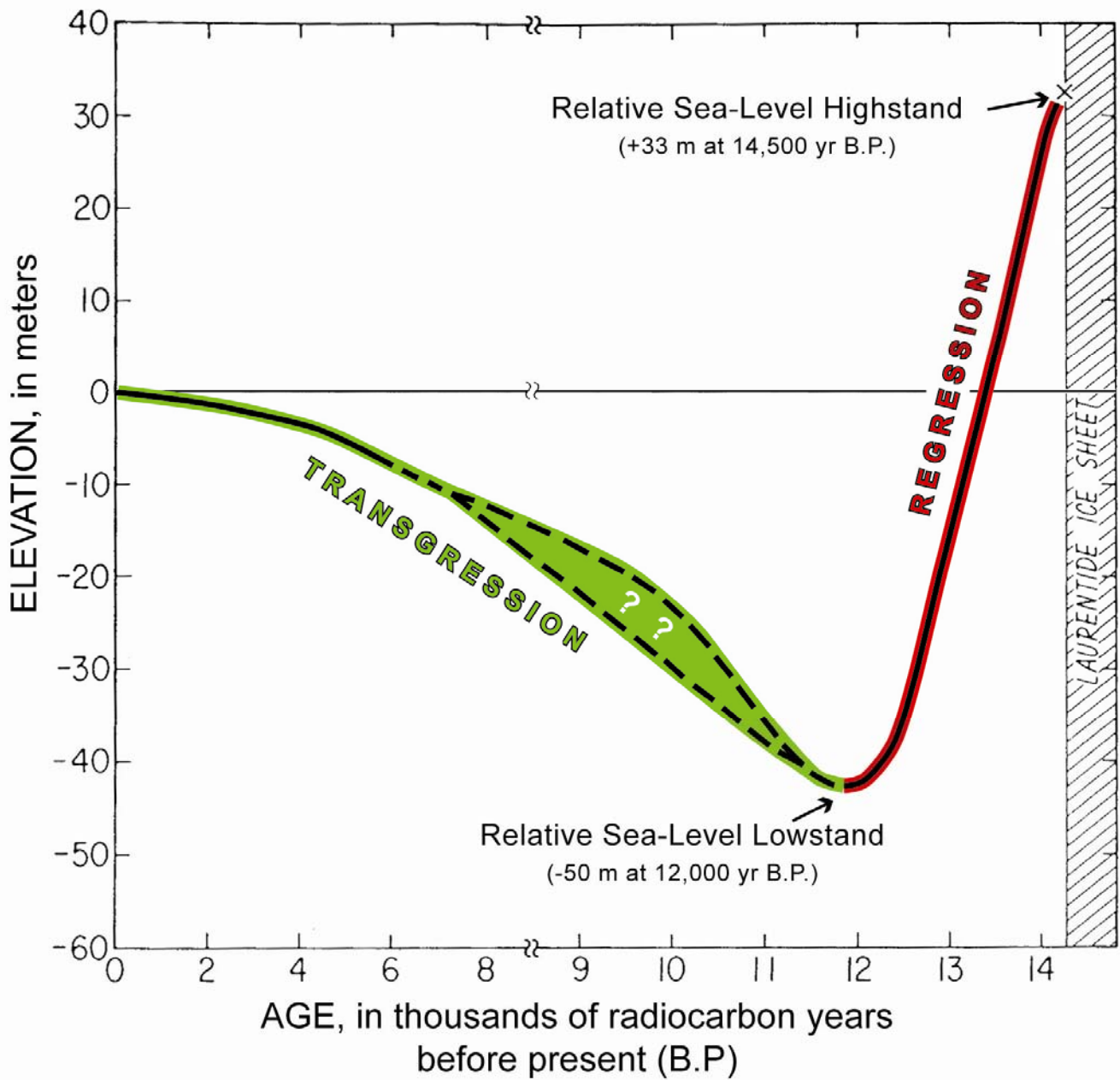


Figure 1.2. Late Quaternary relative sea-level curve for northeastern Massachusetts (modified from Oldale and others, 1993). Over the last 14,500 years, relative sea level fell from a highstand of about +33 m to a lowstand of about -50 m, and then rose at varying rates to the present. The large fluctuations in relative sea level drove regression (red shading) and transgression (green shading) of the shoreline across the inner continental shelf. Dashed lines indicate uncertainty during the early to middle Holocene. Note that the age scale changes at 8,000 years B.P.



Figure 1.3. Air photograph of Plum Island and the mouth of the Merrimack River on the northeastern coast of Massachusetts. A small drumlin (inset) anchors the southern end of the island. Erosion of the drumlin provides sandy sediment to the barrier beach and has left behind a deposit of boulders on the beach and shoreface. (Photograph by Joseph Kelley, University of Maine, March 2005.)



Figure 3.1. Photographs of the RV *Connecticut* (top) and the RV *Ocean Explorer*, both used for mapping surveys in this project.

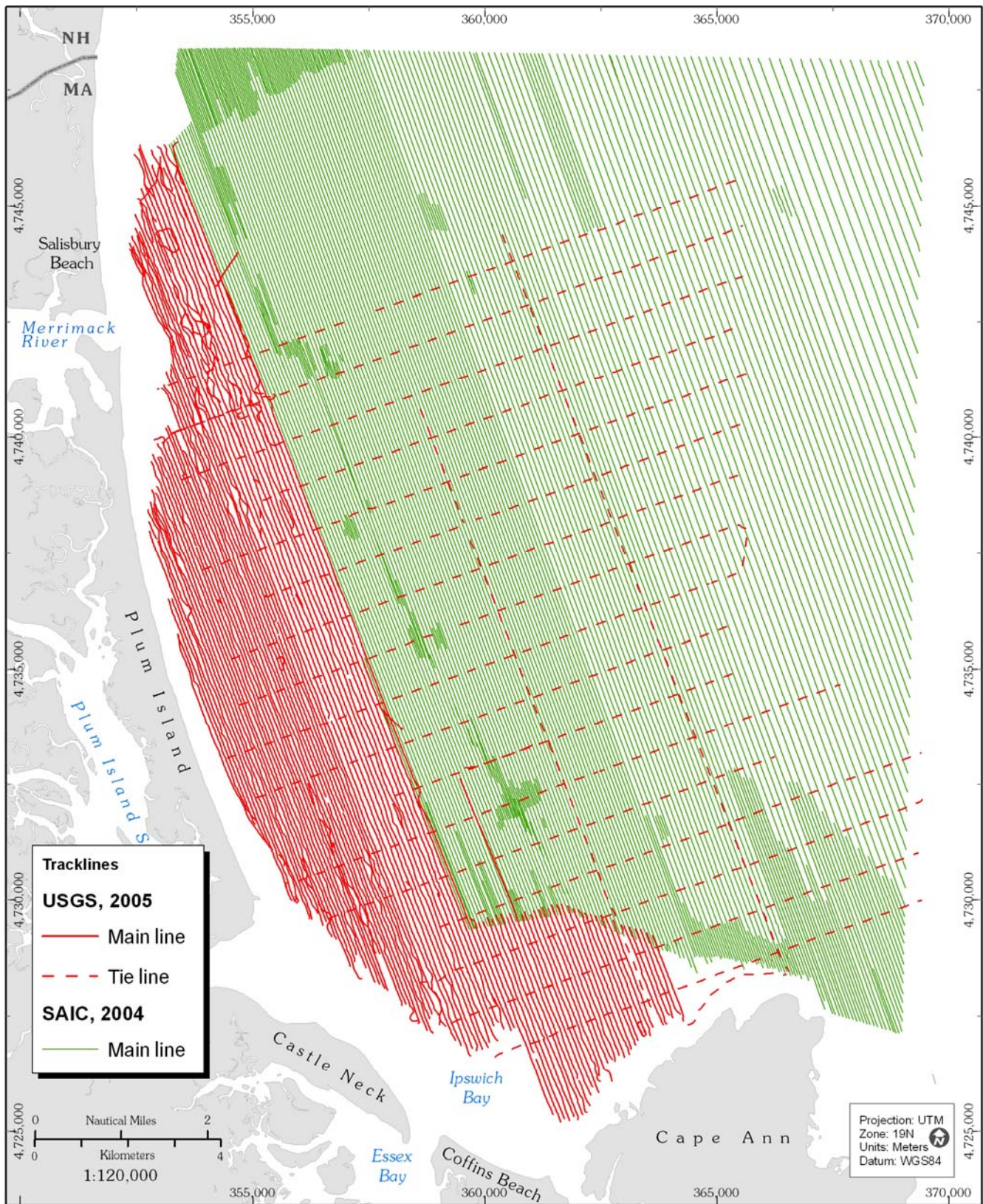


Figure 3.2. Map showing tracklines of geophysical data in the nearshore area (red) and offshore area (green). USGS, U.S. Geological Survey; SAIC, Science Applications International Corporation.

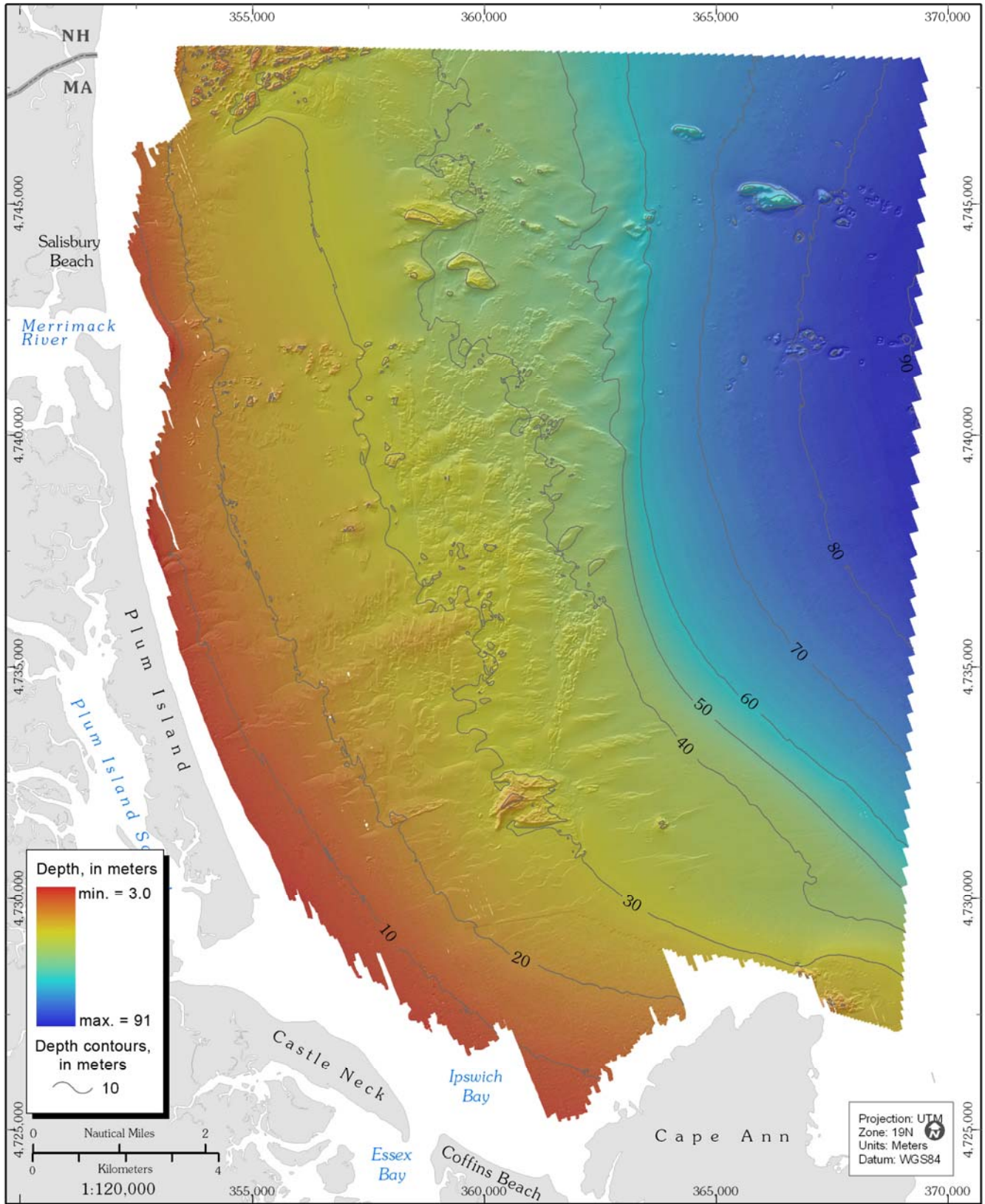


Figure 3.3. Map showing shaded-relief topography of seafloor offshore of northeastern Massachusetts between Cape Ann and Salisbury Beach. Coloring and bathymetric contours represent depths in meters, relative to the local mean lower low water (MLLW) datum.

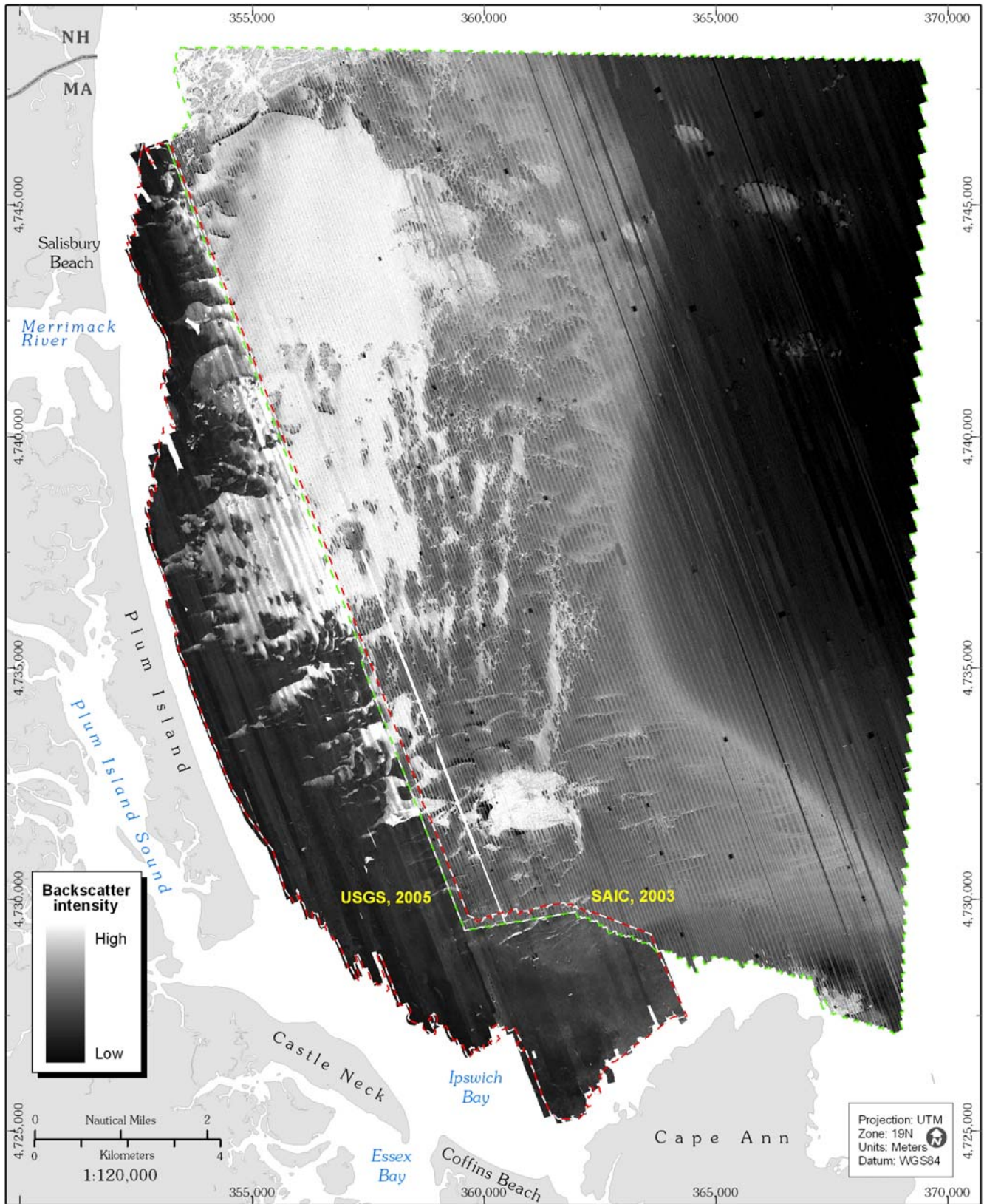


Figure 3.4. Map showing acoustic-backscatter intensity offshore of northeastern Massachusetts between Cape Ann and Salisbury Beach. Backscatter intensity is an acoustic measure of the hardness and roughness of the seafloor. In general, higher values (light tones) represent rock, boulders, cobbles, gravel, and coarse sand. Lower values (dark tones) generally represent fine sand and muddy sediment. Offshore data (green dashed outline) were collected by SAIC in 2004 and nearshore data (red dashed outline) were collected by USGS in 2005.

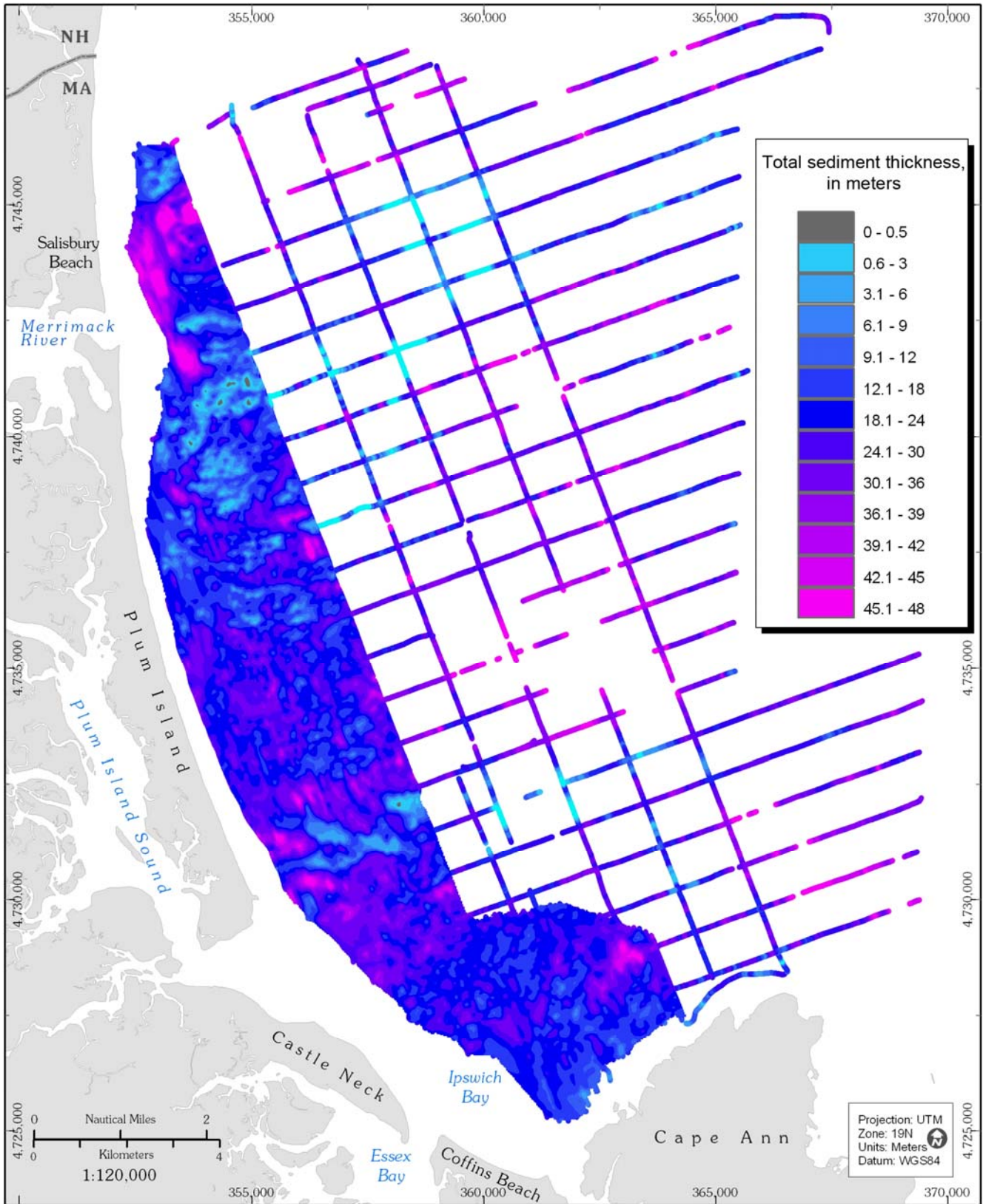


Figure 3.5. Map showing the isopach of total sediment thickness (all sediment that overlies bedrock). Small, isolated exposures of bedrock (dark gray shading) are covered with sediment less than 0.5 m thick. Sediment-thickness values were interpreted from closely spaced seismic-reflection profiles. In the nearshore area, measured values were used to generate an interpolated grid, but in the offshore area, they are only displayed as discrete points along the widely spaced tracklines.

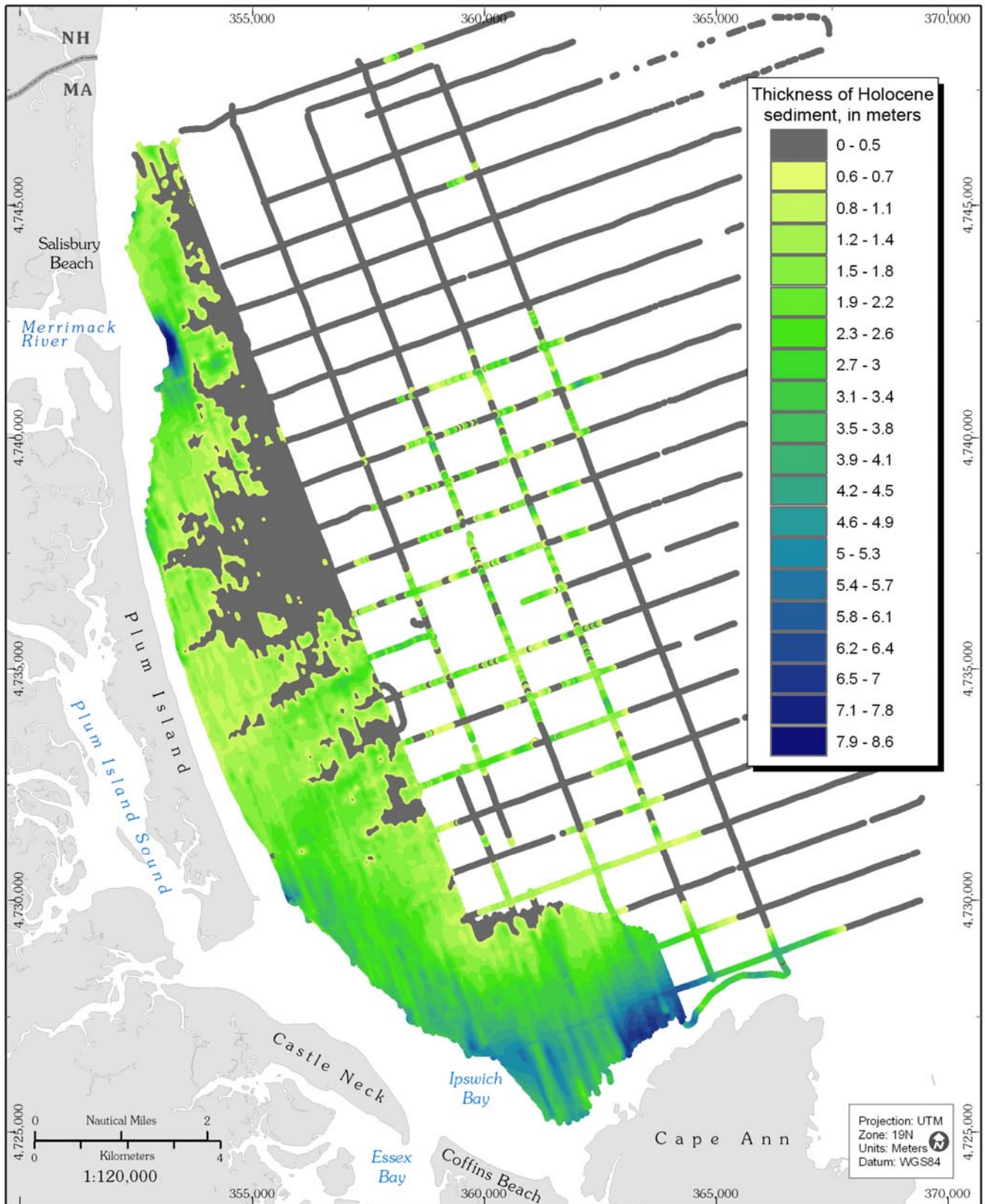


Figure 3.6. Map showing the thickness of sandy Holocene sediment (mobile sediment that overlies the transgressive unconformity). Deposits thicker than 5 m are adjacent to the mouth of the Merrimack River and within Ipswich Bay. Extensive areas offshore of central Plum Island and Salisbury Beach are covered by deposits thinner than 0.5 m. Sediment-thickness values were interpreted from closely spaced seismic-reflection profiles. In the nearshore area, measured values were used to generate an interpolated grid but, in the offshore area, the values are only displayed as discrete points along the widely spaced tracklines.

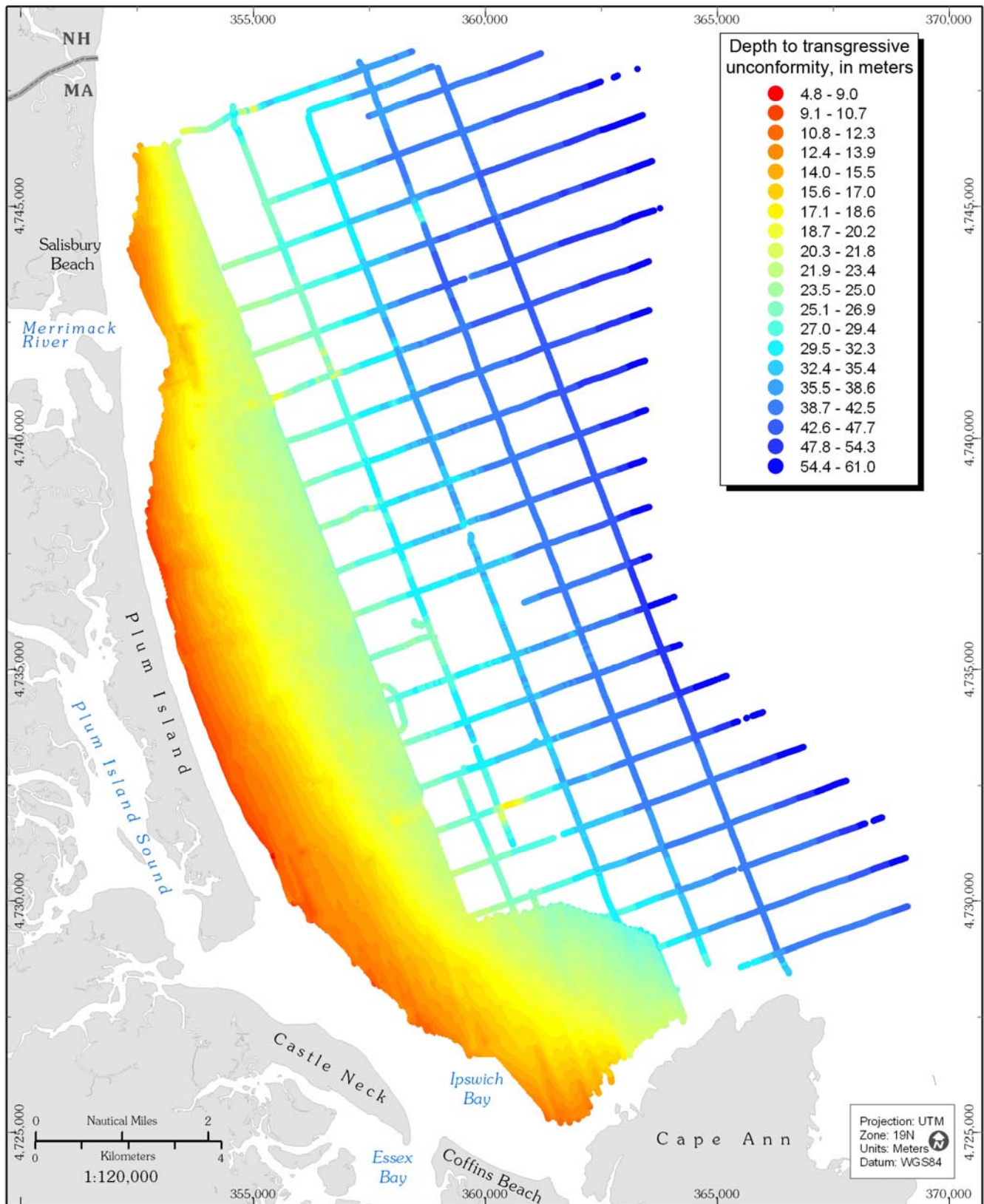


Figure 3.7. Map showing the elevation of the transgressive unconformity, a gently sloping erosional surface that is etched into Pleistocene sediment. Although locally buried by Holocene marine sediment up to 9 m thick, the unconformity is exposed at the seafloor in many locations. Elevations of the transgressive unconformity were calculated by subtracting measured values of Holocene sediment thickness (fig. 3.6) from the combined bathymetric grid (fig. 3.3). In the nearshore area, elevations were used to generate an interpolated grid, but in the offshore area, they are only displayed as discrete points along the widely spaced seismic-reflection tracklines. Depths are relative to the local mean lower low water datum.



Figure 3.8. Photograph of the SEABed Observation and Sampling System (SEABOSS) on the deck of the RV *Connecticut*. Photographic data and sediment samples collected by the system were used to validate geophysical data and characterize seafloor environments.

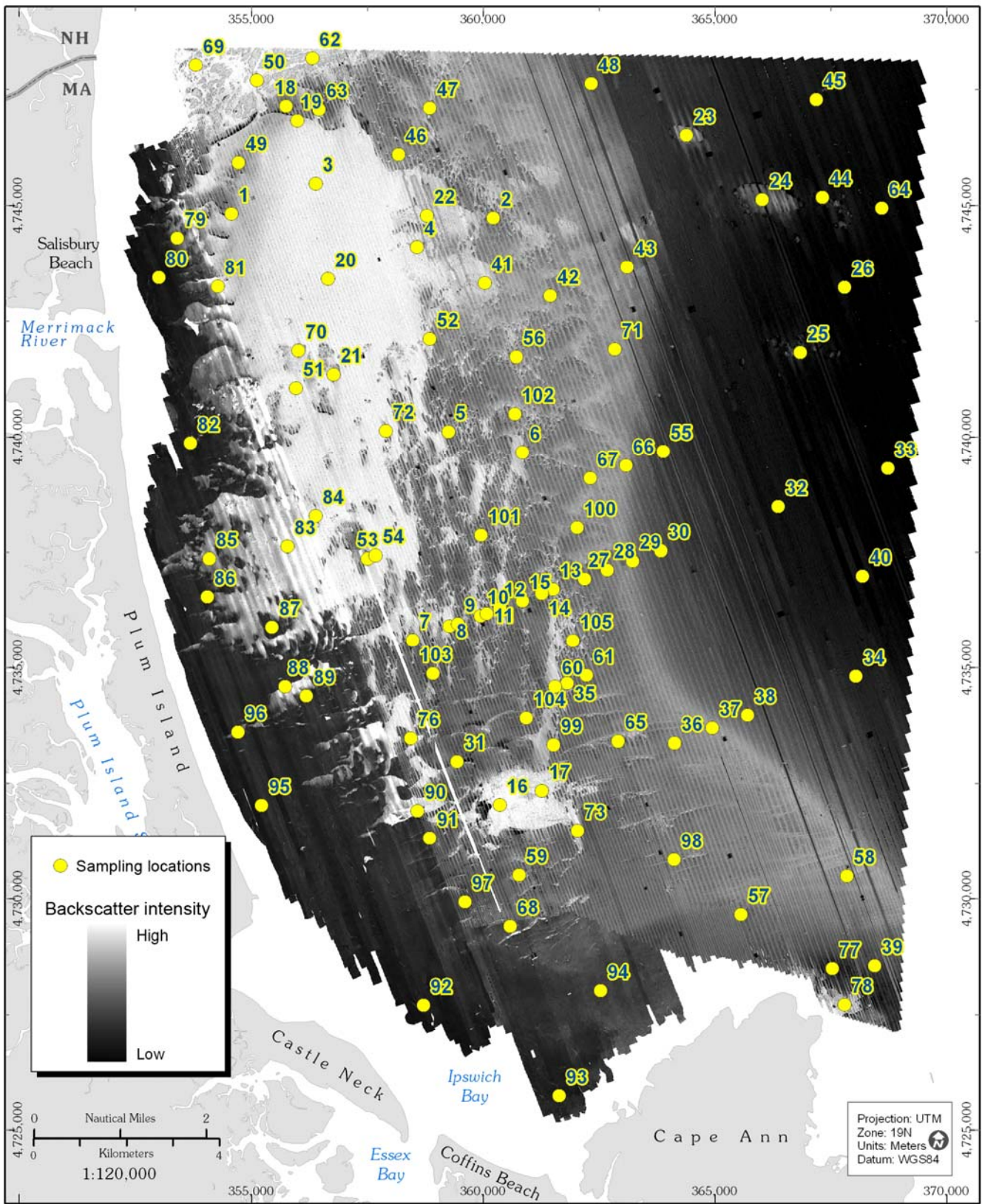


Figure 3.9. Map showing the locations of sediment samples and bottom photographs superimposed on a map of acoustic-backscatter intensity. Each numbered circle indicates a station where bottom photographs, video, and/or samples were collected to validate interpretations of geophysical data.

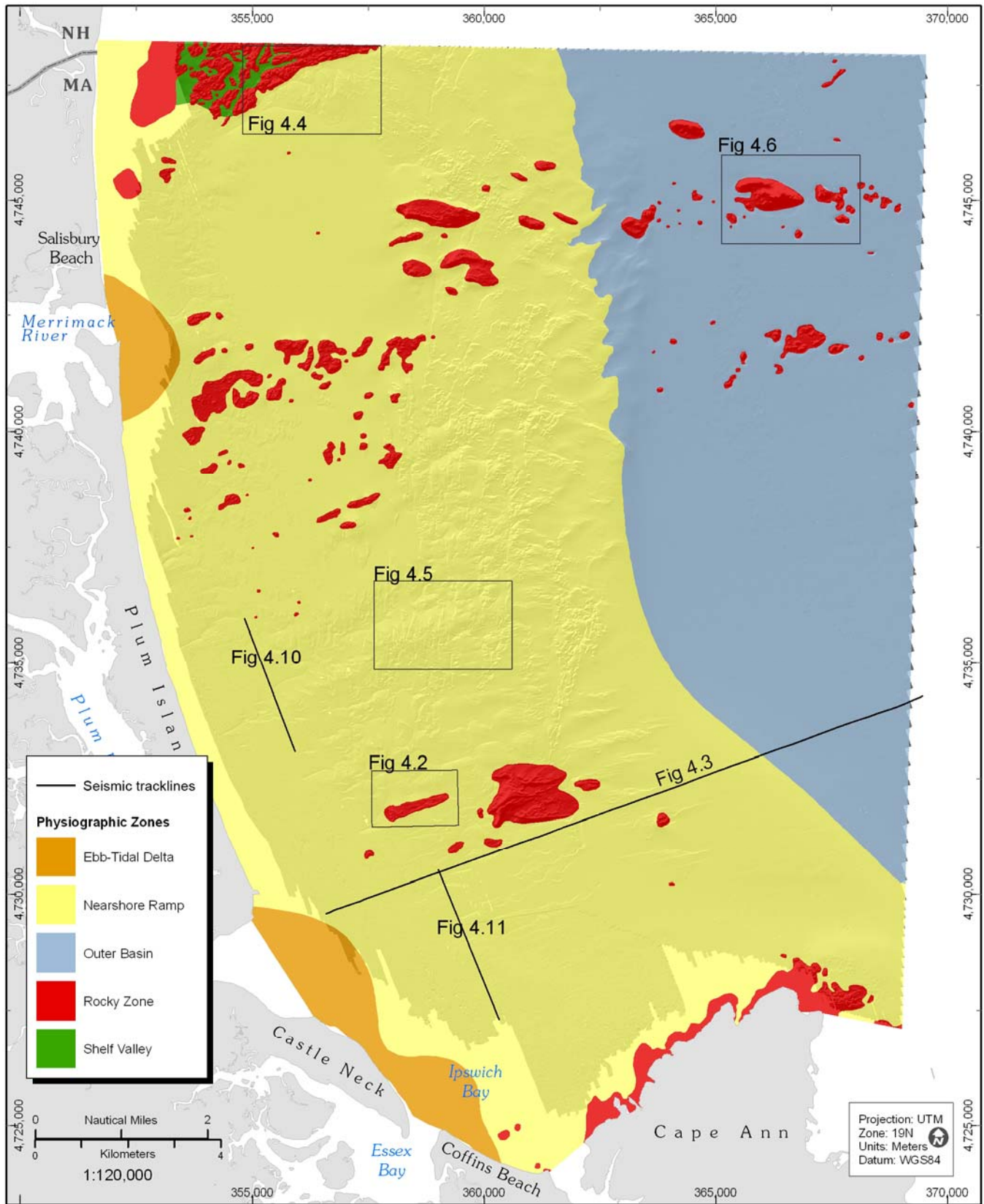


Figure 4.1. Interpretive geologic map showing five physiographic zones on the inner continental shelf, including Ebb-Tidal Delta, Nearshore Ramp, Outer Basin, Rocky Zone, and Shelf Valley. Physiographic zones are superimposed on gray-scale, shaded-relief bathymetry except in areas adjacent to the shoreline in shallow water landward of the survey area. See Section 4 – Interpretive Geologic Mapping for a detailed description of each zone. Index boxes and profile lines show locations for other figures used in this report.

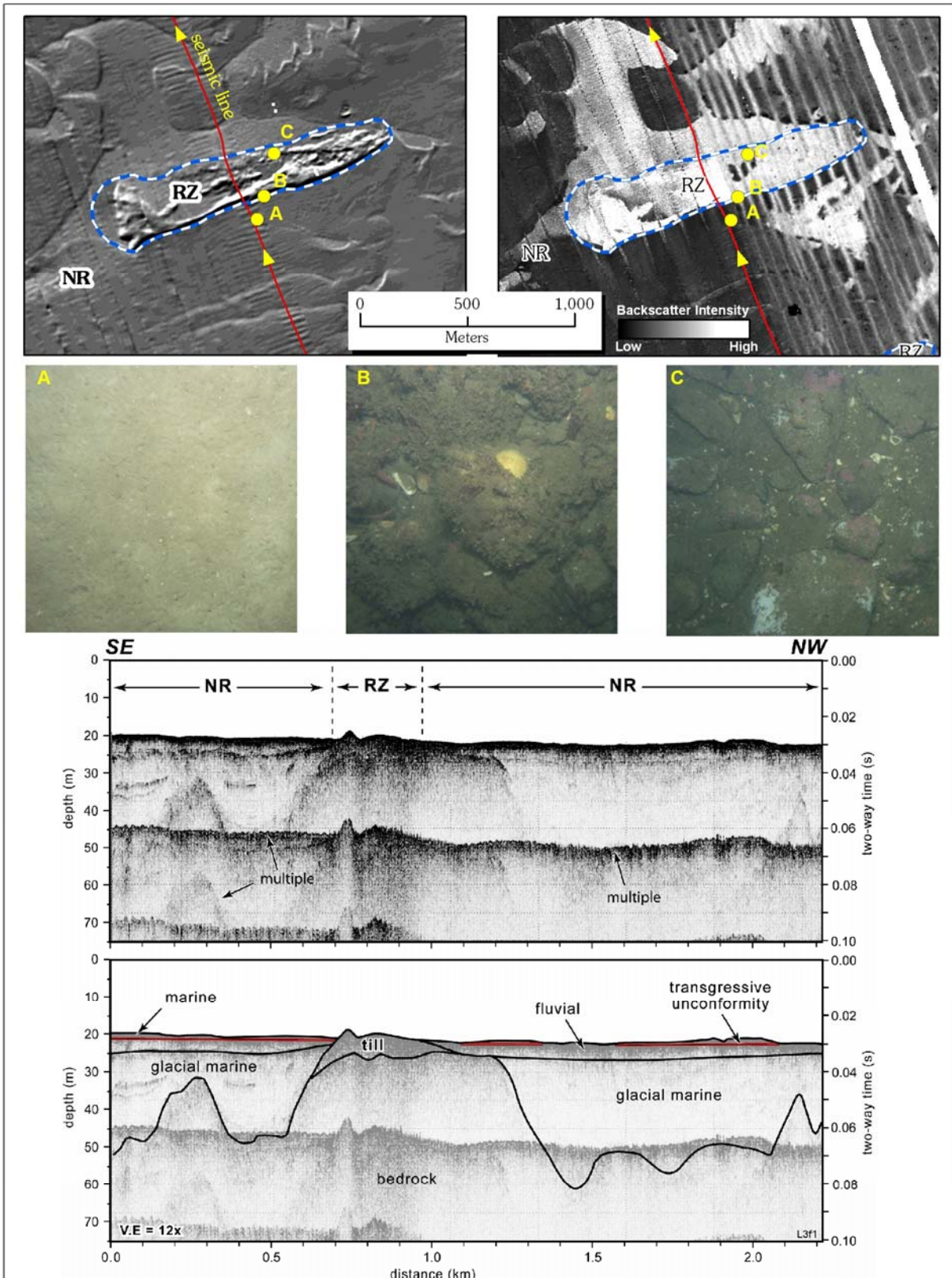


Figure 4.2. Maps showing bathymetry (upper left) and acoustic-backscatter intensity (upper right) in the south-central part of the survey area. The eroded remnants of a large till deposit, probably a drumlin or moraine, represents a discrete Rocky Zone (RZ) surrounded by Nearshore Ramp (NR). Bottom photographs A–C and the seismic-reflection profile (bottom) are indicated by yellow circles and a red line, respectively. The distance across the bottom of the photographs is approximately 50 cm. See Figure 4.1 for location. NR = Nearshore Ramp; RZ = Rocky Zone. A constant seismic velocity of 1500 m/s through water, sediment, and rock was used to convert from two-way travel time to depth.

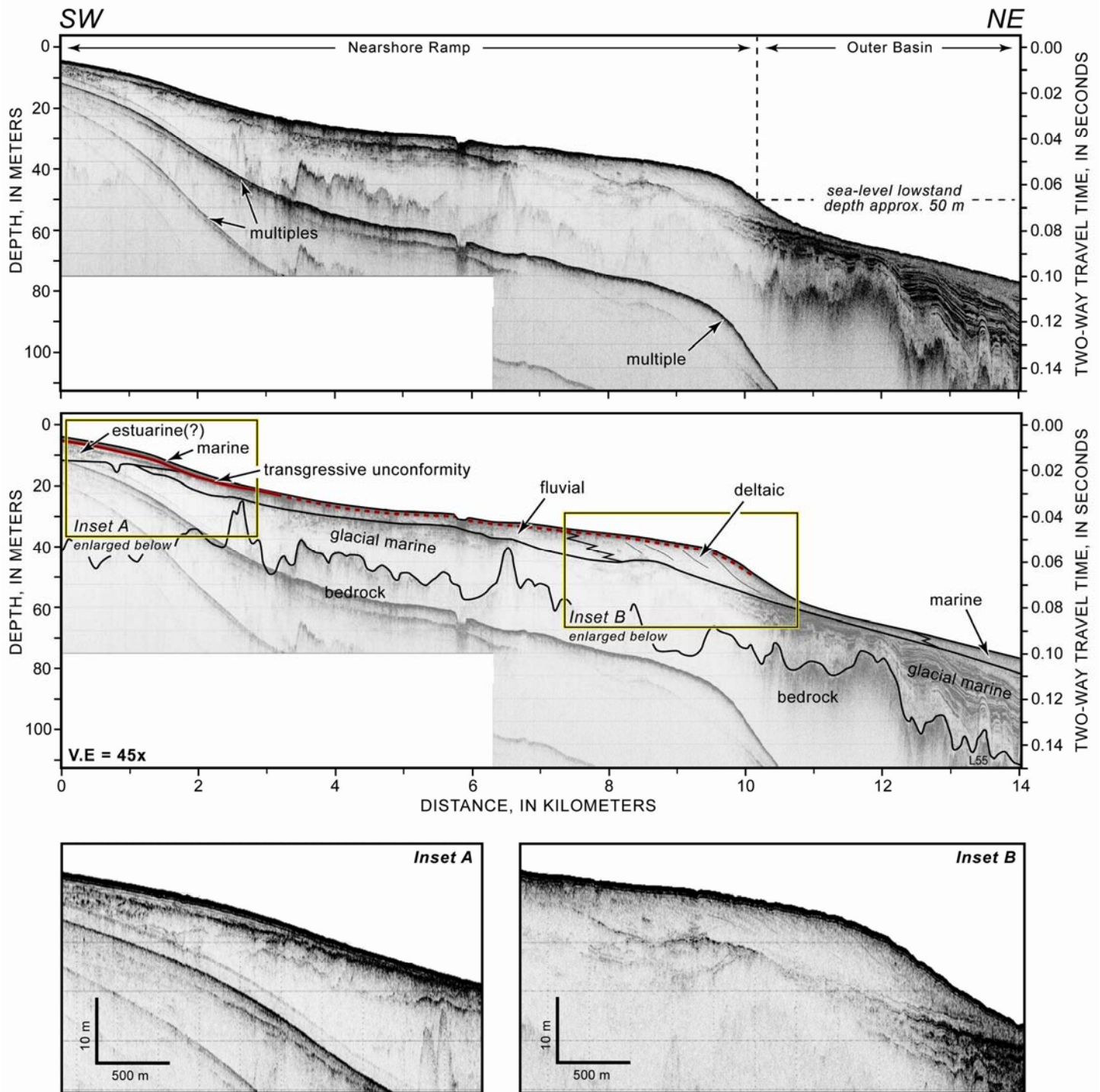


Figure 4.3. Seismic-reflection profile across the inner continental shelf. Stratified glacial-marine sediment rests on bedrock and is overlain by fluvial and deltaic deposits that formed during coastal regression and sea-level lowstand. Seaward-dipping clinoforms (inset B) indicate progradation of the delta offshore into a deep, muddy basin. The prominent transgressive unconformity (red line) is an erosional surface that caps the fluvial/deltaic sequence and grades to conformity below depths of about 50 m. A seaward-thinning wedge of sediment, interpreted as estuarine in origin, underlies shallow parts of the inner shelf (inset A). Holocene deposits of sandy marine sediment locally overlie the transgressive unconformity. See Figure 4.1 for location. A constant seismic velocity of 1500 m/s through water, sediment, and rock was used to convert from two-way travel time to depth.

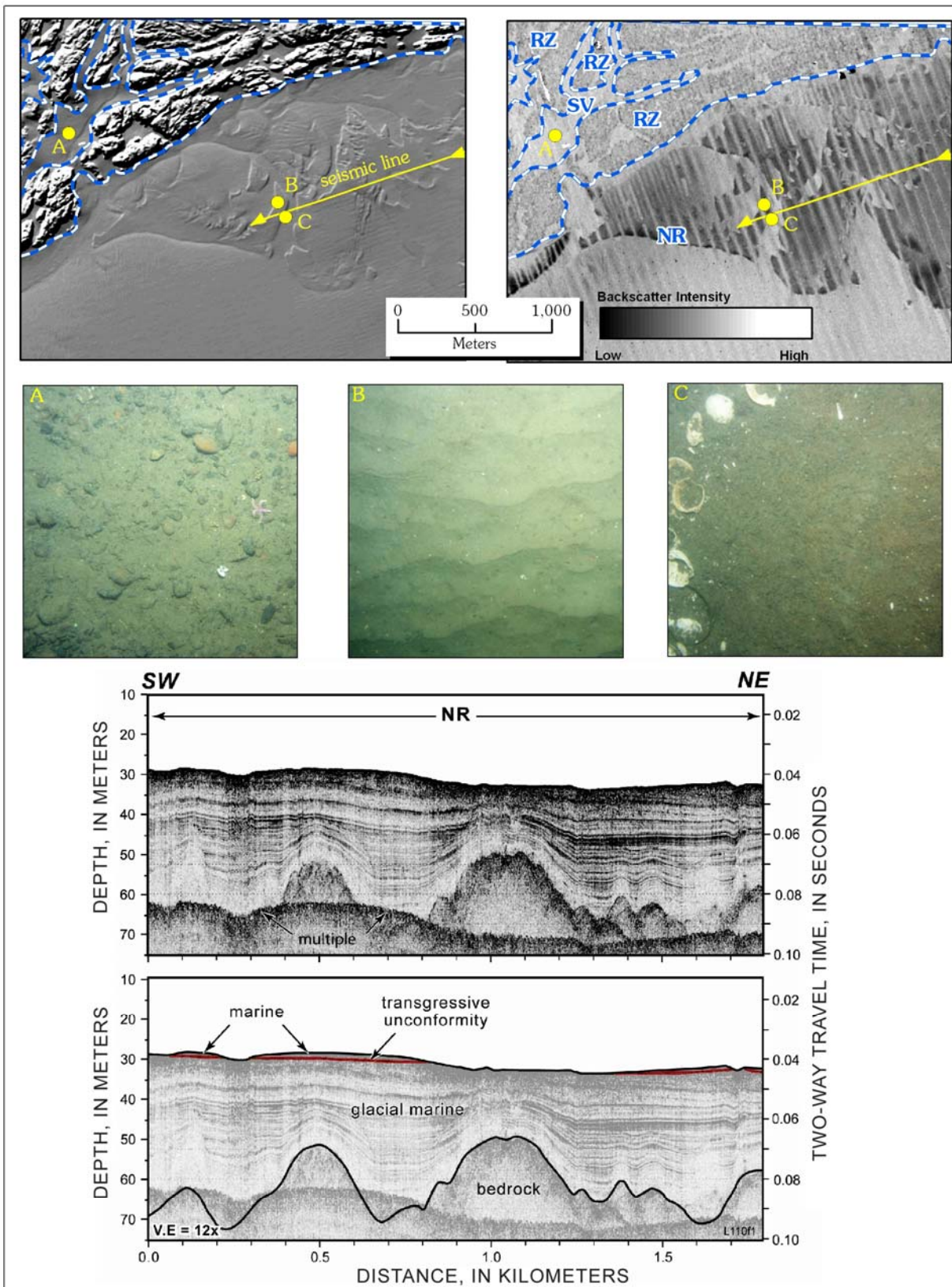


Figure 4.4. Maps showing bathymetry (upper left) and acoustic-backscatter intensity (upper right) in the northwestern part of the survey area. A small Shelf Valley (SV) cuts through a large expanse of Rocky Zone (RZ), adjacent to the relatively smooth, sand- and gravel-covered surface of the Nearshore Ramp (NR). Bottom photographs A–C and seismic-reflection profile (bottom) are indicated by yellow circles and a red line, respectively. The distance across the bottom of the photographs is approximately 50 cm. See Figure 4.1 for location. A constant seismic velocity of 1500 m/s through water, sediment, and rock was used to convert from two-way travel time to depth.

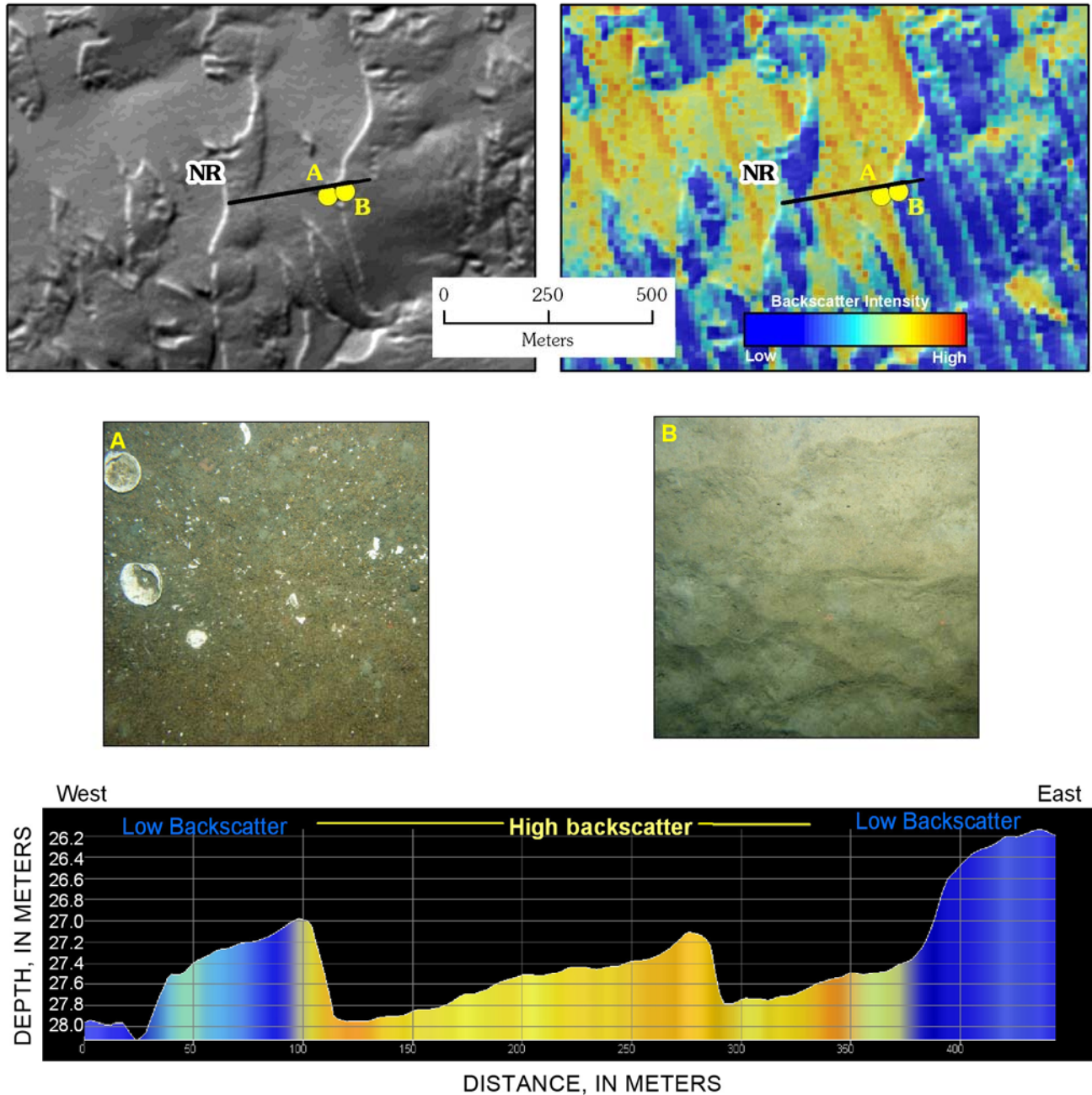


Figure 4.5. Maps showing bathymetry (upper left) and acoustic-backscatter intensity (upper right) on the Nearshore Ramp (NR) in the central part of the survey area. Parallel stripes that trend NW-SE in the backscatter data are artifacts of data collection. Color coding on the depth profile (bottom) shows high backscatter (coarse sand and gravel) in the shallow depression and low backscatter (fine sand) on the adjacent, bathymetrically higher areas. Bottom photographs (A and B) collected on opposite sides of the backscatter transition illustrate the different grain sizes that produce the changes in intensity. The distance across the bottom of the photographs is approximately 50 cm. See Figure 4.1 for location.

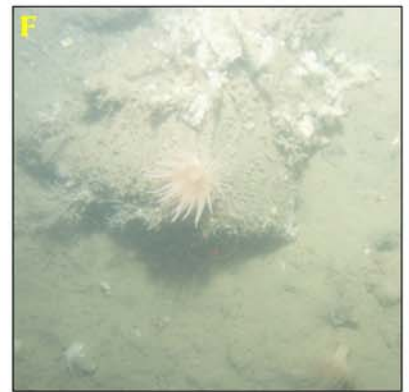
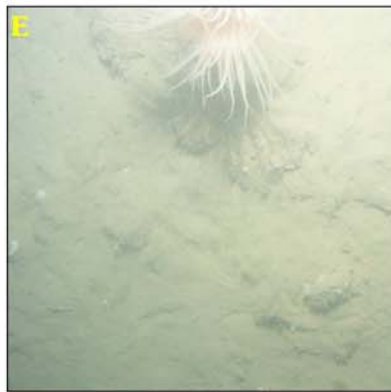
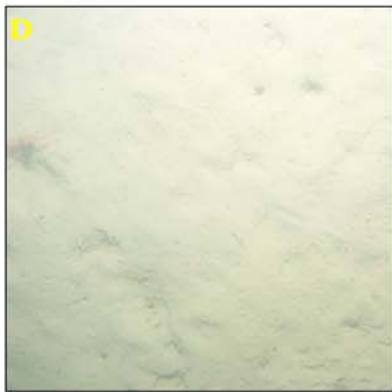
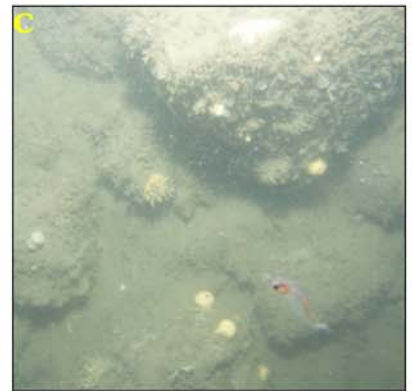
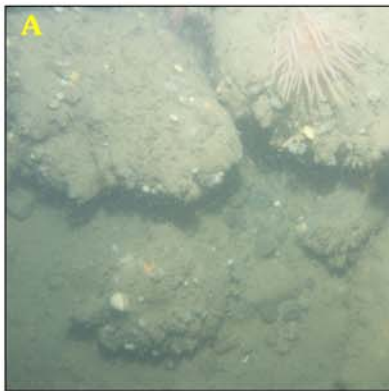
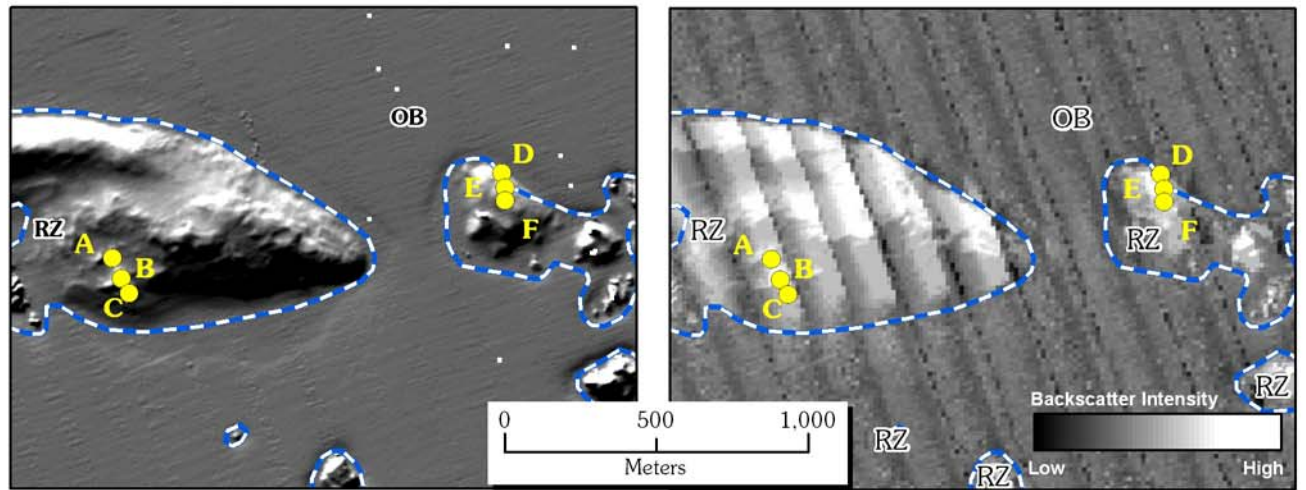


Figure 4.6. Maps showing bathymetry (upper left) and acoustic-backscatter intensity (upper right) in the northeastern part of the survey area. Parallel stripes that trend NW-SE in the backscatter data are artifacts of data collection. Isolated Rocky Zones (RZ) are surrounded by the uniformly flat, muddy seafloor of the Outer Basin (OB). Bottom photographs A–F are indicated by yellow circles. The distance across the bottom of the photographs is approximately 50 cm. See Figure 4.1 for location.

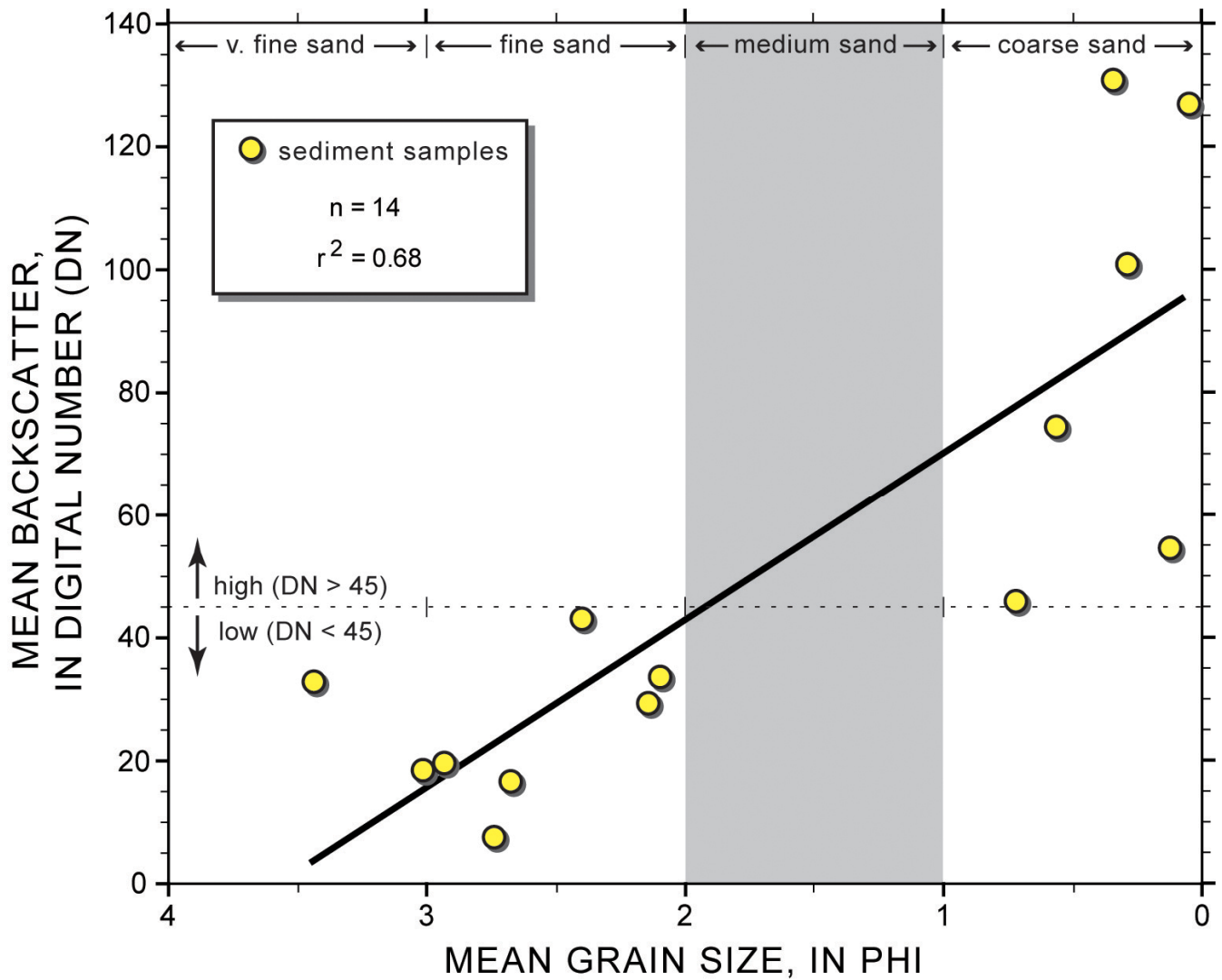


Figure 4.7. Graph showing the relationship between mean backscatter values (DN = digital number) and mean grain size for 14 bottom samples collected in the nearshore area. Sediment in areas of relatively high backscatter (values greater than 45) consists of coarse sand. Sediment in areas of relatively low backscatter (values less than 45) primarily consists of fine sand. No samples of medium sand (gray box) were collected.

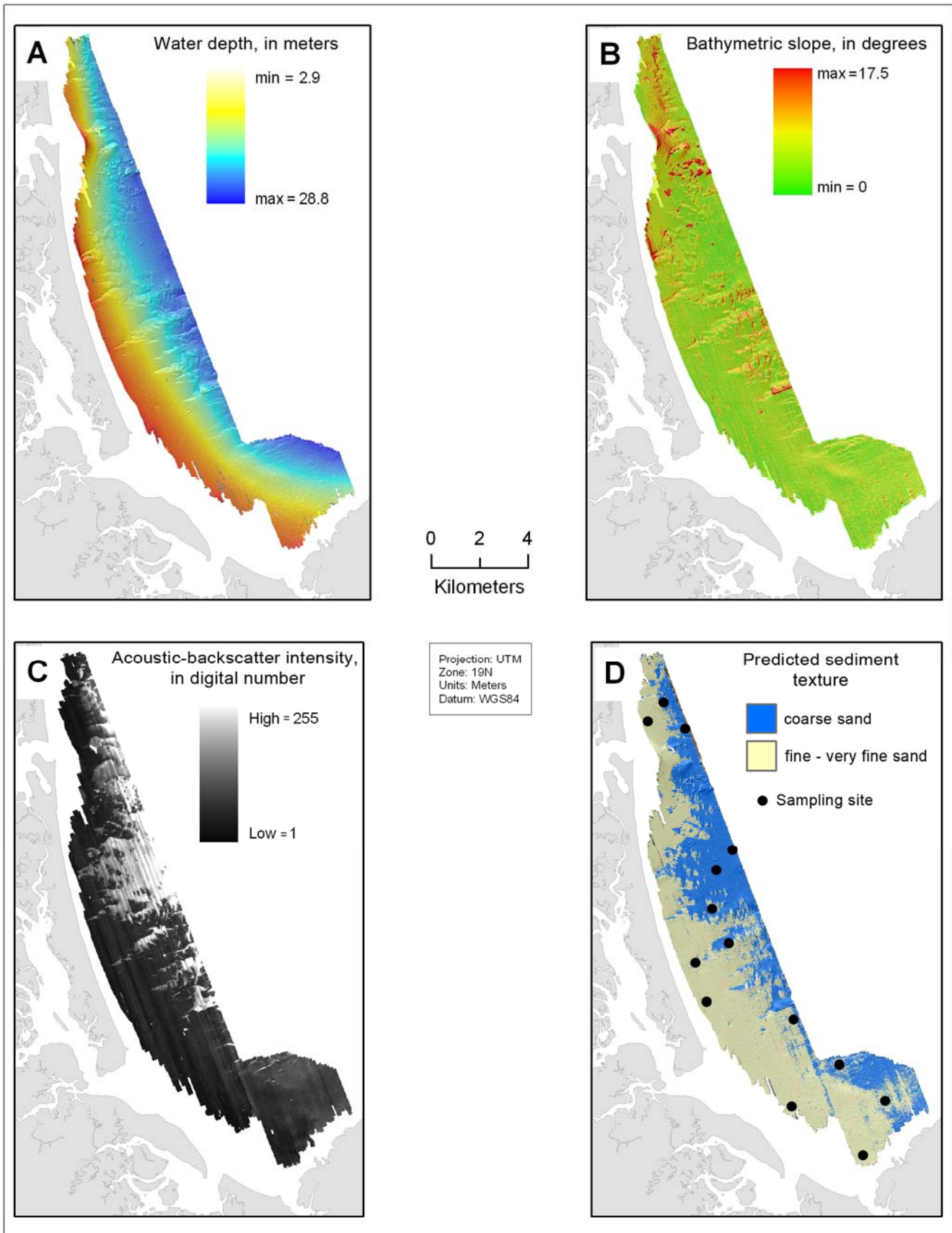


Figure 4.8. Maps of the nearshore area showing the three inputs to the quantitative bottom classification: (A) water depth, (B) bathymetric slope, and (C) acoustic-backscatter intensity. Map D shows the predicted texture of surficial sediment in the area and the mean grain size of the 14 sediment samples represented by the graph in figure 4.7. Appendix IV describes the processing flow for the analysis, input data, and functions used to generate this classification.

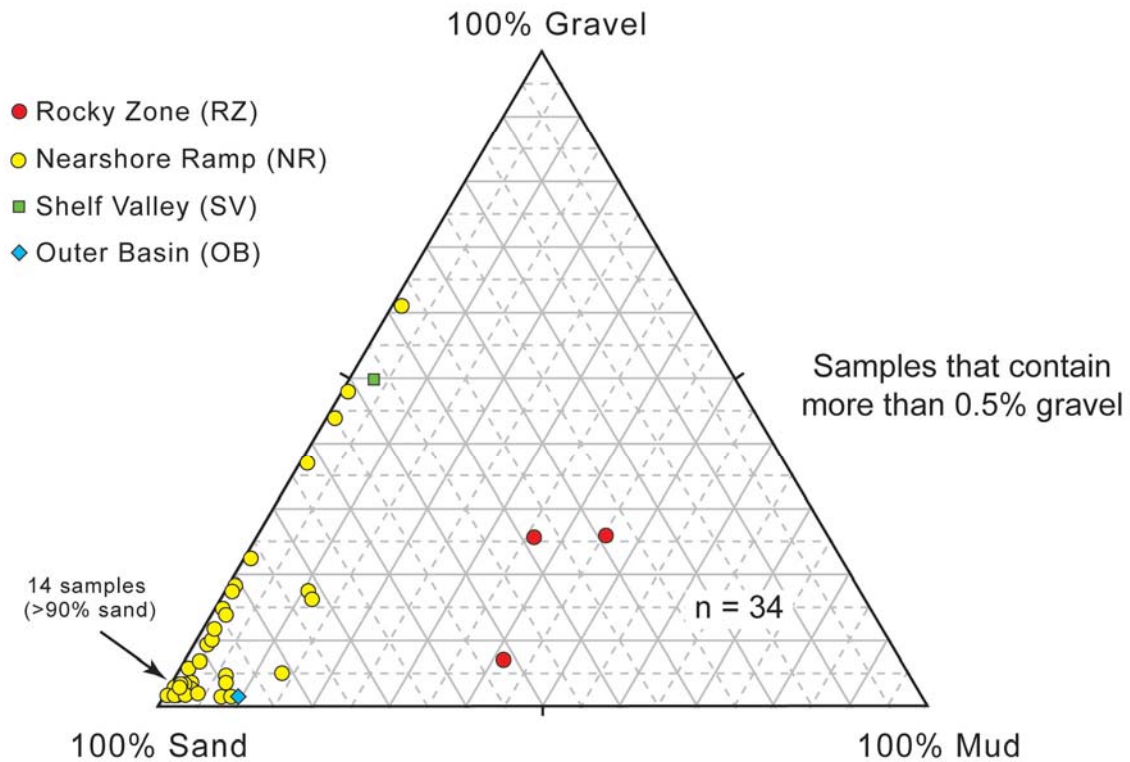
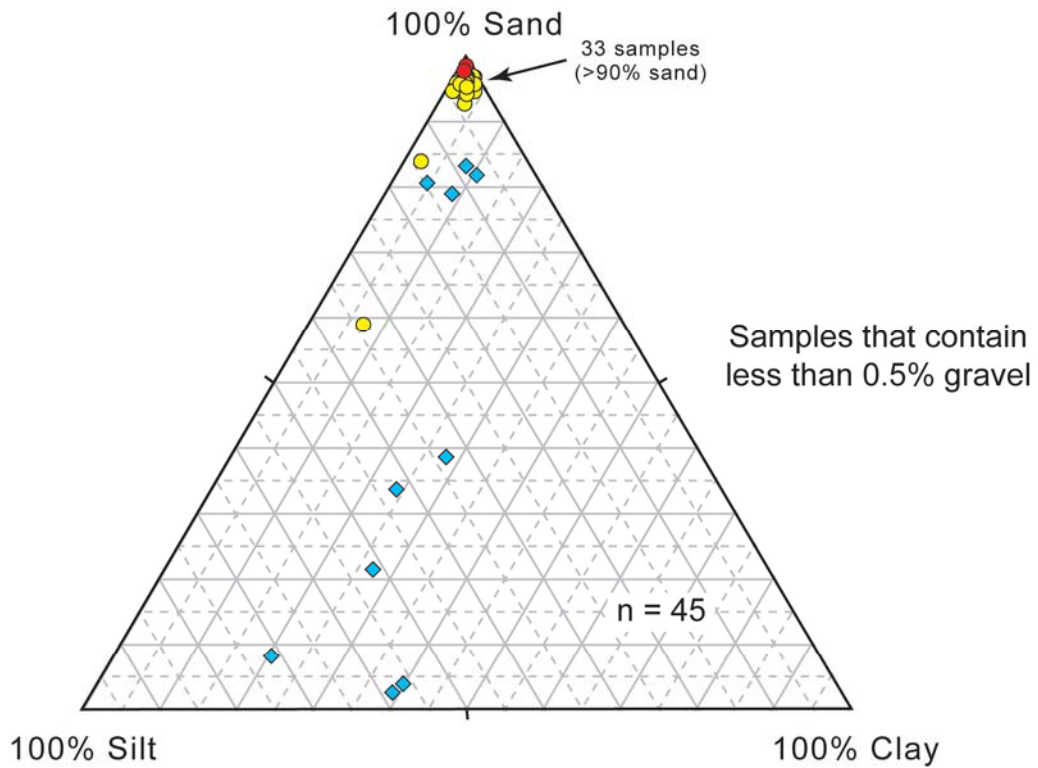


Figure 4.9. Ternary diagrams depicting texture of surficial sediment in samples collected from the survey area. Apexes of the diagrams represent 100 percent of the labeled textural component (i.e., gravel, sand, silt, and/or clay). The upper diagram depicts 45 samples that lack gravel; the lower diagram depicts 34 samples that contain at least 0.5 percent gravel. See table 4.2 for additional information on these samples.

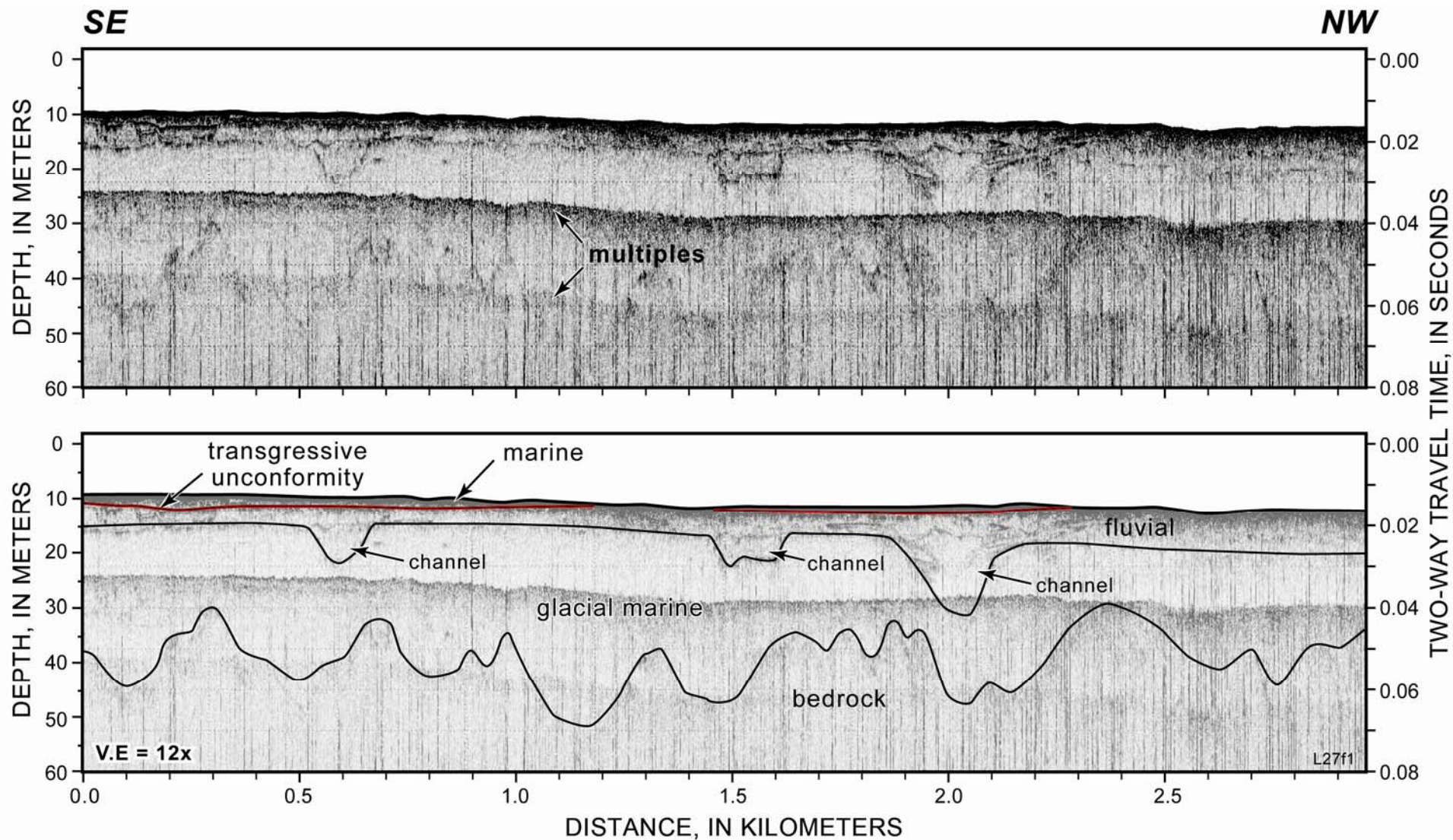


Figure 4.10. Seismic-reflection profile showing three small channels cut into glacial-marine sediment in the central part of the study area. The transgressive unconformity (red line) is eroded into the upper surface of fluvial deposits and locally overlain by a sheet of sandy marine sediment generally less than 1 m thick. See Figure 4.3 for location. A constant seismic velocity of 1500 m/s through water, sediment, and rock was used to convert from two-way travel time to depth.

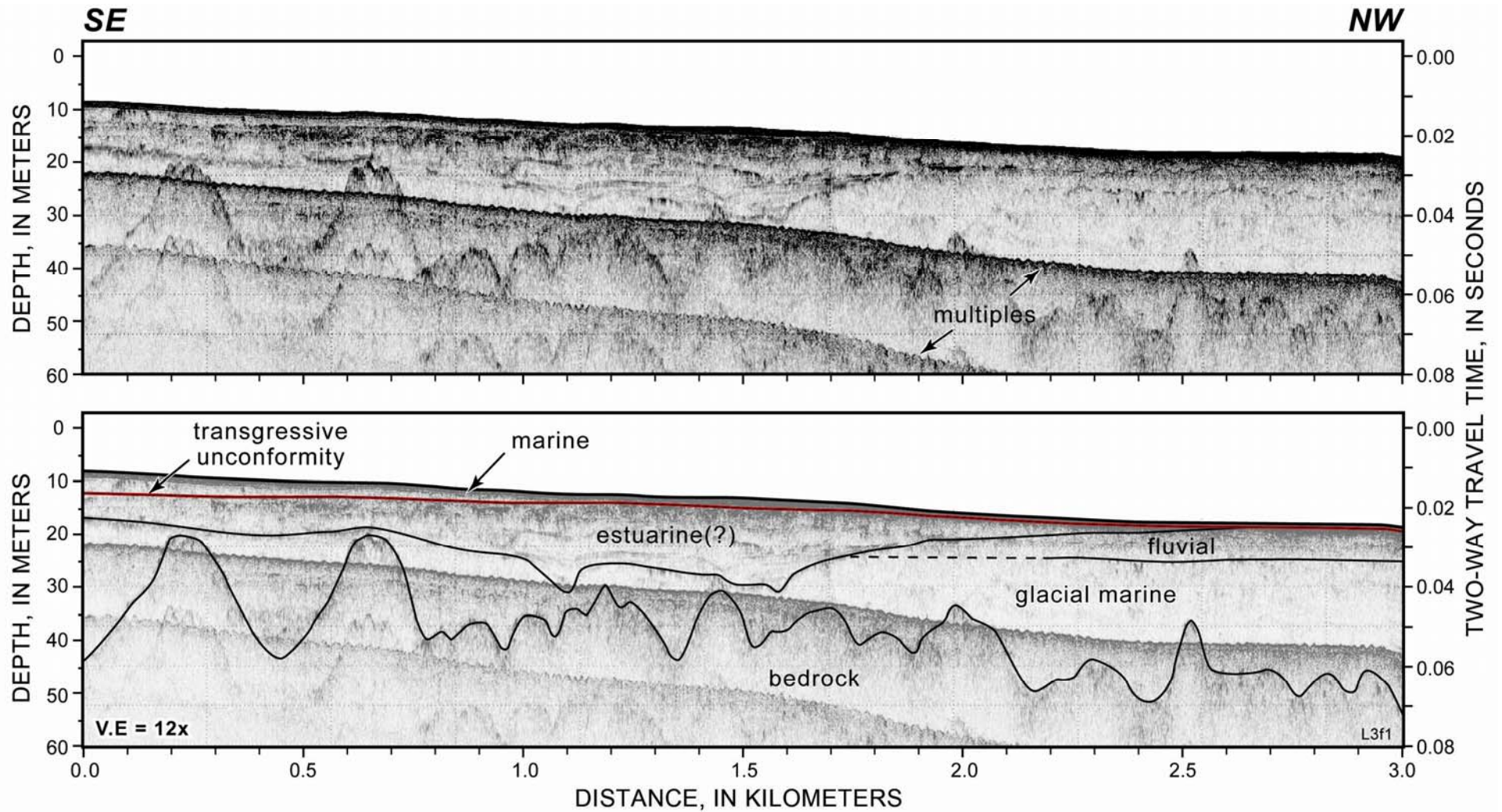


Figure 4.11. Seismic-reflection profile showing a broad channel cut into fluvial and glacial-marine sediment in the southern part of the study area. The well-stratified sediment that fills the channel is interpreted as estuarine sediment. The transgressive unconformity (red line) is overlain by 5 to 6 m of sandy marine sediment, which is among the thickest Holocene deposits in the region. See Figure 4.3 for location. A constant seismic velocity of 1500 m/s through water, sediment, and rock was used to convert from two-way travel time to depth.

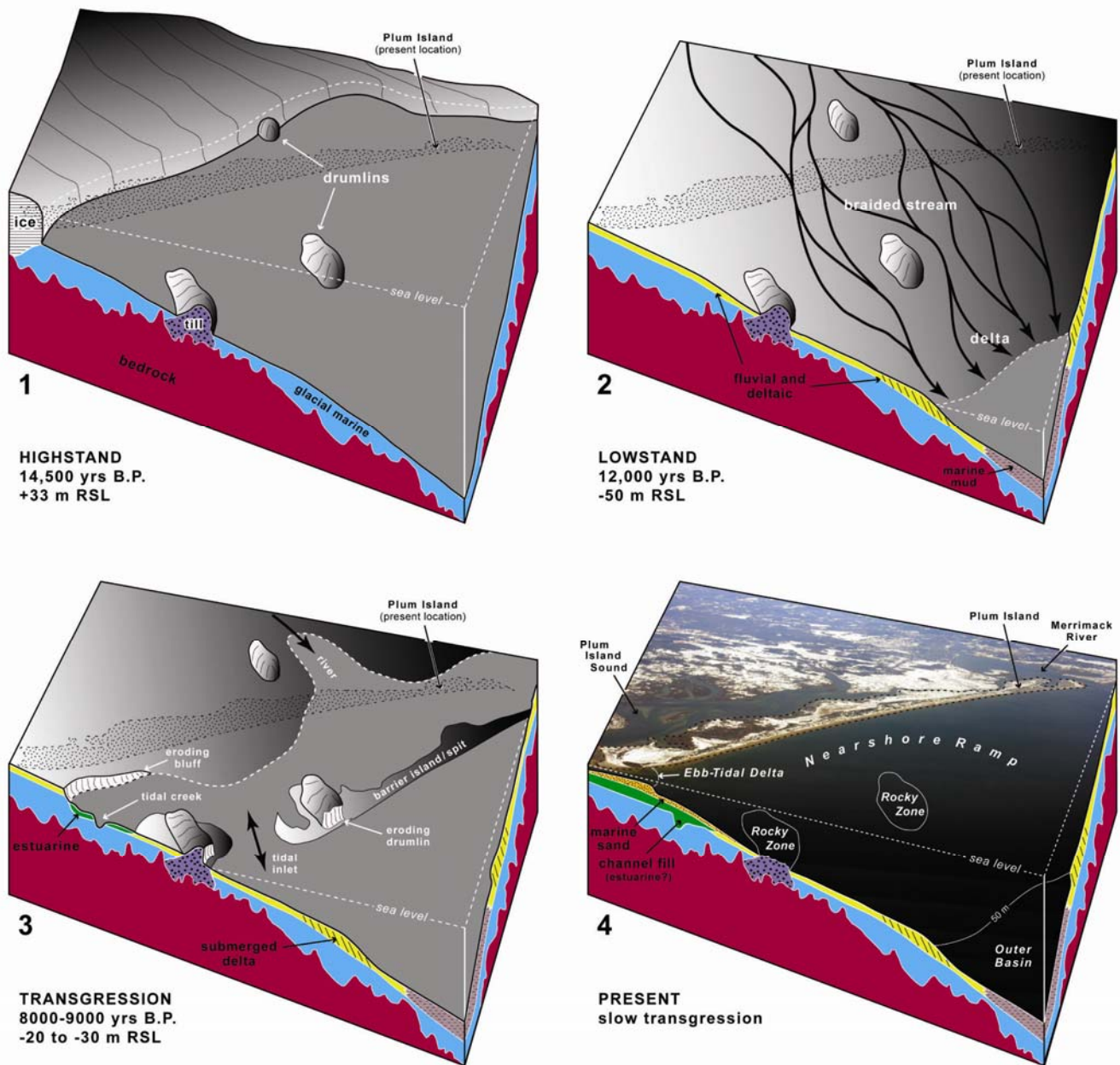


Figure 4.12. A four-phase conceptual model showing evolution of the northeastern Massachusetts coast and inner shelf as interpreted from geologic mapping. Schematic diagrams depict the general configuration of coastal landforms and stratigraphic units. Timing and elevation of relative sea level (RSL) are based on published reports and our best estimates. Each panel includes an outline of Plum Island in its present location. *Phase 1:* Late Pleistocene glaciers retreat across the isostatically depressed landscape, and leave behind drumlins and other till deposits. RSL is about 33 m higher than present. Thick glacial-marine sediment blankets high-relief bedrock. *Phase 2:* With crustal rebound, RSL falls to a lowstand of about -50 m depth. Braided streams flow across the emergent landscape and deposit a broad, relatively thin sheet of fluvial sand and gravel. A large delta forms at the lowstand shoreline about 10 km seaward of the present coast. Muddy marine sediment accumulates in deeper water. *Phase 3:* Early Holocene RSL rises to 20 to 30 m. Shoreline migration reworks the upper surface of the lowstand delta. Erosion produces a transgressive unconformity that is overlain by thin, discontinuous deposits of sandy marine sediment. A barrier island/spit, which is pinned to eroding drumlins, probably has formed seaward of Plum Island. *Phase 4:* RSL rise continues and the barrier/spit system migrates to its present location. Rocky Zone represents ledge or eroded remnants of drumlins. Nearshore Ramp represents the modified, gently sloping delta top. Ebb-Tidal Deltas form seaward of inlets. Channel-fill deposits are interpreted as estuarine sediment that accumulated in a back-barrier setting. Thick muddy sediment is preserved in the Outer Basin below the depth of RSL lowstand. (Photograph in panel 4 by Joseph Kelley, University of Maine, March 2005.)