Prepared in cooperation with the Massachusetts Office of Coastal Zone Management

Shallow Geology, Seafloor Texture, and Physiographic Zones of the Inner Continental Shelf from Nahant to Northern Cape Cod Bay, Massachusetts

By Elizabeth A. Pendleton, Wayne E. Baldwin, Walter A. Barnhardt, Seth D. Ackerman, David S. Foster, Brian D. Andrews, and William C. Schwab

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Contents

Conversion Factors and Datum

SI to Inch/Pound

Multiply	By	To obtain
Length		
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
kilometer (km)	0.5400	mile, nautical (nmi)
meter (m)	1.094	yard (yd)
Velocity		
meters per second (m/s)	3.281	foot per second (ft/s)
Area		
square kilometers (km^2)	0.386102159	square miles (mi^2)

Vertical coordinate information is referenced to North American Vertical Datum of 1988 (NAVD 88) or Mean Sea Level (MSL).
Elevation, as used in this report, refers to distance above the vertical datum.

Horizontal coordinate information is referenced to the World Geodetic System of 1984 (WGS84) in a Geographic Coordinate System.

Particle size in phi units may be converted to millimeters (mm) as follows:
$mm=2^{-phi}$

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Abstract

The Massachusetts inner continental shelf between Nahant and northern Cape Cod Bay has been profoundly affected by the occupation and retreat of glacial ice sheets and relative sea-level change during the Quaternary. Marine geologic mapping of this area is a component of a statewide cooperative effort involving by the U.S. Geological Survey and the Massachusetts Office of Coastal Zone Management. Interpretation of high-resolution geophysical data (interferometric and multibeam swath bathymetry, lidar, backscatter, and seismic reflection), sediment samples, and bottom photographs was used to produce a series of maps that describe the distribution and texture of seafloor sediments, shallow geologic framework, and physiographic zones of this inner-shelf region. These data and interpretations are intended to aid efforts to inventory and manage coastal and marine resources, and provide baseline information for research focused on coastal evolution and environmental change.

Introduction

Purpose and Scope

This report describes the glacial and postglacial geologic framework of the Massachusetts inner continental shelf between Nahant and northern Cape Cod Bay (fig. 1). We present interpretations that describe the distribution and texture of seafloor sediments, physiographic zones, surficial geology, and shallow stratigraphy of this inner-shelf region. Our interpretations are primarily based on geophysical data and bottom photographs, and samples published in U.S. Geological Survey (USGS) reports by Ackerman and others (2006), Butman and others (2007), Barnhardt and others (2010), and Andrews and others (2010) and in sample databases (Ford and Voss, 2010; McMullen and others, 2011) modified by the Massachusetts Office of Coastal Zone Management (CZM). Interpretations and associated data are provided as geospatial data layers in Esri ArcGIS formats (Appendix 1– Geospatial Data). This research was part of a cooperative seafloor mapping program between the USGS and the CZM (http://woodshole.er.usgs.gov/project-pages/coastal_mass/). This cooperative fosters data collection and the production of interpretive geologic datasets that can be used by managers and scientists to delineate marine resources, assess environmental change, inventory marine habitats, and support research concerning sea-level change, sediment supply, and coastal evolution.

The geologic framework and surficial sediment distribution of the coastal zone of Massachusetts is complex and difficult to map. Previous studies have defined the geology and texture of the seafloor in this region based on widely spaced geophysical tracklines or samples (Oldale and Bick, 1987; Oldale and O'Hara, 1990; Rendigs and Oldale, 1990; Knebel and others, 1993; Knebel and Circe, 1995; Rendigs and Knebel, 2002; Ford and Voss, 2010). Other mapping methods in homogenous, nonglaciated regions rely on contouring changes in grain size (Hollister, 1973), but the frequent substrate changes in this region occur over spatial scales that are smaller than a sampling grid can resolve. In this study, high-resolution geophysical datasets at full seafloor coverage, supplemented with sediment samples and bottom photographs, provide the basis for surficial to shallow stratigraphic geologic maps, high-resolution sediment texture maps, and physiographic zone delineations that were previously unfeasible because of a lack of high-quality, high-density seafloor mapping data.

Geologic Setting

The geology of Boston Harbor, western Massachusetts Bay, and northern Cape Cod Bay was profoundly affected by the occupation and retreat of glacial ice sheets during the Pleistocene (Larson, 1982; Stone and Borns, 1986). Most of the glacial till and stratified drift overlying pre-Quaternary bedrock and coastal plain sediments were deposited by the Wisconsinan Laurentide ice sheet, which reached its maximum extent in eastern Massachusetts at Martha's Vineyard and Nantucket about 20,000 to 24,000 years before present (BP; Uchupi and others, 1996; Oldale, 2001; Boothroyd and Sirkin, 2002). Sometime after 18,000 years BP, the Cape Cod Bay lobe of the ice sheet retreated sufficiently north of present-day Cape Cod to create an ice dam and supply sediment-laden meltwater to a pro-glacial lake that occupied the area of present-day Cape Cod Bay (Larson, 1982; Oldale, 1982, 1988), allowing extensive glaciolacustrine sediments to be deposited within the lake. The size of the lake fluctuated as the ice lobe receded from the Sandwich Moraine location and subsequently readvanced forming the Billingsgate Shoal Moraine along the southern margin of the bay (fig. 1; Larson, 1982; Oldale and O'Hara, 1984; Ridge, 2004). As the ice continued to retreat, the sea simultaneously submerged the isostatically depressed landscape, resulting in widespread deposition of glaciomarine sediments across northern Cape Cod Bay and Massachusetts Bay (Oldale and Bick, 1987; Oldale, 1988; Oldale and O'Hara, 1990). After the glaciers retreated north of Boston about 14,500 years BP, relative sea-level change became the dominant influence over regional evolution (Oldale and O'Hara, 1990; Oldale and others, 1993). Between about 14,000 and 12,000 years BP, relative sea level fell rapidly as the region isostatically rebounded and the subaerially exposed shelf was deeply incised by meltwater fluvial systems (Oldale and Bick, 1987; Oldale and O'Hara, 1990). After about 12,000 years BP, eustatic sea-level rise eventually outpaced waning isostatic rebound, causing the onset of the Holocene marine transgression that continues today (Oldale and O'Hara, 1990; Oldale and others, 1993). Low-lying valleys incised during the previous regression were partially filled by fluvial and estuarine deposits along the leading edge of the transgression, and coastal waves and currents effectively eroded, reworked, and redistributed sediments across the inner shelf seaward of the transgressing shoreline.

Along the western margins of Cape Cod and Massachusetts Bays between Hull and Duxbury (fig. 1), inner-shelf sediments in water depths less than about 40 meters (m) have been extensively reworked and winnowed, resulting in seafloor textures much coarser than those in deep parts of Cape Cod Bay (Knebel and Circe, 1995; Knebel and others 1996). This zone is characterized by outcropping pre-Quaternary bedrock, rocky pavements consisting of boulders, cobbles, and gravel mixed with sand, and narrow channels and valleys filled with sand and gravel (Oldale and Bick, 1987; Oldale and O'Hara, 1990). Erosion of the inner shelf has provided the sand and gravel for building marsh-backed Holocene beaches along the adjacent coast. A transition to fine-grained sediment occurs in water depths between about 20 and 50 m in northern Cape Cod Bay. Variably thick sand ridges and shoals present in water depths less than about 30 m thin seaward, exposing underlying glacial drift and fluvial and estuarine channel fills at the seafloor in water depths between about 30 and 50 m. Deeper than about 50 m, Holocene marine muds blanket the seafloor (Oldale and O'Hara, 1990; Rendigs and Knebel, 2002; Uchupi and others, 2005).

Unlike the unprotected, erosional inner shelf, Boston Harbor is a semienclosed basin that acts as a fine-grained sediment trap (Knebel and Circe, 1995). The Precambrian bedrock of the harbor basin crops out locally (Kaye, 1982; Rendigs and Oldale, 1990). Two glaciations have been identified in the sediments of Boston Harbor; the older glaciation is thought to be of Illinoian age and is represented by compacted till with cobbles and boulders, characterizing the drumlins of the Boston Harbor Islands (Newman and others, 1990; Oldale and Colman, 1992). The late Wisconsinan glacial sediments consist of till, outwash sand, gravel, and glacial-marine mud (Kaye, 1982; Oldale and Bick, 1987; Rendigs and Oldale, 1990). Marine transgression has reworked large areas of the harbor floor, eroded drumlins, constructed beaches and marshes, and stranded coarse lag deposits along the seafloor.

Previous Work

Many authors have discussed the geology and geologic evolution of Cape Cod, the Islands, and the surrounding Massachusetts inner continental shelf, and findings from most have been synthesized by Uchupi and others (1996). Oldale and Bick (1987), Rendigs and Oldale (1990), and Oldale and O'Hara (1990) represent the most recent and extensive geologic framework studies for Massachusetts Bay, Boston Harbor, and Cape Cod Bay, respectively. These investigations are based on widely spaced boomer and 3.5-kilohertz (kHz) seismic-reflection profiles, sidescan sonar data, and vibracores, as well as observations from previous studies on the inner-shelf and adjacent mainland, and provide thorough descriptions of pre-Quaternary, glacial, and postglacial stratigraphy. In addition, Foster and Poppe (2003), Poppe and others (2006), and Uchupi and others (2005) provide stratigraphic interpretations for nearshore portions of eastern-most Cape Cod Bay based on boomer and chirp seismic-reflection profiles.

Knebel and Circe (1995), Knebel and others (1996), and Rendigs and Knebel (2002) investigated seafloor sediments and sedimentary environments within Boston Harbor, Massachusetts Bay, and Cape Cod Bay, respectively. Based on reconnaissance sidescan sonar data and supplemental geologic and hydrodynamic data, these authors classified the seafloor by zones of erosion or nondeposition, sediment reworking, or deposition, and discussed their distributions in relation to regionally variable geologic and oceanographic conditions. Rendigs and Knebel (2002) also described the general distribution of sand, silt, and clay sediments in Cape Cod Bay by adding sediment sample analysis to sidescan sonar data. Subsequently, Poppe and others (2005) investigated seafloor sediments and sedimentary environments for a nearshore part of northeastern-most Cape Cod Bay utilizing multibeam bathymetry and backscatter, seafloor sediment samples, and bottom photographs. A comprehensive multidisciplinary investigation in Boston Harbor and Massachusetts Bay built on previous studies by incorporating sedimentary environments, acoustic data, geochemistry, numerical models, and observations to describe the processes influencing contaminated sediment transport (Bothner and Butman, 2007). Finally, Ford and Voss (2010) used more than 16,000 seafloor sediment samples to classify bottom type in Massachusetts State waters using Thiessen polygon analysis.

Methods

The following section describes how the geologic interpretations presented in this report were generated. Detailed descriptions of software, source information, scale, and accuracy assessments for each dataset are provided in the metadata files for geospatial data layers in the appendix.

Geophysical Data and Interpretations

During the past two decades, several organizations have collected acoustic backscatter, topography and bathymetry, and chirp seismic-reflection profile data within the coastal waters of Massachusetts (table 1). A seamless acoustic backscatter image and digital elevation model (DEM) were created from previously processed and published datasets (figs. 2 and 3; table 1). Each source backscatter mosaic GeoTIFF image was resampled to 10 meters per pixel (to achieve a common resolution) and mosaicked together (fig. 2) using PCI Geomatics (version 10.1). Each topographic and bathymetric source dataset was imported into ArcGIS (version 9.3.1), where all grids were resampled to 30 meters per pixel. The data were projected to a common horizontal coordinate system, and VDATUM (version 3.1; using the Maine, New Hampshire, Massachusetts-Gulf of Maine, version 01 (1983–2001) regional transformation grid) was used to define a common vertical coordinate system (North American Vertical Datum of 1988 (NAVD 88)). The grids were then mosaicked into a DEM using a blend algorithm (fig. 3).

More than 5,000 kilometers of chirp seismic-reflection profiles were collected and processed (table 1; fig. 4) using the techniques described in Barnhardt and others (2010) and Andrews and others (2010). Shallow stratigraphy and surficial geology interpretations were made in Landmark SeisWorks 2D (Haliburton, 2012) and consisted of (1) identifying and digitizing erosional unconformites defining the boundaries between Holocene, Pleistocene, and pre-Quaternary seismic units (figs. 5, 6, and 7); and (2) digitizing the extent over which each of the defined subsurface seismic units crops out on the seafloor (figs. 7 and 8).

Isochrons of the Holocene seismic units were exported and converted to thickness in meters using a constant seismic velocity of 1,500 meters per second (m/s). The resulting isopachs were imported into ArcGIS (version 9.3.1), as point features (easting, northing, and depth) and used to generate interpolated DEMs with 50-m cell sizes. The Holocene isopach DEMs were each added to a regional swath-bathymetry DEM (30-m cell size) to produce DEMs of the bounding unconformities (50-m cell sizes) relative to NAVD 88.

The digitized seafloor outcrops for each seismic unit were imported into ArcGIS as point features (easting, northing, seismic unit) and used to guide manual digitizing of polygons representing discrete areas of seismic-unit outcrop. The resulting polygon dataset provides a seamless representation of surficial geology for the seismic-reflection survey area (fig. 8).

Sediment Samples and Sediment Texture Classification Schemes

Sediment sample databases of Ford and Voss (2010) and McMullen and others (2011) were supplemented with National Oceanic and Atmospheric Administration chart sampling data and more than 2,000 bottom photographs and descriptions at more than 400 stations (fig. 9;

Emily Huntley, CZM, unpub. data, 2012). This study used the Barnhardt and others (1998) and Shepard (1954), as modified by Schlee (1973), sediment texture classification schemes (figs. 10 and 11). The Barnhardt and others (1998) system is based on four basic, easily recognized sediment units: gravel (G), mud (M), rock (R), and sand (S). Because the sea floor is often a nonuniform mixture of these units, which are too small to define separately, the classification is further divided into 12 composite units, which are 2-part combinations of the 4 basic units (fig. 10). The classification is defined such that the primary unit, representing more than 50 percent of an area's texture, is given an upper case letter, and the secondary texture, representing less than 50 percent of an area's texture, is given a lower case letter. If one of the basic sediment units represents more than 90 percent of the texture, only its upper case letter is used. The units defined under the Barnhardt and others (1998) classification within this study area include Rg, Rs, Rm, Gr, Gs, S, Sg, Sm, M, and Ms. The Shepard (1954), as modified by Schlee (1973) (fig. 11), scheme for this study area includes gravel, sand, sandy-silt, silty-sand, and clay classes, with the addition of a solid class to encompass rocky areas.

Sediment Texture Mapping

The texture and spatial distribution of sea-floor sediment were analyzed qualitatively in ArcGIS using several input data sources, including acoustic backscatter, bathymetry, lidar, seismic-reflection profile interpretations, bottom photographs, and sediment samples (fig. 12). First, sediment texture polygons were outlined using backscatter intensity data (available at 1- to 10-m resolutions; table 1) to define changes in the seafloor based on acoustic return (fig. 2). Areas of high backscatter (light colors) have strong acoustic reflections and suggest boulders, gravels, and generally coarse seafloor sediments characterize the seafloor. Low-backscatter areas (dark colors) have weak acoustic reflections and generally are characterized by fine-grained material such as muds and fine sands.

The polygons were then refined and edited using gradient, rugosity, and hillshaded relief images derived from interferometric and multibeam swath bathymetry and lidar (available at 2.5- to 30-m resolutions; fig. 3; table 1). Areas of rough topography and high rugosity typically are associated with rocky areas, whereas smooth, low-rugosity regions tend to be blanketed by fine-grained sediment. These bathymetric derivatives helped to refine polygon boundaries where changes from primarily rock to primarily gravel may not have been apparent in backscatter data, but could easily be identified in hillshaded relief (fig. 12).

The third data input was the stratigraphic interpretation of seismic-reflection profiles, which further constrained the extent and general shape of seafloor sediment distributions and rocky outcrops, and also provided insight concerning the likely sediment texture based on the pre-Quaternary, glacial, or postglacial origin (figs. 8 and 12).

Finally, bottom photographs and sediment samples (fig. 9) were used to define sediment texture for each polygon that was drawn using geophysical data (fig. 12). Average gravel, sand, silt, clay, and phi size for each sediment texture polygon were calculated using grain size statistics of sediment samples with laboratory analysis. Of the more than 5,000 samples total within the study area, 615 were analyzed in the laboratory for grain size. Samples with laboratory grain size analysis were preferred over visual descriptions when defining sediment texture throughout the study area. Sediment texture statistics can be found within the geospatial data file for sediment texture in the appendix. Average phi size and average particle content by weight data should be used cautiously in rock and gravel areas, where large particle sizes often are underrepresented using sediment sampling techniques. The average texture statistics in combination with the sediment sample count per polygon (where higher count numbers indicate a higher number of samples used in the average) are most applicable to the sand and silt sediment classes.

Some polygons had more than one sample, and some polygons lacked sample information. For multiple samples within a polygon, the dominant sediment texture (or average phi size) was used to classify sediment type. In rocky areas, bottom photographs were used in the absence of sediment samples to qualitatively define sediment texture. Polygons that lacked sample information were defined texturally through extrapolation from adjacent or proximal polygons of similar acoustic character that did contain sediment samples.

Physiographic Zones

The distribution of seafloor physiographic zones was analyzed qualitatively in ArcGIS using the same input sources and digitization techniques used to determine sediment texture and distribution. Following the methods used in the Gulf of Maine to produce geologic maps (Kelley and Belknap, 199; Kelley and others, 1996; Barnhardt and others, 2006; and Barnhardt and others, 2009), the seafloor within the study area was divided into physiographic zones based on seafloor morphology and dominant sediment texture. Physiographic mapping allows efficient mapping of large areas and presents geomorphic and textural data in a single classification scheme. This simplified designation especially is useful in complex inner-shelf settings such as northeastern Massachusetts, New Hampshire, and Maine. An added advantage of physiographic zones is that they do not require full data coverage and can be defined from a variety of data sources. Physiographic zones identified within the study area include rocky zones, outer basins, nearshore basins, ebb-tidal deltas, hard-bottom plains, nearshore ramps, sand waves, shelf valleys, and dredged channels. These zones are further described in the “Results” section in terms of their location, size, morphology, geologic setting, and substrate properties.

Results

Sediment Texture and Distribution

Using the Barnhardt and others (1998) (fig. 10) and the Shepard (1954), as modified by Schlee (1973; fig. 11), classifications, sediment texture and distribution were mapped more than 1,000 square kilometers (km^2; figs. 13 and 14). The data were generated at a scale between 1:8,000 and 1:25,000 depending on the resolution of the source geophysical grids and the sample data density.

Sediments within the study area represent nearly all particle sizes. Sediment texture ranges from muddy sediments within Boston Harbor and Cape Cod Bay to pebbles, cobbles, and boulders in rocky areas of the inner shelf between Hull and Duxbury (figs. 13 and 14). There is no meaningful correlation between mean grain size and water depth within sediment texture polygons. Both coarse- and fine-grained sediment exist in all water depths; however, in general, fine-grained sediments are located in the deeper (greater than about 50 m), more quiescent environments of central Cape Cod Bay and Boston Harbor, and rocky textures are more prevalent along the nearshore margins of western Massachusetts and northern Cape Cod Bays (figs. 13 and 15). A mean sorting value of 1.63 suggests that the sediment is poorly sorted in the region, which is consistent with a reworked glacial environment.

Sand is the dominant bottom sediment type for all sediment samples within the study area with laboratory grain size analysis information, representing more than 52 percent of sediment samples by weight. Sandy sediments are interpreted to cover 32 percent of the seafloor by area (fig. 16). Muddy sediments, which include silt and clay size particles less than 0.062 millimeter (mm) in diameter, represent an average of more than 43 percent of all sediment samples by weight and about 27 percent of the seafloor by area (fig. 16). Samples with the highest mud percentages were collected from Boston Harbor and north-central Cape Cod Bay. Sediment from the western margin of Massachusetts Bay is highly variable in terms of mud content, ranging from 0 percent to 70 percent mud with an average of 20 percent. Samples from dominantly rocky areas averaged only 2 percent mud. Gravel or particles greater than 2 mm (-1 phi) in diameter compose an average of 5 percent of all samples by weight, and are interpreted to be the primary sediment cover for 15 percent of the seafloor. Bottom photographs indicate that gravel content is underrepresented in the sediment sample data for this area. Photographs often document the occurrence of gravel and cobble in rocky areas where sediment samplers were unable to recover large-diameter particles. Primarily rocky areas are interpreted to cover about 26 percent of the seafloor by area, and are mostly present in western margins of Massachusetts and Cape Cod Bays (figs. 13 and 16).

Physiographic Zones

Areal distribution of physiographic zones in the 1,000-km^2 study area was generated at a scale of 1:12,000 to 1:25,000 depending on the resolution of the source geophysical grids. Following the classification of Kelley and others (1996), physiographic zones identified within the study area include rocky zones, outer basins, nearshore basins, hard-bottom plains, nearshore ramps, and shelf valleys. Three additional physiographic zones, sand waves, ebb-tidal delta, and dredged channel, were created to distinguish areas with large bedforms, depositional features associated with inlet mouths, and anthropogenically modified navigation routes, respectively.

Rocky zones are rugged areas of high bathymetric relief ranging from nearly vertical rock cliffs to relatively flat, gravel-covered plains with boulders as much as 4 m in diameter. Although coarse-grained sediments locally occur in all physiographic zones, they dominate the seafloor in rocky zones. Rocky zones are found most extensively in the nearshore from Nahant to Duxbury (fig. 17). They make up more than 25 percent of the total seafloor area, and are concentrated on the inner shelf, with almost no rocky zones occurring within Boston Harbor and Cape Cod Bay (fig. 18).

Outer basins are generally found in water depths greater than 40 meters and are of a fine texture, but may contain occasional rock outcrops. Outer basins are the most extensive single physiographic feature within the study area, making up the majority of northern and central Cape Cod Bay (fig. 17). By total area the outer basins are nearly 12 percent of the seafloor (fig. 18), and sediment samples within the outer basins range from sand to clayey silt, with muddy sediments being the primary texture. The surficial sediments of the outer basins can be characterized as Holocene marine muds that overlay glacial-marine and glacial-lacustrine muds (Oldale, 1988).

Nearshore basins are areas of shallow, low-relief seafloor adjacent to the mainland, which are separated from offshore areas by islands or shoals. Nearshore basins make up more than 6 percent of the seafloor by area (fig. 18) and are interspersed along the inner shelf, usually adjacent to rocky zones. Surficial sediment samples within Nearshore Basins indicate that these features are filled with gravel to clayey silt and the composition is related to their location and the character of adjacent features, such that fine grained nearshore basins occur in and around Boston Harbor and Cape Cod Bay, whereas coarse grained nearshore basins lie along the margin of western Massachusetts Bay.

Ebb-tidal deltas are lobate sandy shoals found on the seaward side of tidal inlets that form through the interaction of waves and ebb-tidal currents. There is only one ebb-tidal delta (1 percent of the seafloor) within the study area at the mouth of the North River. These young depositional features form at the mouth of rivers where fluvial and nearshore sediments are reworked by tidal currents and waves. The ebb-tidal delta at the mouth of the North River primarily comprises sand.

Hard-bottom plains tend to have low bathymetric relief, with a coarse sediment texture consisting of primarily gravel, sand, and rock. Hard-bottom plains account for about 5 percent of the seafloor within the study area and are concentrated in western Massachusetts Bay in intermediate water depths (15–30 m) (fig. 17).

Nearshore ramps 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 cobbles and boulders locally crop out on the seafloor. Nearshore ramps are most often gently sloping seaward extensions of mainland beaches within the study area. As such, they most often comprise sand and gravel with occasional subordinate concentrations of silt or rock. Nearshore ramps are found off Revere Beach, Hull, Humarock, and Duxbury and Plymouth Bay and are the largest physiographic zone by area (about 40 percent of the seafloor within the study area) (figs. 17 and 18).

Sand waves are features developed by currents over the seafloor and may comprise gravel to fine sand. Sand waves make up about 3 percent of the seafloor by area and are concentrated east of Brant Rock in water depths generally between 20 and 30 m (figs. 17 and 18). These areas are characterized by large abundant bedforms (tens to hundreds of meters in wavelength) comprising sand and gravel.

Shelf valleys are elongated depressions that extend offshore often perpendicular to the trend of the coastline, and slope gently seaward. Shelf valleys represent less than 3 percent of the study area, but subbottom data suggest that numerous shelf valleys exist in Cape Cod Bay partially buried beneath Holocene marine mud. These features are interpreted to be valleys formed by fluvial erosion during periods of lower than present sea level.

Dredged channels are anthropogenic features where the seafloor has been modified to accommodate navigation. Dredged channels occur within Boston Harbor and are primarily filled with gravel, sand, and muddy sediments (figs. 17 and 18).

Stratigraphy

Five primary seismic stratigraphic units and three major erosional unconformities were interpreted and mapped within the seismic survey area (fig. 6). Two interpretive geologic cross sections illustrate the general distributions and thicknesses of the seismic units and elevations of the unconformities along the western margin of the inner shelf (northwest to southeast) and across northern Cape Cod Bay (northeast to southwest) (fig. 7). The seismic units were correlated with previous USGS seismic-stratigraphic interpretations by Oldale and Bick (1987), Rendigs and Oldale (1990), and Oldale and O’Hara (1990) for western Massachusetts Bay, Boston Harbor, and Cape Cod Bay, respectively. Although the closely spaced, high-resolution, chirp seismic-reflection profiles used for interpretation in this study were particularly useful for mapping relatively shallow, Holocene subsurface units, they did not consistently provide adequate penetration for reliable mapping of the deep Pleistocene and pre-Quaternary units. For this reason, discussion of the pre-Holocene stratigraphy mostly relies on the interpretations of Oldale and Bick (1987) and Oldale and O'Hara (1990), which were based on more widely spaced, but deep-penetrating Uniboom seismic data and vibracores.

Pz(?)/Tcp(?)/Qt(?), the lowermost stratigraphic unit, is identified by the major erosional unconformity, U_1, which defines its upper surface (fig. 7). Chirp seismic data typically were unable to penetrate beneath this surface and provided little information regarding the seismic character of the unit. Pz(?)/Tcp(?)/Qt(?)is shallowest along the western margin of the inner shelf, where bedrock crops out locally in the nearshore, and deepens to the east (figs. 7 and 8). We infer from the interpretations of Oldale and Bick (1987) and Oldale and O'Hara (1990) that Pz(?)/Tcp(?)/Qt(?) mostly consists of pre-Quaternary units (fig. 6). The oldest components are probably bedrock (Pz?), seaward extensions of the consolidated crystalline, volcanic, and sedimentary rocks of Precambrian to Paleozoic age that underlie the adjacent mainland. Locally, the bedrock is overlain by eroded remnants of unconsolidated, coastal-plain deposits (Tcp?) that are Late Cretaceous to Tertiary in age. Thin deposits of Pleistocene glacial till and coarse drift (Qt?) may also locally overlie the pre-Quaternary units.

U_1 is a composite unconformity that was shaped at least in part by subaerial and fluvial erosion that occurred during Jurassic, Early Cretaceous, and middle Tertiary times, as well as glacial erosion during two or more Pleistocene glacial episodes. The U_1 surface generally deepens to the east, eventually exceeding the penetration limit of the seismic data; however, in certain places, U_1 also merges with the late Wisconsinan regressive (U_r) and Holocene transgressive (U_t) unconformities (fig. 7).

Four stratigraphic units overlying Pz(?)/Tcp(?)/Qt(?) are interpreted to represent Quaternary sedimentary deposits (fig. 6).

Qd is the oldest unit and is identified by Ur, which generally defines its surface (fig. 7). Chirp seismic penetration into Qd varied spatially, and the deepest records were obtained in areas where younger, overlying units were thinnest. Seismic character within Qd commonly consists of vertically laminated, roughly horizontal to broadly undulating reflectors or zones of near acoustic transparency (fig. 19). Vertical stacking of these seismic signatures separated by unconformities is indicative of internal sub-units within Qd. The Qd unit is thinnest along the western margin of Massachusetts Bay where it is locally absent and generally thicker to the east and south beneath Massachusetts and Cape Cod bays (figs. 7 and 8). We infer that Qd correlates with the thick (as much as 120 m), primarily late Wisconsinan, glacial-drift units described by Oldale and Bick (1987) and Oldale and O'Hara (1990). They distinguished three sub-units within the stratified glacial drift—Qdl, Qgm, Qa (fig. 6).

Qdl is the oldest component; it is restricted to the subsurface of Cape Cod Bay and comprises mostly sand with some gravel. Qdl is interpreted to have been deposited within a proglacial lake that occupied Cape Cod Bay soon after the ice front withdrew from Cape Cod, until it receded north of Provincetown.

Qgm is the second subunit, lies stratigraphically adjacent to Qdl beneath Massachusetts Bay and the northwest corner of Cape Cod Bay, and primarily comprises mud with minor lenses of sand and gravel. Deposition of Qgm is interpreted to have occurred after the ice front receded north of Provincetown, while the sea submerged the increasingly ice-free, yet isostatically depressed region. Glacial-marine sediments were delivered to the sea by submarine and subaerial melt-water flows sourced by the retreating ice (fig. 19).

Qa, the youngest subunit, is primarily sandy and overlies parts of Qdl and Qgm within north-central Cape Cod Bay and south-central Massachusetts Bay. Qa is thought to represent nonglacial, submarine, mass flow, and (or) fluvial (deltaic) deposition that occurred when the ice front had receded north to Boston or beyond.

Ur marks the elevation of the late Wisconsinan regressive unconformity (fig. 20). Insufficient penetration due to water depth and overlying sediment thickness prohibited its identification across a substantial part of eastern Cape Cod Bay. Ur generally deepens from west to east, and its elevation ranges between approximately –3 and –73 m (NAVD 88). The unconformity clearly illustrates a complex network of fluvial valleys incised into the Qd surface across western and central Cape Cod Bay (figs. 8 and 20). The fluvial incision is less extensive and generally shallower along the western margin of the survey area where drift cover is relatively thin to absent across the more resistant, underlying pre-Quaternary surface. As a result, U_r merges with U_1 and U_t over much of this part of the study area (fig. 7). U_r was shaped while the region became subaerially exposed during the late Wisconsinan, when this part of the margin isostatically rebounded in delayed response to unloading of the glacial ice at a rate that outpaced eustatic sea-level rise.

The remaining three Quaternary stratigraphic units overlying Pz(?)/Tcp(?)/Qt(?) and Qd are interpreted to represent Holocene sedimentary deposits (fig. 6).

Qfe, the lowermost unit, fills the fluvial valleys incised into the surface of Qd (figs. 7 and 21). It produces variable seismic signatures that typically consist of vertically laminated, horizontal to concave-up reflectors or zones of near acoustic transparency that locally indicate cut and fill (figs. 22 and 23). Qfe is thickest beneath Cape Cod Bay, locally exceeding 19 m, and thin to absent along much of the western margin of the inner shelf (figs. 7 and 21). Vibracores collected by Oldale and Bick (1987) and Oldale and O'Hara (1990) recovered predominantly sands and clays with some gravels and peats from this unit. Qfe is interpreted to have been deposited within fluvial and estuarine environments as eustatic sea-level rise eventually exceeded isostatic rebound and submerged the region during the Holocene.

$U_{t,}$ which generally defines the surface of Qfe, formed as coastal waves and currents broadly truncated Qfe and older adjacent units along the inner shelf and shoreline during the ongoing Holocene transgression. The elevation of U_t ranges between approximately –3 and –64 m (NAVD 88) and generally deepens to the northeast (fig. 24). Morphologically, U_t is rather low relief beneath most of Cape Cod Bay, illustrating the effectiveness of transgressive ravinement across the Qd and Qfe units; however, subtle linear depressions on this part of the unconformity indicate slight preservation of the broader antecedent fluvial valley topography. This could indicate that Qfe sediments are slightly less resistant and eroded to greater depths than the adjacent Qd units, or simply that Qfe deposition was only sufficient to subdue the antecedent topography of the paleodrainage systems. Along the western margin of the inner shelf, U_t is more rugged where it merges with U_1 and U_r over broad areas where Pz(?)/Tcp(?)/Qt(?) and Qd crop out on the seafloor (figs. 8 and 24).

Qmn and Qmd are posttransgressive Holocene sediments recognized as two distinct stratigraphic units overlying U_t (figs. 6 and 8). The Qmn and Qmd units produce similar seismic signatures, typically consisting of faint, vertically laminated, horizontal reflectors or near acoustic transparency (figs. 22 and 23); however, they are readily distinguished based on their texture and location on the inner shelf. Qmn deposits are predominantly sandy with varying proportions of gravel and mud, and mostly restricted to Nearshore Ramps on the inner shelf. They are thickest along western Cape Cod Bay adjacent to Duxbury and Plymouth bays, where they form low-relief, shore-oblique ridges and bars as much as 13 m thick (figs. 2 and 25). Qmn thins substantially northward along the coast between Duxbury and Hull, where it is essentially absent with the exception of several isolated pockets along the coastline (figs. 7 and 25). These nearshore deposits have formed along the landward-migrating shoreline as coastal waves, and currents have eroded and reworked sediments from the underlying stratigraphic units during the ongoing Holocene transgression. Qmd deposits are mostly muddy with varying proportions of sand, and are generally confined to Outer Basin parts of Cape Cod Bay that are deeper than 45 m. Qmd is thickest in the southeastern part of the survey area, locally exceeding 16 m, and thins northward toward the mouth of the bay, and towards its eastern and western margins (figs. 7 and 25). These sediments were also derived through erosion and reworking of the underlying stratigraphic units, but due to their fine grain size, they have been transported by currents over long distances, and eventually concentrated in the deep parts of the bays.

Discussion

High-resolution geophysical data at dense seafloor coverage provide a previously unavailable means of viewing and delineating seafloor morphology. Interpretations of high-resolution geophysical data combined with ground truth information (sample data) have produced geologic interpretations at unprecedented resolutions and are superior to maps produced from sample information alone or widely spaced survey data. Each of the interpretations produced in this study contributes insight to the evolution and environments on the inner continental shelf between Nahant and northern Cape Cod Bay and can be used as layers for mapping marine habitats and resources. The following section outlines our confidence in the interpretations, some of the limitations, and indicates how these data interface to create an in-depth look at the seafloor and shallow subsurface in the region.

Confidence and Limitation in Interpretations

Seismic-reflection data did not extend through Boston Harbor and its approaches on the westernmost edge of Massachusetts Bay, or within an offshore, triangular-shaped part of the study area located between Scituate and Marshfield, Massachusetts (figs. 1 and 4). As a result, surficial geology polygons derived from the seismic data interpretations are not as extensive as the sea-floor sediment and physiographic zone polygons that encompassed the bathymetry and acoustic-backscatter datasets (figs. 2 and 3). Because all data input sources were not available in all parts of the study area, qualitatively defined polygons of sediment texture were assigned a data interpretation confidence value between 1 and 4 based on the quality and number of data sources (fig. 26). Sediment texture regions that were defined based on the highest resolution bathymetry (5 m) and backscatter (1 m), bottom photographs, sediment samples, and seismic interpretations were given the highest data interpretation confidence value of 1. Areas with a confidence value of 1 include the Duxbury to Hull and northern Cape Cod Bay geophysical and sample data areas published by Barnhardt and others (2010) and Andrews and others (2010), respectively. Areas where sediment texture was defined based on bathymetry of 30-m resolution, backscatter of 1-m resolution, bottom photographs, and sediment samples, but no seismic data were assigned an interpretation confidence value of 2. Confidence 2 was assigned to the Boston Harbor and approaches geophysical and sample data area published by Ackerman and others (2006). A confidence value of 3 was given to areas with multibeam bathymetry and backscatter data of 10-m resolution and sediment samples, but no bottom photographs or high-density seismic interpretations were available. The data confidence 3 area is located offshore of Marshfield, Mass., generally in water depths greater than 20 m, where multibeam data were collected for Massachusetts Bay and Stellwagen Bank National Marine Sanctuary (Butman and others, 2007). The lowest confidence values (4) were given to nearshore areas (typically shallower than 5 m), where only lidar data of 2.5-m resolution (and near full coverage) and sediment samples were available.

Limitations associated with qualitative interpretations exist because the scale of the source geophysical data and the spacing of samples do not capture all changes in seafloor texture. The data were mapped between 1:8,000 and 1:25,000, but the recommended scale for application of these data is greater than 1:25,000. In general, features below 5,000 square meters (m^2) or less than 50 m wide were not digitized due to positional uncertainty, lack of sample information, and the often ephemeral nature of small-scale seafloor features. Not all digitized seafloor features contained sample information; therefore, the seafloor character often is determined by the nearest similar feature that contains a sample. Conversely, sometimes a digitized feature contained multiple samples and not all of the samples within the feature were in agreement (of the same texture). In these cases, the dominant sediment texture within the polygon was chosen. Samples from rocky areas often only consist of bottom photographs because large particle size often precludes the recovery of a sediment sample. Bottom photograph classification based on interpretation is subjective, such that determining the dominant sediment type within the view frame is estimated by the interpreter and may differ among interpreters. Bottom photograph transects often reveal changes in the seafloor over distances of less than 100 m and these changes are often not observable in acoustic data. Heterogeneous seafloor texture can change quickly, and many small-scale changes will not be detectable or mappable at a scale of 1:25,000. The boundaries of polygons are often inferred based on sediment samples, and even boundaries that are traced based on amplitude or rugosity changes in geophysical data are subject to migration. Polygon boundaries should be considered an approximation of the location of a change in texture.

Sediment Classification

The Barnhardt and others (1998) classification is considered the best representation of sea-floor texture for this study area due to the complex nature and heterogeneity of sea-floor material and the scale at which these data are mapped. This system works well for inner-shelf environments where one sediment unit is generally inadequate for representing sea-floor texture, such as the New England coast, where reworked tills and rocky pavements are common. We could not apply the full complexity of the Shepard (1954), as modified by Schlee (1973), ternary classification to our data due to variable input resolutions and sample densities. Instead, we applied a modified scheme limited to the gravel, sand, sandy-silt, silty-sand, and clay classes, with the addition of a ‘solid’ class to encompass rocky areas. Our sample-data spacing and geophysical-data resolution typically did not support the discrimination between clayey sand, silty sand, and sand silt clay. For example, a large (nearly 240-km^2) muddy area of uniformly low backscatter and low slope in northern and central Cape Cod Bay was digitized and classified as silt because the randomly spaced sediment samples within the area indicated that the sea floor comprised 56 percent clayey silt, 15 percent silt, 15 percent sandy silt, and 10 percent silty sand (fig. 14). In the absence of additional sediment samples to further resolve distribution of the fine grain sizes, the prudent solution was to aggregate the area to its common class and rely on the continuity of the backscatter signature.

Integrating the Interpretations

Each subsurface stratigraphic unit composes some part of the seafloor in the survey area (fig. 8), and the areal distribution of the units is closely related to the surficial sediment distribution and physiographic zone interpretations. Geologic units either directly crop out at the seafloor or are buried beneath surficial sediments too thin to be detected in the seismic data (less than about 0.5 m). Outcrops of Pz(?)/Tcp(?)/Qt(?) are most extensive along the nearshore of western Massachusetts Bay, and account for roughly 15 percent of the seafloor by area (fig. 27). They generally correspond to rocky zones and hardbottom plains, where the most common sediment textures are Rg and Gr. Qd crops out throughout western Massachusetts Bay and along the eastern and western margin of northern Cape Cod Bay. Dominant surficial sediment textures associated with Qd include R, G, and S. Sandy Qd seafloor textures occur primarily within Cape Cod Bay. Qd is associated with rocky zones, nearshore and outer basins, and hardbottom plains physiographic zones. Qfe crops out across roughly 20 percent of the study area and is primarily associated with S and G sediment textures that coincide with shelf valleys, nearshore ramps, nearhsore basins, and hardbottom plains. Qmn and Qmd blanket half of the study area, and Qmn is concentrated in the nearshore of Massachusetts and northern Cape Cod bays, while Qmd is wholly within central and eastern Cape Cod Bay. Qmn has dominant sediment textures of S and G, and is associated with nearshore ramps and basins. Qmd has a dominant sediment texture of M with subordinate S, and is located in the outer basin.

Seafloor geologic composition and sediment texture are most variable along the western margin of Massachusetts Bay north of Brant Rock, where exposures of Qd and Qfe are interspersed in complex patterns among relatively abundant and broad outcrops of Pz(?)/Tcp(?)/Qt(?). The complicated outcrop patterns are controlled by the shallow and rugged antecedent topography of the underlying pre-Quaternary surface, which only accommodated relatively thick Quaternary deposition within its depressions (fig. 8). The outcrop patterns likely evolved during the Holocene transgression, where truncation of the inner shelf has reduced the areal extent of Quaternary units and further exposed the pre-Quaternary surface. The only mappable accumulations of Qmn across this part of the survey area are restricted to several narrow zones near the coast. To the southeast, outcrops of Pz(?)/Tcp(?)/Qt(?) become progressively narrower and more isolated along the western margin of northern Cape Cod Bay. The inner shelf adjacent to Duxbury and Plymouth bays is otherwise dominated by Qmn, with limited exposures of underlying Qd and Qfe units occurring adjacent to Pz(?)/Tcp(?)/Qt(?) outcrops where Qmn sediments are thin or absent. Farther bayward, Qd and Qfe are the dominant seafloor units, and they form sublinear to sinuous outcrop patterns that clearly illustrate their relation as valley-fill deposits and adjacent interfluves (figs. 7, 19, and 21). Throughout the central and eastern parts of northern Cape Cod Bay, Qmd dominates the seafloor, except for an area adjacent to Provincetown where Qd units are capped by a small accumulation of Qmn that extends bayward from the Provincetown recurved spit.

Comparison between the spatial distributions of outcropping geologic units and seafloor sediment textures provides additional insight concerning seafloor composition and the physical processes that have affected regional sediment textural trends (figs. 8, 13, and 15). As would be expected, the coarsest textures (Rg, Rs, and Gr) are most prevalent along the western margin of Massachusetts Bay, where outcrops of Pz(?)/Tcp(?)/Qt(?) are relatively expansive. Textures generally fine to the south and east into deep parts of Massachusetts and northern Cape Cod bays. Adjacent to Duxbury and Plymouth bays, sandy Qmn sediments are most common, and coarse zones are centered on isolated outcrops of Pz(?)/Tcp(?)/Qt(?). As Qmn sands thin bayward (fig. 22), seafloor textures transition to interfingered zones of predominantly sandy and muddy sediments across the seafloor outcrops of Qfe valley fills and Qd glaciolacustrine interfluves. Fining continues into the basin, where Qmd muds dominate. Farther east, textures coarsen slightly up the slope of the eastern margin from muds to sands toward the northeast and nearshore around the Provincetown recurved spit.

Knebel and Circe (1995), Knebel and others (1996), and Bothner and others (2007) suggest that textural distributions are primarily a function of regional variability in geologic composition and coastal oceanographic processes between the shallow-margin and deep basin areas of Boston Harbor, Massachusetts Bay, and Cape Cod Bay. Their analyses of atmospheric and oceanographic data showed that waves and currents, primarily driven by northerly storms between late fall and early spring, tend to preferentially erode, rework, and winnow the seafloor along the shallow margins of the bays, force southward circulation and sediment transport along their eastern and western margins, and preferentially redistribute fine-grained sediments to the south and deep parts of the bays. Although the high-energy environment of the western margin of Massachusetts Bay is primarily a function of the shallow subsurface presence of the pre-Quaternary surface and relatively thin to absent Quaternary sediment cover, the preferential effect of strong waves and currents causes this part of the shelf to be erosional or nondepositional, and undoubtedly maintains or accentuates this seafloor character. As fine-grained sediments are episodically winnowed from the outcropping surfaces of relatively finer-grained Qd-glaciomarine and Qfe-valley-fill units, they become armored by concentrated lags of coarser material, which is probably augmented by clasts liberated and mobilized from adjacent Pz(?)/Tcp(?)/Qt(?) outcrops. Indeed, despite being generally located within zones classified as having coarse surface character, several vibracores reported by Oldale and Bick (1987) recovered predominantly clayey and sandy material from as much as 12 m into the subsurface. The southward and basinward fining of sediment textures down the transitional slopes of the bay margins indicates that progressively finer grain sizes are transported over progressively greater distances. It appears that sandy sediments (S) are primarily concentrated across the slopes of the bay margins in areas that Knebel and Circe (1995) and Knebel and others (1996) classified as zones of sediment reworking, and we have mapped progressions from Qmn sand ridges and shoals to outcrops of Qd glaciolacustrine and Qfe valley fills. The striking correlation between sublinear patterns of seafloor sediment texture and relatively sharp contacts between outcrops of Qd glaciomarine and Qfe valley fills on the margin slope of northeast and north-central Cape Cod Bay provides indirect evidence of reduced wave and current effect on the seafloor. The thick and widespread blanket of marine muds across the deepest parts of the bays indicates that oceanographic conditions are typically quiescent and conducive to deposition. Similar quiescent conditions generally exist within Boston Harbor, which is protected from much of the storm-driven wave and current energy produced in adjacent Massachusetts Bay. Fine-grained sediment deposited in the harbor are winnowed from glacial drift deposits within the bay and delivered to the bay from small upland tributaries.

Summary

The interpretations presented in this report represent a unique geologic dataset. Each of the interpretive maps contributes new insight to the evolution and sedimentary environments of the Massachusetts inner continental shelf at a resolution that was previously not possible due to a lack of high-resolution geophysical data. Interpretations of high-resolution geophysical data and sediment samples suggest that the shallow geologic framework and surficial geology from Nahant to northern Cape Cod Bay is a complex and variable distribution of sediments and geomorphic features that can be primarily attributed to the advances, occupations, and retreats of Wisconsinan glaciation and reworking during Holocene sea-level change. Glacial, marine, and terrestrial processes have acted on this region during the last 20,000 to 24,000 years, creating a complex geologic history and a heterogeneous seafloor character. Thick deposits of glacial and nonglacial sediment bury bedrock over most of Cape Cod Bay and Boston Harbor, but on the unprotected western margin of Massachusetts Bay, rocky zones are prevalent and are attributed to eroded bedrock or winnowed glacial deposits, which are virtually indistinguishable in shallow seismic records. Glacial sediments within the entire region are locally overlain by nearshore marine (beach and bar deposits), fluvial, estuarine, and marine muds. The wide variety of sedimentary environments within the study area provide habitat for many marine organisms. The high-resolution geologic interpretations provided in this report are valuable input for identifying marine habitats on the Massachusetts inner continental shelf.

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Tables and Figures

Table 1. Data sources for the digital elevation model, backscatter mosaic, and seismic-reflection profile interpretations for the Inner Continental Shelf from Nahant to northern Cape Cod Bay, Massachusetts.

Vessel	Date	Bathymetry/Topography	Backscatter	Seismic	Citation
Fredrick G. Creed	1994-1998	Simrad Subsea EM1000 Multibeam Echo Sounder	Simrad Subsea EM1000 Multibeam Echo Sounder	none	Poppe and others, 2006
Fredrick G. Creed	1994-1998	Simrad Subsea EM1000 Multibeam Echo Sounder	Simrad Subsea EM1000 Multibeam Echo Sounder	none	Butman and others, 2007
Whiting and NOAA launches	2000-2001	RESON SeaBat 8101MBS and Odom Echotrac DF3200 MKII single beam system	Edgetech 272-T and Klein T-5500	none	Ackerman and others, 2006
Rafael	2003-2004	SEA Submetrix 2000 series interferometric sonar	Edgetech DF1000 dual frequency sidescan sonar	Knudsen 320b chirp system	Barnhardt and others, 2006
Ocean Explorer and *Connecticut*	2004-2005	RESON SeaBat 8101MBS, and an SEA SWATHplus interferometric sonar system	RESON SeaBat 8101MBS, and Klein 3000 dual-frequency sidescan-sonar	EdgeTech Geo-Star FSSB sub-bottom profiling system and an SB-0512i towfish	Barnhardt and others, 2009
Atlantic Surveyor	2005	RESON SeaBat 8101	RESON SeaBat 8101*	none	National Oceanic and Atmospheric Administration and University of New Hampshire, 2005
Thomas Jefferson	2006	EM1002 MBS and Odom Echotrac DF3200 MKII single beam system	EM1002 MBS*	none	National Oceanic and Atmospheric Administration, 2006
Megan T. Miller, *Rafael*, and NOAA launches	2006-2007	RESON SeaBat 3101 or 8125 MBS, and an SEA SWATHplus interferometric sonar system	RESON SeaBat 3101 or 8125, Klein 3000 dual-frequency sidescan-sonar, or an SEA SWATHplus interferometric sonar system	EdgeTech Geo-Star FSSB sub-bottom profiling system and an SB-0512i towfish	Barnhardt and others, 2010
Megan T. Miller and *Rafael*	2006-2008	SEA SWATHplus interferometric sonar system	Klein 3000 dual-frequency sidescan-sonar, or an SEA SWATHplus interferometric sonar system	EdgeTech Geo-Star FSSB sub-bottom profiling system and an SB-0512i towfish	Andrews and others, 2010
JALBTCX lidar plane	2007	SHOALS-1000T	none	none	U.S. Army Corps of Engineers, Joint Airborne Lidar Bathymetry Center of Expertise, 2008

*These data were not used in the composite backscatter image.

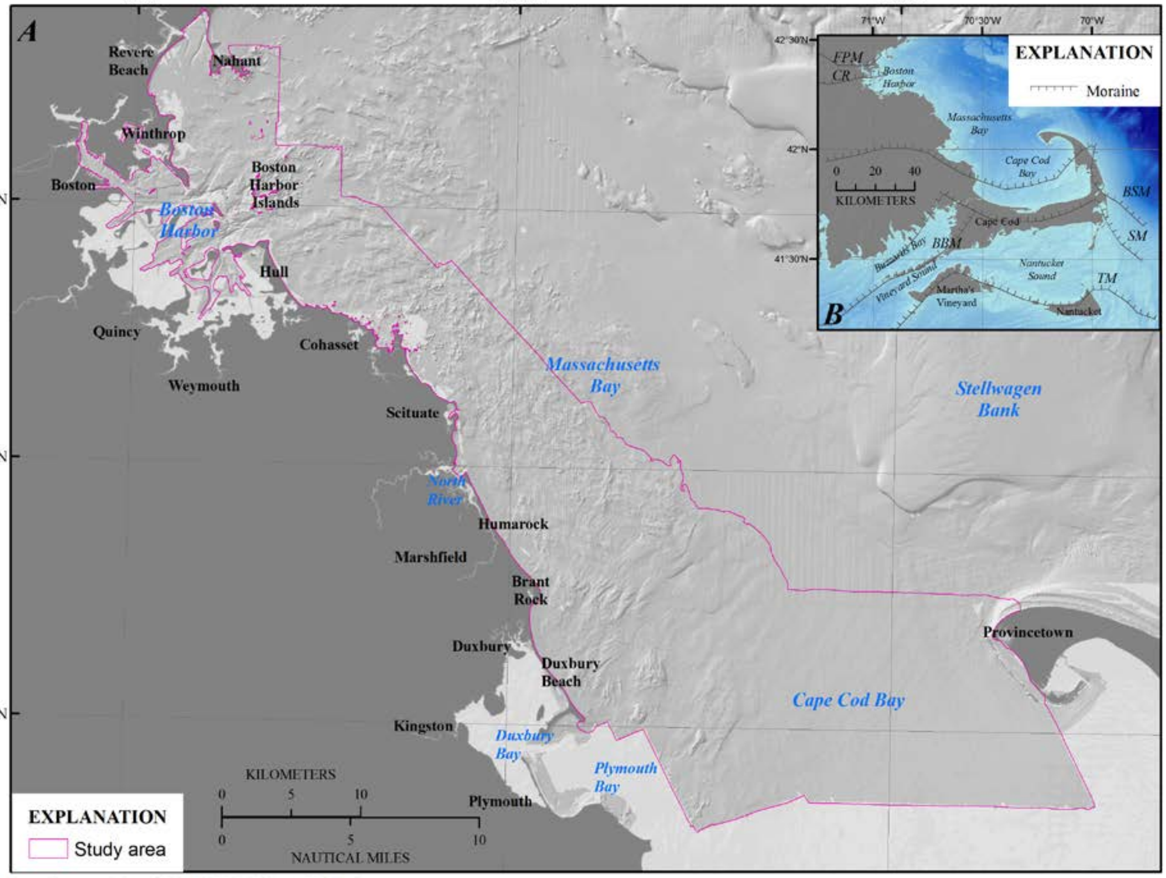
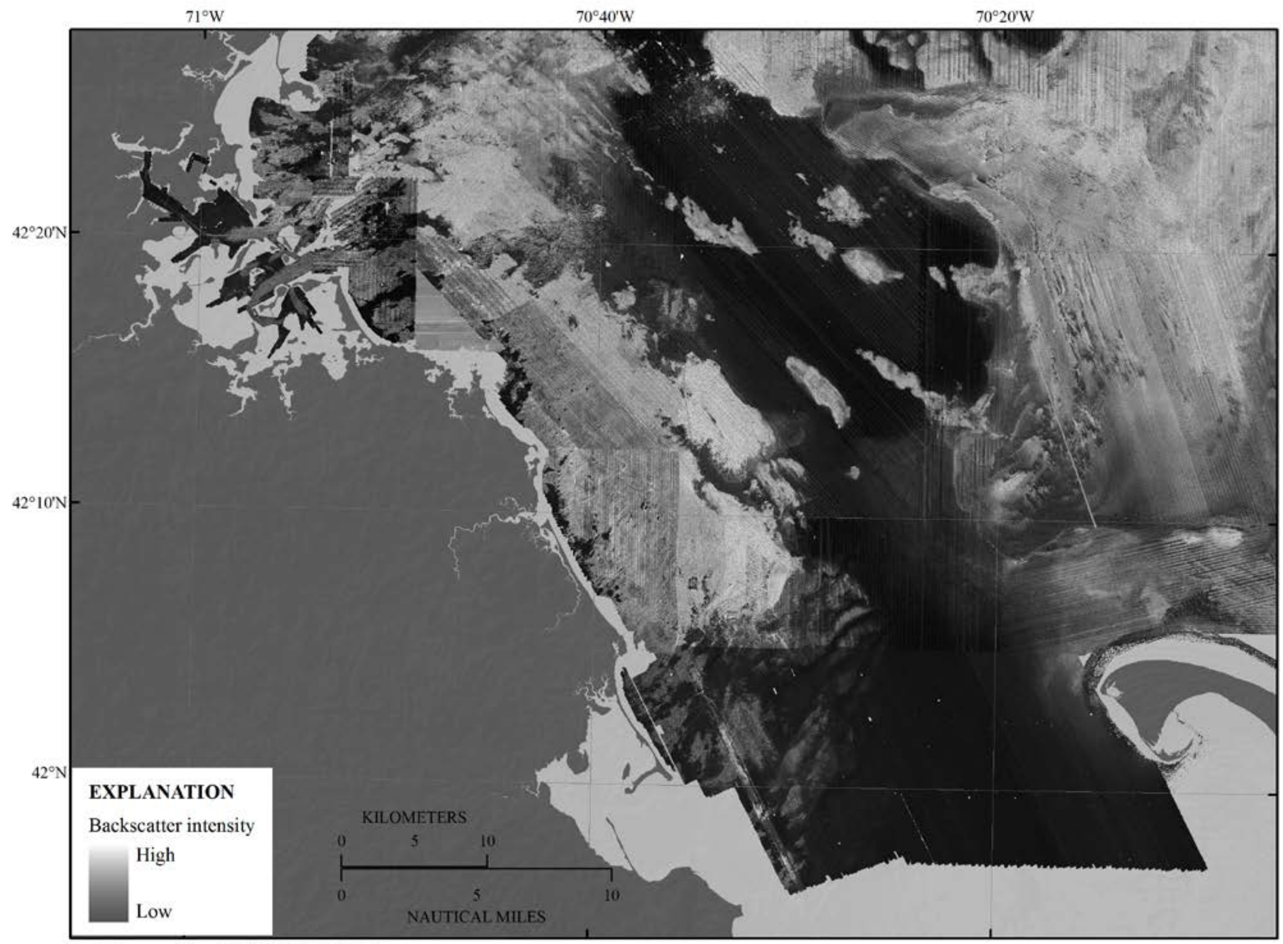


Figure 1. A) Location map of the study area from Nahant to northern Cape Cod Bay, Massachusetts and B, map of eastern Massachusetts showing the moraines associated with the Laurentide ice sheet. The outline in A is drawn based on the extent of the physiographic zones and surficial sediment texture maps. The approximate moraine locations are modified from Ridge (2004). BBM, Buzzards Bay Moraine; BSM, Billingsgate Shoal Moraine; CR, Chicopee Readvance Moraine; FPM, Fresh Pond Moraine; SM, Sandwich Moraine; TM, terminal moraine through Martha's Vineyard and Nantucket.



Data Source: MassGIS, USGS, NOAA

Figure 2. A composite backscatter image at 10-meter resolution was created from a series of published backscatter images (table 1). Areas of high backscatter have strong acoustic reflections and suggest boulders, gravels, and generally coarse seafloor sediments. Low backscatter areas have weak acoustic reflections and are generally finer grained material such as muds and fine sands.

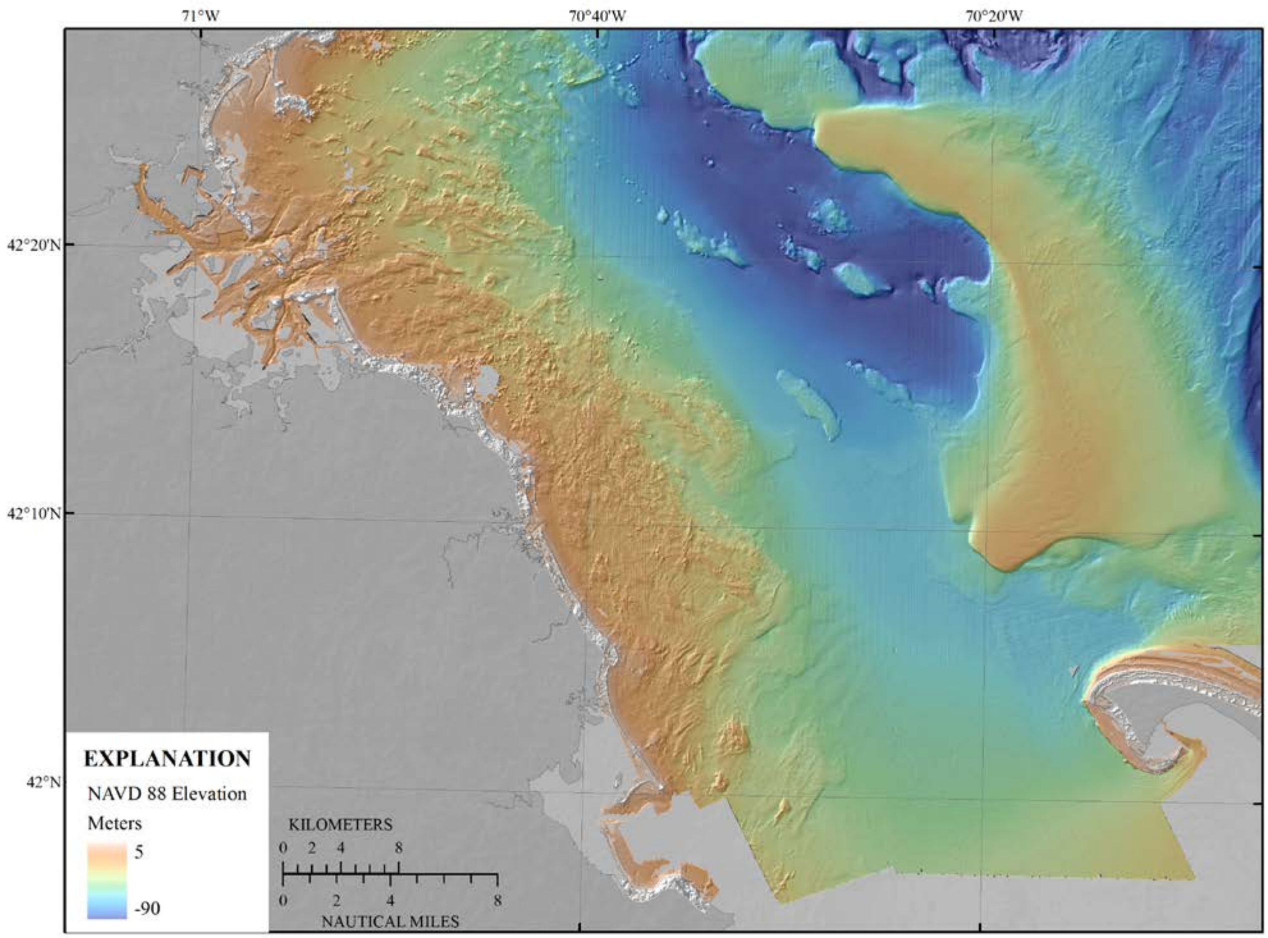


Figure 3. A digital elevation model (DEM) was produced from swath interferometric, multibeam bathymetry, and lidar at 30-meter resolution (table 1). High rugosity and high relief are most often associated with rocky areas, whereas smooth, low relief regions tend to be blanketed by fine-grained sediment deposits. NAVD 88, North American Vertical Datum of 1988.

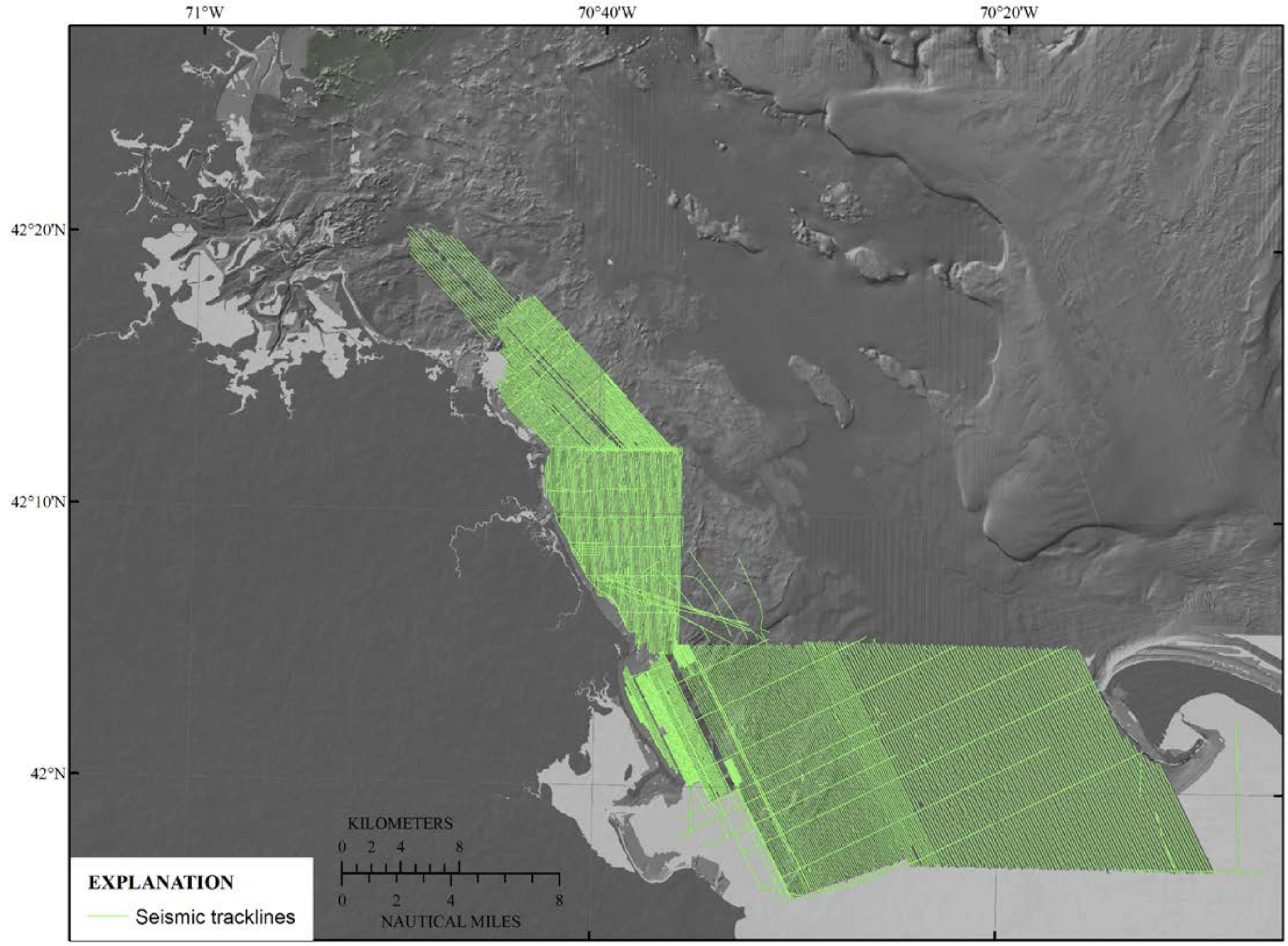


Figure 4. Map showing tracklines of chirp seismic-reflection profiles from Andrews and others (2010) and Barnhardt and others (2010) used to interpret surfical geology and shallow stratigraphy.

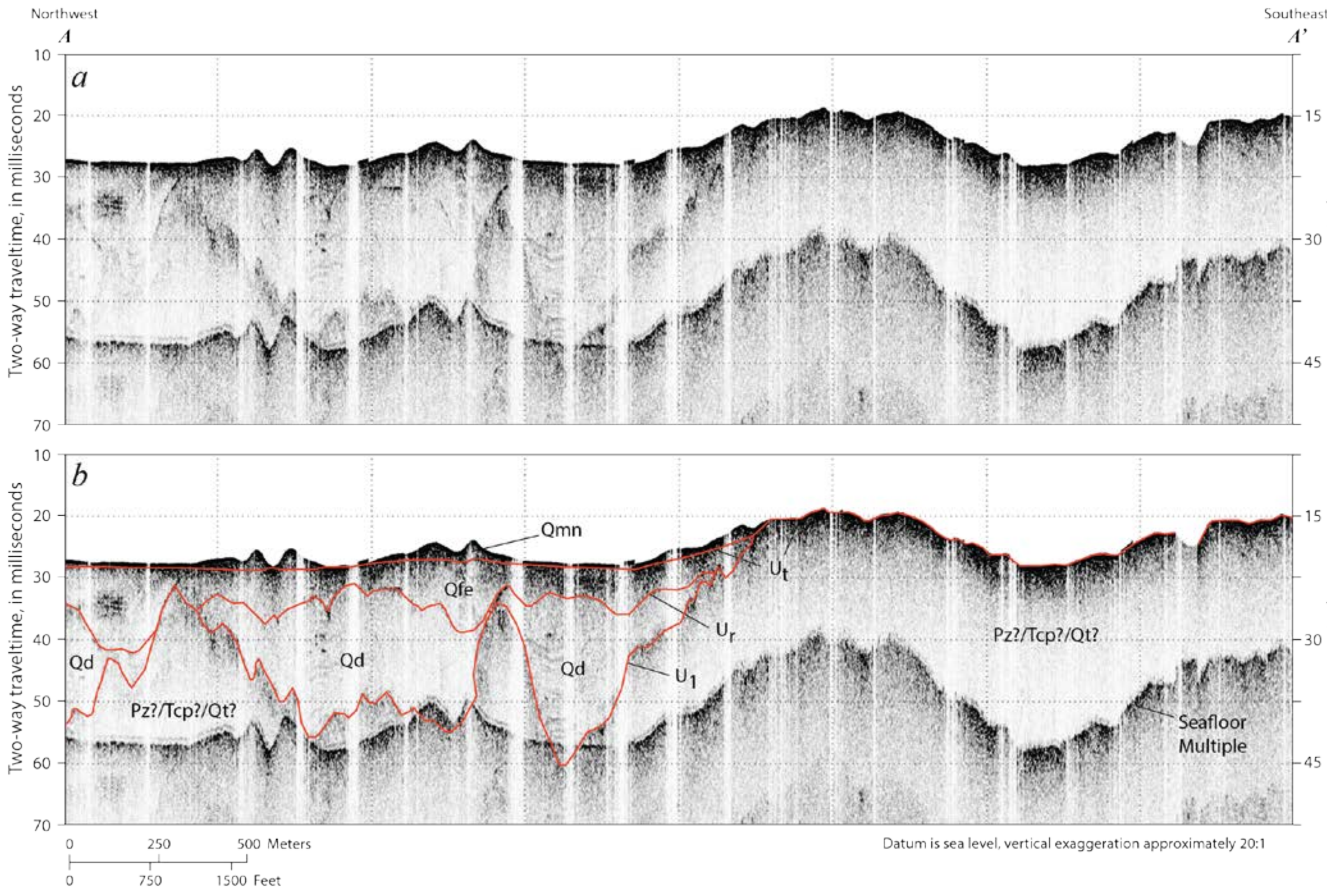


Figure 5. Chirp seismic reflection profile (a) A-A' with seismic stratigraphic interpretation B, illustrating the subsurface stratigraphy of the study area. Qmn, Holocene nearshore marine sediments; Qfe, Holocene fluvial and estuarine sediments; Qd, undifferentiated Pleistocene glacial drift sediments; Pz(?)/Tcp(?)/Qt(?), undifferentiated Paleozoic bedrock, late-Cretaceous to Tertiary coastal plain sediments, or Pleistocene glacial tills; Ul, fluvial unconformity marking the upper surface of Pz(?)/Tcp(?)/Qt(?); Ur, late Wisconsinan regressive unconformity; Ut, transgressive unconformity over Qfe and Qd. See figure 6 for detailed descriptions of stratigraphic units and major unconformities (indicated by red lines). See figure 8 for profile location. A constant sound velocity of 1,500 meters per second was used to convert two-way travel time to depth in meters.

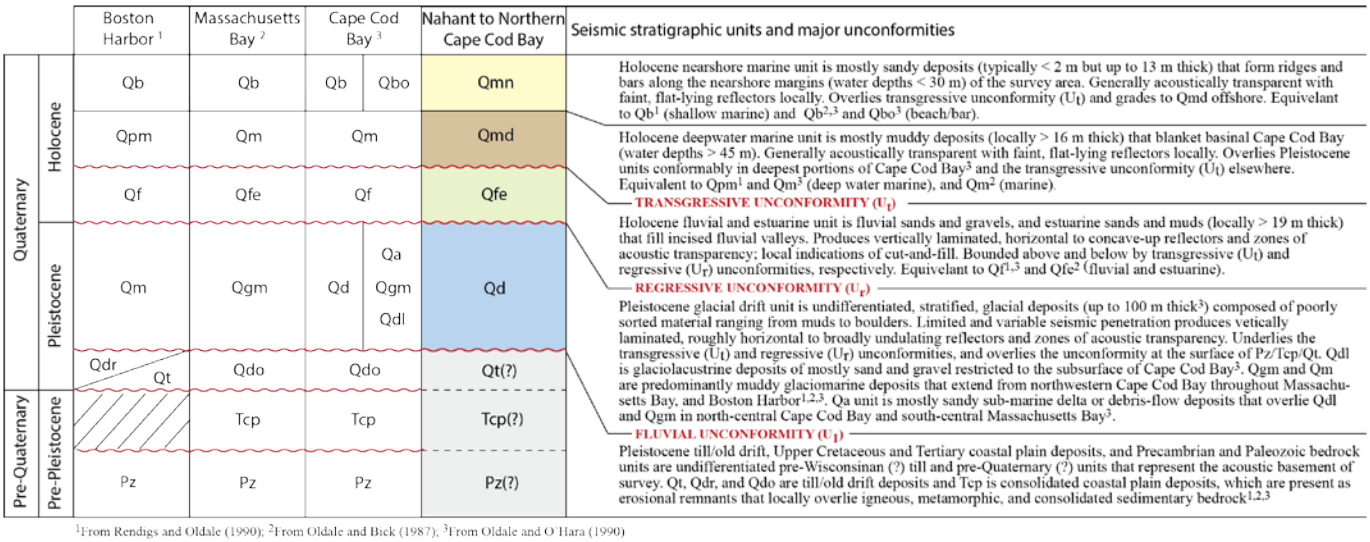


Figure 6. Seismic stratigraphic units and major unconformities interpreted within Boston Harbor by Rendigs and Oldale (1990), Massachusetts Bay by Oldale and Bick (1987), Cape Cod Bay by Oldale and O'Hara (1990), and between Nahant and northern Cape Cod Bay in this study.

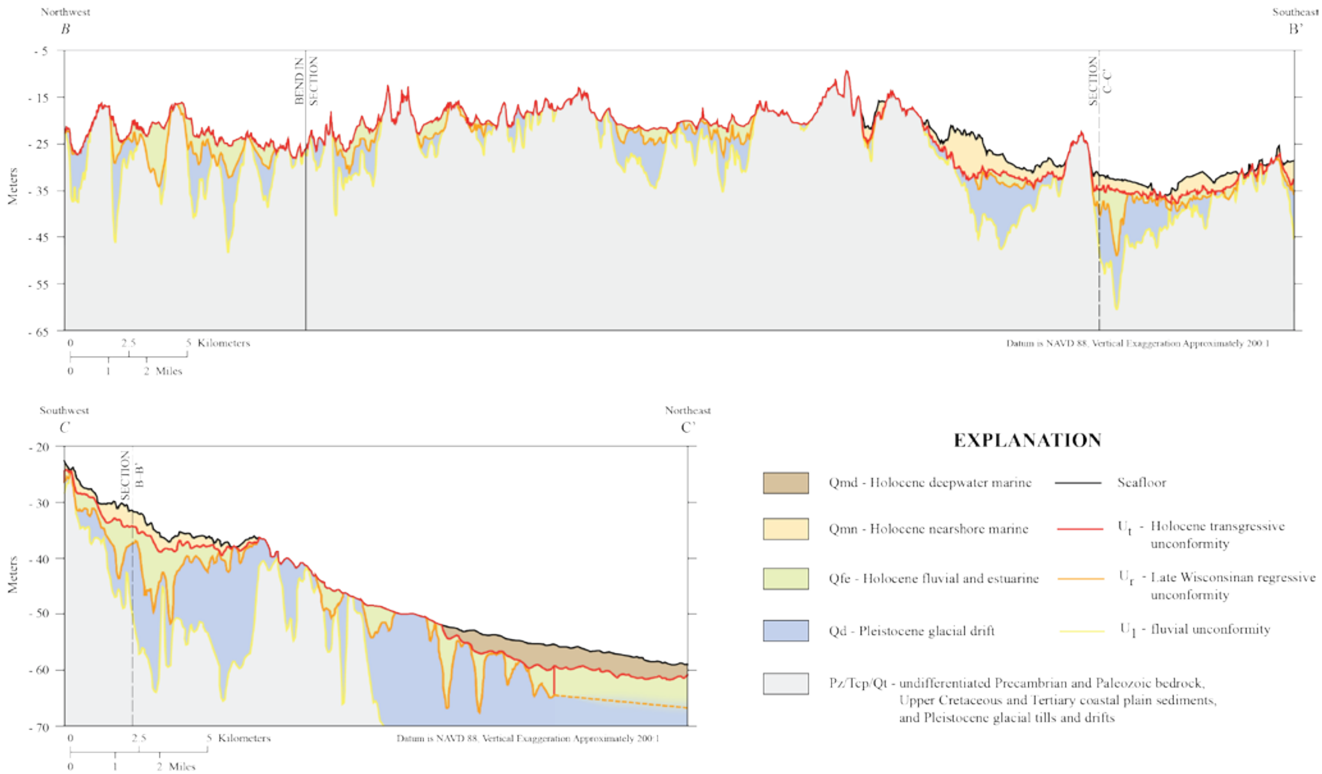


Figure 7. Geologic cross sections (*B–B*' and *C–C*') illustrating the general distributions and thicknesses of seismic stratigraphic units and elevations of major unconformities beneath the Massachusetts inner shelf between Nahant and northern Cape Cod Bay. Geologic cross sections are interpreted from Chirp seismic reflection profiles. Vertical scale is elevation in meters NAVD88. Solid vertical black line denotes bend in section, and dashed vertical black lines indicate intersections. See figure 6 for descriptions of stratigraphic units and unconformities. Geologic section locations are identified on figure 8.

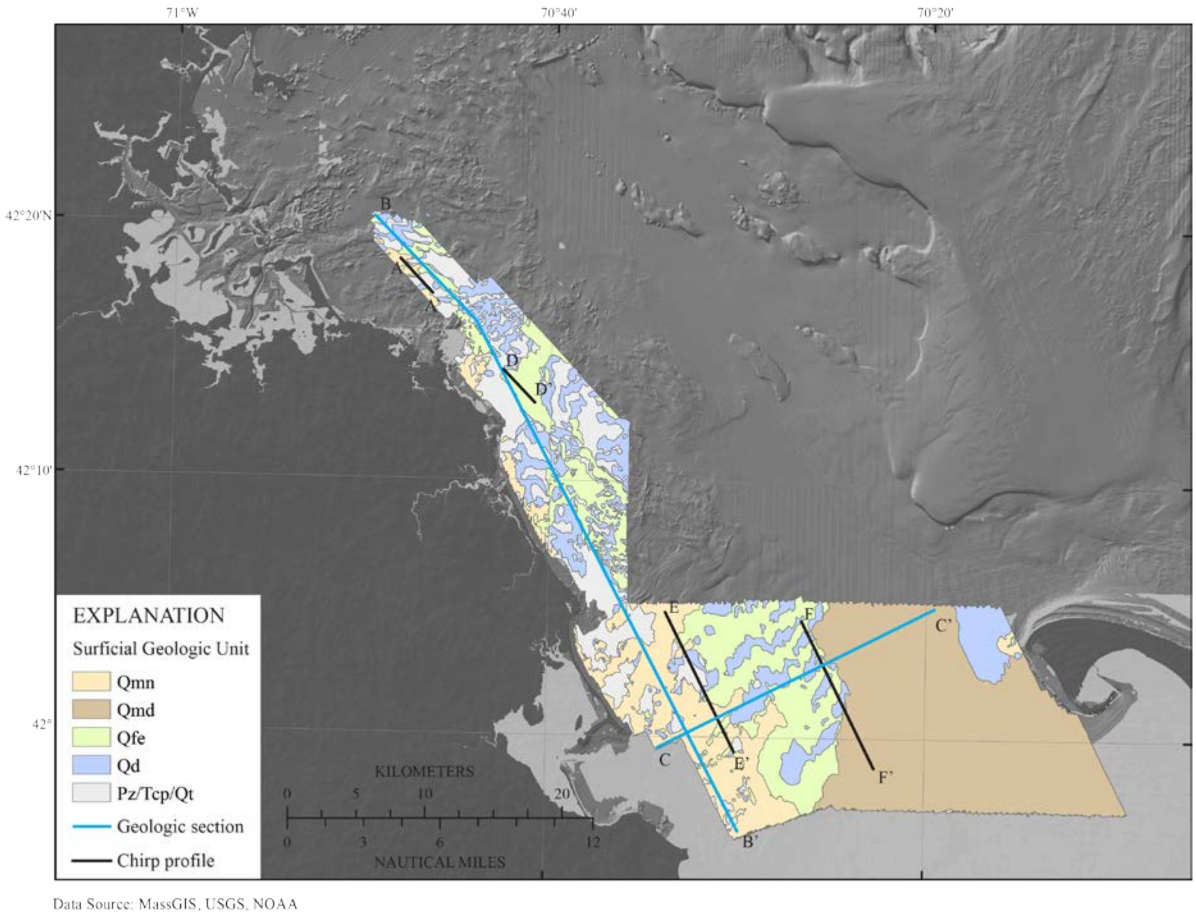
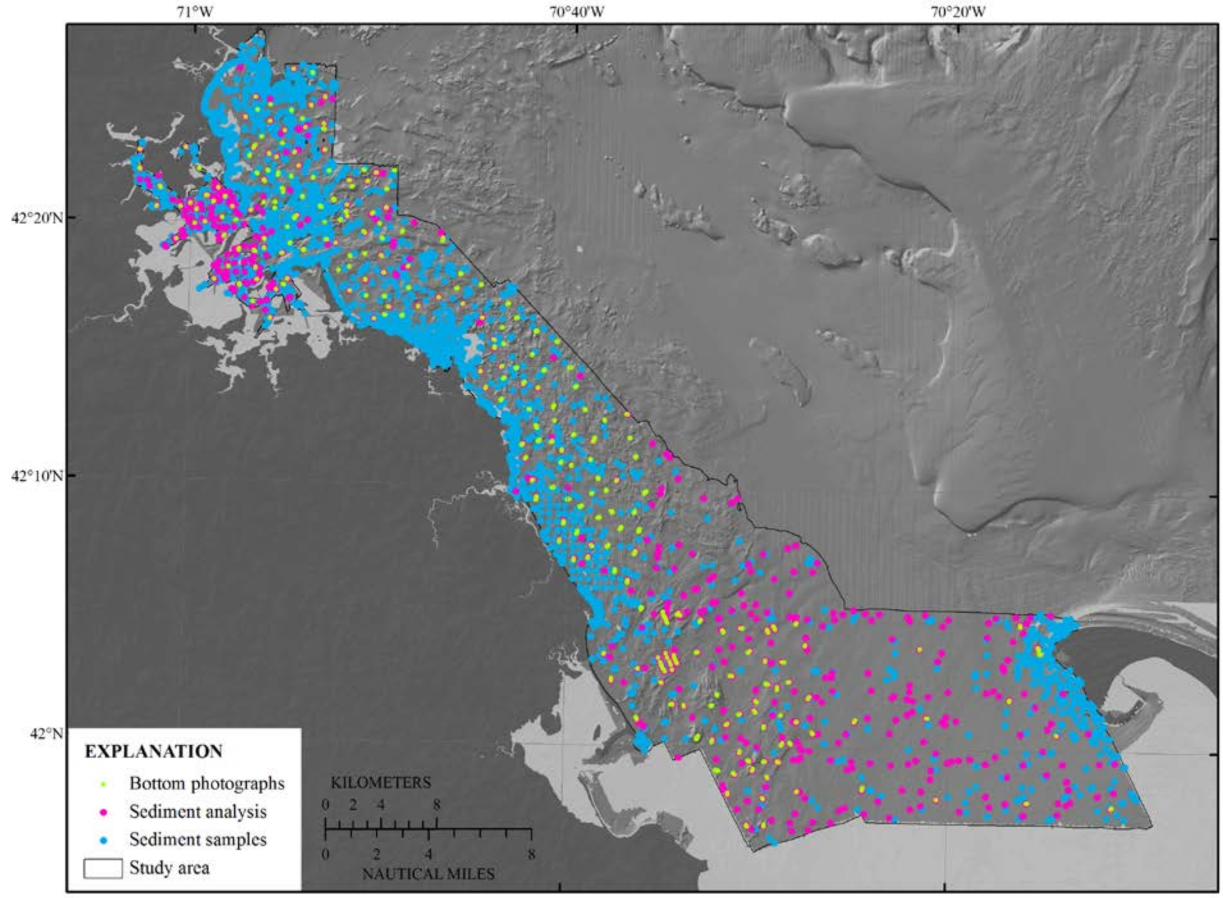


Figure 8. Surficial geologic map of the Massachusetts inner shelf between Nahant and northern Cape Cod Bay. The areal extents over which subsurface geologic units crop out at the seafloor were interpreted from seismic-reflection data. Detailed descriptions of the primary geologic units are figure 6. Qmn, Holocene nearshore marine sediments; Qmd, Holocene deepwater marine sediments; Qfe, Holocene fluvial and estuarine sediments; Qd, undifferentiated Pleistocene glacial drift sediments; Pz(?)/Tcp(?)/Qt(?), undifferentiated Paleozoic bedrock, late Cretaceous to Tertiary coastal plain sediments, or Pleistocene glacial tills. Holocene sediment veneers too thin to be detected in the seismic-reflection data (less than about 0.5 meter) may overlie outcrops of pre-Holocene units (blue and gray areas) locally. The locations of geologic cross sections B-B' and C-C' (fig. 8) are indicated by cyan lines, and the locations of chirp seismic-reflection profiles A-A', D-D', E-E', and F-F' are indicated by black lines.



Data Source: MassGIS, USGS, NOAA

Figure 9. Bottom photographs and sediment samples collected within the study area were used to aid interpretations. Sediment samples with laboratory analysis are shown as magenta dots, while blue dots are visual descriptions. Data are from Ford and Voss (2010), McMullen and others (2011) and Emily Huntley (Massachusetts Office of Coastal Zone Management, unpub. data, 2012).

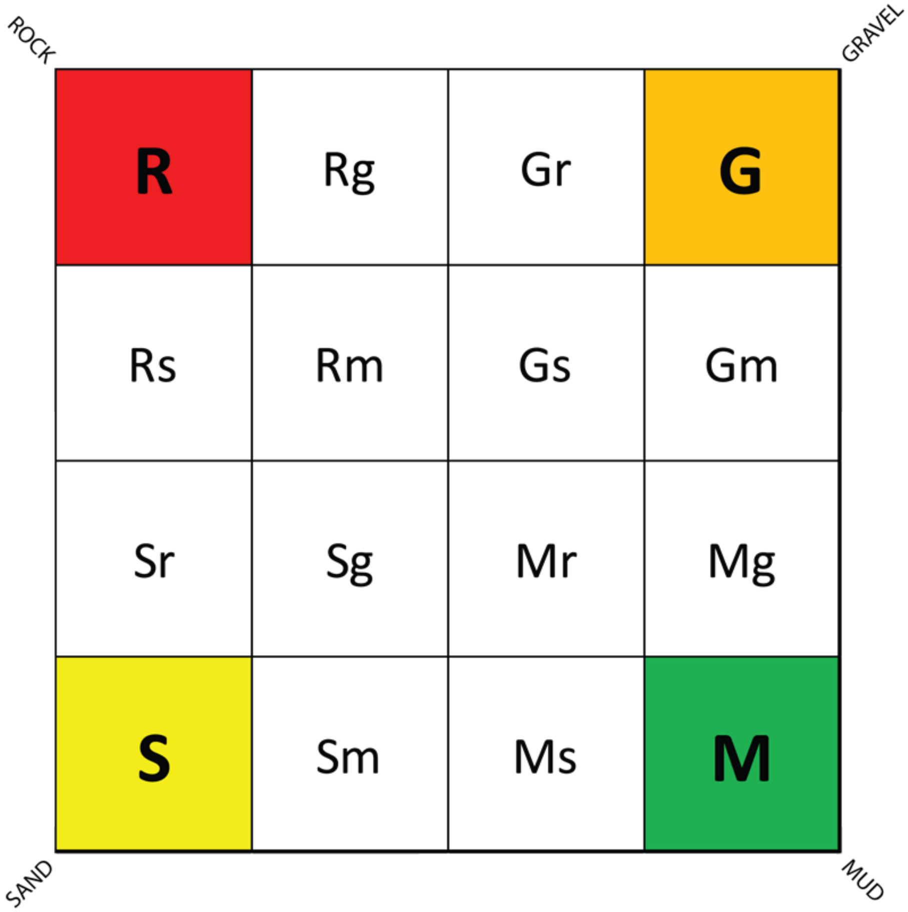


Figure 10. Barnhardt and others (1998) bottom-type classification based on four basic sediment units: Rock (R), Gravel (G), Sand (S), and Mud (M). Twelve additional two-part units represent combinations of the four basic units, where the primary texture (greater than 50 percent of the area) is given an upper case letter and the secondary texture (less than 50 percent of the area) is given a lower case letter.

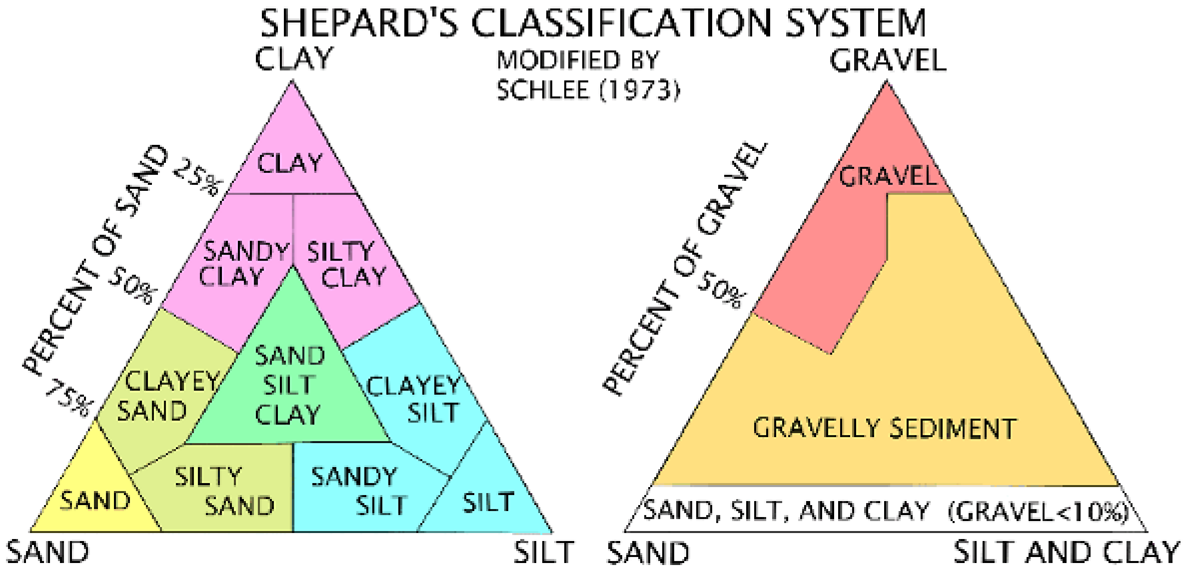


Figure 11. Sediment classification scheme by Shepard (1954), as modified by Schlee (1973) and McMullen and others (2011).

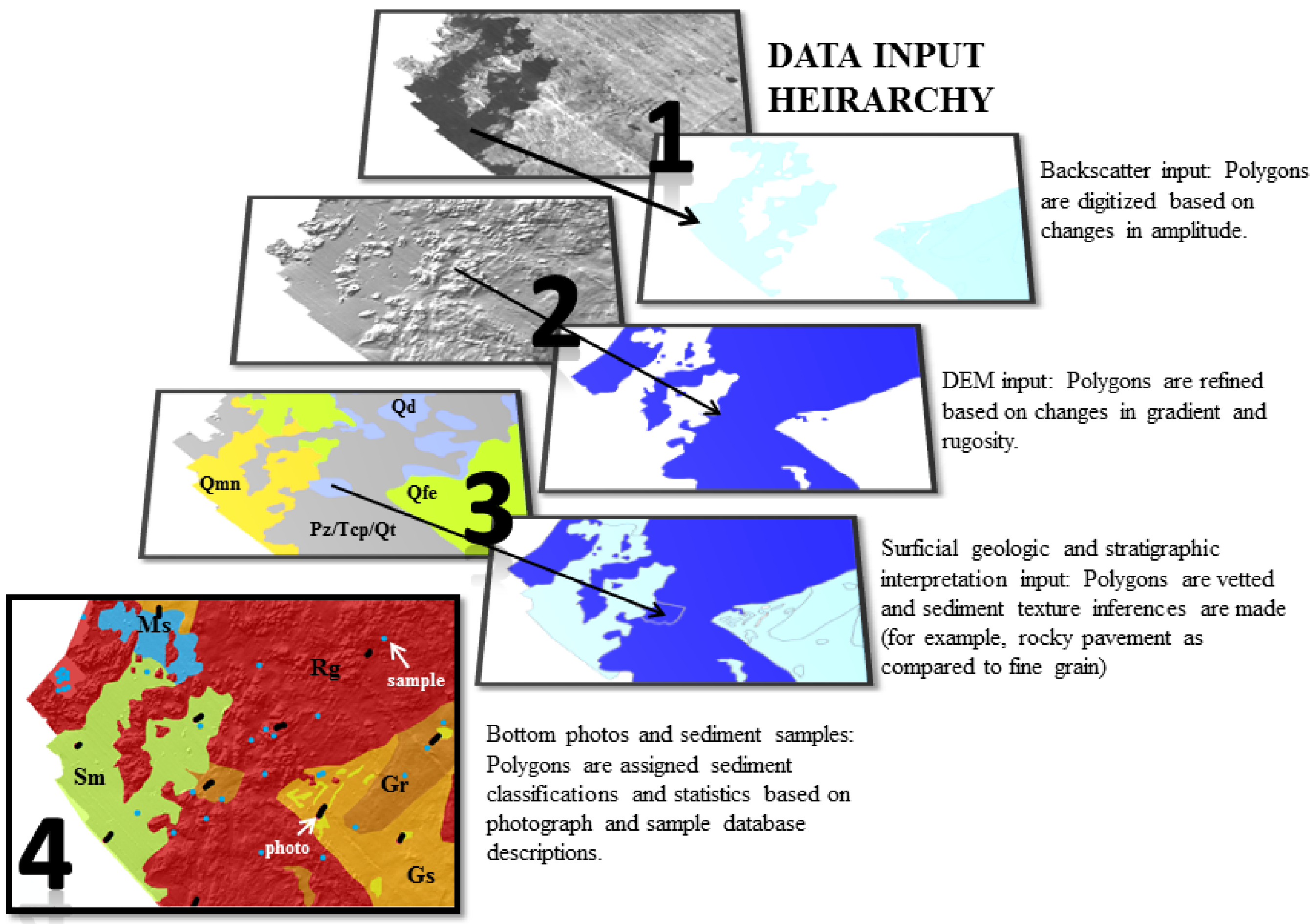


Figure 12. Sediment texture and distribution data were mapped qualitatively in ArcGIS using a hierarchical methodology. Backscatter data were the first input, followed by bathymetry, surficial geologic and shallow stratigraphic interpretations, and photo and sample databases.

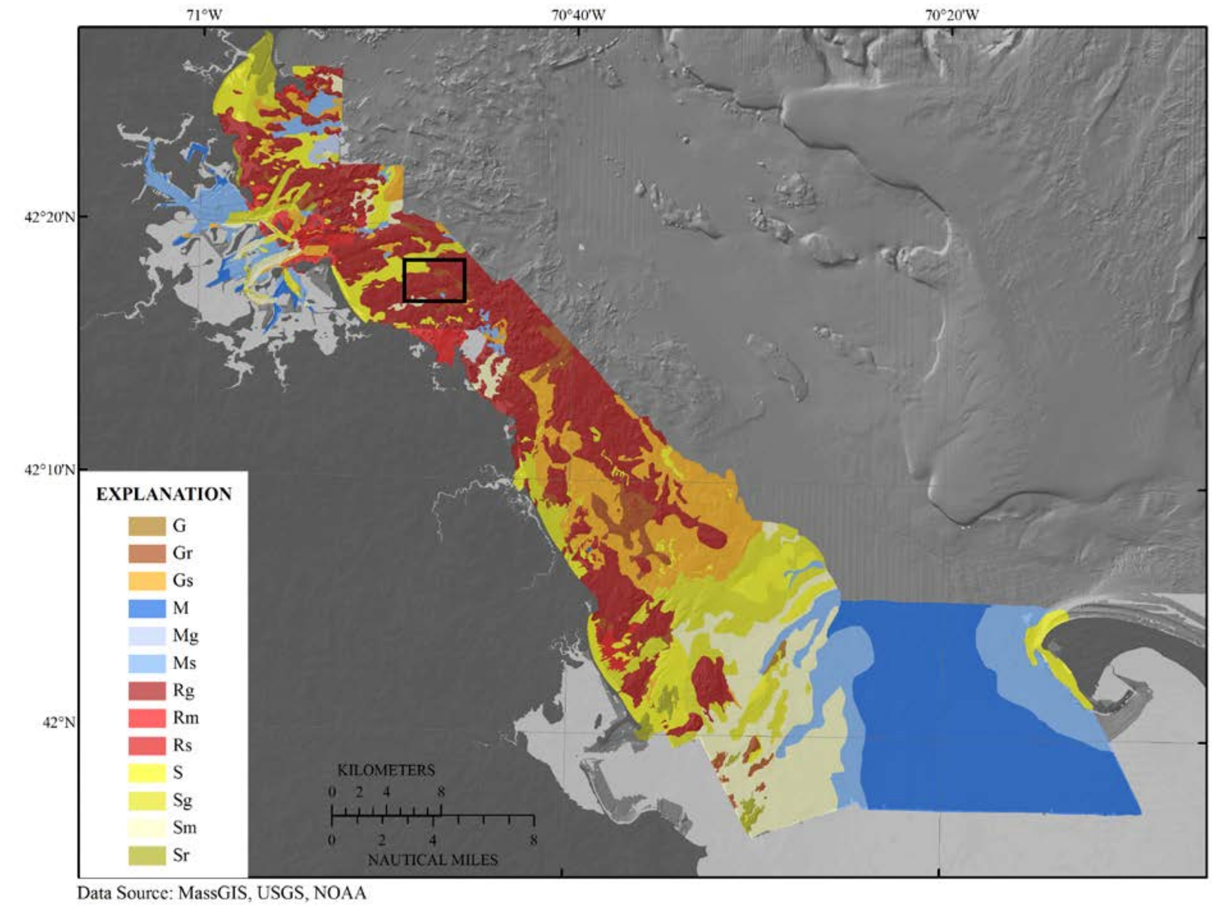


Figure 13. The distribution of sediment textures within the study area from Nahant to northern Cape Cod Bay. The bottom-type classification is from Barnhardt and others (1998) and is based on 16 sediment classes, where the first letter in the legend is the primary sediment unit (more than 50 percent) and the second letter is the secondary sediment unit (less than 50 percent). The classification is based on four easily recognizable sediment units that include gravel (G), mud (M), rock (R), and sand (S) (fig. 11). The black rectangle is indicating the location of figure 15.

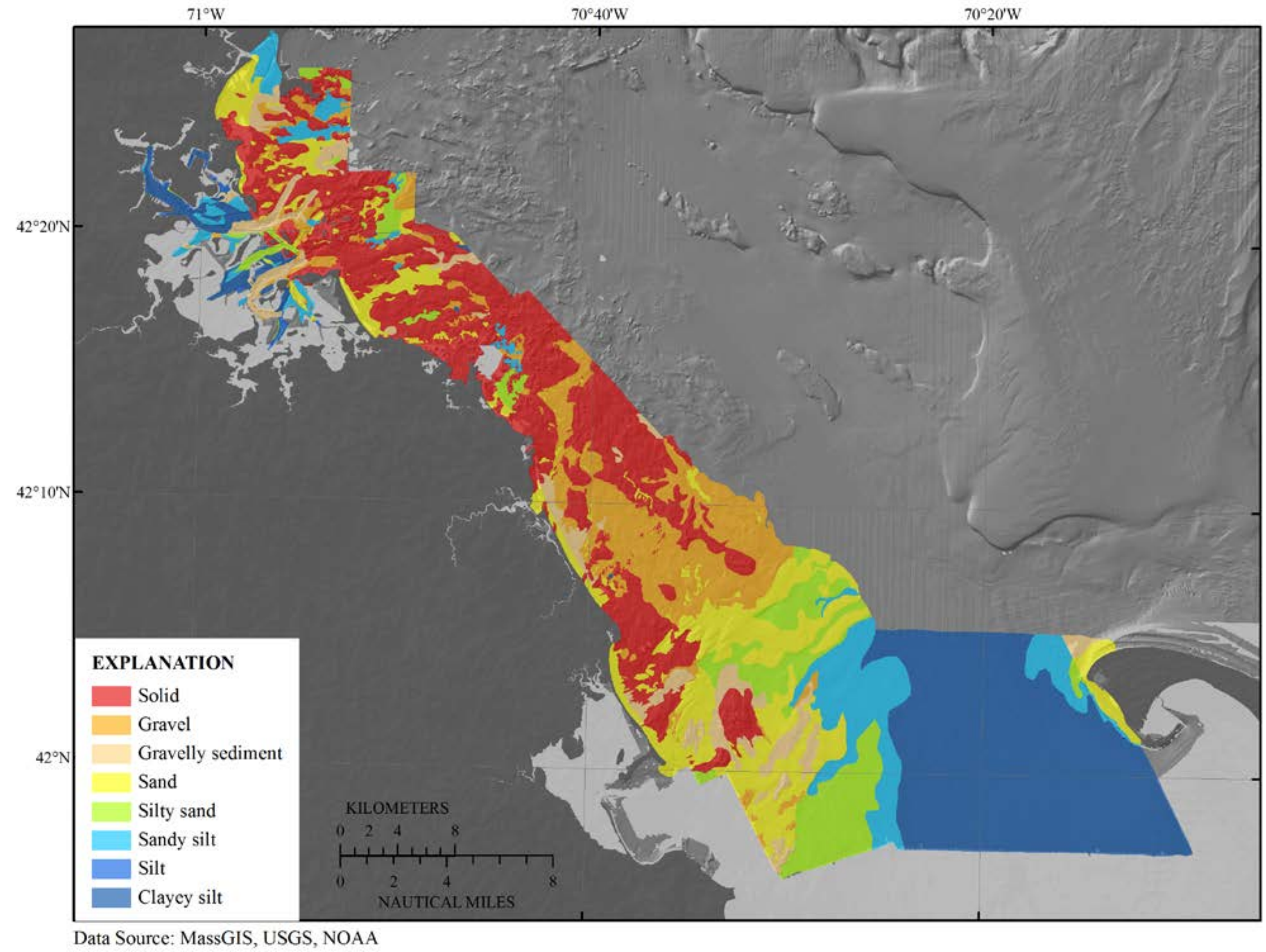


Figure 14. The distribution of sediment textures based on a modified Shepard (1954) and Schlee (1973) classification within the study area from Nahant to northern Cape Cod Bay. The classification used here is based on eight units, which include solid (for rocky substrates), gravel, gravelly sediment, sand, sandy silt, silty sand, silt, and clayey silt.

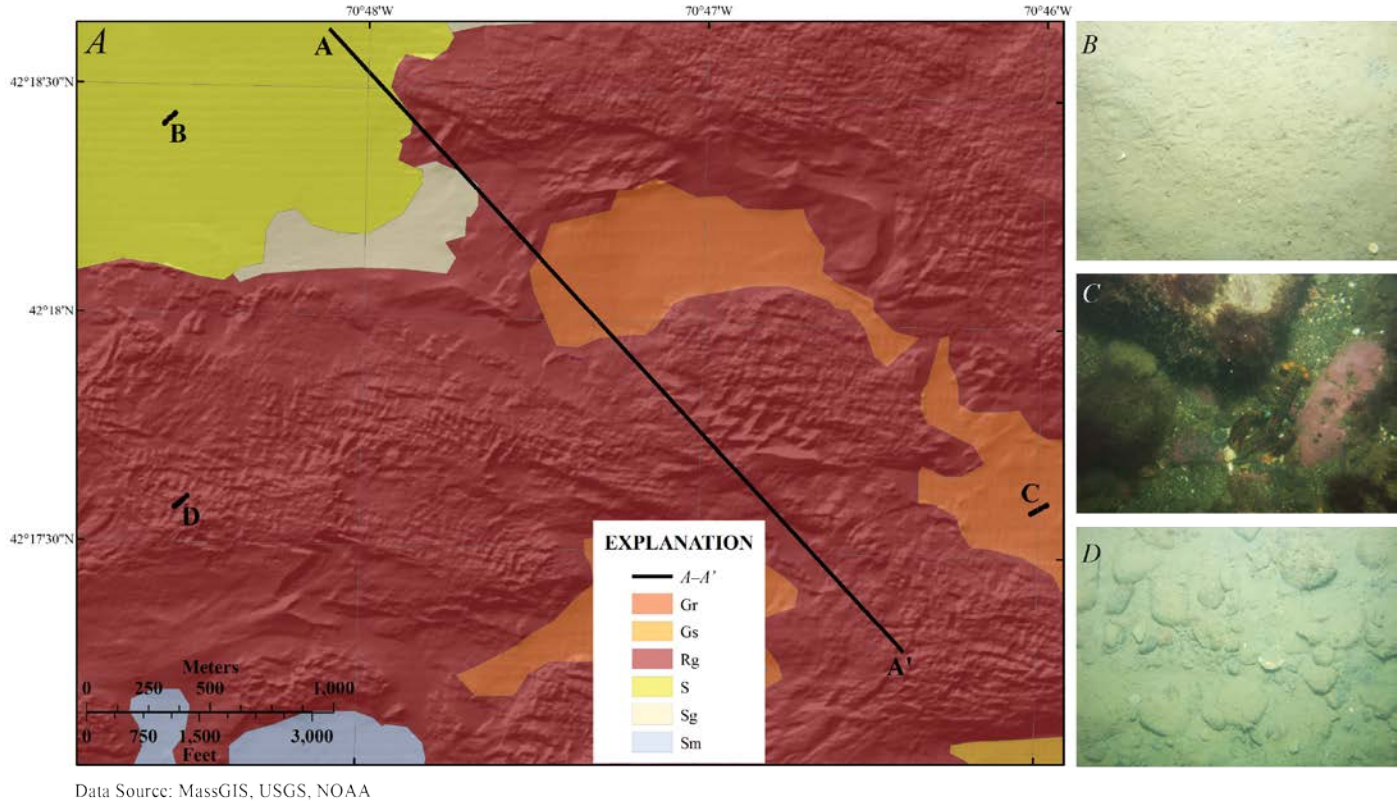


Figure 15. A, Sediment textures within an approximately 3- by 2-kilometer area in western Massachusetts Bay (see fig. 13 for location). The location of seismic profile A–A' from figure 5 is shown; the lines B, C, and D indicate where the photographs in B, C, and D were taken. B, A photograph of the sea floor within an area classified as sand (S). C, A photograph of a section of sea floor classified as primarily rock with some gravel (Rg). D, A photograph from a section of sea floor classified as primarily gravel with some rock (Gr). The viewing frame for photographs B, C, and D is approximately 50 centimeters.

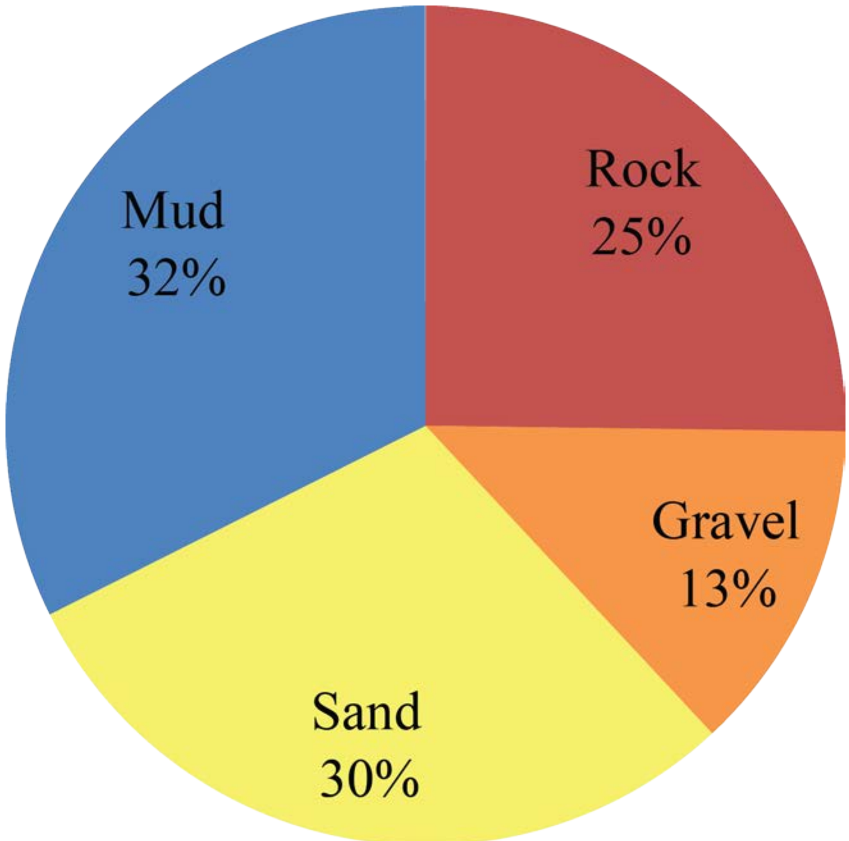


Figure 16. The chart shows the percentage of each primary sediment unit within the study area.

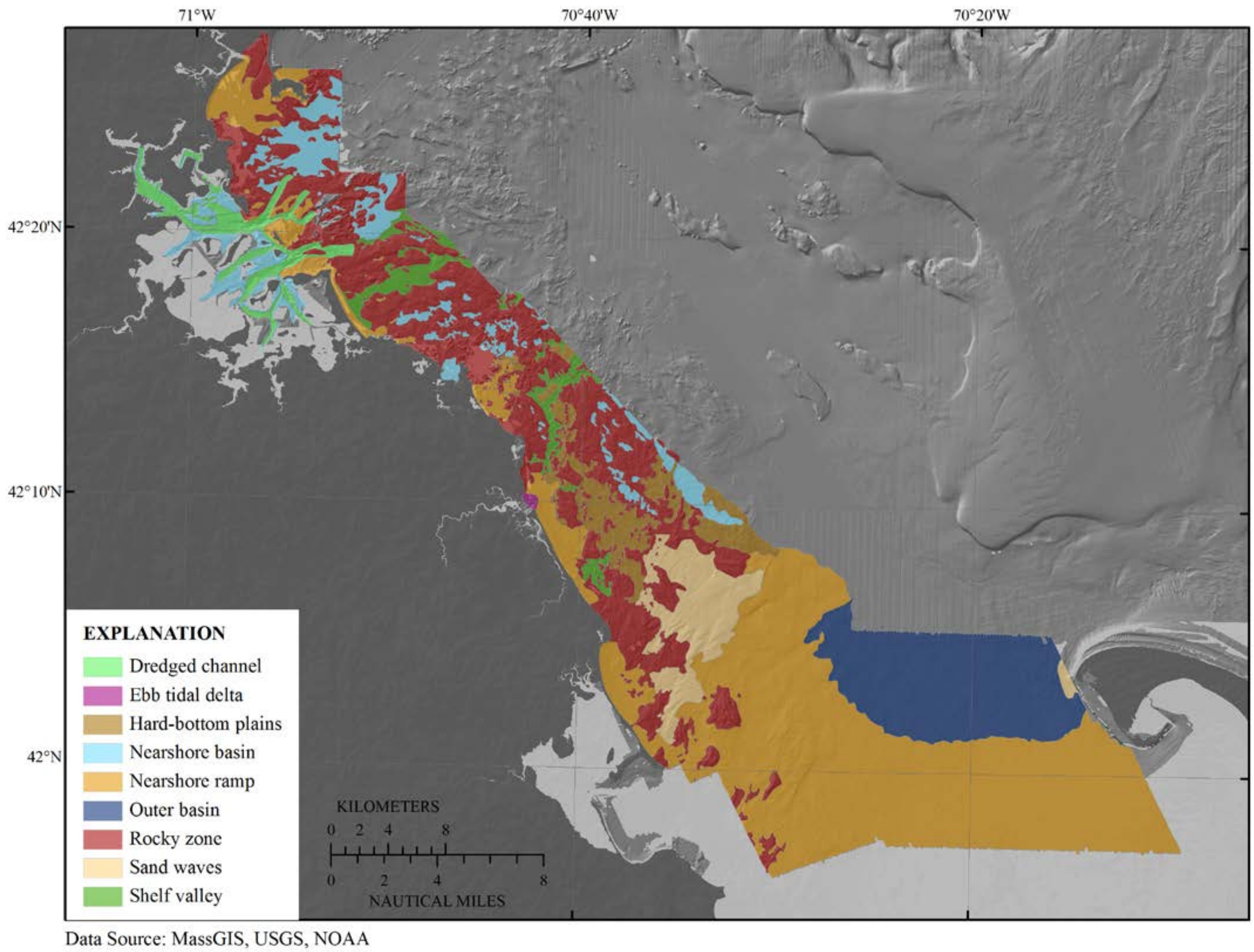


Figure 17. The distribution of physiographic zones within the study area from Nahant to northern Cape Cod Bay. The physiographic zone classification is based on Kelley and others (1989), and the zones are delineated based on sea-floor morphology and the dominant texture of surficial material.

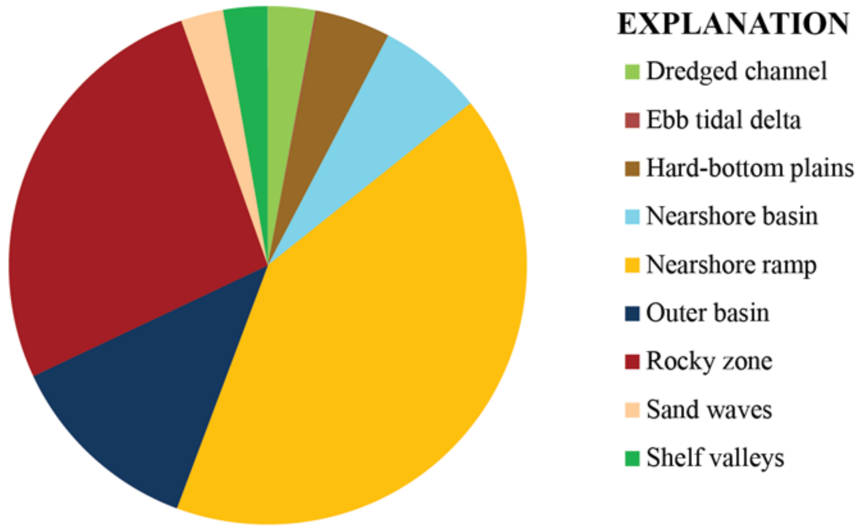


Figure 18. Chart showing the relative percentage of each physiographic zone within the study area.

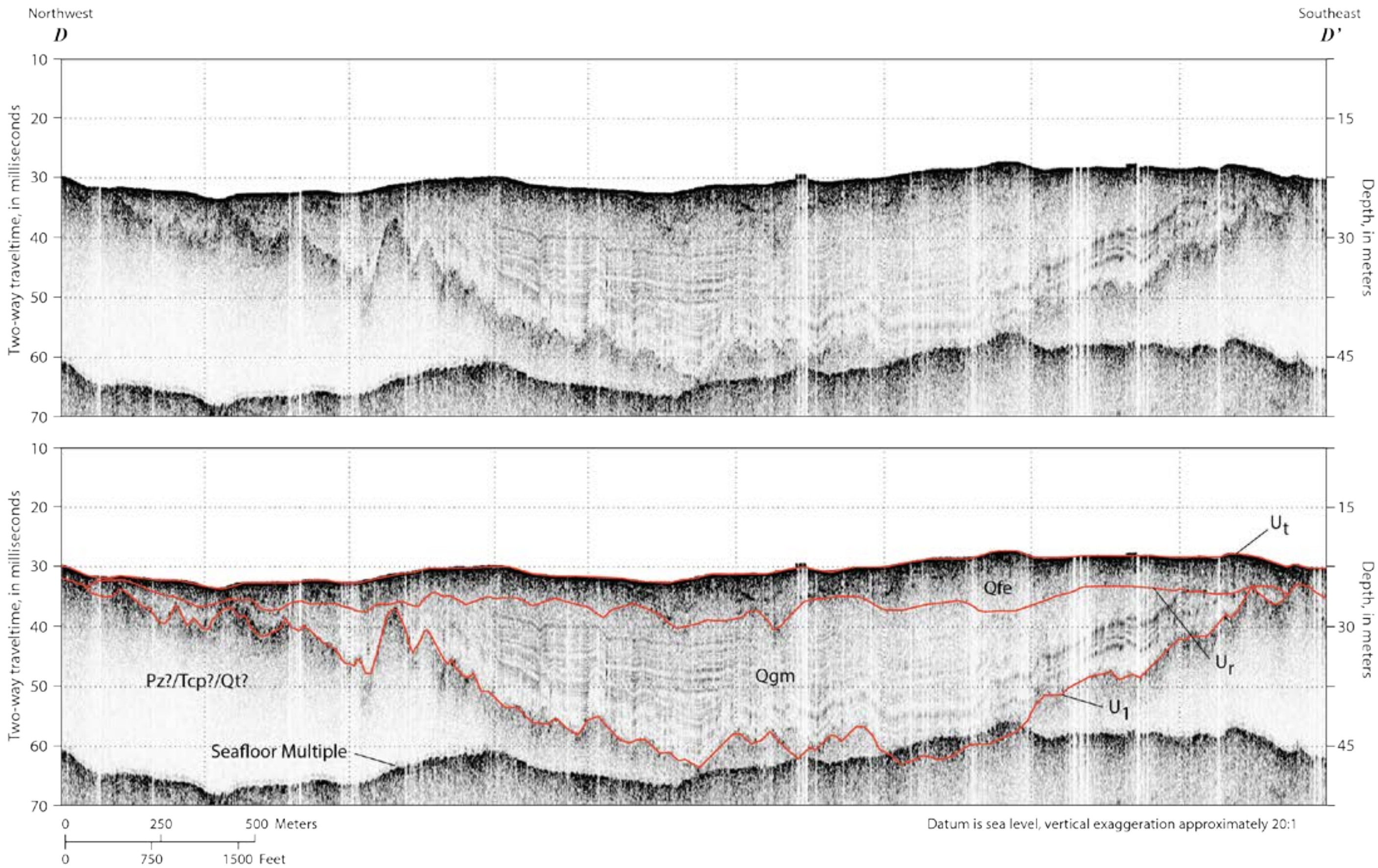
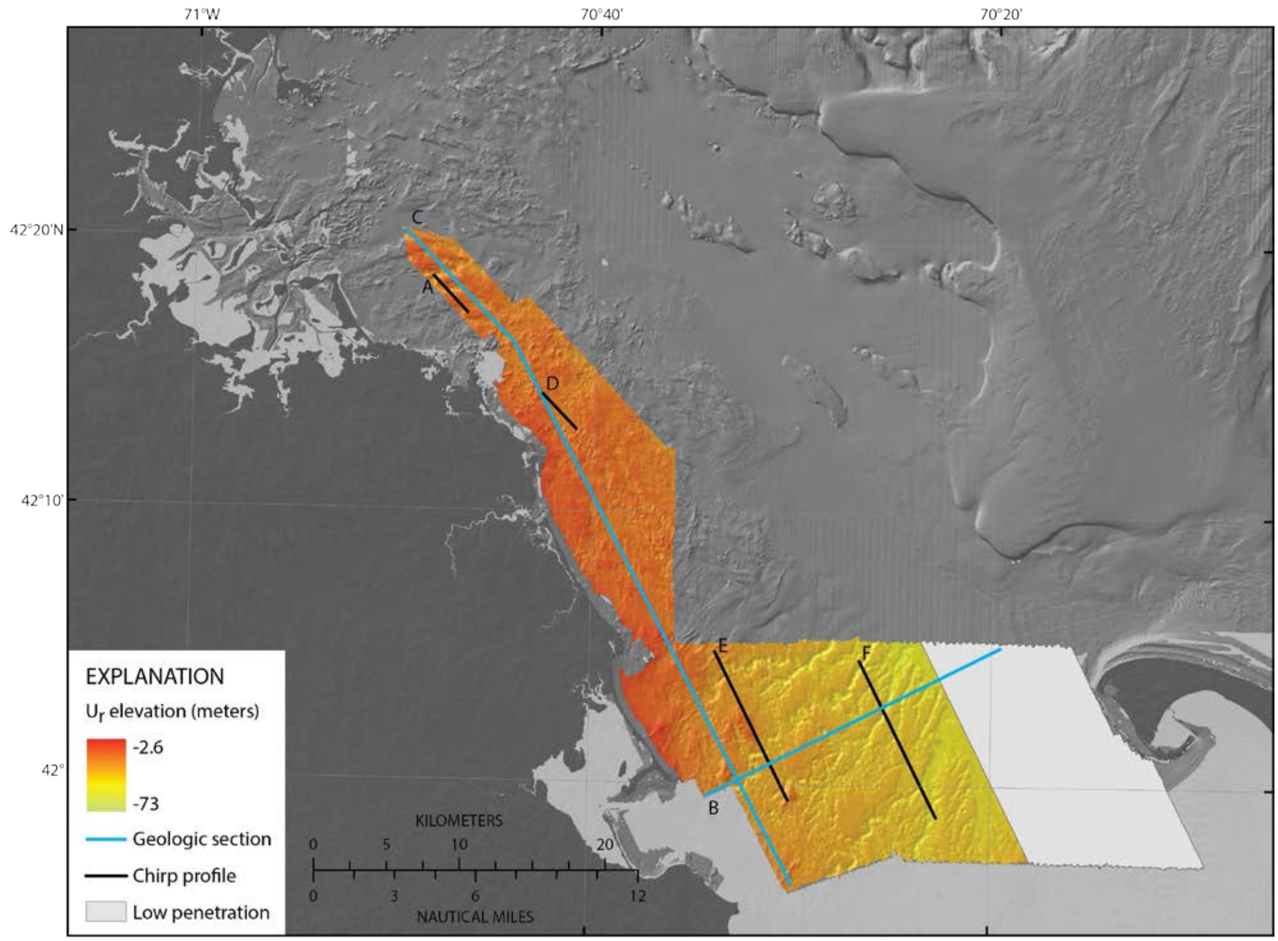
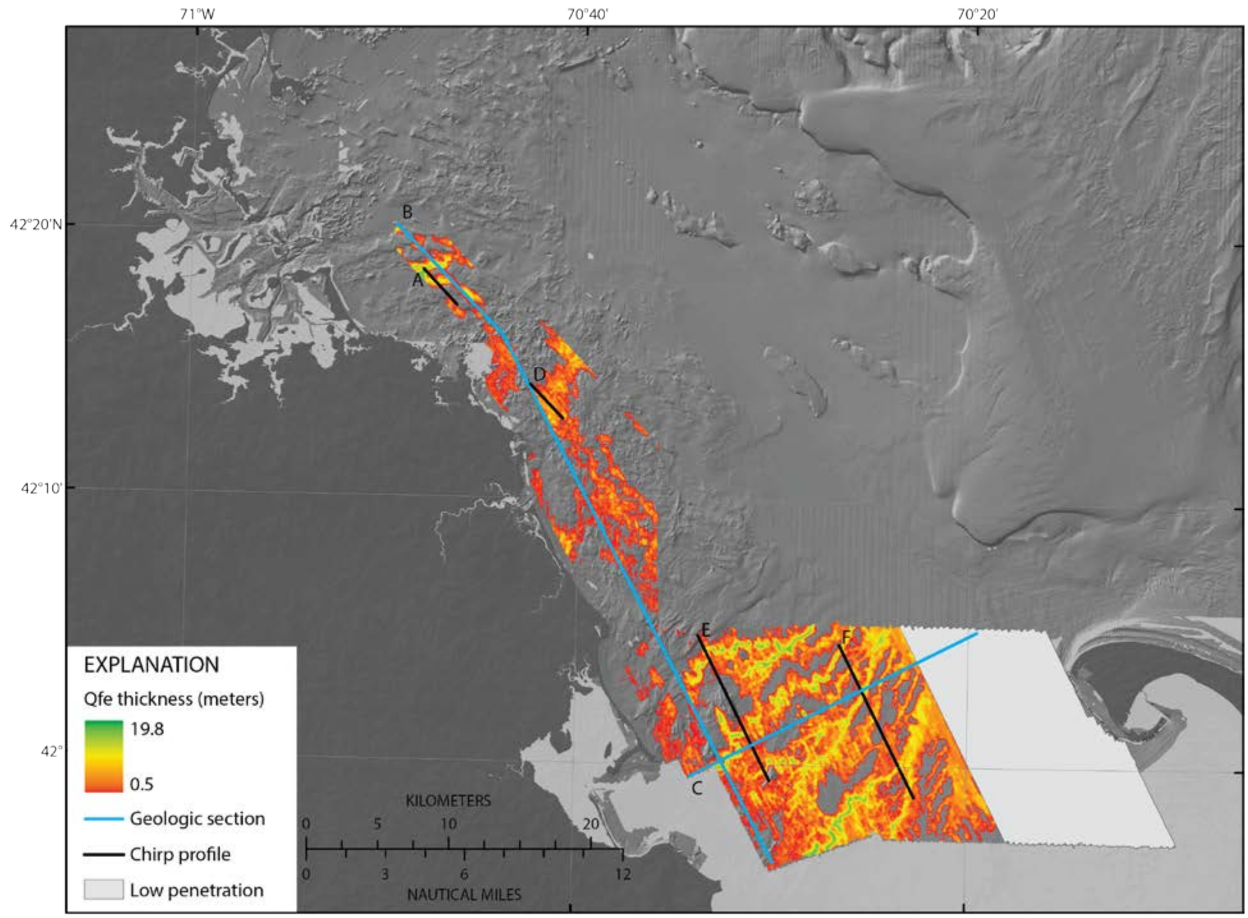


Figure 19. Chirp seismic-reflection profile D-D' with seismic stratigraphic interpretation. This profile illustrates the stratigraphy beneath western Massachusetts Bay offshore of Scituate, Massachusetts, where a relatively broad depression in the underlying pre-Quaternary surface (Pz/Tcp/Qt) is filled by Pleistocene glaciomarine (Qgm) and overlying Holocene fluvial and estuarine (Qfe) sediments. See figure 6 for descriptions of stratigraphic units and major unconformities (indicated by red lines). See figure 8 for profile location. A constant sound velocity of 1500 m/s was used to convert two-way travel time to depth in meters.



Data Source: MassGIS, USGS, NOAA

Figure 20. Map showing the elevation (from the North American Vertical Datum of 1988) of the late Wisconsinan regressive unconformity Ur, which identifies the truncated surface of Pleistocene glacial drift (Qd) and older adjacent units beneath the Massachusetts inner shelf between Nahant and northern Cape Cod Bay. The grey shaded area indicates where Ur was not identified and mapped due to insufficient seismic penetration. Ur represents a composite unconformity where it locally merges with the oldest fluvial unconformity (U1), Holocene transgressive unconformity (Ut), or both (fig. 7). The locations of geologic cross sections B-B' and C-C' (fog. 8) are indicated by cyan lines, and the locations of chirp seismic-reflection profiles A-A', D-D', E-E', and F-F' are indicated by black lines.



Data Source: MassGIS, USGS, NOAA

Figure 21. Map showing the thickness of Holocene fluvial and estuarine (Qfe) sediments beneath the Massachusetts inner shelf between Nahant and northern Cape Cod Bay. The grey shaded area indicates where Qfe thickness could not be evaluated due to insufficient seismic penetration to adequately map the underlying Ur surface. The locations of geologic cross sections B and C in figure 7 are indicated by cyan lines, and locations of chirp seismic-reflection profiles A, D, E, and F are indicated by black lines.

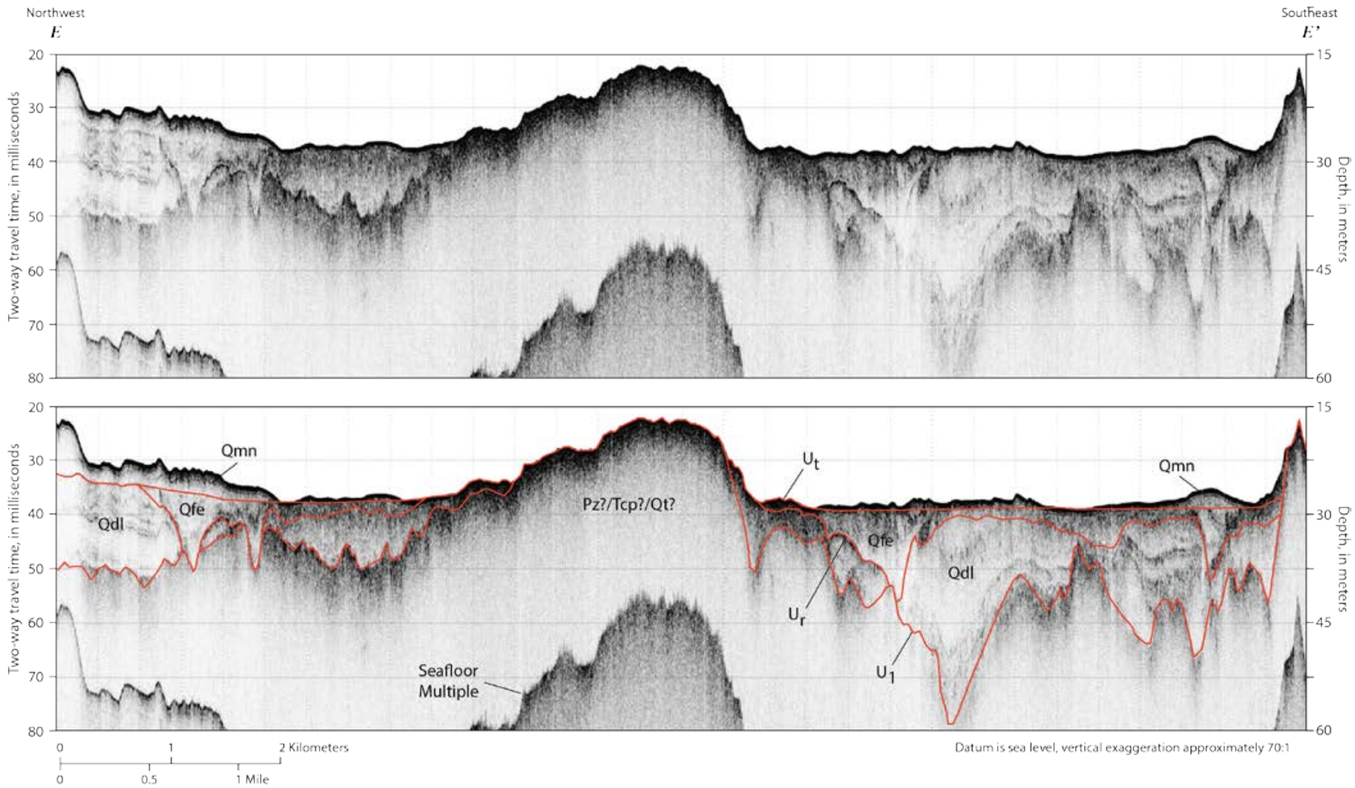


Figure 22. Chirp seismic-reflection profile E-E' with seismic stratigraphic interpretation. This profile illustrates the stratigraphy beneath northern Cape Cod Bay offshore of Duxbury Beach and Plymouth Bay, Massachusetts, where two depressions in the underlying pre-Quaternary surface (Pz/Tcp/Qt), located on either side of a broad outcrop, are filled by a succession of Pleistocene glaciolacustrine (Qdl), Holocene fluvial and estuarine (Qfe), and Holocene nearshore marine (Qmn) sediments. See figure 6 for descriptions of stratigraphic units and major unconformities (indicated by red lines). See figure 8 for profile location. A constant sound velocity of 1500 m/s was used to convert two-way travel time to depth in meters.

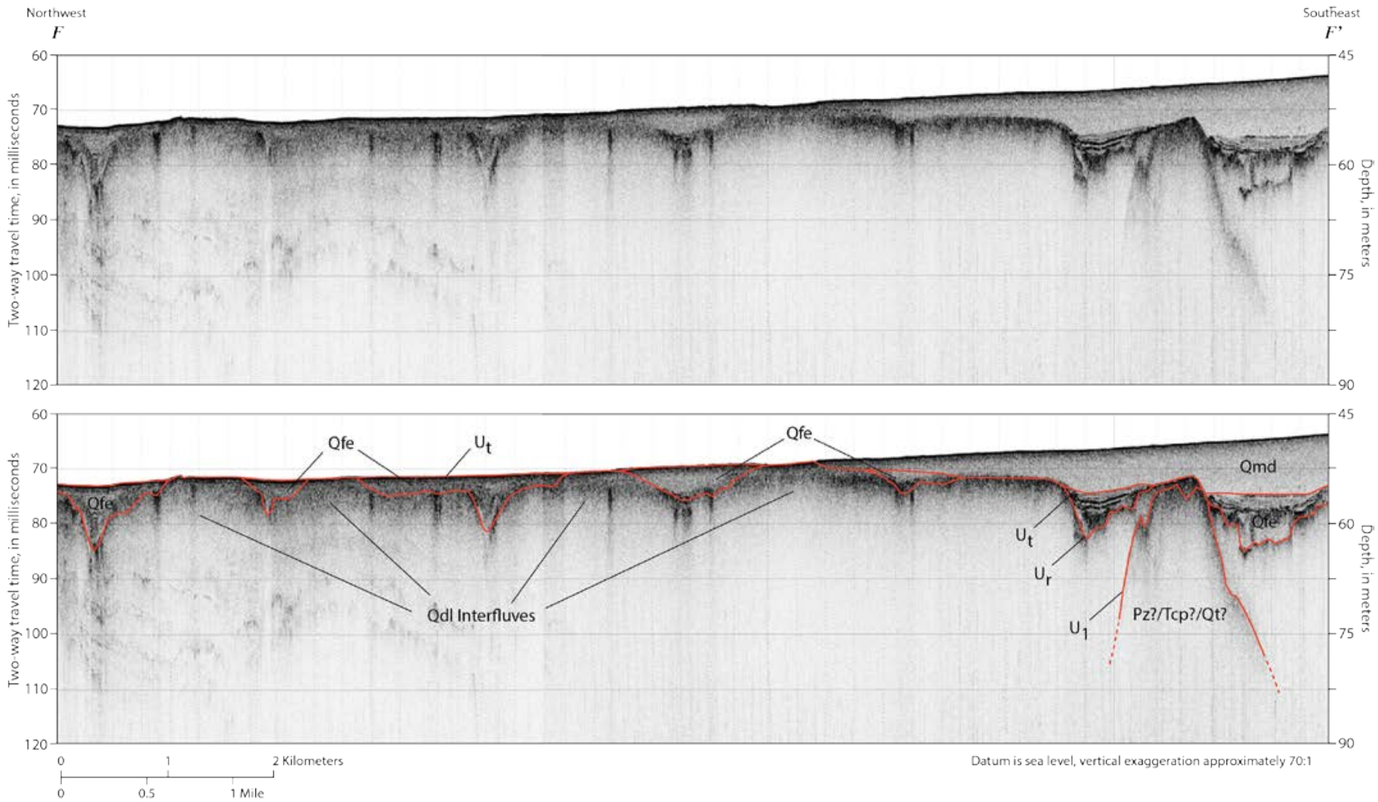
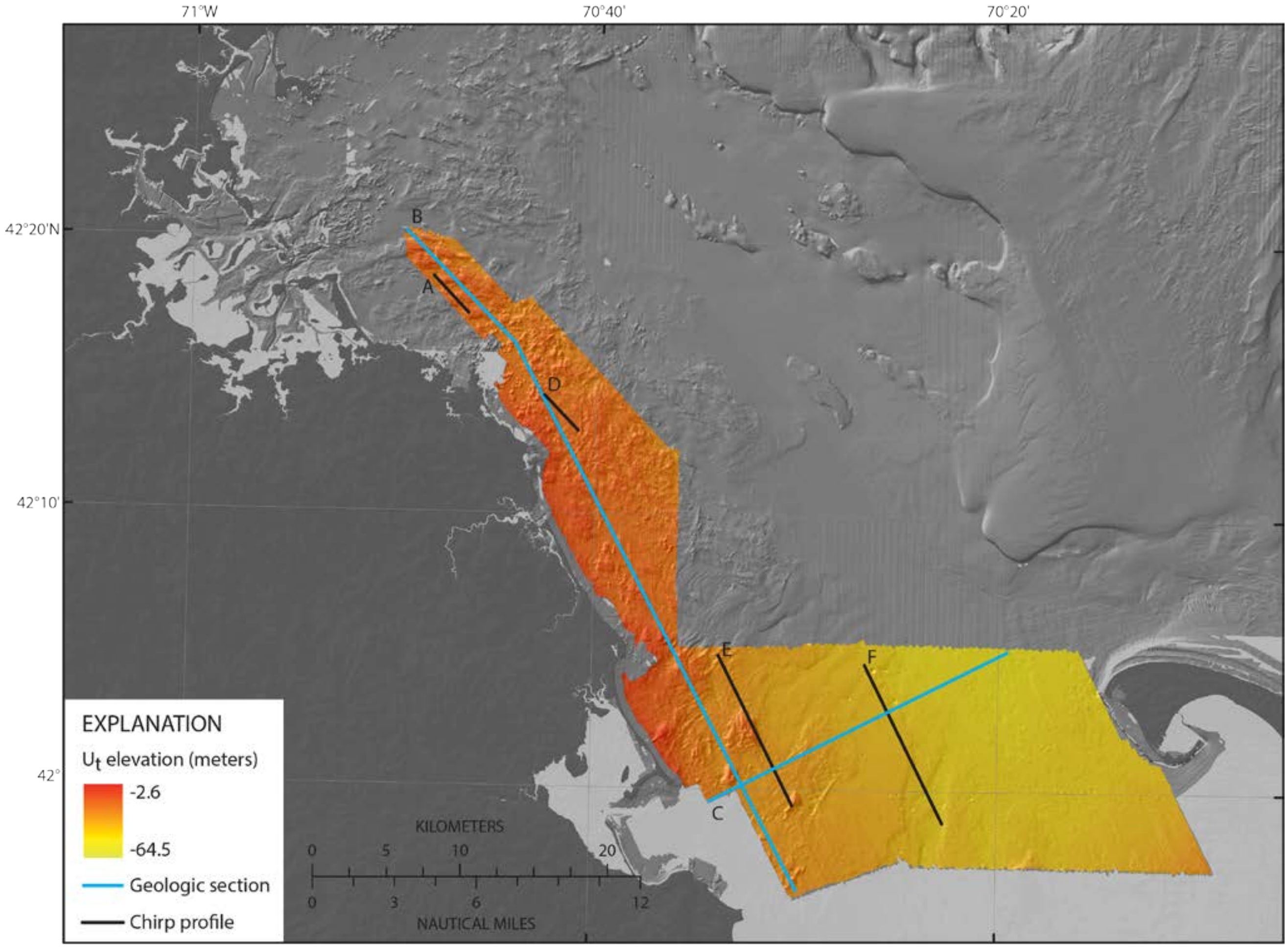
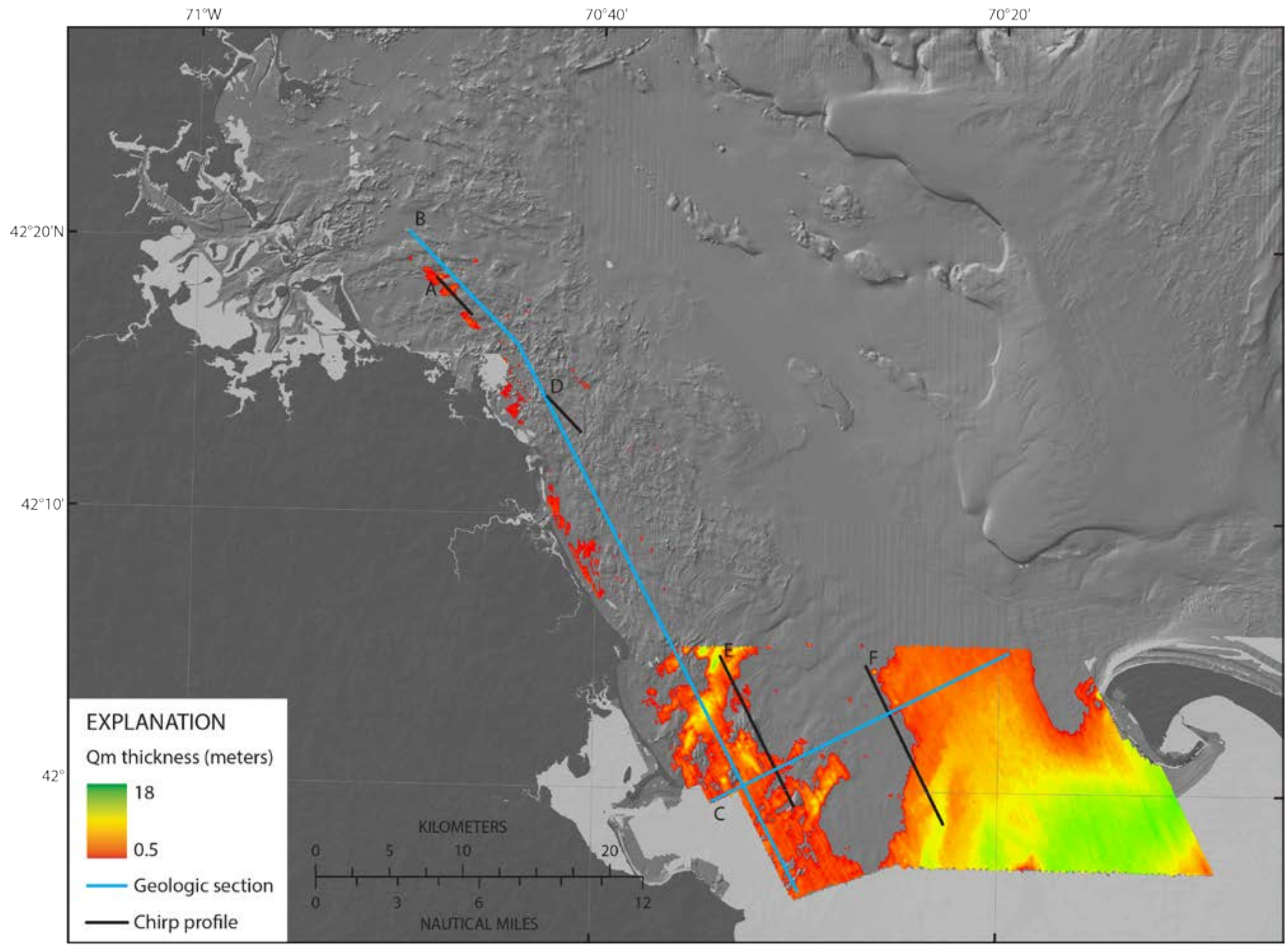


Figure 23. Chirp seismic-reflection profile F-F' with seismic stratigraphic interpretation. This profile illustrates the stratigraphy beneath northern Cape Cod Bay offshore of Duxbury Beach and Plymouth Bay, Massachusetts seaward of profile E-E' in Figure 22. Deep fluvial channels incised into the surface of thick glaciolacustrine (Qdl) sediments are filled with Holocene fluvial and estuarine (Qfe) deposits. The truncated Qd and Qfe units are broadly exposed at the seafloor to the northwest, but buried beneath increasingly thick Holocene deepwater marine (Qmd) sediments to the southeast. See figure 6 for descriptions of stratigraphic units and major unconformities (indicated by red lines). See figure 8 for profile location. A constant sound velocity of 1500 m/s was used to convert two-way travel time to depth in meters.



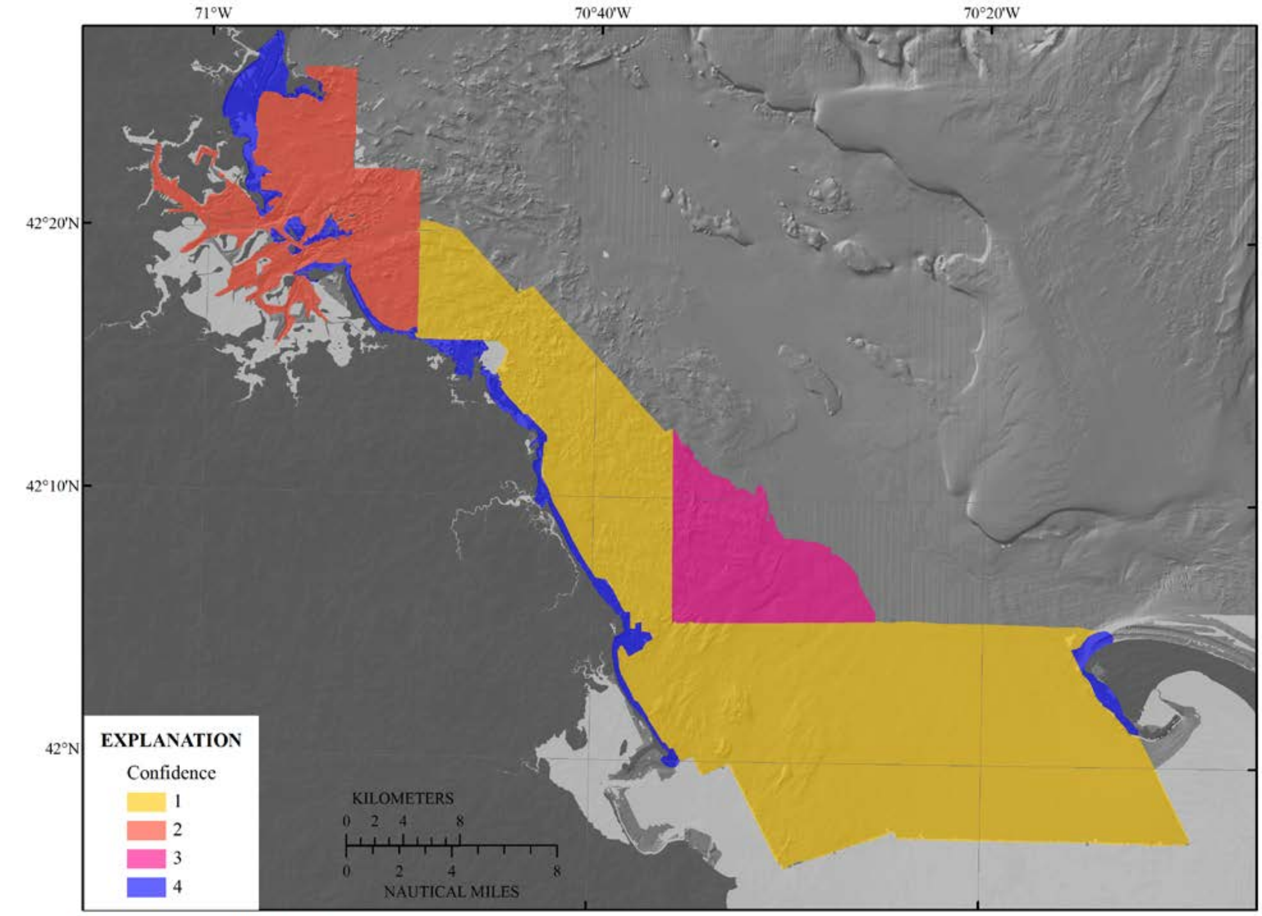
Data Source: MassGIS, USGS, NOAA

Figure 24. Map showing the elevation (from the North American Vertical Datum of 1988) of the Holocene transgressive unconformity Ut, which identifies the truncated surface of Holocene fluvial and estuarine (Qfe) sediments and older adjacent units beneath the Massachusetts inner shelf between Nahant and northern Cape Cod Bay. Ut represents a composite unconformity where it locally merges with the oldest fluvial (U1) unconformity, the late Wisconsinan regressive (Ut) unconformity, or both (fig. 7). The locations of geologic cross sections B-B' and C-C' (fig. 8) are indicated by cyan lines, and the locations of chirp seismic-reflection profiles A-A', D-D', E-E', and F-F' are indicated by black lines.



Data Source: MassGIS, USGS, NOAA

Figure 25. Map showing the thickness of Holocene marine (Qmn and Qmd) sediments on the Massachusetts inner shelf between Nahant and northern Cape Cod Bay. The locations of geologic cross sections B-B' and C-C' (fig. 8) are indicated by cyan lines, and the locations of chirp seismic-reflection profiles A-A', D-D', E-E', and F-F' are indicated by black lines.



Data Source: MassGIS, USGS, NOAA

Figure 26. Sediment texture polygons are assigned a data interpretation confidence value from 1-4 based on the resolution and number of input data sources. 1 is the highest interpretation confidence value and 4 is the lowest.

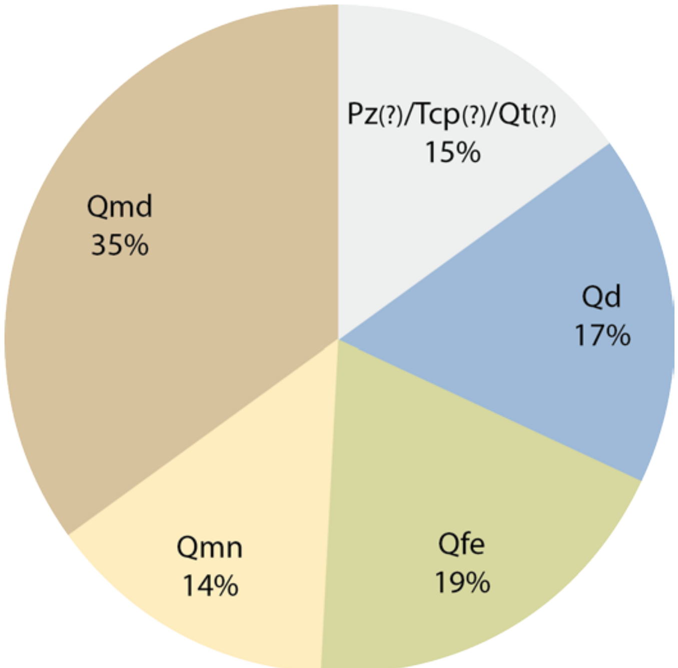


Figure 27. Chart showing the relative percentage of sea-floor outcrop for each of the primary seismic stratigraphic units.