



Sidescan-Sonar Imagery and Surficial Geologic Interpretations of the Sea Floor in Central Rhode Island Sound

By K.Y. McMullen, L.J. Poppe, J.F. Denny, T.A. Haupt, and J.M. Crocker

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Contents

Contents.....	iii
Introduction	1
Geologic Setting.....	1
Data Acquisition and Processing.....	2
Bathymetry.....	2
Historic Seismic-Reflection Data.....	2
Sidescan-Sonar Imagery.....	3
Sand Waves.....	3
Boulders.....	3
Benches.....	3
Low Backscatter.....	4
Moderate Backscatter.....	4
High Backscatter.....	4
Trawl Marks.....	4
Sedimentary Environments.....	4
Erosion or Nondeposition.....	4
Coarse-Grained Bedload Transport.....	5
Sorting and Reworking.....	5
Fine-Grained Deposition.....	5
Discussion.....	5
Summary.....	6
GIS Data Catalog.....	6
Sidescan Sonar Imagery.....	8
Bathymetric Imagery.....	8
Bathymetric Grids.....	8
Interpretive Data.....	8
Basemap Data.....	9
Acknowledgments.....	9
Contacts.....	9
References Cited.....	10

Figures

- Figure 1.** Location map of NOAA Survey H11321 study area in Rhode Island Sound (red polygon). NOAA Survey H11320 (McMullen and others, 2007) overlaps the eastern end of the study area (black outline). Location of interpreted stratigraphy profile A-A' (fig. 3) is also shown. 13
- Figure 2.** Map showing the outline of the study area (black outline), locations of historic seismic-reflection data shown in figures 7 and 8 (red lines), the locations of detailed views shown in figures 11, 12, and 13 (green outlines), and the location of a sand sample (yellow circle) from the NOS Hydrographic Database (Poppe and others, 2003). 14
- Figure 3.** Interpreted stratigraphy profile across Rhode Island Sound, modified from Needell and others (1983b). Stratigraphy includes: PzZ – pre-Mesozoic bedrock, Ku – mostly late Cretaceous coastal plain and continental shelf sediments, Qdo – mostly late Wisconsin glacial drift, Qdm – late Wisconsin moraine deposits, Qfe – Holocene transitional (fluvial and estuarine) deposits,

Qpt – Holocene marine sediments. Contacts are dashed where inferred. Vertical exaggeration: 19X. Location of profile shown in fig. 1..... 15

Figure 4. Map showing the location of end moraines (black polygons) in southern New England and Long Island, New York. The Ronkonkoma-Nantucket moraine represents the Laurentide Ice Sheet's maximum glacial advance about 20 ka and the Harbor Hill-Roanoke Point-Charlestown-Buzzards Bay moraine represents a retreated ice sheet position from around 18 ka (Uchupi and others, 1996). Underwater extensions of the moraines are shown as dashed lines. Study area is shown as gray polygon. Modified from Gustavson and Boothroyd (1987). 16

Figure 5. Photo of NOAA Ship RUDE (courtesy of NOAA). 17

Figure 6. Bathymetric image of study area from sounding and multibeam data. Light tones represent shallower depths and dark tones represent deeper areas. A ridge is located across the northern and western parts of the study area. A channel is located south of the ridge and north and west of a bathymetric high in the southeast. Another bathymetric low is located in the southeastern corner of the study area..... 18

Figure 7. Seismic-reflection profile across eastern end of study area from Needell and others (1983a) with interpretation and corresponding sidescan-sonar image. Paleozoic bedrock, Wisconsin glacial drift including till, moraine, and glaciolacustrine sediments, and Holocene marine and transitional deposits are shown. Stratified drift in the south may be glaciolacustrine sediment. Sidescan-sonar image shows areas of sand waves, benches, trawl marks, and high backscatter. Benches tend to coincide with a contact between glaciolacustrine sediment and till. Depths are based on an assumed compressional wave velocity of 1500 m/s. Vertical exaggeration: 13X. Location of profile shown in fig. 2. 19

Figure 8. Seismic-reflection profile across western end of study area from Needell and others (1983a) with interpretation and corresponding sidescan-sonar image. Interpretation includes: Paleozoic bedrock, possible Cretaceous coastal plain sediments, Wisconsin glacial till and glaciolacustrine sediments, and Holocene marine and transitional deposits. Sidescan-sonar image shows sand waves in the north and benches, high backscatter, and trawl marks in the south. Benches occur at the contact between fluvial and glaciolacustrine sediments and within the glaciolacustrine sediment near the exposure of till. Depths are based on an assumed compressional wave velocity of 1500 m/s. Vertical exaggeration: 13X. Location of profile shown in fig. 2..... 20

Figure 9. Sidescan-sonar image of the study area. Dark tones represent lower backscatter and generally finer grained sediment; light tones represent higher backscatter and generally coarser grained sediment. Light and dark bands oriented northeast-southwest are artifacts of the sidescan-sonar processing..... 21

Figure 10. Interpretation of sidescan-sonar imagery of the study area. Sand waves are visible across much of the study area, and boulders are scattered throughout. Two lines of benches cross the study area, large areas of high backscatter are located mostly in the south, and low backscatter and trawl marks are seen in the deeper waters. 22

Figure 11. Detailed sidescan-sonar and bathymetry images of sand waves along a channel on the northern ridge. Sand waves adjacent to the channel are straight-crested and oriented north-south; away from the channel sand waves have more curved and sinuous crests that are oriented east-west. In the channel in the central part of the image, both east-west and north-south oriented sand waves are present, suggesting complex flow and transport directions. Benches are also visible on the sidescan-sonar image where there is a sharp curvilinear change in backscatter. A trawl mark is visible in the southeastern corner of the sidescan-sonar image. Light and dark bands oriented northeast-southwest are artifacts in the sidescan sonar. Location of figure shown in fig. 2. 23

Figure 12. Detailed sidescan-sonar image of trawl marks on the floor of the channel. Lines of low backscatter or paired high and low backscatter indicate trawl marks. Benches cross the northern part of the image where there is a sharp curvilinear change in backscatter and sand waves are located throughout the north. An area of low backscatter indicates finer grained sediment. Location of figure shown in fig. 2.24

Figure 13. Detailed sidescan-sonar image of the southeastern part of the study area showing boulders, sand waves, and benches. Boulders are visible as high-backscatter targets with low-backscatter shadows. Higher backscatter (lighter tones) in the center of the image represents coarser grained sediment; lower backscatter (darker tones) represents finer grained sediment. Location of figure shown in fig. 2.....25

Figure 14. Map of the sedimentary environments in the study area including those characterized by processes of erosion or nondeposition, coarse-grained bedload transport, sorting and reworking, and fine-grained deposition.26

Conversion Factors

Multiply	By	To obtain
Length		
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
Area		
square kilometer (km ²)	247.1	acre

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83). Vertical datum, as used in this report, refers to mean lower low water.

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Introduction

The U.S. Geological Survey (USGS) has been working with the National Oceanic and Atmospheric Administration (NOAA) to interpret the surficial geology of areas along the northeastern coast of the United States. During 2004, the NOAA Ship RUDE conducted Hydrographic Survey H11321 in Rhode Island Sound. This sidescan-sonar and bathymetry survey covers an area of 93 km² located 12 km southeast of Brenton Point, RI in water depths of 28-39 m (fig. 1). The purpose of this report is to delineate sea floor features and sedimentary environments of this area in central Rhode Island Sound using sidescan-sonar and bathymetric data from NOAA Survey H11321 and seismic-reflection data from a previous USGS field study (Needell and others, 1983a). This is important for the study of benthic habitats and provides a framework for future research.

Prior work in this area includes the mapping of surface sediments and surficial geology. McMaster (1960) collected sediment samples from Rhode Island Sound and Narragansett Bay and mapped our study area as having a sandy sea floor. In addition, one sample of sand from the National Ocean Service (NOS) Hydrographic Database came from a location in the northeast part of our study area in 1939 (fig. 2; Poppe and others, 2003). McMaster and others (1968) used seismic-reflection profiles to map the locations of a cuesta of Cretaceous sediments crossing Rhode Island Sound and post-Cretaceous drainage channels. Knebel and others (1982) identified sedimentary environments in Rhode Island Sound using sidescan sonographs. Needell and others (1983b) studied the Quaternary geology and mapped the structure, sedimentary environments, and geologic hazards in Rhode Island Sound using sidescan-sonar and seismic-reflection data.

Sidescan-sonar and bathymetric data from NOAA Survey H11320, which overlaps the far eastern edge of our study area, was interpreted to consist of basins surrounded by a moraine and bathymetric highs composed of till with areas of rocks, sand waves, hummocks, glaciolacustrine erosional outliers, small scarps and elongate hills (fig. 1; McMullen and others, 2007). Some of those features extend into this study area.

Geologic Setting

The stratigraphy in Rhode Island Sound is composed of a south-southeasterly dipping basement of mostly pre-Mesozoic gneiss and schist, overlain in the south by late Cretaceous coastal plain sediments and throughout the sound by Pleistocene glacial drift and Holocene fluvial and transgressional sediments (fig. 3; McMaster and others, 1968). The coastal plain sediments, which

contain deeply eroded channels, form a cuesta across southern Rhode Island Sound (McMaster and others, 1968; McMaster and Ashraf, 1973). Two glacial advances across Rhode Island Sound are marked by the Ronkonkoma-Nantucket end moraines and the Harbor Hill-Roanoke Point-Charlestown-Buzzards Bay end moraines, as well as glacial drift over 40 m thick northward of the moraines (fig. 4; McMaster, 1960; McMaster and others, 1968). During glacial recession proglacial lakes formed behind the end moraines (Needell and others, 1983c). During and after lake drainage, while sea levels were near low stand, the sea floor was exposed and rivers cut drainage channels into the glacial drift, often in the locations of previously eroded valleys (McMaster and Ashraf, 1973; Needell and others, 1983c). As sea level rose, estuarine and marine sediments were deposited, while the transgressing shoreline eroded parts the sea floor (Needell and others, 1983c).

Data Acquisition and Processing

Sidescan-sonar and bathymetric data were collected aboard the NOAA Ship RUDE in 2004 (fig. 5). A Klein 5500 towfish (455 kHz) acquired sidescan-sonar data, which were recorded using Triton ISIS software and archived in extended Triton format (xtf). Sidescan-sonar data were processed using USGS software packages XSonar and ShowImage (Danforth, 1997). A median filtering routine was applied to the sidescan-sonar data to remove speckle noise. Sonar data were further processed to correct for slant-range and radiometric distortion inherent in the sonar data and corrected for towfish layback. Sonar data were mosaicked using XSonar, resulting in an enhanced, geographically correct, sidescan-sonar mosaic with 1 meter/pixel resolution.

An Odom Echotrac DF3200 MKII dual-beam echo sounder operating at 24 and 200 kHz acquired sounding data aboard the NOAA Ship RUDE. In areas of interest, shallow-water multibeam echo-sounder data were acquired with a Reson SeaBat 8125 operating at 455 kHz. Bathymetric data were processed using CARIS HIPS/SIPS software. Sounding and multibeam data were used with IVS Fledermaus software to create a bathymetric surface with full coverage of the study area and 45-m resolution, which eliminated gaps between track lines.

About 580 km of seismic-reflection data with 1-2 m resolution were collected by USGS in 1980 aboard the R/V NEECHO using an EG&G Uniboom seismic system that filtered 400-4000 Hz and recorded at a quarter-second sweep rate (Needell and others, 1983a, b).

Bathymetry

A broad, low ridge extends across the northern and western parts of the study area and a central channel stretches southwestward between the ridge and another bathymetric high to the southeast (fig. 6). Water depth increases to the north of the ridge, along the northern edge of the study area. The ridge crest lies in water depths of about 30 m and is cut by both northward and southward trending channels. The central channel is as much as 39 m deep and has a small central bathymetric high about 34 m deep. The bathymetric high in the southeast part of the study area is about 31 m deep. There is a bathymetric low in the southeastern corner of the study area. The sea floor in the channel and bathymetric low tends to be relatively smooth, whereas the sea floor on the ridge and the other bathymetric high tends to have bed forms.

Historic Seismic-Reflection Data

Seismic-reflection data from a previous study in Rhode Island Sound cross the study area (fig. 2; Needell and others, 1983a). The bottom-most unit of the seismic-reflection data is delineated by a prominent reflector that denotes Paleozoic bedrock of mostly gneiss and schist (fig.

7; Needell and others, 1983b). A prominent reflector that forms a northward-facing escarpment in the southern part of the study area overlying the bedrock was interpreted to be Cretaceous coastal plain sediments (fig. 8; Needell and others, 1983b). Overlying the bedrock and coastal plain sediments is a unit with irregular and discontinuous reflectors, interpreted to be Wisconsin glacial till. Overlying the till across much of the northern and western parts of the study area are laminated sediments that are mostly horizontal, but conform to the underlying surface (figs. 7 and 8; Needell and others, 1983a). These rhythmically laminated deposits are interpreted to be composed of glaciolacustrine sediments that were deposited during recession of the Laurentide Ice Sheet as meltwater was impounded behind mounded glacial drift, much like the varved sediments in Block Island Sound described by Bertoni and others (1977). Holocene marine and transitional deposits fill fluvially eroded channels near the surface that cut into the glaciolacustrine and till deposits (figs. 7 and 8).

Sidescan-Sonar Imagery

Sidescan-sonar imagery shows that 7 backscatter patterns exist in the study area (fig. 9). These patterns have been interpreted using bathymetric and seismic-reflection data (fig. 10). The patterns are interpreted to be: sand waves, boulders, benches, low, moderate, and high backscatter, and trawl marks. These areas are often gradational, many overlap, and the boundaries are inferred.

Sand Waves

Areas of tiger-striped backscatter can be seen across most of the northern, western, and southeastern parts of the study area. These features occur on the bathymetric highs and are interpreted to be sand waves (fig. 11). Most sand waves in the northwestern part of the study area have straight crests that are oriented north-south with 10-20 m wavelengths. Sand waves that lie closer to the channel, in the central, eastern, and southern parts of the study area, tend to have curved and sinuous crests oriented to the east or east-northeast and wavelengths of 20 to over 100 m. Superimposed on some of the sand waves near the channel are megaripples with several-meter wavelengths and crests oriented to the northwest (fig. 12). The sediment transport direction in the central part of the study area is interpreted to be north-south between the ridge and channel, perpendicular to the sand-wave crests. Along the northern part of the study area, sediment transport is in an east-west direction, as indicated by orientations of the sand-wave crests. Sand waves along channels in the north tend to be oriented both north-south and east-west, suggesting there is a component of north-south flow through the smaller channels in addition to the east-west flow (fig. 11).

Boulders

High-backscatter targets with low-backscatter shadows exist throughout the study area, with the highest concentration in the southeast (fig. 13). These targets are interpreted to be boulders up to several meters wide. They are present on both bathymetric highs and in the channel where glacial drift is exposed. The boulders are glacial erratics and ice-rafted debris deposited during the Wisconsin glacial period.

Benches

Discontinuous, curvilinear, sharply contrasting high- and low-backscatter patterns cross through the central and southeastern parts of the study area in a northeast-southwest direction (fig.

10). These features, which occur along the northern edge of the central channel and along the northern edge of the bathymetric low in the southeast in water depths of 30-36 m (figs. 11, 12, and 13), are composed of paired scarps and horizontal sea floor notched into the regional bathymetric slope. The features in the western and southeastern corners of the study area are mostly 35-36 m deep and those in the northeast are generally 32-33 m deep. The features tend to exist near the edge of stratified sediments and where fluvial sediments or till outcrop (figs. 7 and 8). Similar backscatter patterns seen in the sidescan-sonar imagery of NOAA Survey H11320 were associated with small hills and scarps up to 0.5 m in height in the multibeam bathymetry and were interpreted to be wave-cut terraces along paleoshorelines (McMullen and others, 2007). Although these features are smaller than the resolution of the bathymetric and seismic-reflection data in the study area, they are presumed to be benches with small hills and scarps, like those to the east, because they continue through both surveyed areas (McMullen and others, 2007).

Low Backscatter

Several areas of low backscatter are visible in the sidescan-sonar imagery within the bathymetric lows in the northwest, south-central, and southeast (figs. 9 and 10). Low backscatter generally indicates finer grained sediments and lower energy conditions. These areas are located in the deepest parts of the study area.

Moderate Backscatter

Areas of moderate backscatter that are otherwise featureless are located in much of the central trough and on parts of the bathymetric highs (fig. 10).

High Backscatter

Four areas of high backscatter are located in the southern part of the study area, where they occur on the flanks of bathymetric highs (fig. 10). High backscatter is usually associated with coarser grained sediment and higher energy conditions.

Trawl Marks

Several areas with lines of either low backscatter or paired high and low backscatter are located in the channel in the central part of the study area and along the northern and southeastern edges of the study area (fig. 12). These are interpreted to be trawl marks from fishing boats. Driscoll (1996) found that between 1991 and 1994, trawl marks increased in distribution and density in Block Island Sound, suggesting an increasing impact of anthropogenic activity on the sea floor.

Sedimentary Environments

Four different sedimentary environments are present in the study area including environments that are characterized by processes associated with erosion or nondeposition, coarse-grained bedload transport, sorting and reworking, and fine-grained deposition (fig. 14).

Erosion or Nondeposition

Areas with sedimentary environments characterized by processes of erosion or nondeposition are located in two southward-facing channels incised into the ridge and along the

southeastern bathymetric high. These areas with high backscatter in the sidescan-sonar image and clusters of boulders indicate coarser grained sediment reflective of higher energy environments.

Coarse-Grained Bedload Transport

The majority of the study area is characterized by processes of coarse-grained bedload transport. These areas occur throughout much of the bathymetric highs in the northern, western, and southeastern parts of the study area where there are sand waves. The orientation of the sand-wave crests indicates that sediment transport directions are generally east-west along much of the northern ridge and north-south between the ridge and channel.

Sorting and Reworking

Areas of sediment sorting and reworking are located in the channels and on parts of the bathymetric highs. These areas tend to have moderate backscatter and the sea floor tends to be relatively smooth. Trawl marks concentrated within areas characterized by these processes suggest a preference by the targeted commercial species for this sea floor environment.

Fine-Grained Deposition

Although this area was previously mapped by McMaster (1960) as being uniformly sandy, Knebel and others (1982) mapped the bathymetric lows as fine-grained sediment and attributed the difference with McMaster's (1960) study to be from the types and spacing of data. In our study, parts of the channel and bathymetric lows in the southeast and northwest have low backscatter. These areas are interpreted to contain finer grained sediment and to be characterized by depositional environments as Knebel and others (1982) have also mapped them. The water energy in these deeper locations is probably low enough for finer grained sands and perhaps mud to accumulate.

Discussion

The bathymetric highs in the study area are composed of glacial till and have surficial features including sand waves and erosional benches and scarps. The central channel in our study area was probably once part of a southerly and southwesterly flowing glacial drainage network (McMaster and Ashraf, 1973). The channel's sea floor is generally lacking bedforms, but has many trawl marks.

Evidence of fresh water lakes is found in the sounds and bays near Rhode Island Sound. A system of lakes that once stretched eastward from Long Island Sound through Block Island Sound, Rhode Island Sound, Narragansett Bay and Buzzards Bay left varved deposits 80-150 m thick in Long Island Sound (Lewis and DiGiacomo-Cohen, 2000). Clay concretions on the sea floor and laminated sediments up to 160 m thick are evidence of freshwater lakes that were scattered throughout Block Island Sound during a period between 19 ka and 14 ka; the lakes eventually coalesced into one lake covering about 650 km² (Bertoni and others, 1977; Needell and Lewis, 1985). Like the nearby sounds and bays, stratified sediments in the study area, which are up to 30 m thick and cover much of the northern, western, and southeastern parts of the study area, are evidence for the presence of these freshwater lakes.

Tiger-striped backscatter patterns, which we interpreted to be sand waves, are located across much of the northern and southeastern part of the study area. Knebel and others (1982) interpreted backscatter patterns of patches and lineations in their sidescan-sonar data from these areas to be

reworked sediments; however, they were unsure of whether erosion, deposition, or a combination of the two was responsible for these patterns. We infer that the sand waves are formed in environments characterized by coarse-grained bedload transport. In Knebel and other's (1982) sidescan-sonar imagery, coarser grained patches had areas of megaripples with wavelengths up to 1.2 m, which are visible in our sonar data and have wavelengths as great as several meters.

Erosional benches notched into the regional bathymetric slope occur at depths of 30-36 m in the study area and are interpreted to represent paleoshorelines. The hills, scarps, and level areas that characterize these features tend to occur linearly across southward-facing slopes at a consistent range of depths. Areas of higher backscatter along the line of benches tend to have megaripples on the surface. The benches tend to occur in glaciolacustrine sediment at or near contacts with the subaerial erosion surface or the till (figs. 7 and 8). In Long Island Sound, steps in Pleistocene glacial drift and Cretaceous sediments along with lens-shaped seismic units and broad terraces at depths including 30 m and 37-38 m have been interpreted to be paleoshorelines (Gayes and Bokuniewicz, 1991). Closer to our study area, but at shallower depths, a submerged barrier spit off Block Island was inferred to represent a paleoshoreline with a depth of 24.5 m (McMaster and Garrison, 1967). The benches and scarps in our study area are thought to have formed around 9-10 ka based on a sea-level-rise curve for southeastern Massachusetts (Oldale and O'Hara, 1980).

Summary

Bathymetric and seismic-reflection data show a northern ridge in the study area composed largely of glaciolacustrine sediments. A northeast-southwest oriented channel crossing the center of the study area, which was cut by fluvial processes, is now partly filled by Holocene marine and transitional deposits. The sidescan-sonar imagery indicates seven backscatter patterns consisting of sand waves, boulders, benches, low backscatter, moderate backscatter, high backscatter, and trawl marks. Sand waves cover much of the northern ridge and bathymetric high in the southeast. Boulders are scattered throughout the study area, but are mostly concentrated in the southeast. Erosional benches occur on the northern banks of the central channel and southeastern bathymetric low and are interpreted to represent paleoshorelines from 9-10 ka. Areas of low backscatter in some of the deepest parts of the study area are interpreted to be finer grained sediments; areas of high backscatter are interpreted to reflect coarser grained sediments. Trawl marks are plentiful in the central channel. Four sedimentary environments are found in the study area including those characterized by processes of erosion or nondeposition, coarse-grained bedload transport, sorting and reworking, and fine-grained deposition.

GIS Data Catalog

This report contains several data layers (or themes) that show bathymetric and sidescan sonar imagery of Rhode Island Sound. GeoTIFFs produced from grids of the NOAA sidescan sonar and bathymetric surveys are provided in geographic and universal transverse mercator projections, along with the bathymetry grids. Available vector data consists of polygon data layers that provide the coastline for the Rhode Island Sound GIS project area, interpretive data layers, and an outline of the study area.

Data layers are provided with geographic coordinates to allow the data to be integrated into a Geographic Information System (GIS). Data layers archived here do not require additional processing to be utilized within the Environmental Systems Research Institute's (ESRI) ArcView and ArcGIS software. This does not mean that a user will not wish to do additional processing,

especially if utilizing a different GIS software package or spheroid, but that it is not necessary to do additional processing simply to utilize the data in its minimum archive format.

For those who do not have the ESRI software or a compatible GIS data browser available on their computer, a free viewer, ArcExplorer, is available from ESRI. The key functionality of ArcExplorer is the viewing of spatial data. The user will need to add the selected data layers by using ArcExplorer's add data button.

Each GIS data layer from this publication is cataloged below for easy access. The individual data layers are described below and include the GeoTIFF, grid, or shapefile name (e.g. h11321_45m_geo) which is linked to a browse graphic showing the data layer extent and coverage. Selecting the data layer name will result in the browse graphic being displayed in a separate browser window.

When accessing this report from the DVD-ROM, the top level of the report contains an ArcView project file (h11321.apr) created in ArcView 3.3 and an ESRI ArcMap document (h11321.mxd) created in ArcMap 9.2, but saved as an ArcMap 9.0/9.1 document to make it accessible in older versions.

Federal Geographic Data Committee (FGDC) metadata for the individual data layers is provided in HTML, FAQ html, and text versions. Selecting associated metadata files from the table below will open the information in a new browser window.

A 'zip' compressed, downloadable archive file containing the components of the ESRI shapefile for each data layer is also provided. Compressed downloadable files were created using the Windows program WINZIP v9.0. For those users who do not have software capable of uncompressing the archived zip files, they may obtain a free version of the software from Winzip Computing, Inc. or Pkware, Inc.

Sidescan Sonar Imagery

Data Layer Name and Description	Metadata	Files
h11321_1m_sss_geo_str - stretched sidescan sonar imagery of NOAA survey H11321 (geographic)	HTML FAQ txt	zip
h11321_1m_sss_geo - composite sidescan sonar imagery of NOAA survey H11321 (geographic)	HTML FAQ txt	zip
h11321_1m_sss_utm_str - stretched sidescan sonar imagery of NOAA survey H11321 (UTM zone 19, NAD83 spheroid)	HTML FAQ txt	zip
h11321_1m_sss_utm - composite sidescan sonar imagery of NOAA survey H11321 (UTM zone 19, NAD83 spheroid)	HTML FAQ txt	zip

Bathymetric Imagery

Data Layer Name and Description	Metadata	Files
h11321_geo.tif – representation of bathymetric data from NOAA survey H11321 (geographic)	HTML FAQ txt	zip
h11321_utm.tif – representation of bathymetric data from NOAA survey H11321 (UTM zone 19, NAD83 spheroid)	HTML FAQ txt	zip

Bathymetric Grids

Data Layer Name and Description	Metadata	Files
h11321_geo45m - bathymetric grid of NOAA survey H11321 (geographic)	HTML FAQ txt	zip
h11321_utm45m - bathymetric grid of NOAA survey H11321 (UTM zone 19, NAD83 spheroid)	HTML FAQ txt	zip
h11321_1m_utm19nad83.txt - space delimited ASCII text file of the bathymetric grid of NOAA survey H11321 (UTM zone 19, NAD83 spheroid)	HTML FAQ txt	zip

Interpretive Data

Data Layer Name and Description	Metadata	Files
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h11321environs - interpretation of the sedimentary environments in NOAA survey H11321 (geographic)	HTML FAQ txt	zip
h11321interp - interpretation of the sidescan sonar and bathymetric imagery from NOAA survey H11321 (geographic)	HTML FAQ txt	zip

Basemap Data

Data Layer Name and Description	Metadata	Files
nos80k_84 - medium resolution digital vector U.S. shoreline shapefile for the Rhode Island Sound GIS project area (geographic)	HTML FAQ txt	zip
h11321outline - outline of sidescan sonar imagery from NOAA Survey H11321 (geographic)	HTML FAQ txt	zip

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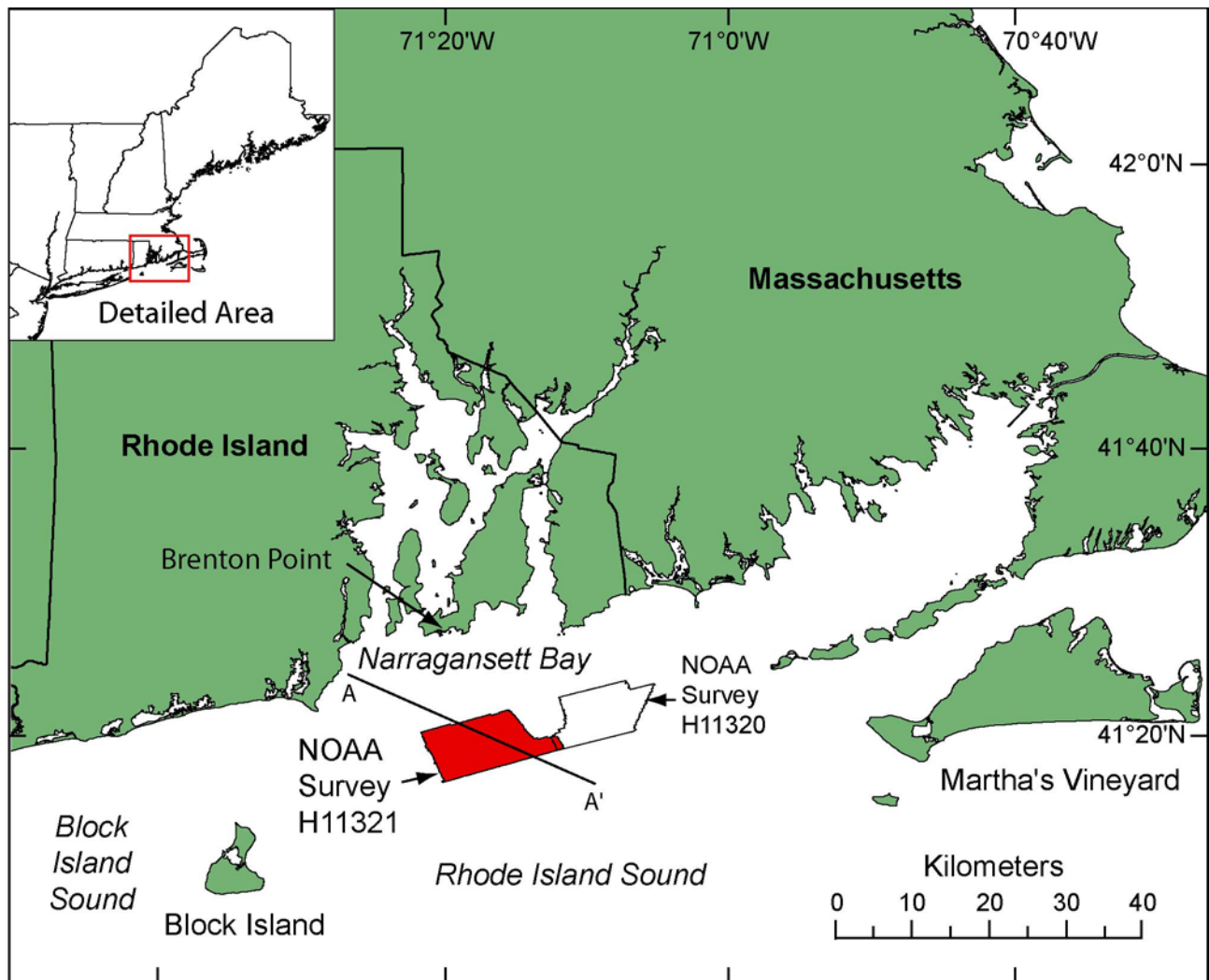


Figure 1. Location map of NOAA Survey H11321 study area in Rhode Island Sound (red polygon). NOAA Survey H11320 (McMullen and others, 2007) overlaps the eastern end of the study area (black outline). Location of interpreted stratigraphy profile A-A' (fig. 3) is also shown.

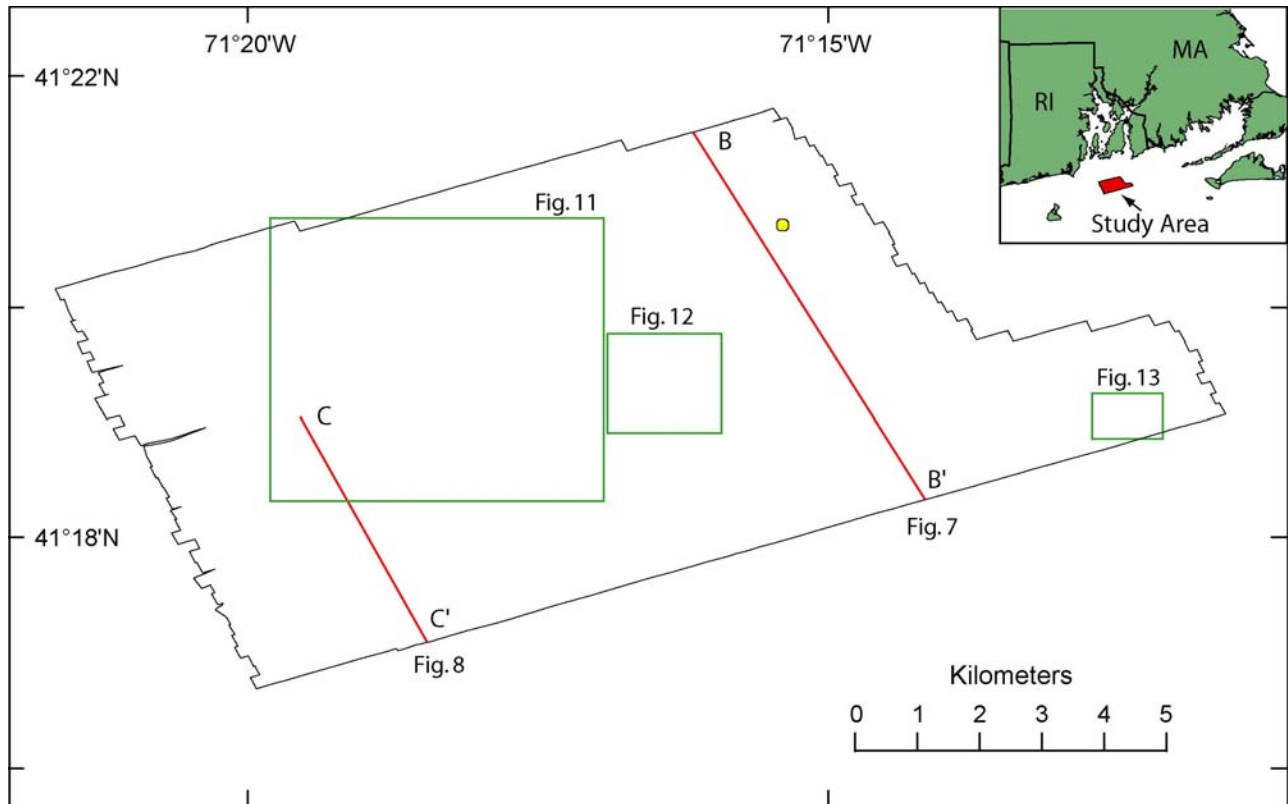


Figure 2. Map showing the outline of the study area (black outline), locations of historic seismic-reflection data shown in figures 7 and 8 (red lines), the locations of detailed views shown in figures 11, 12, and 13 (green outlines), and the location of a sand sample (yellow circle) from the NOS Hydrographic Database (Poppe and others, 2003).

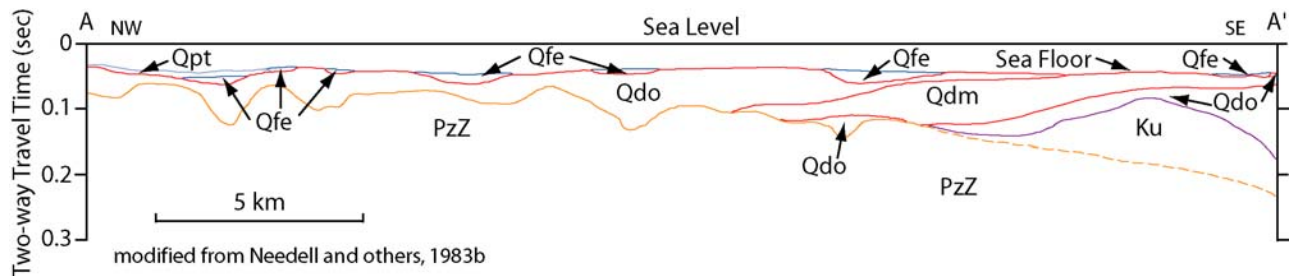


Figure 3. Interpreted stratigraphy profile across Rhode Island Sound, modified from Needell and others (1983b). Stratigraphy includes: PzZ – pre-Mesozoic bedrock, Ku – mostly late Cretaceous coastal plain and continental shelf sediments, Qdo – mostly late Wisconsin glacial drift, Qdm – late Wisconsin moraine deposits, Qfe – Holocene transitional (fluvial and estuarine) deposits, Qpt – Holocene marine sediments. Contacts are dashed where inferred. Vertical exaggeration: 19X. Location of profile shown in fig. 1.

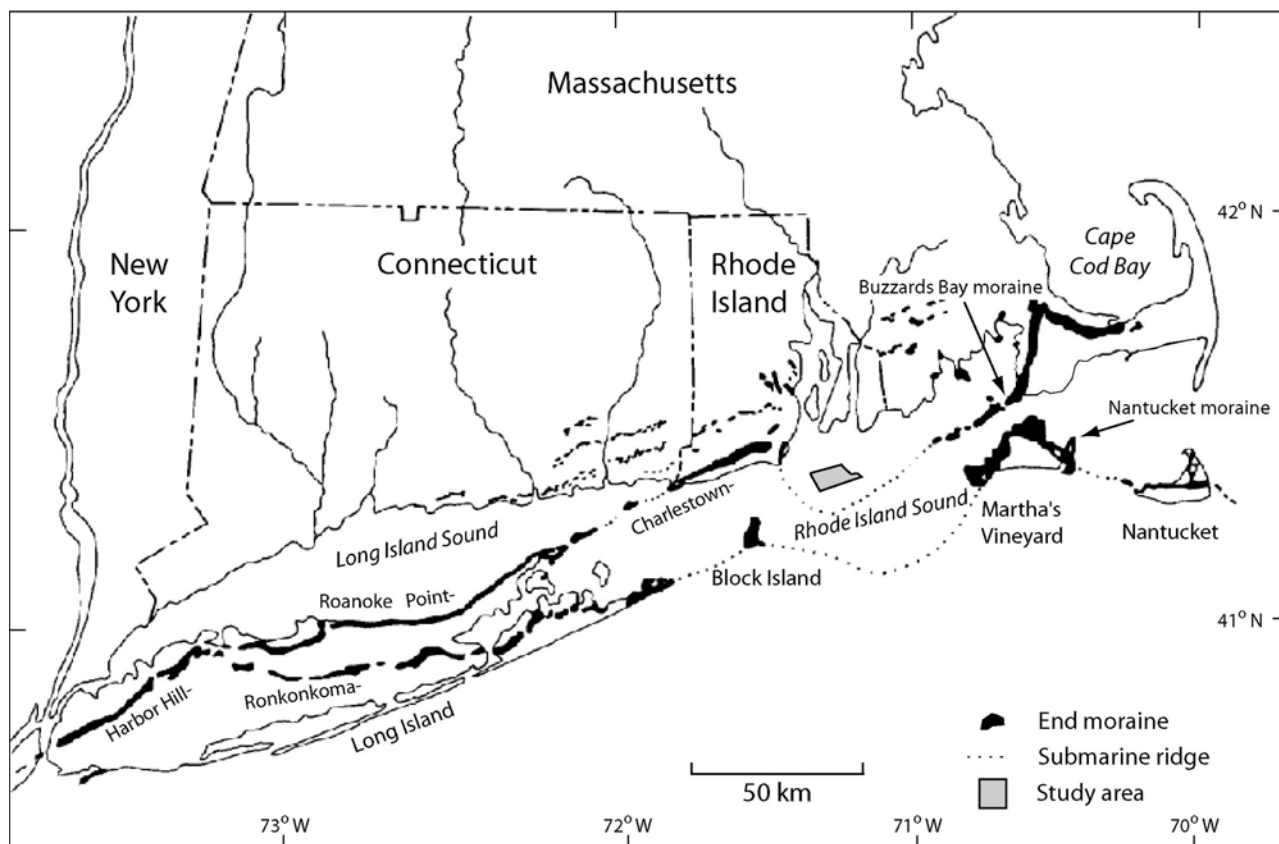


Figure 4. Map showing the location of end moraines (black polygons) in southern New England and Long Island, New York. The Ronkonkoma-Nantucket moraine represents the Laurentide Ice Sheet's maximum glacial advance about 20 ka and the Harbor Hill-Roanoke Point-Charlestown-Buzzards Bay moraine represents a retreated ice sheet position from around 18 ka (Uchupi and others, 1996). Underwater extensions of the moraines are shown as dashed lines. Study area is shown as gray polygon. Modified from Gustavson and Boothroyd (1987).



Figure 5. Photo of NOAA Ship RUDE (courtesy of NOAA).

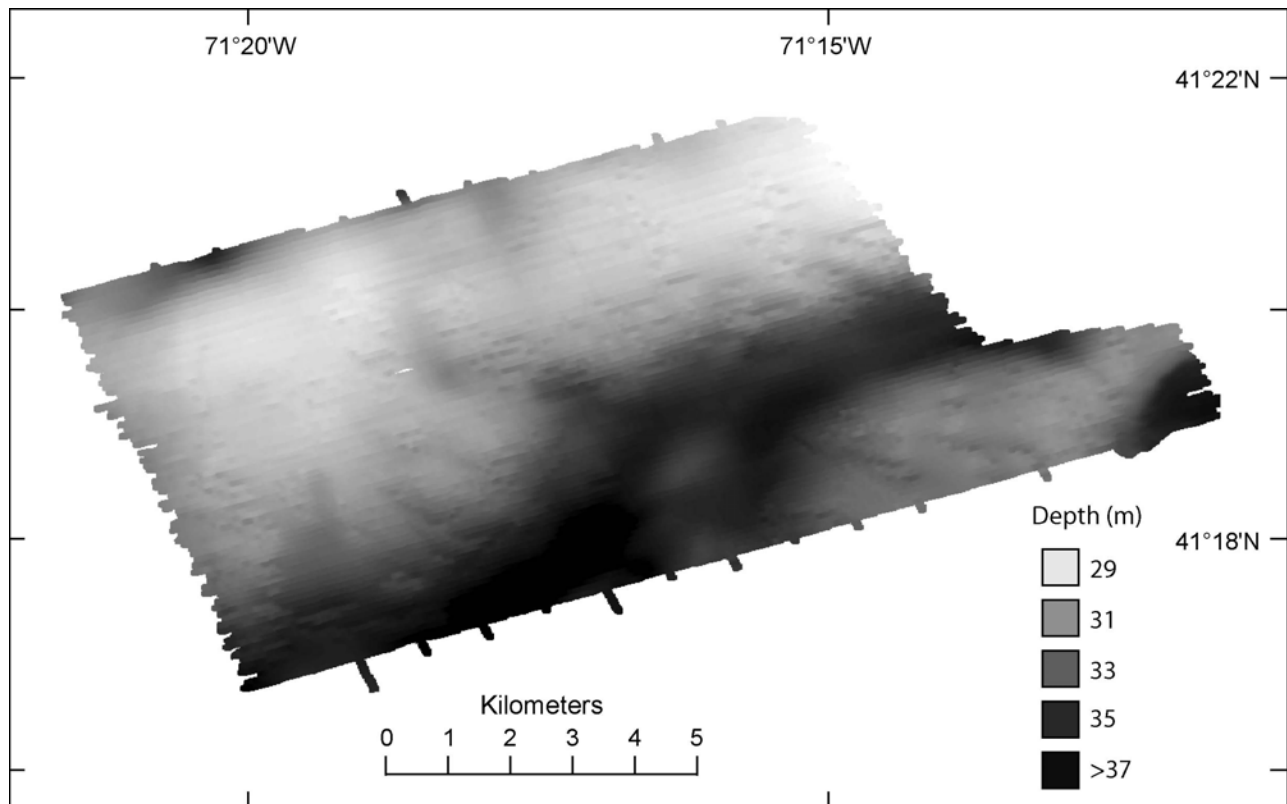


Figure 6. Bathymetric image of study area from sounding and multibeam data. Light tones represent shallower depths and dark tones represent deeper areas. A ridge is located across the northern and western parts of the study area. A channel is located south of the ridge and north and west of a bathymetric high in the southeast. Another bathymetric low is located in the southeastern corner of the study area.

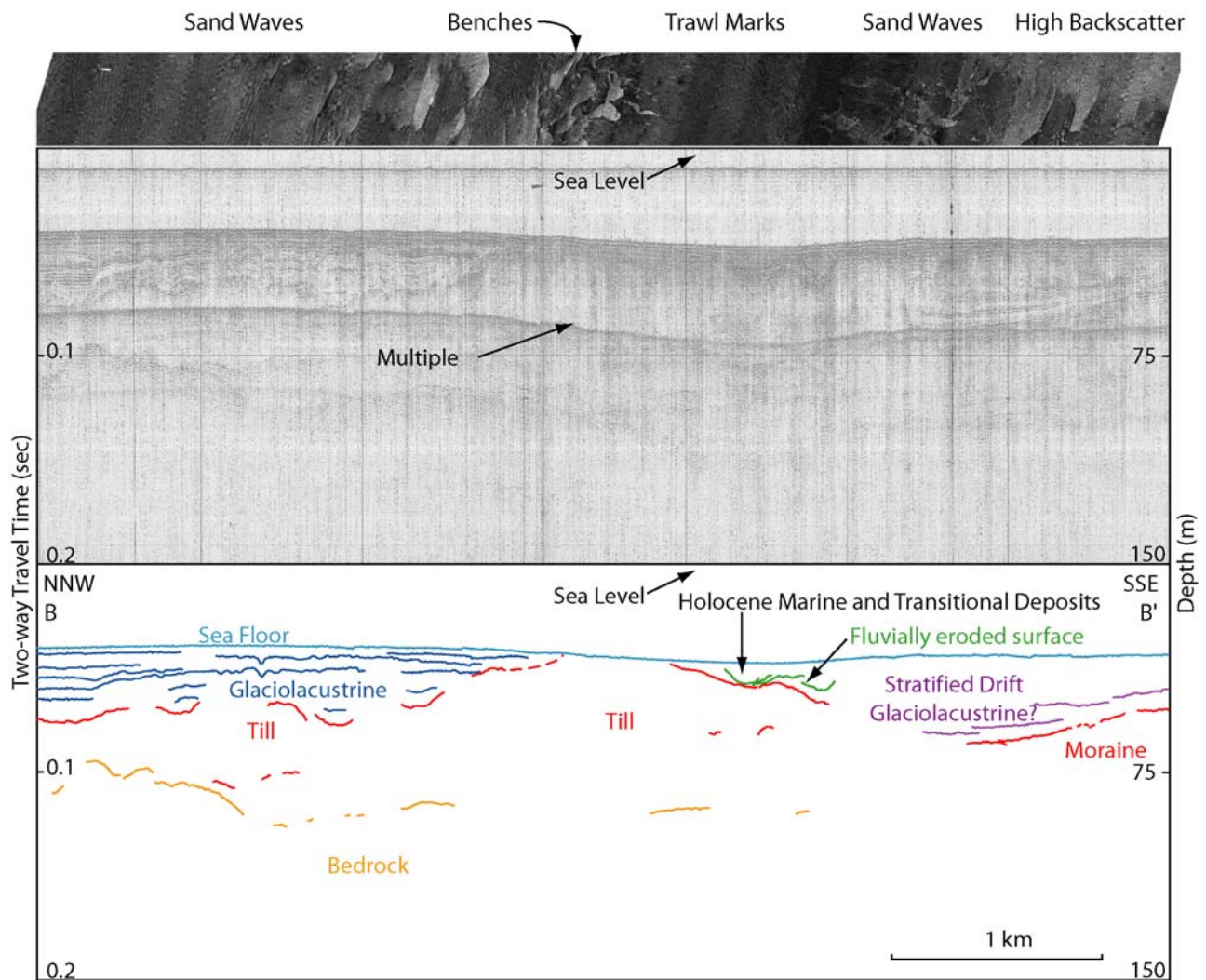


Figure 7. Seismic-reflection profile across eastern end of study area from Needell and others (1983a) with interpretation and corresponding sidescan-sonar image. Paleozoic bedrock, Wisconsin glacial drift including till, moraine, and glaciolacustrine sediments, and Holocene marine and transitional deposits are shown. Stratified drift in the south may be glaciolacustrine sediment. Sidescan-sonar image shows areas of sand waves, benches, trawl marks, and high backscatter. Benches tend to coincide with a contact between glaciolacustrine sediment and till. Depths are based on an assumed compressional wave velocity of 1500 m/s. Vertical exaggeration: 13X. Location of profile shown in fig. 2.

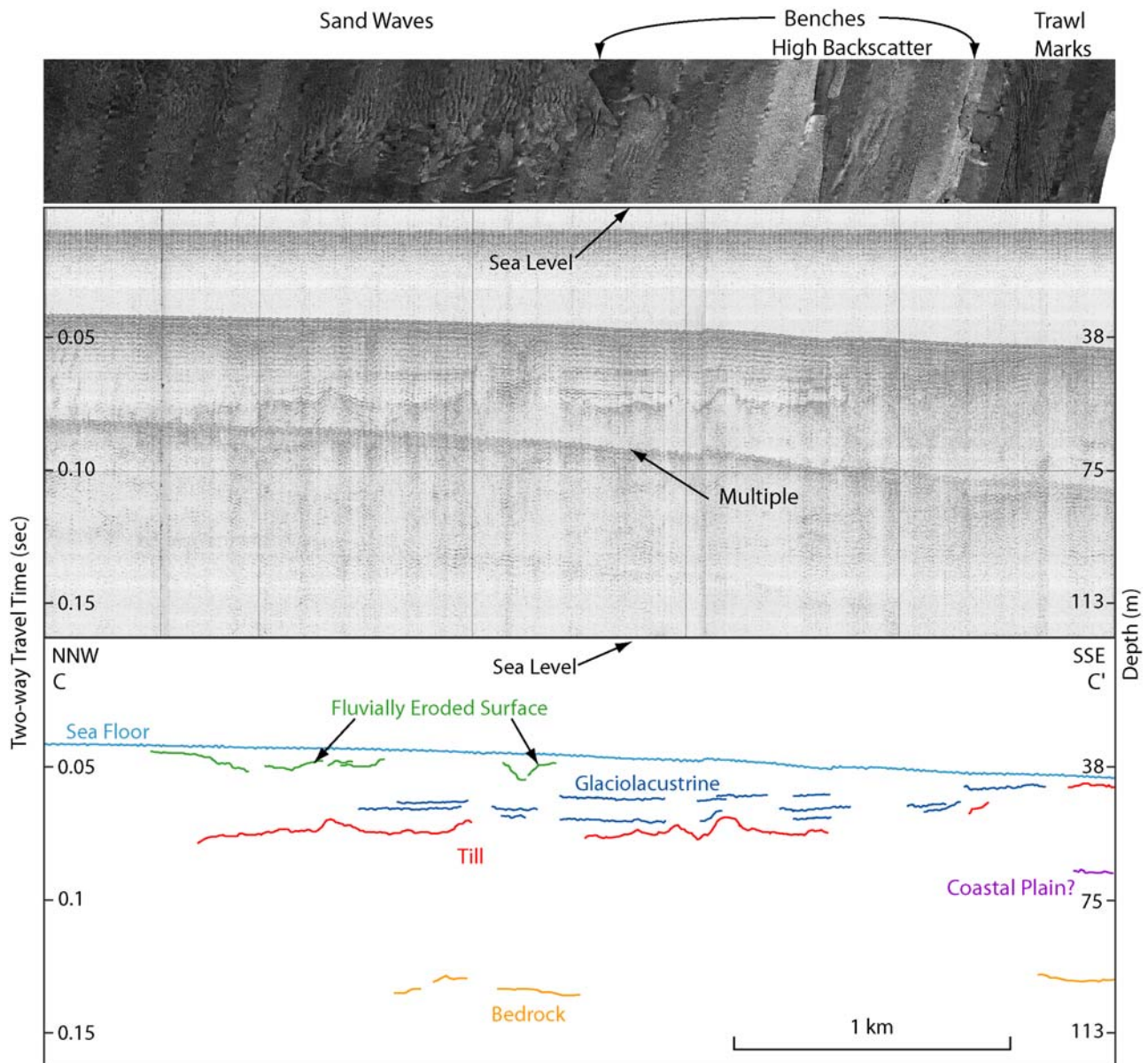


Figure 8. Seismic-reflection profile across western end of study area from Needell and others (1983a) with interpretation and corresponding sidescan-sonar image. Interpretation includes: Paleozoic bedrock, possible Cretaceous coastal plain sediments, Wisconsin glacial till and glaciolacustrine sediments, and Holocene marine and transitional deposits. Sidescan-sonar image shows sand waves in the north and benches, high backscatter, and trawl marks in the south. Benches occur at the contact between fluvial and glaciolacustrine sediments and within the glaciolacustrine sediment near the exposure of till. Depths are based on an assumed compressional wave velocity of 1500 m/s. Vertical exaggeration: 13X. Location of profile shown in fig. 2.

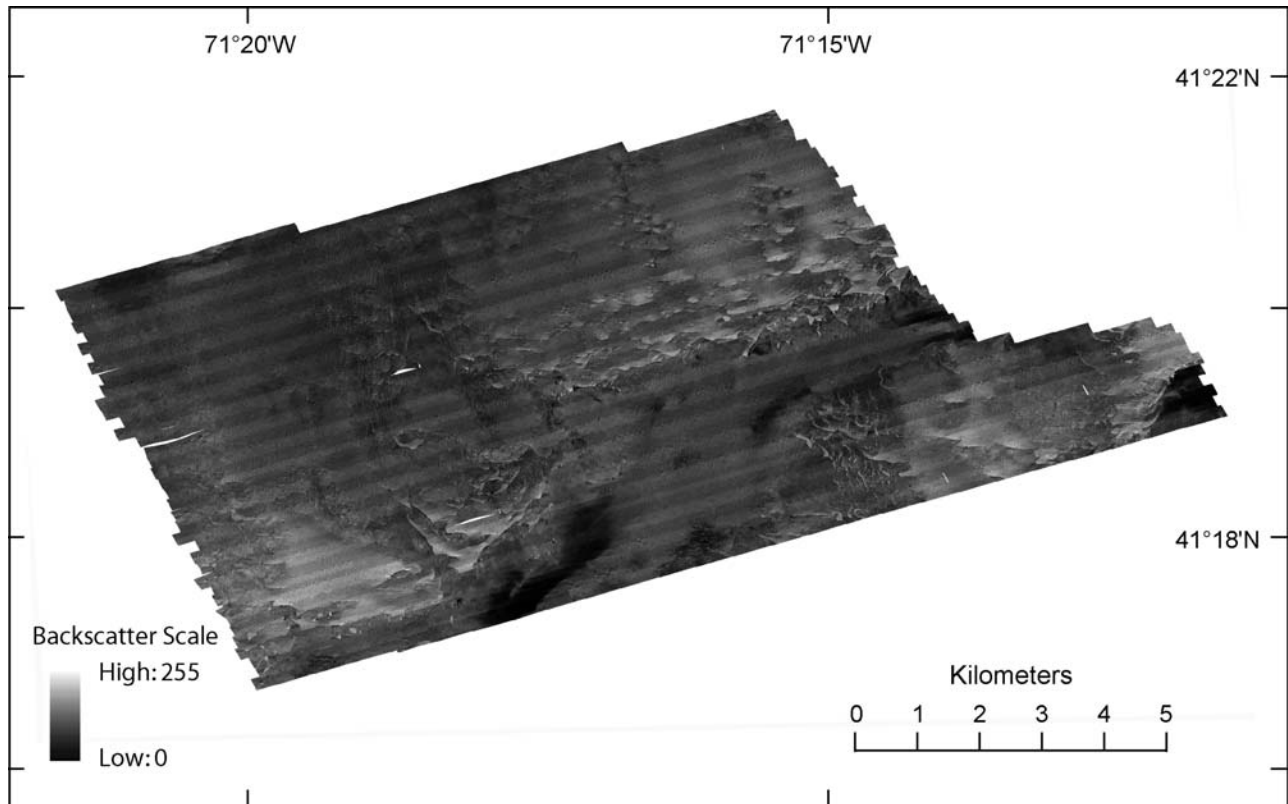


Figure 9. Sidescan-sonar image of the study area. Dark tones represent lower backscatter and generally finer grained sediment; light tones represent higher backscatter and generally coarser grained sediment. Light and dark bands oriented northeast-southwest are artifacts of the sidescan-sonar processing.

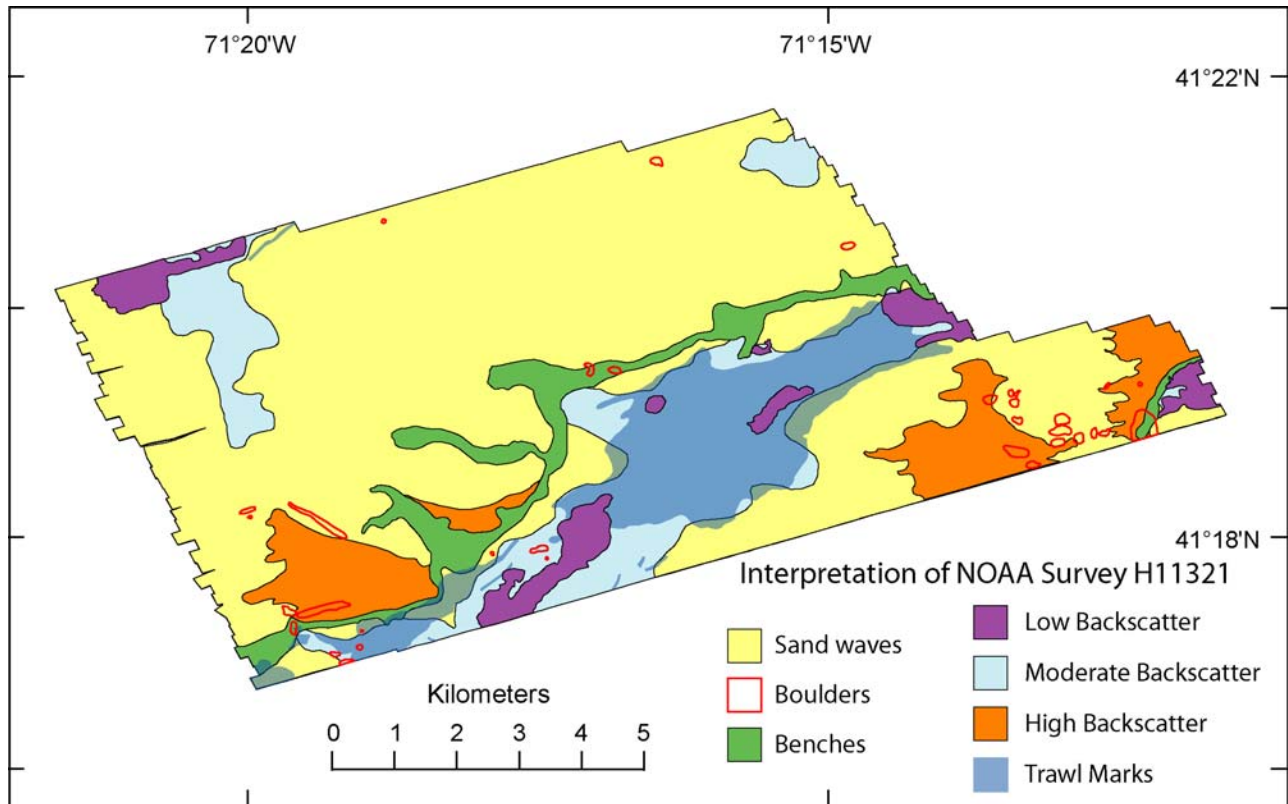


Figure 10. Interpretation of sidescan-sonar imagery of the study area. Sand waves are visible across much of the study area, and boulders are scattered throughout. Two lines of benches cross the study area, large areas of high backscatter are located mostly in the south, and low backscatter and trawl marks are seen in the deeper waters.

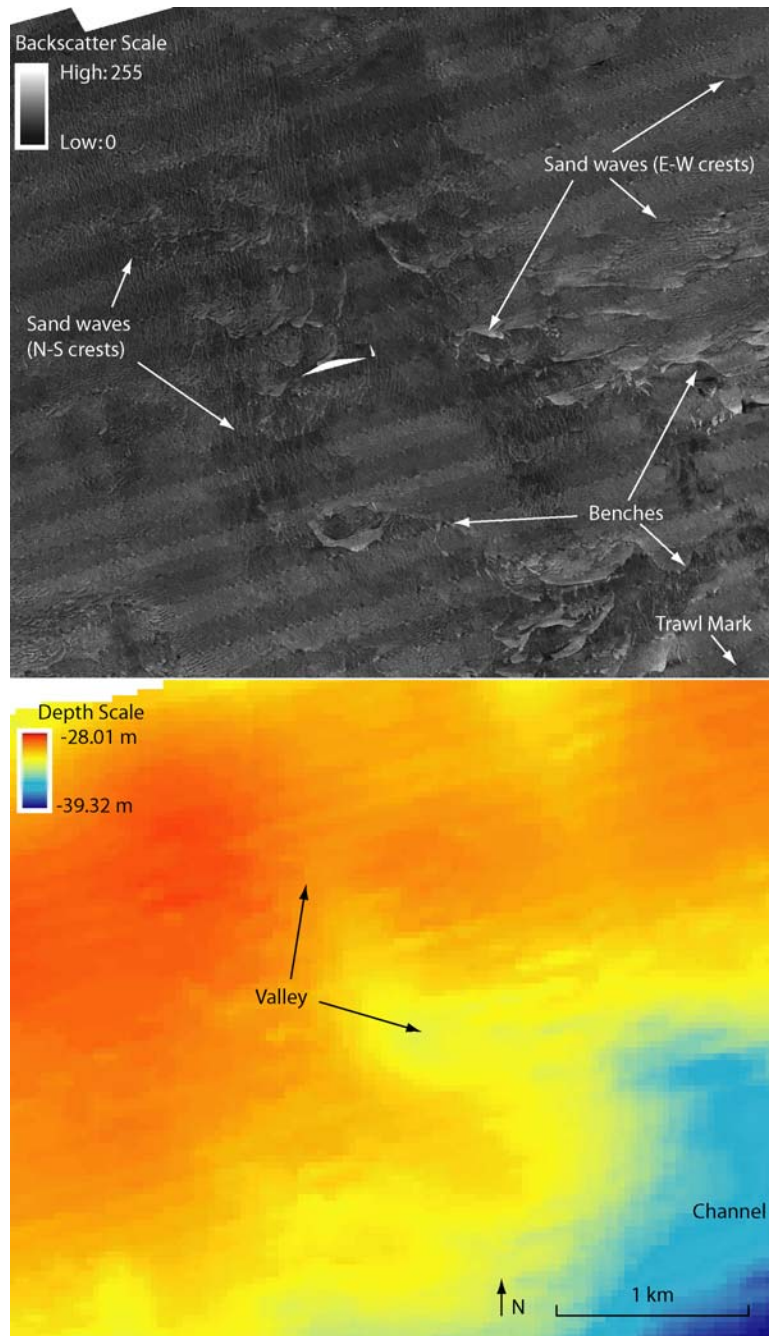


Figure 11. Detailed sidescan-sonar and bathymetry images of sand waves along a channel on the northern ridge. Sand waves adjacent to the channel are straight-crested and oriented north-south; away from the channel sand waves have more curved and sinuous crests that are oriented east-west. In the channel in the central part of the image, both east-west and north-south oriented sand waves are present, suggesting complex flow and transport directions. Benches are also visible on the sidescan-sonar image where there is a sharp curvilinear change in backscatter. A trawl mark is visible in the southeastern corner of the sidescan-sonar image. Light and dark bands oriented northeast-southwest are artifacts in the sidescan sonar. Location of figure shown in fig. 2.

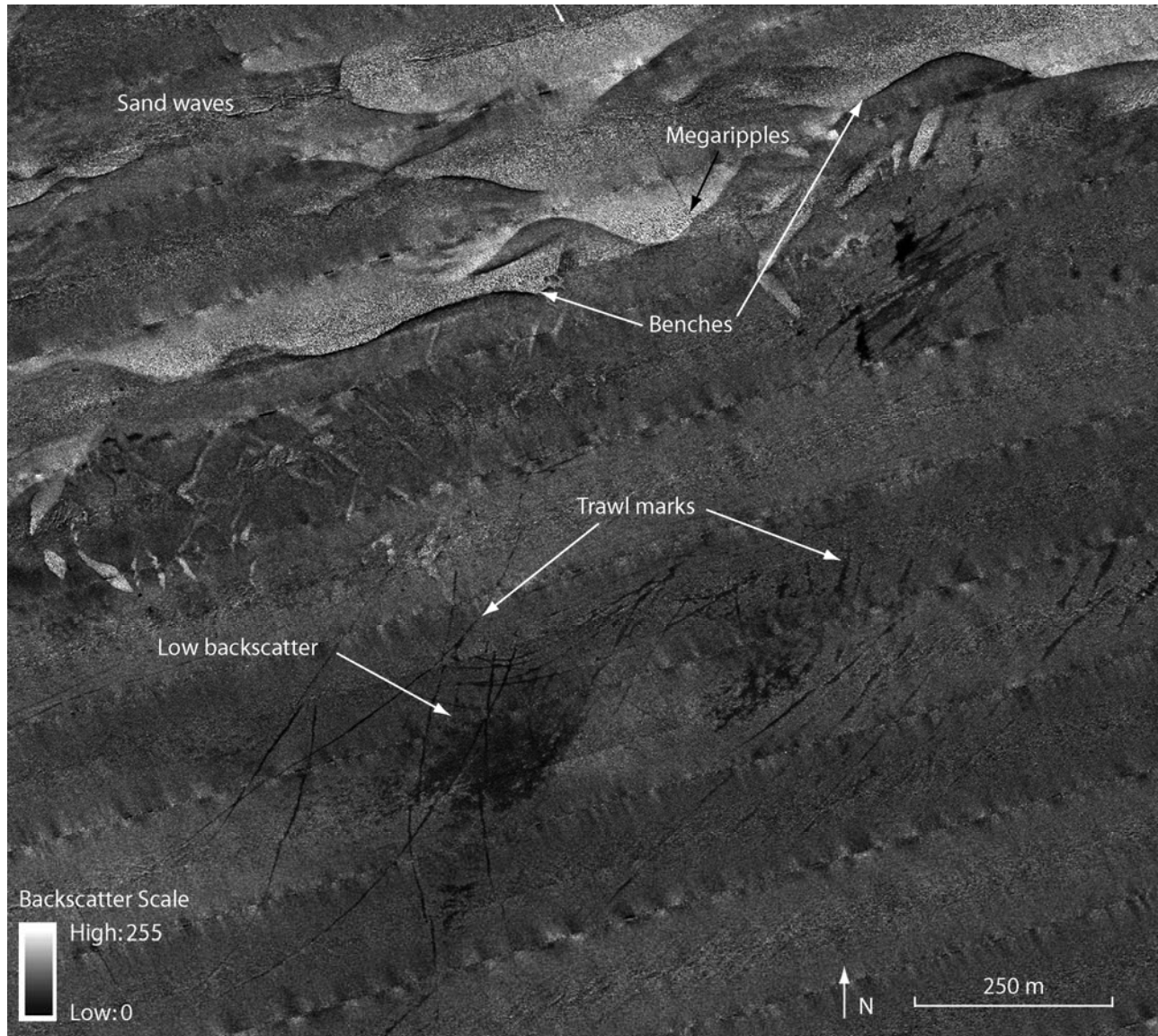


Figure 12. Detailed sidescan-sonar image of trawl marks on the floor of the channel. Lines of low backscatter or paired high and low backscatter indicate trawl marks. Benches cross the northern part of the image where there is a sharp curvilinear change in backscatter and sand waves are located throughout the north. An area of low backscatter indicates finer grained sediment. Location of figure shown in fig. 2.



Figure 13. Detailed sidescan-sonar image of the southeastern part of the study area showing boulders, sand waves, and benches. Boulders are visible as high-backscatter targets with low-backscatter shadows. Higher backscatter (lighter tones) in the center of the image represents coarser grained sediment; lower backscatter (darker tones) represents finer grained sediment. Location of figure shown in fig. 2.

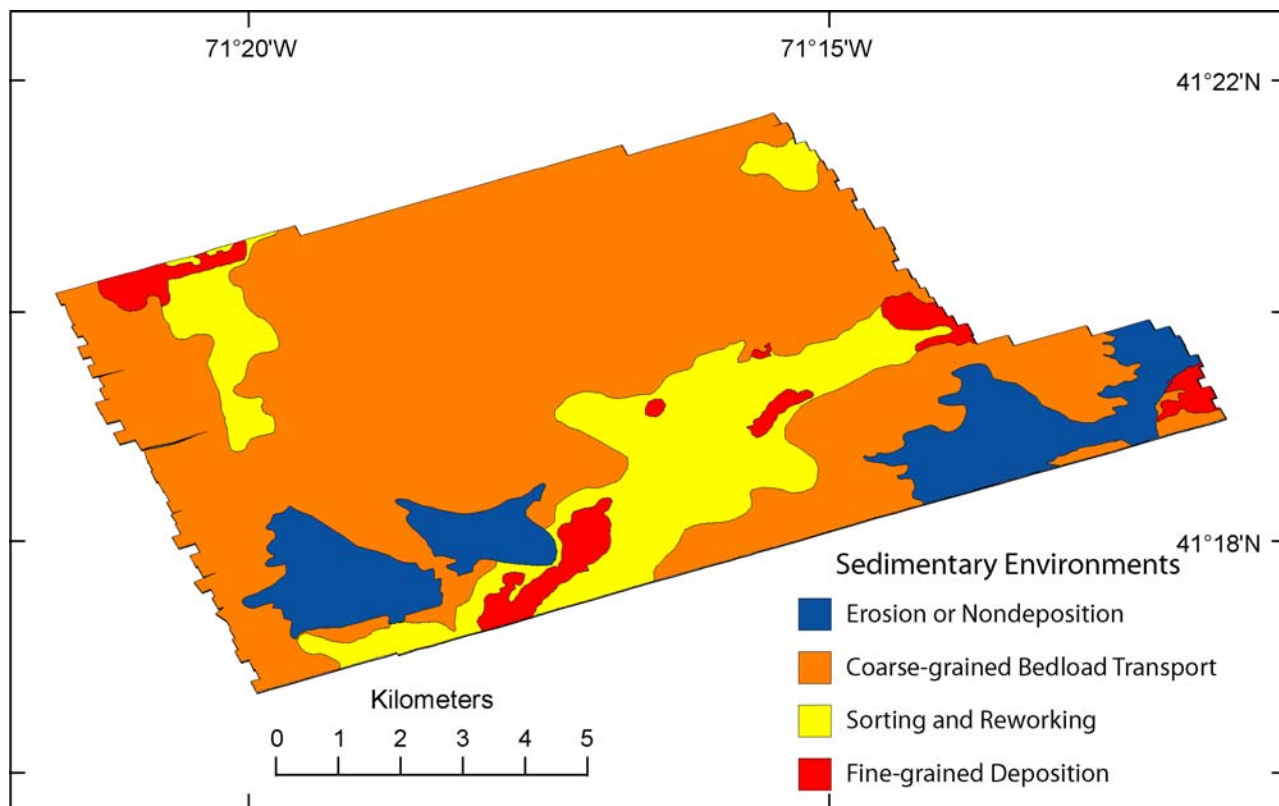


Figure 14. Map of the sedimentary environments in the study area including those characterized by processes of erosion or nondeposition, coarse-grained bedload transport, sorting and reworking, and fine-grained deposition.