U.S. DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

HIGH-RESOLUTION SEISMIC-REFLECTION SURVEYS IN THE NEARSHORE OF OUTER CAPE COD, MASSACHUSETTS

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This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards and stratigraphic nomenclature. Any use of trade names is for descriptive purposes only and does not imply endorsement by the U.S. Geological Survey.

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Introduction

The U.S. Geological Survey (USGS) Woods Hole Field Center (WHFC), in cooperation with the USGS Water Resources Division conducted high-resolution seismic-reflection surveys along the nearshore areas of outer Cape Cod, Massachusetts from Chatham to Provincetown, Massachusetts (Fig. 1).

The objectives of this investigation were to determine the stratigraphy of the nearshore in relation to the Quaternary stratigraphy of outer Cape Cod by correlating units between the nearshore and onshore and to define the geologic framework of the region.

Previous Work

Earlier seismic-reflection surveys of Cape Cod Bay and east of Cape Cod began with Hoskins and Knott (1961) who collected high-resolution seismic profiles in Cape Cod Bay and defined a seismic stratigraphic framework of the region. Oldale and O'Hara (1990) established the relationship of the onshore regional geology of the Cape (Oldale, 1982) and the stratigraphy of the Gulf of Maine to the seismic stratigraphy of Cape Cod Bay. Uchupi and others (1996) have added interpretations of the stratigraphy and coastal evolution of outer Cape Cod. They based their interpretations on their own seismic profiles and those of Aubrey and others (1982) located east of Cape Cod as well as the Cape Cod Bay seismic data collected by Oldale and O'Hara (1990). More recently, water gun profiles were collected in the Stellwagen Bank area (Fig. 1) with profiles that extend to Cape Cod Bay and the Atlantic side of outer Cape Cod (USGS, R. Oldale and R. Rendigs, unpublished data).

Geologic Setting

The bedrock geology beneath outer Cape Cod is not well known. It has been presumed to consist of Paleozoic and Precambrian igneous and metamorphic rocks similar to those exposed in southeastern Massachusetts (Hoskins and Knott, 1961; Oldale, 1969; Oldale and O'Hara, 1990). Two deep USGS boreholes (Gerhard and Phillips, 1989), one in North Eastham and the other located in Chatham (Fig. 2), reached

granitic bedrock. A rift basin filled with sedimentary rocks of Triassic-Early Jurassic age trends east-west beneath the town of Truro (Ballard and Uchupi, 1975). Sedimentary coastal plain rock has been inferred to overlie bedrock in places beneath Cape Cod Bay (Hoskins and Knott, 1961; Oldale and O'Hara, 1990).

Outer Cape Cod was formed between two major ice lobes during the Late Wisconsinan deglaciation. The Cape Cod Bay lobe occupied what is now Cape Cod Bay and was the source for the Harwich outwash plain deposit to the south (Fig. 3). With the retreat of the Cape Cod Bay lobe, a proglacial lake formed as is evidenced by the delta and glaciolacustrine deposits along the northern side of Cape Cod. A readvance of the Cape Cod Bay lobe formed a moraine where there is now a bathymetric high (Fig. 2) known as Billingsgate Shoal (Oldale and O'Hara, 1984).

The South Channel lobe bounded outer Cape Cod to the east and also occupied the Nauset Inlet area. Evidence for the position of the South Channel lobe in the Nauset inlet area is seen in seismic profiles interpreted by Aubrey and others (1982), where shore-parallel seismic lines east of Nauset Inlet show a distinct undulating reflector that pinches out at the sea floor to the north and south. Aubrey and others (1982) interpreted this surface to have formed at the base of the South Channel lobe. The South Channel lobe was a source of a series of outwash plain deposits that form outer Cape Cod (Fig. 3). The Nauset Heights, Wellfleet, Highland, and Truro outwash plain deposits are successively younger in relative age from south to north (Oldale, 1982; Oldale and Barlow, 1986; Uchupi and others, 1996). However, the Eastham outwash plain, deposited between the Nauset Heights and Wellfleet outwash plains, is believed to be the youngest outwash deposit derived from the South Channel lobe. The Eastham outwash plain was probably deposited while part of the South Channel lobe occupied the topographic low at Nauset Inlet.

Sea level was lower than it is at present during the Wisconsinan glaciation, and the Earth's crust was depressed by glacial loading. Sea level rose as the Cape Cod Bay and South Channel lobes retreated north. This marine incursion is evident from glaciomarine deposits in Stellwagen Basin and northern Cape Cod Bay (Oldale, 1988). In Cape Cod Bay there is a prominent seismic reflector between the glaciolacustrine and glaciomarine units. In the outer Cape Cod area, these units only underlie the Holocene Provincetown Hook, as the marine transgression did not reach the remaining outer Cape. Interfingered with the glaciomarine unit and deposited above glacial drift deposits in northern Cape Cod Bay is a predominantly seismically amorphous unit that thickens to south, indicating a southerly source (Oldale and O'Hara, 1990). West of Provincetown this unit contains concave to dipping internal reflectors that suggest a deltaic origin. Oldale (1988) suggests that the unit may have been deposited by a debris flow based on the amorphous seismic signature. An alternate interpretation from Birch (in Oldale and O'Hara, 1990) suggests that the amorphous unit is an ancestral progradational feature similar to the Holocene-age Provincetown Hook. This unit is restricted to the Provincetown area of outer Cape Cod.

Following glacial retreat and the marine incursion, isostatic rebound of the crust exceeded eustatic sea-level rise. As a result, outer Cape Cod and Cape Cod Bay remained above sea level as is marked by a regressive, erosional unconformity observed in seismic profiles in Cape Cod Bay (Oldale and O'Hara, 1990). Fluvial valleys cut into Pleistocene deposits indicate a northward drainage of Cape Cod Bay.

When eustatic sea-level rise exceeded isostatic rebound, relative sea level transgressed Pleistocene glacial deposits and the regressive fluvial deposits in Cape Cod Bay. Oldale and O'Hara's (1990) seismic profiles show a mostly planar reflector resulting from wave-cut erosion during the Holocene transgression. This unconformity underlies the Holocene progradational Provincetown Hook but pinches out where Holocene beaches overlie glacial deposits of the outer Cape Cod area.

The paper by Uchupi and others (1996) summarizes the work of others that have studied the coastal evolution of outer Cape Cod. It is important to note that the post-glacial eastern side of outer Cape Cod initially extended 4 to 2.5 km east of the present erosional bluffs. Therefore, a considerable amount of the stratigraphic section (~30 m) where our seismic profiles are located on the east side of outer Cape Cod has been eroded as a result of the Holocene transgression. A wave cut terrace forms the nearshore on the east side where this wedge of glacial sediment has been removed. The volume of sediment removed during bluff erosion and terrace formation during the last 6,000 years provided the sediment needed for the progradation of Provincetown Hook and the spits along southeastern outer Cape Cod (Zeigler and others, 1965; Uchupi, 1996). Similarly, a wave-cut terrace bounds the Truro shoreline on the Cape Cod Bay side.

Data Acquisition and Processing

The R/V Rafael, operated by the USGS Woods Hole Field Center (WHFC), was used for data acquisition during two field operations. In the fall of 2000 the survey was conducted on the Cape Cod Bay side of the outer Cape (Figs. 2 and 4). During the summer of 2001, more data were acquired on the seaward side, east of the outer Cape, and additional lines were collected in Cape Cod Bay (Figs. 2 and 4). The vessel was navigated with a differential global positioning system (DGPS) that provided real-time horizontal positioning accuracy of 10 m or better. Navigational data, along with bathymetric soundings, were digitally logged with Hypack (Coastal Oceanographics, Inc.) hydrographic and navigation software. In addition, navigation from the DGPS was logged on the seismic acquisition computers.

Two single-channel subbottom-profiling systems were used mostly simultaneously during both phases of data acquisition. A dual frequency Knudsen 320BR 3.5 kHz Chirp and 200 kHz echosounder system was deployed using transducers on a side-mount pole. The Knudsen acquisition software recorded the data in standard SEG-Y (Barry and others, 1975) digital format. Shot-point navigation files recorded DGPS position in relation to shot point. The 3.5 kHz Chirp system recorded 67 ms two-way travel time (TWT) of reflection data. The second system, a Boomer seismic-profiling system, provided a higher energy source (100 joules) than the Chirp system. This

provided deeper penetration of the subbottom than the Chirp system. However, with a peak frequency of about 1800 Hz, the vertical resolution is not as high as the Chirp. The Boomer data were also acquired in SEG-Y format using a Triton-Elics Delph seismic system. Shot-point navigation recorded DGPS location in the SEG-Y header. The Boomer fired at a rate of 0.5 s and recorded 250 ms TWT of data. All of the digital data acquired were copied to optical CD-R media in the field.

Knudsen Chirp SEG-Y data were processed from raw Chirp format to an amplitude-detected format and saved as a SEG-Y file using SIOSEIS (http://sioseis.ucsd.edu) seismic processing software. Additional processing with SIOSEIS applied heave removal by shifting traces to a smoothed (21 point moving average) auto-detected sea floor. Automatic Gain Control (AGC) was applied using a 10 ms window. The processed data were saved in SEG-Y format, plotted using Seismic Unix (Cohen and Stockwell, 2003) software and saved in JPEG format.

Boomer seismic data were processed with a 500-2000 Hz band-pass filter and automatic gain control (AGC) using a 20 ms window length. We also applied a heave removal filter similar to that used in the Chirp processing. The processed Boomer SEG-Y data were plotted using Seismic Unix (Cohen and Stockwell, 2003) software and were saved in JPEG format.

We loaded the processed SEG-Y files into SeisVision interpretation software (Landmark Graphics Corp.). Selected horizons were digitized using SeisVision and exported for surface modeling in EarthVision (Dynamic Graphics Corp). Gridded data were then exported to ArcView GIS (ESRI) for display.

Seismic-Reflection Interpretation

Our interpretation of the seismic profile data utilizes the seismic stratigraphic names used by Oldale and O'Hara (1990). From oldest to youngest they are: bedrock of Paleozoic age (Pz); sedimentary Tertiary age coastal plain deposits (Tcp); undifferentiated glacial drift (Qd) and glaciolacustrine deposits (Qdl) of Pleistocene age; post-glacial fluvial channel fill (Qf) of late Pleistocene and Holocene age; and marine deposits (Qm) of Holocene age. Unconformities occur between Pz, Tcp, and Qd. Unconformities, other than bedrock boundaries, include the glacial to post-glacial boundary, a regressive surface (ru), and the Holocene transgressive surface (tu).

The Paleozoic bedrock (Pz) surface mapped in Cape Cod Bay by Oldale and O'Hara (1990) could not be mapped closer to shore with our data. The Boomer profiles in the nearshore did not have sufficient penetration to image this surface. Tertiary Coastal Plain (Tcp) was not resolved or is not present in the nearshore area east or west of outer Cape Cod.

A series of 15 in^3 water gun seismic profiles (USGS, R. Oldale and R. Rendigs, unpublished data) that extend from Cape Cod Bay, north of Provincetown, and to the eastern side of the outer Cape were interpreted to map the bedrock surface (Fig. 4). A

single water gun line extends along the eastern side of outer Cape Cod approximately 2-3 km from shore (Fig. 4). The bedrock surface rises from about 150 meters below sea level (mbsl) off Provincetown to about 100 mbsl off Chatham. A bedrock high east of Nauset Heights rises to 85 mbsl. A deposit of possible Tertiary coastal plain sediments (Tcp) were interpreted from the water gun profiles north of Provincetown but was not observed east of Cape Cod. There was no evidence of the Triassic rift valley (Ballard and Uchupi, 1975) in this seismic profile.

Most of the profiles on both the east and west sides of outer Cape Cod are characterized by discontinuous and chaotic internal reflectors with occasional areas of layered reflectors. The layered reflectors appear to be deformed in some areas. This unit is inferred to represent part of the glacial drift unit (Qd) that Oldale and O'Hara (1990) mapped in Cape Cod Bay. More specifically, the layered portion of this unit is inferred to be stratified drift or glaciolacustine deposits (Qdl).

On the east side of outer Cape Cod, east of Nauset Inlet, there is a continuous undulating reflector above glacial drift in two areas, east of Pleasant Bay and east of Nauset Inlet, which pinches out at the sea floor to north and south (Fig. 5). This is the same reflector mapped by Aubrey and others (1982), which they inferred to be the basal surface of the South Channel lobe that formed these depositional lows. They infer that glacial drift lies below this reflector. Above this surface there are numerous cut-and-fill structures within the unit that fills these depressions. The unit above the undulating reflector was originally believed to originate from glaciofluvial outwash. However, it is possible that this unit which contains prograding internal reflectors is Holocene marine fill derived from the erosion of glacial deposits to the north (Aubrey and others, 1982; Uchupi and others, 1996). We do not observe the progradational fill in this unit on our seismic profiles, and the unit seems to be dominated by fluvial cut-and-fill structures.

A few locations along the outer Cape Cod nearshore showed a significant seismic facies within the Qd unit. This facies is characterized by closely spaced (rhythmic) internal reflectors and is mapped on the Atlantic Ocean side of South Wellfleet and North Eastham (Fig. 6). These internal reflectors are clearly imaged in the Chirp profiles (Fig. 7). In other areas of the nearshore, Chirp profiles barely penetrated the subbottom, indicating a physically different facies. Poor subbottom penetration and discontinuous-to-chaotic reflectors may represent sand and gravel glacial drift deposits; good penetration and resolution of continuous internal reflectors suggest silt and clay glaciolacustrine deposits (Qdl). We mapped the depth to the upper surface of glaciolacustrine deposits (Qdl) located east of South Wellfleet and North Eastham (Fig. 8). In this location, the upper part of the unit has been eroded away by the Holocene transgression in parts of the nearshore (Figs. 7 and 8). The base of the unit (Fig. 9) is not as clearly defined as the upper surface, but the unit is at least 50 m thick (Fig. 10). The glaciolacustrine deposits (Qdl) dip to the southwest, on the Atlantic Ocean side to underlie subaerial glacial drift with no indication of a horizontal facies change (Fig. 7). A similar area of closely spaced reflectors is located close to shore on the Cape Cod Bay side of Eastham (Fig. 11).

We mapped the altitude of this upper surface, which is at the same altitude as the

surface on the Atlantic Ocean side (Fig. 8). Based on this, the similarities of the seismic facies, and their position beneath the Eastham plain deposit, we infer that they are of the same unit. In Cape Cod Bay, this unit lies above deformed but relatively continuous reflectors. These deeper reflectors are within the glacial drift (Qd), and are likely to be glaciolacustrine deposits that were overridden by readvancing ice that formed the Billingsgate Shoal Moraine. Therefore, the glaciolacustrine facies would have been deposited during or after the readvance. There is an abrupt vertical facies change along the north side of the unit (Fig. 11) that suggests it was deposited close to an ice front (Cape Cod Bay lobe). Alternatively, the glaciolacustrine unit may postdate the readvance of the Cape Cod Bay lobe and the South Channel lobe may have been the source of fine-grained glaciolacustrine deposits. The glaciolacustrine deposit is capped by sand and gravel outwash of the Eastham Plain that was derived from the South Channel lobe (Oldale, 1982). We have no evidence from the offshore seismic profiles that the glaciolacustrine facies extends beneath the Wellfleet outwash plain. The glaciolacustrine unit pinches out to the north along the eastern shore near the Eastham Plain and Wellfleet Plain contact onshore (Fig. 10). There is evidence from onshore boreholes that glaciolacustrine deposits are extensive beneath all of the outwash plains of outer Cape Cod (E. Uchupi, written communication, 2003).

We observe an extensive reflector in the nearshore of Cape Cod Bay that appears to be an extensive erosional surface. This surface is the regressive unconformity (ru) interpreted by Oldale and O'Hara (1990). The surface is preserved as fluvial channels cut into glacial drift beneath Wellfleet Harbor and southeast Cape Cod Bay (Fig. 11). Paleochannels, which are not as well preserved, extend across the wave-cut-terrace in the nearshore area of Truro and Wellfleet of Cape Cod Bay. Most notable is a channel complex that extends west from the Pamet River Valley. East of outer Cape Cod, the regressive unconformity (ru) is not observed in the seismic profiles because much of the upper stratigraphic record east of our seismic profiles was removed by marine erosion during the Holocene transgression.

The Holocene transgressive unconformity is the surface (tu) mapped by Oldale and O'Hara (1990) in the deeper water of Cape Cod Bay. This surface is best observed as a flat and continuous reflector that is traced from the deeper water of Cape Cod Bay to the shallow nearshore terrace along the west side of Truro. This surface is at the base of the Holocene marine and progradational deposits comprising the Provincetown Hook (Fig. 12). The surface was traced close to shore near North Truro where it likely continues towards land and pinches out beneath the modern beach.

Integration with Land-based Stratigraphy

Oldale and O'Hara (1988) integrated the onshore geology (Oldale, 1982) with the offshore stratigraphy of Cape Cod Bay, and there is little new information on the subsurface geology of Outer Cape Cod. However, the USGS drilled two deep boreholes (Fig. 3) that reach bedrock (Gerhard and Phillips, 1989). We have used information from the borehole located in North Eastham to construct a geologic cross section that ties with

our seismic interpretation from the nearshore (Fig. 13).

The North Eastham borehole was drilled through glacial deposits to the Paleozoic bedrock surface (Fig. 13). The upper 38.1 m of the core is coarse sand with traces of gravel interbedded with zones of fine sand and silt and is interpreted to be glaciofluvial outwash. At about 20 mbsl there is a sharp change in lithology to glaciolacustrine-laminated silt with traces of clay and very fine-to-fine sand. This fine-grained unit predominates to about 130 mbsl where there is about 6 m of basal till over the bedrock surface at 136 m below sea level. We believe the glaciolacustrine deposits recovered from this core correlate in part with the well-layered seismic facies mapped in the nearshore in Cape Cod Bay and offshore, east of South Wellfleet and North Eastham (Figs. 8-10).

Conclusions

The nearshore seismic stratigraphy reveale by our data complements the stratigraphic and geologic mapping previously completed in the vicinity of Outer Cape Cod. The interpretations to the west of outer Cape Cod extend the Cape Cod Bay framework (Oldale and O'Hara, 1990) into the shallower nearshore areas of Cape Cod Bay and into Wellfleet Harbor. The stratigraphy east of Nauset Inlet coincides well with and expands the previous work of Aubrey and others (1982). The seismic profiles along the eastern nearshore of outer Cape Cod, north of Nauset Inlet, provide subsurface data for the first time.

The data show that fine-grained glaciolacustrine deposits are extensive in the nearshore subsurface off South Wellfleet and North Eastham, and may be extensive in the subsurface beneath the subaerial outwash in this area. The stratigraphic relationship between the glaciolacustrine unit and the glaciofluvial Eastham plain deposit that lies above is not clear. Our seismic profiles do not indicate the presence of extensive glaciolacustrine facies beneath the nearshore, north of Wellfleet.

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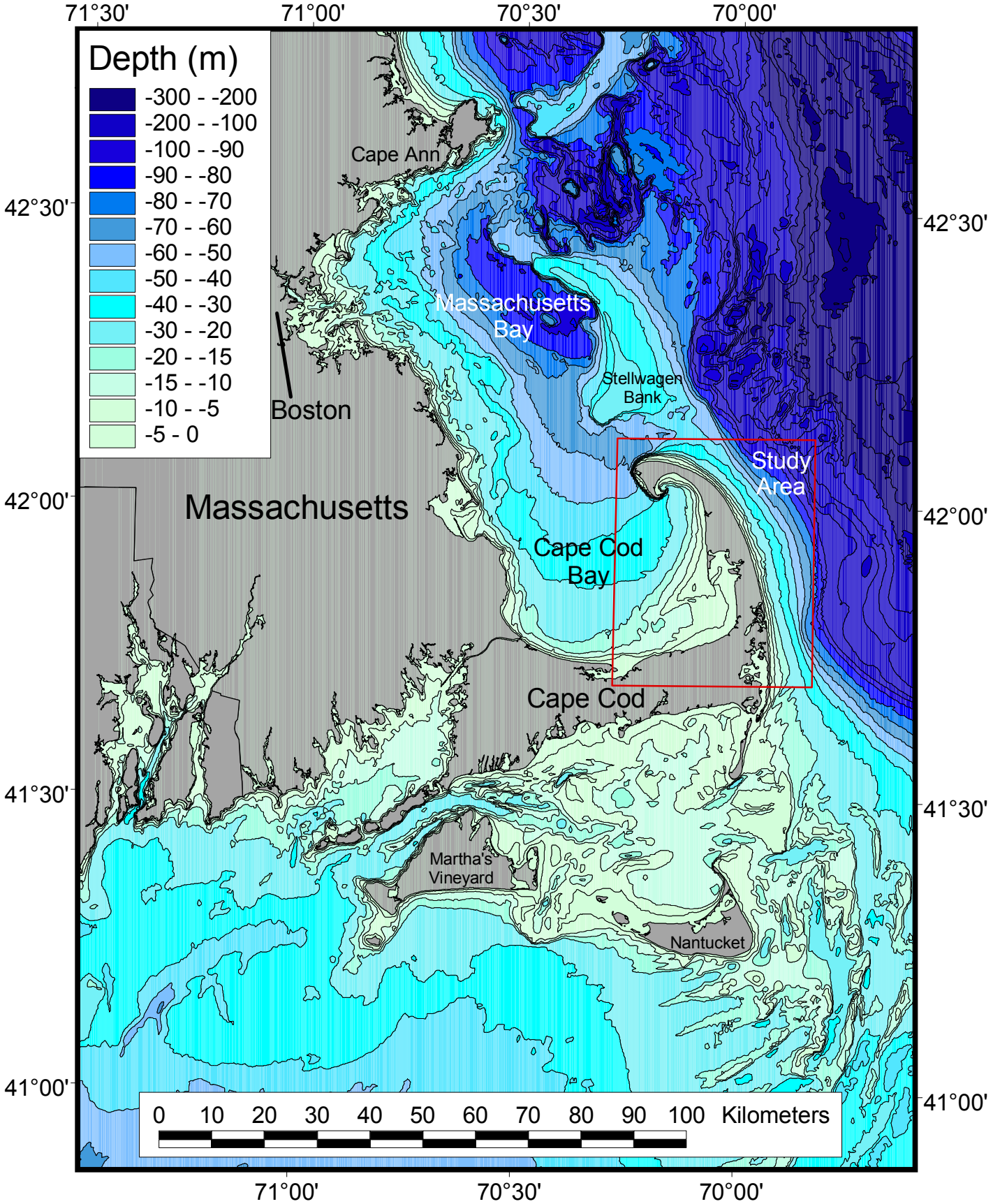


Figure 1. Index map of eastern Massachusetts showing the lower Cape Cod study area. Bathymetry processed by Mass GIS, Executive Office of Environmental Affairs (www.state.ma.us/mgis/bathymgm.htm).

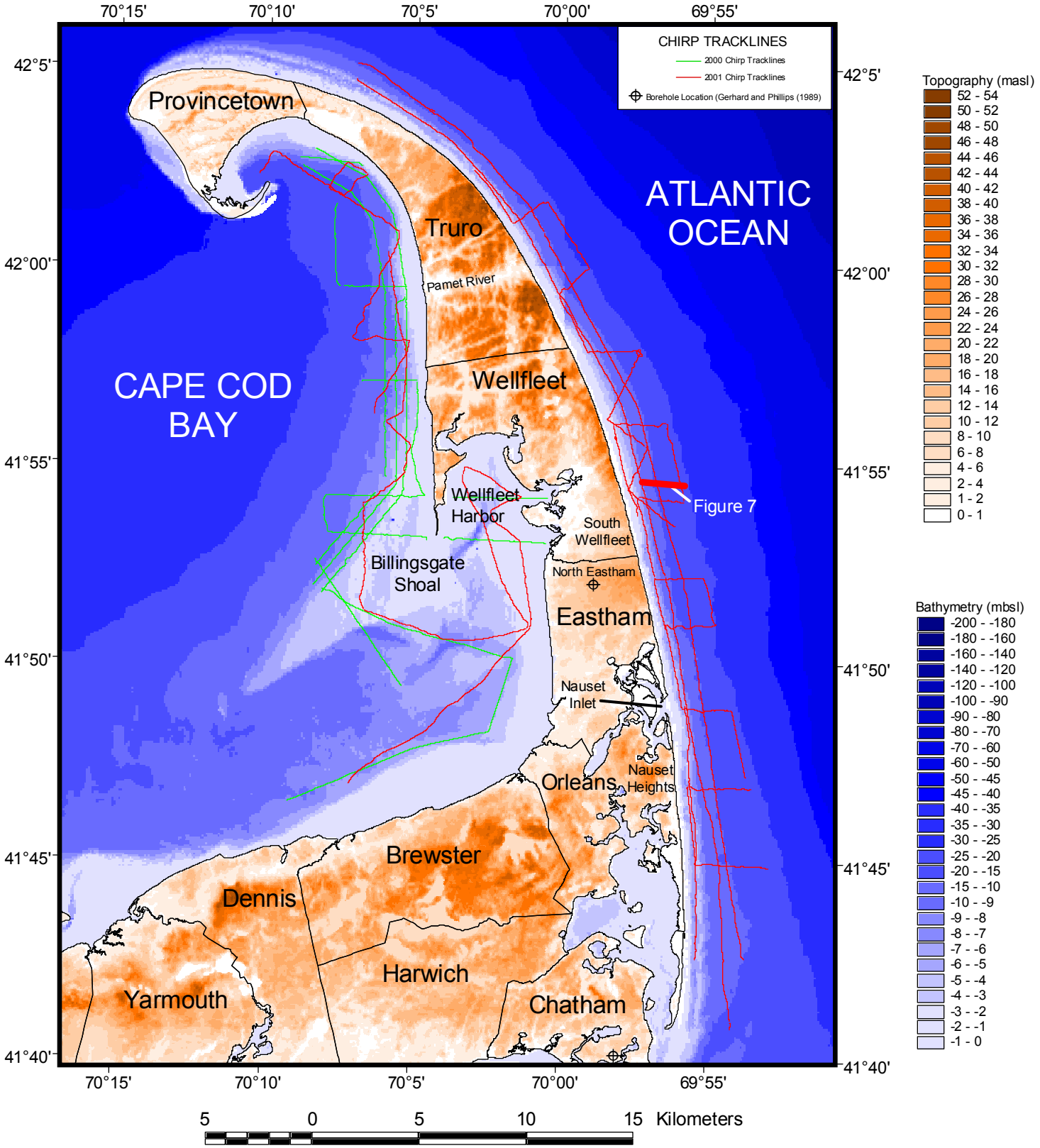
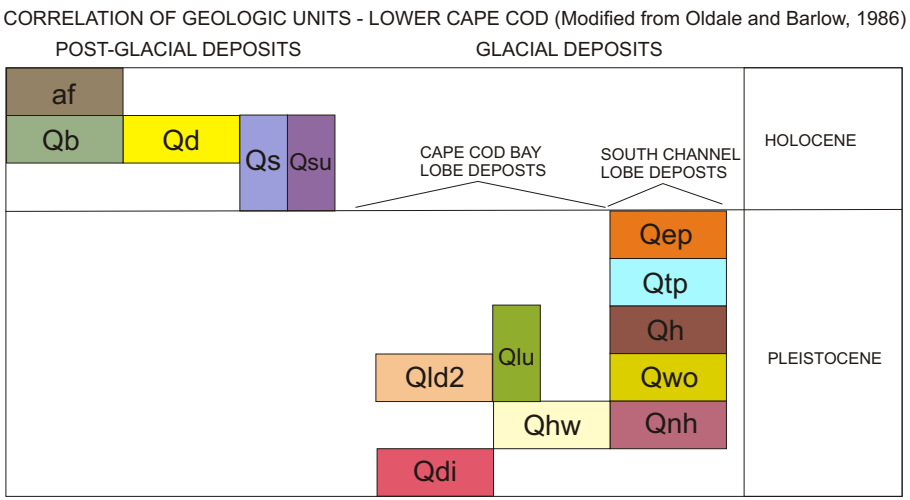


Figure 2. Trackline map showing locations of Chirp subbottom profiles. Bold line segment shows location of profile in figure 7. Topography is from USGS 3-arc second Digital Elevation Model. Bathymetry is from NOAA Coastal Relief Model. (www.ngdc.noaa.gov/mgg/coastal/coastal.html).



Geologic Map Units

POST-GLACIAL DEPOSITS
- Af - Artificial Fill
- Qd - Dune Deposits
- Qb - Beach Deposits
- Qsu - Sand and Gravel, Undifferentiated
- Qs - Marsh and Swamp Deposits

GLACIAL DEPOSITS
- Qep - Eastham Plain Deposits
- Qtp - Truro Plain Deposits
- Qh - Highland Plain Deposits
- Qwo - Wellfleet Plain Deposits
- Qnh - Nauset Heights Deposits
- Qlu - Cape Cod Bay Lake Deposits
- Qld2 - Older Cape Cod Bay Lake Deposits
- Qhw - Harwich Outwash Plain Deposits
- Qdi - Dennis Ice-Contact Deposits

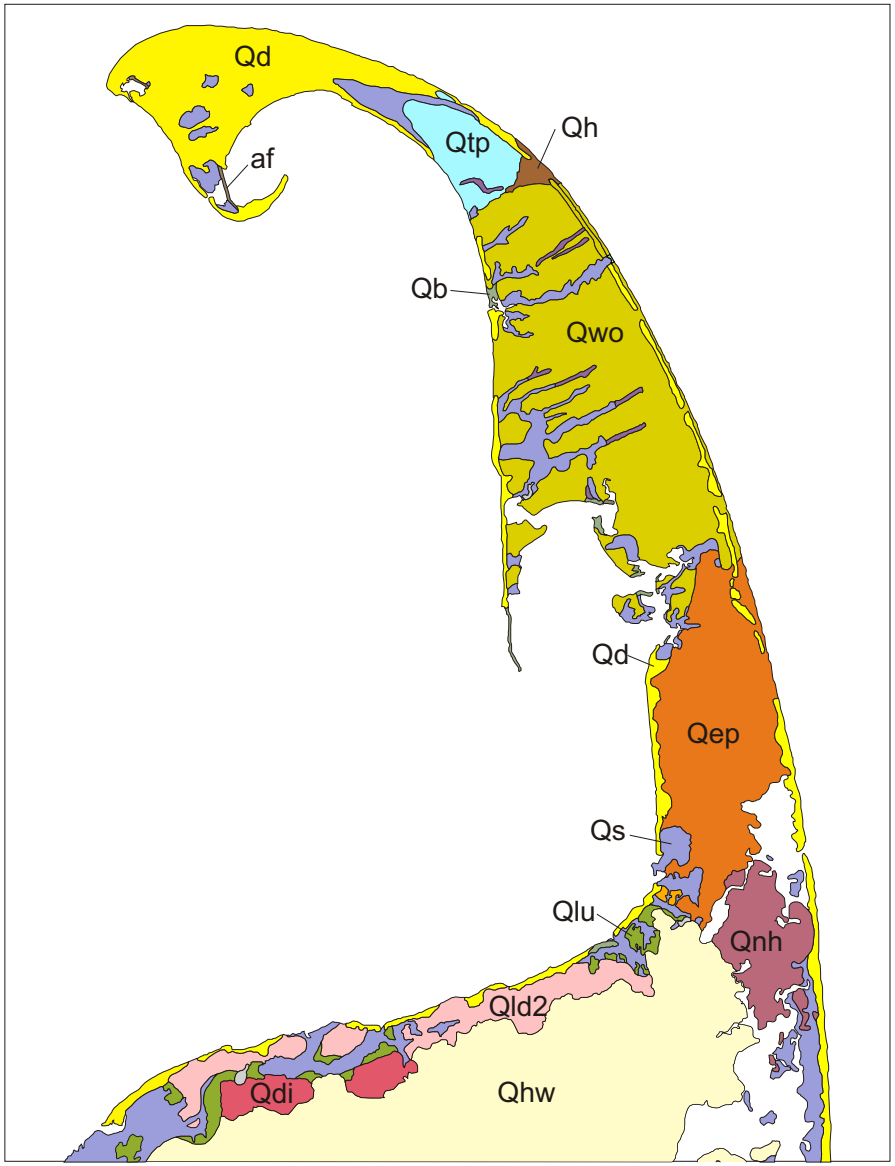


Figure 3. Surficial geologic map and correlation of geologic units of Lower Cape Cod (from Oldale and Barlow, 1986). See figure 4 for place names and town boundaries.

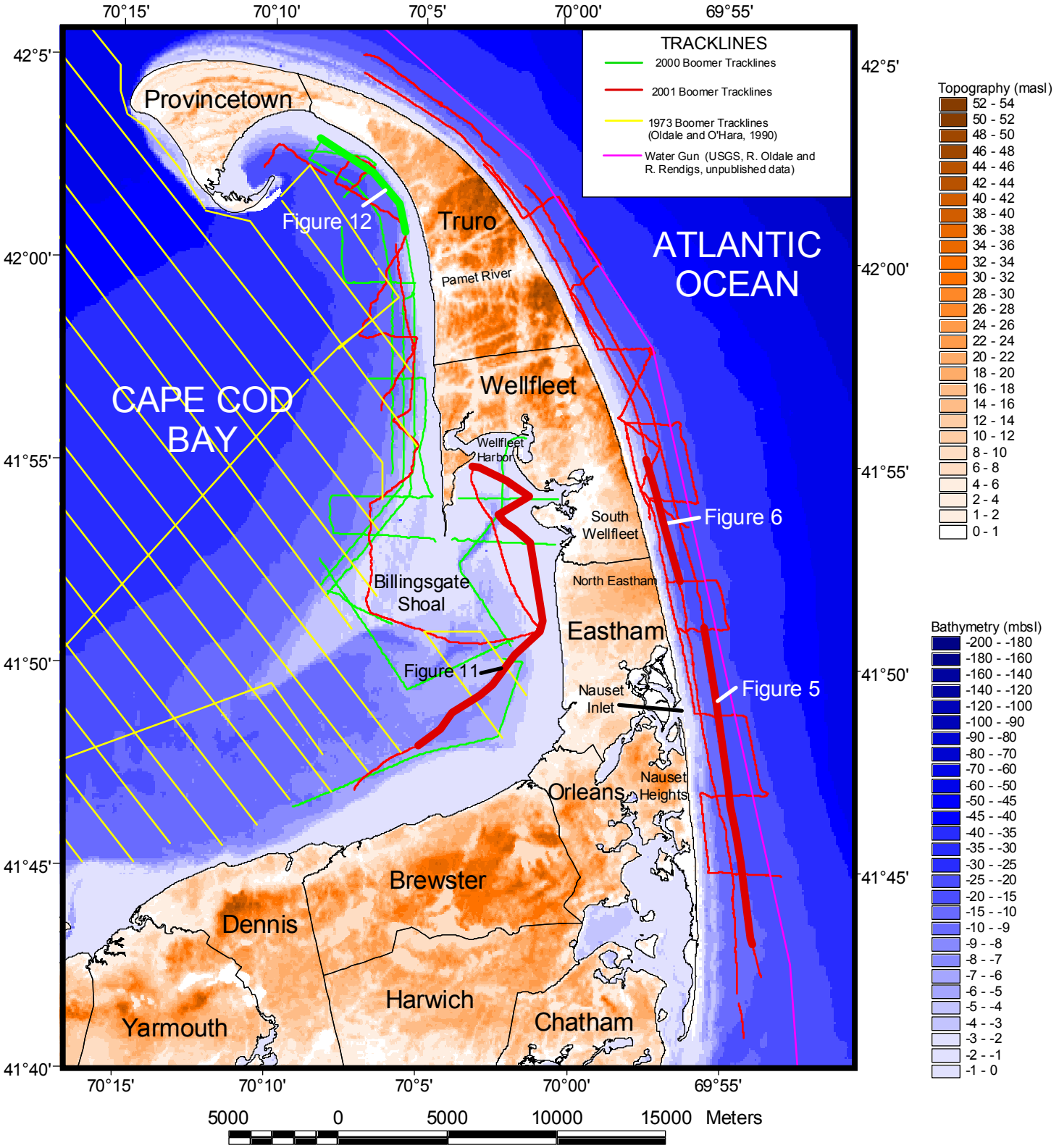


Figure 4. Trackline map showing locations of Boomer subbottom profiles. Bold sections of tracklines indicate locations of seismic profiles in figures 5, 6, 11, and 12. Boomer tracklines from Oldale and O'Hara (1990) and USGS watergun profiles are shown. Topography is from USGS 3-arc second Digital Elevation Model. Bathymetry is from NOAA Coastal Relief Model (www.ngdc.noaa.gov/mgg/coastal/coastal.html).

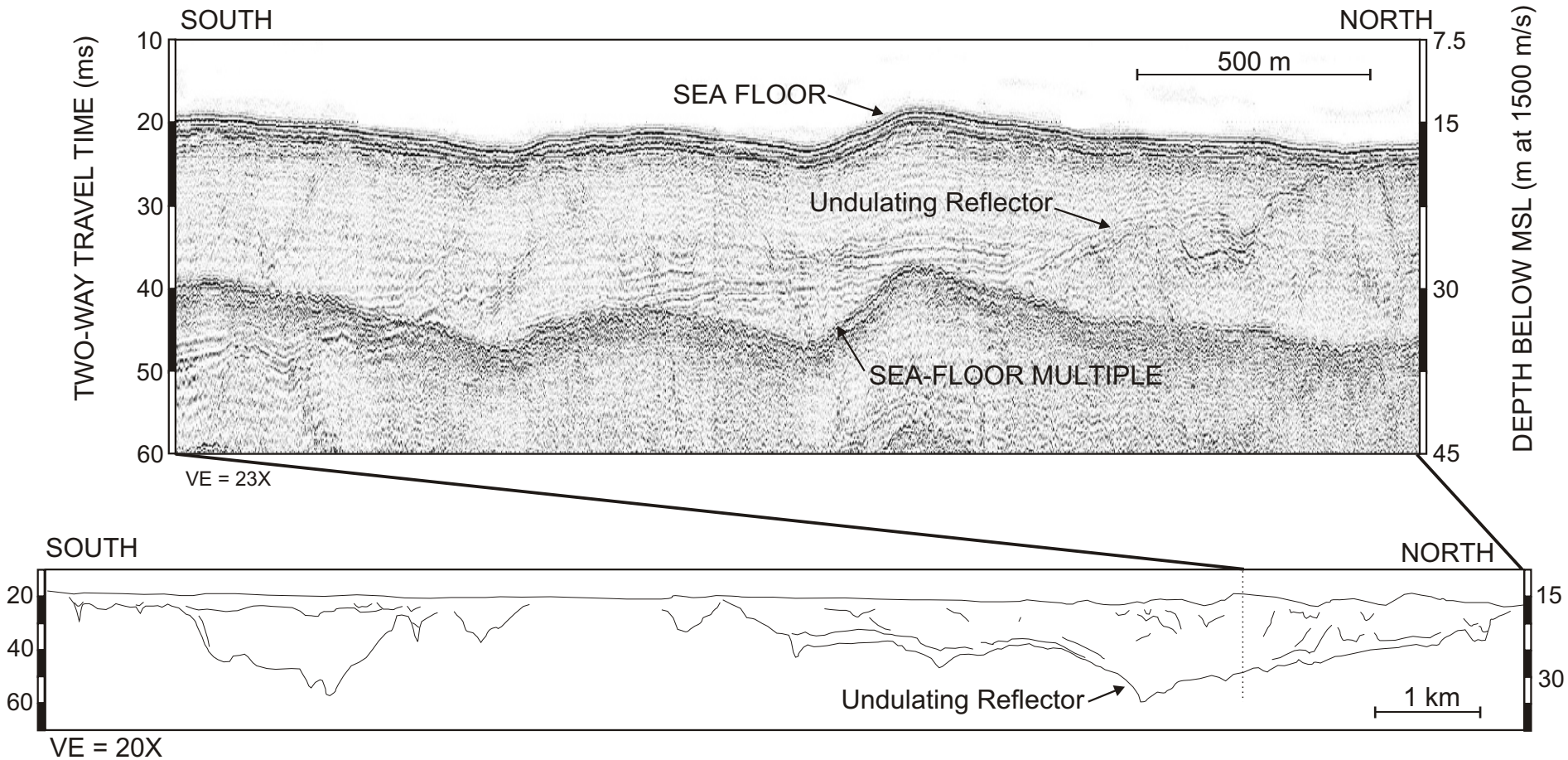


Figure 5. Interpretive cross section and section of Boomer seismic profile located east of Orleans and Eastham (see Fig. 4 for profile location). Undulating reflector is the same horizon mapped by Aubrey and others (1982).

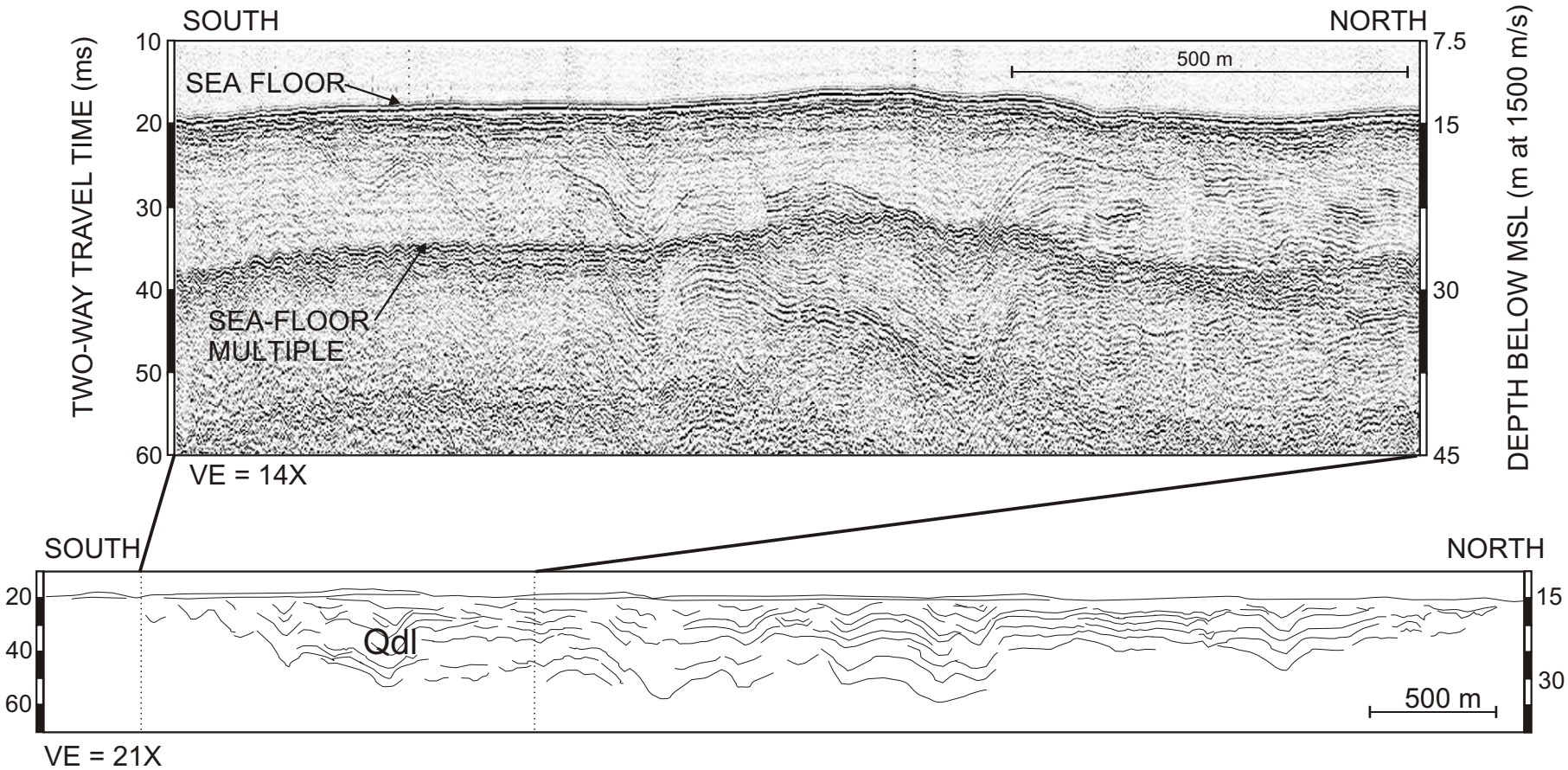


Figure 6. Interpretive cross section and Boomer profile located east of South Wellfleet and North Eastham (see Fig. 4 for profile location). The interpretation shows the extent of glaciolacustrine deposits (Qdl).

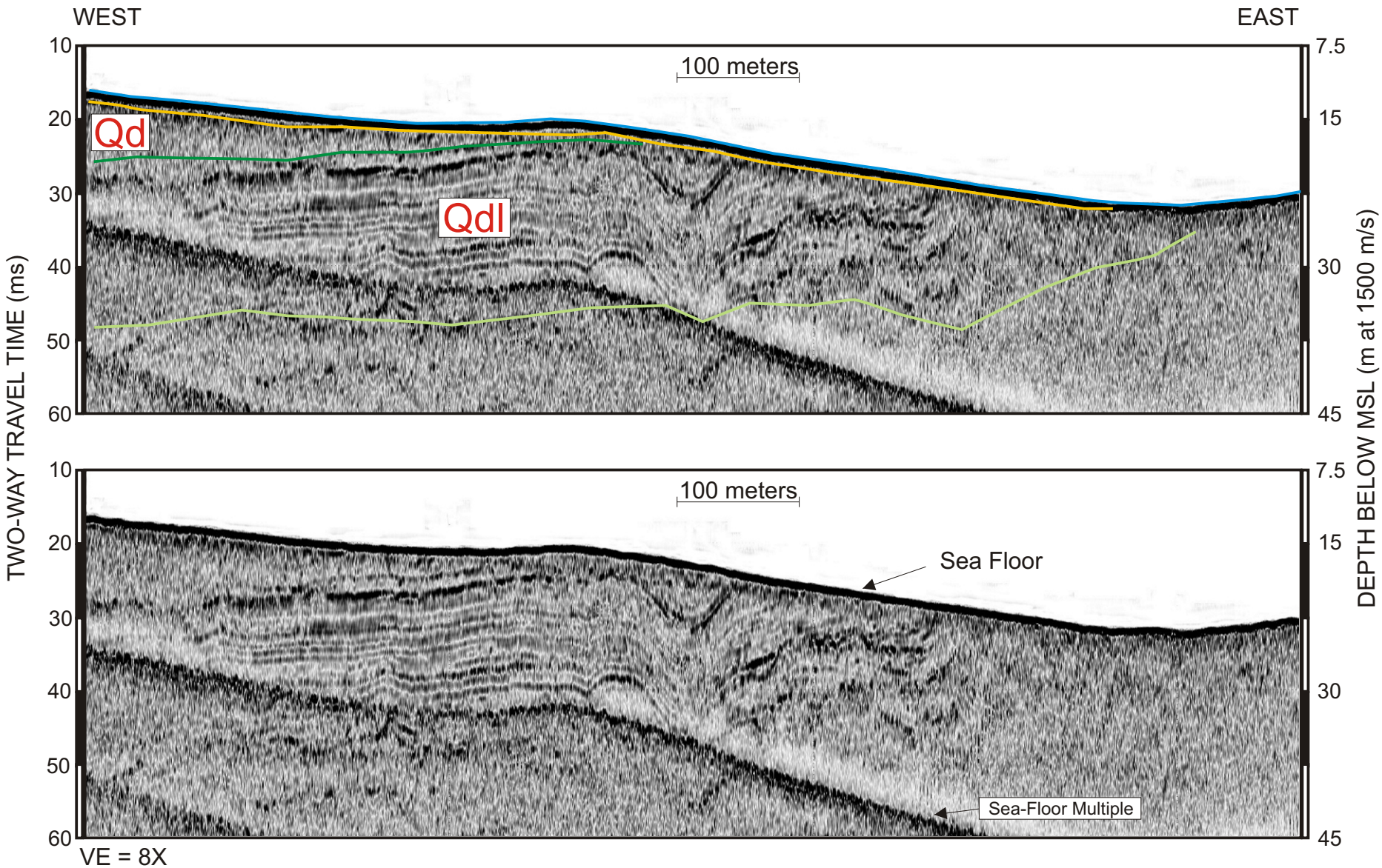


Figure 7. Chirp profile showing well stratified glacial drift interpreted to be glaciolacustrine deposits (Qdl). The unit has an apparent landward dip. The deformation of the stratified unit to the east may indicate it was deposited in close proximity to the South Channel lobe. The light green horizon is interpreted to be the base of the glaciolacustrine. The dark green horizon is the top of the unit where there is a facies change to non-stratified glacial drift (Qd). The yellow horizon is the Holocene transgressive unconformity. This surface truncates Qdl to the east. See figure 2 for location of Chirp profile.

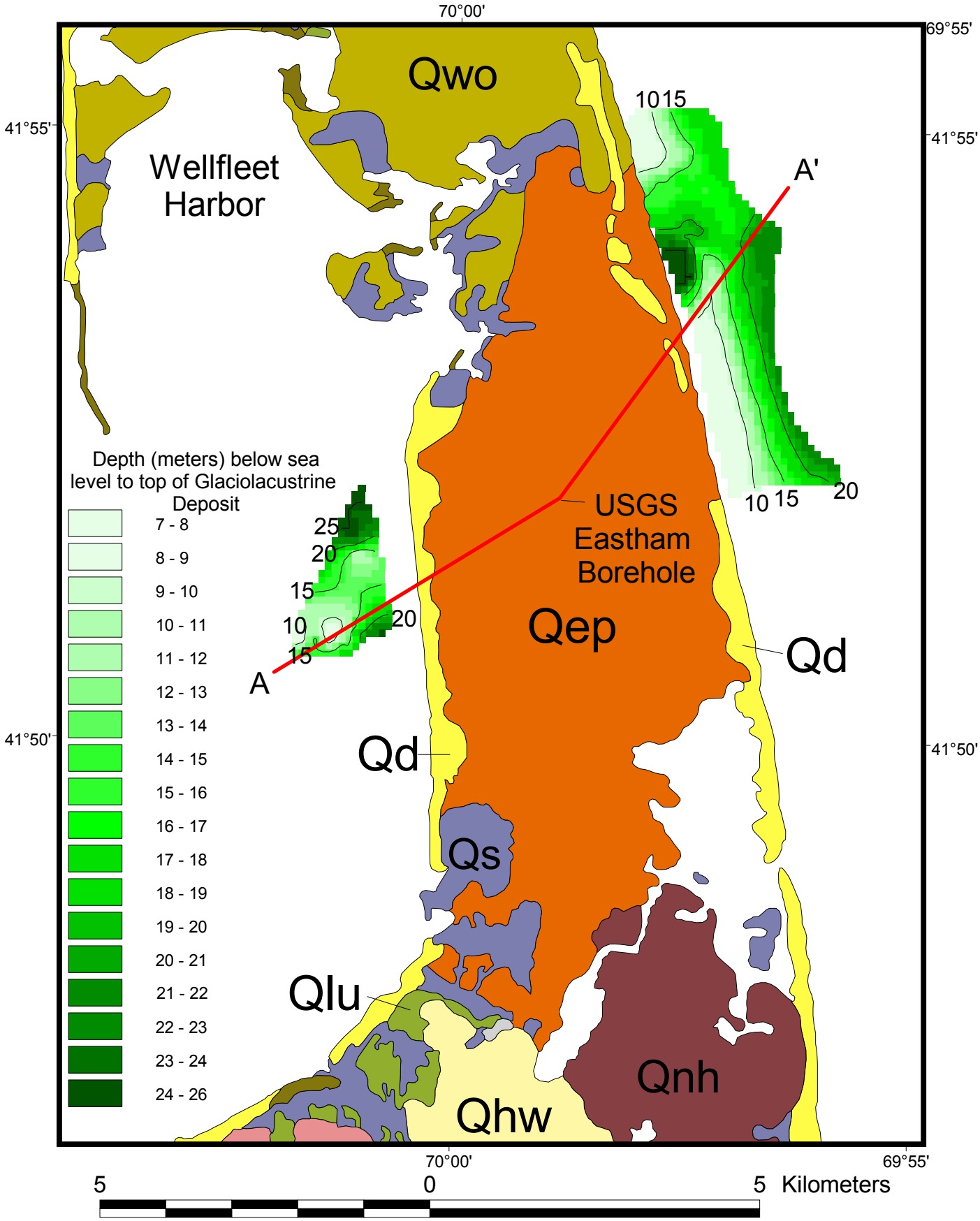


Figure 8. Map showing the depth (meters) to the surface of glaciolacustrine (Qdl). Cross-lined area indicates area where the Holocene transgression has eroded Qdl. Location of cross section A (Fig. 13) shown by red line. Surficial geologic units are described in figure 3.

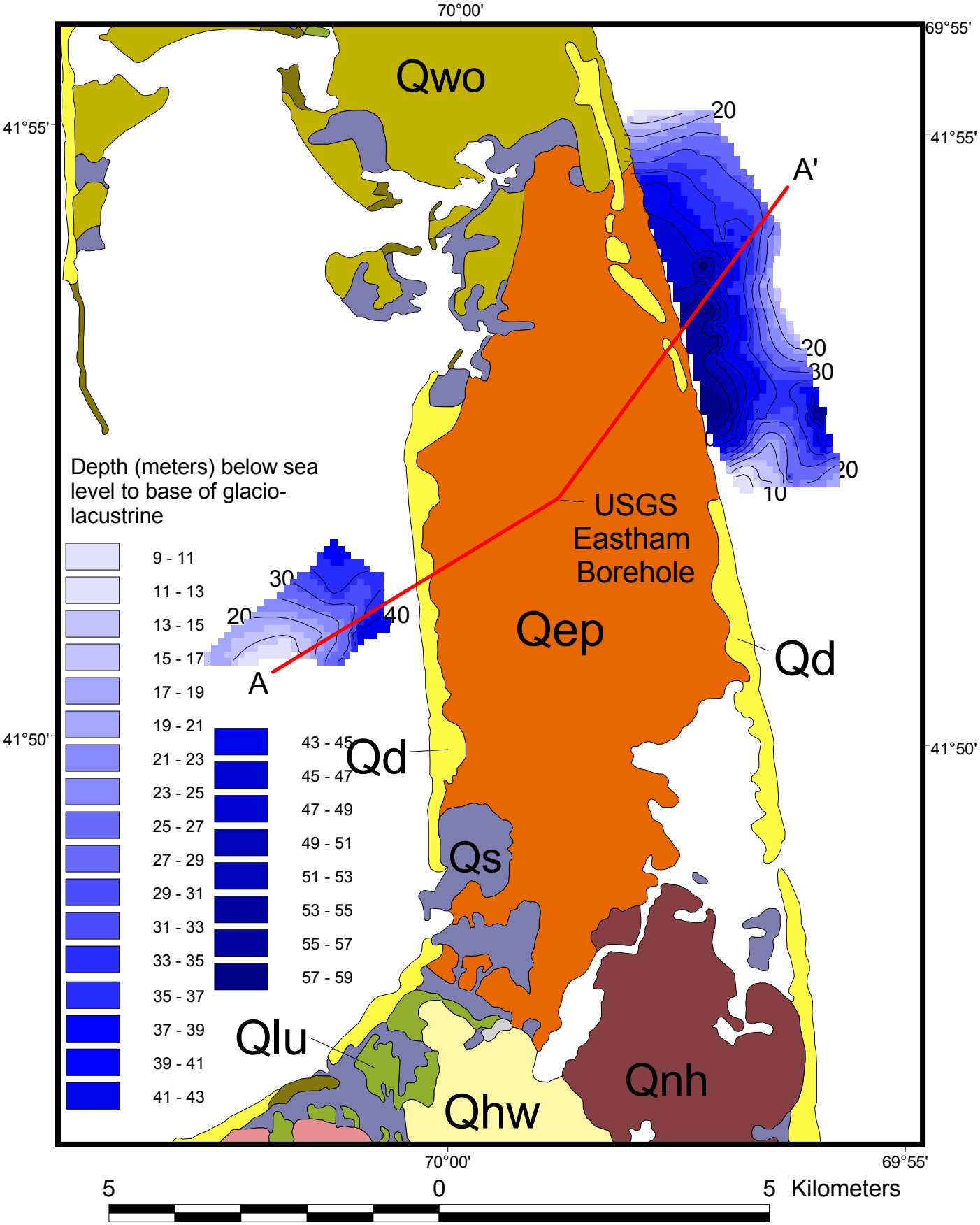


Figure 9. Map showing the depth (meters) to the base of glaciolacustrine (Qdl). Location of cross section A (Fig. 13) shown with red line. Surficial geologic units are described in figure 3.

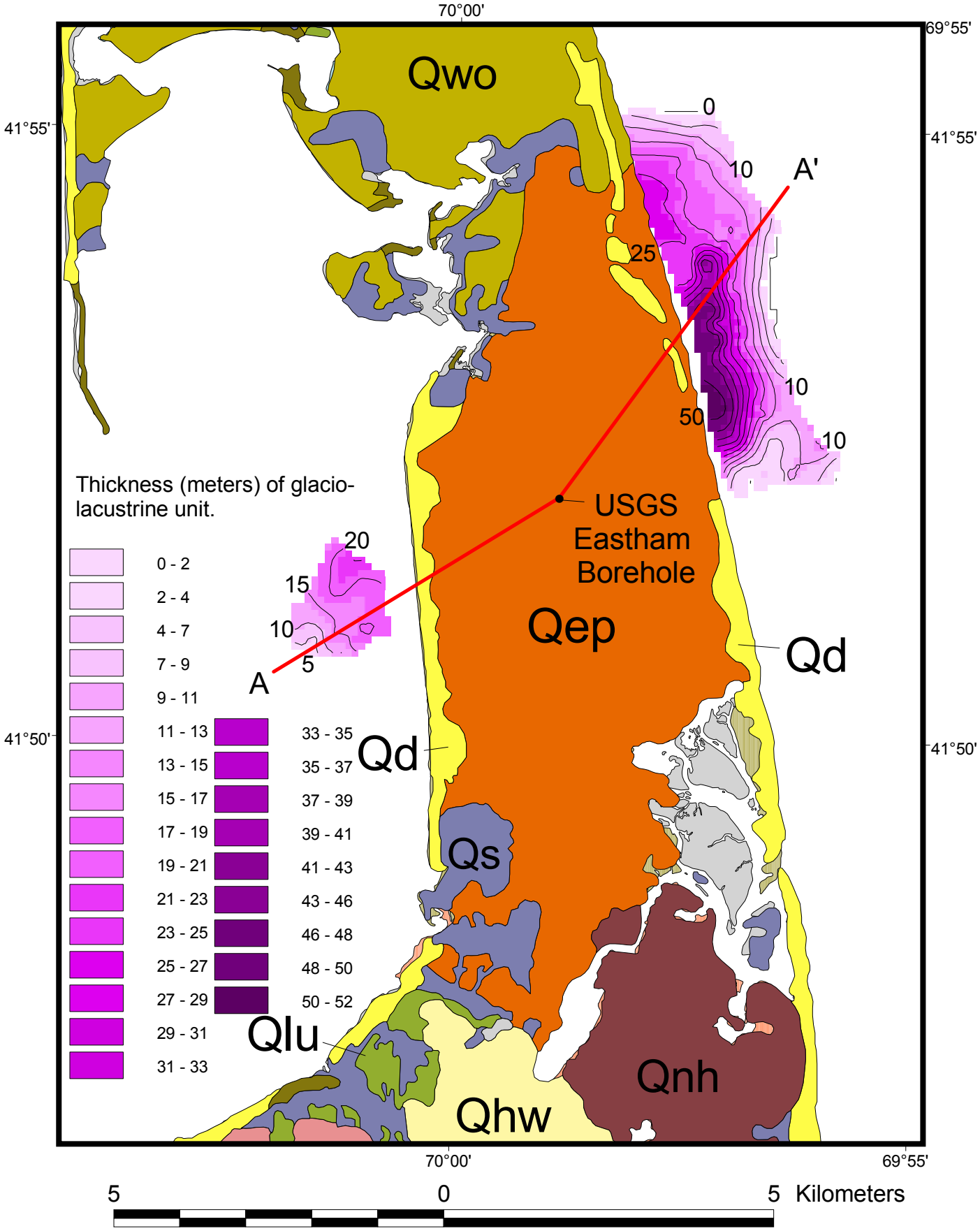


Figure 10. Map showing the thickness (meters) of glaciolacustrine (Qdl). Location of cross section A (Fig. 13) shown with red line. Surficial geologic units are described in figure 3.

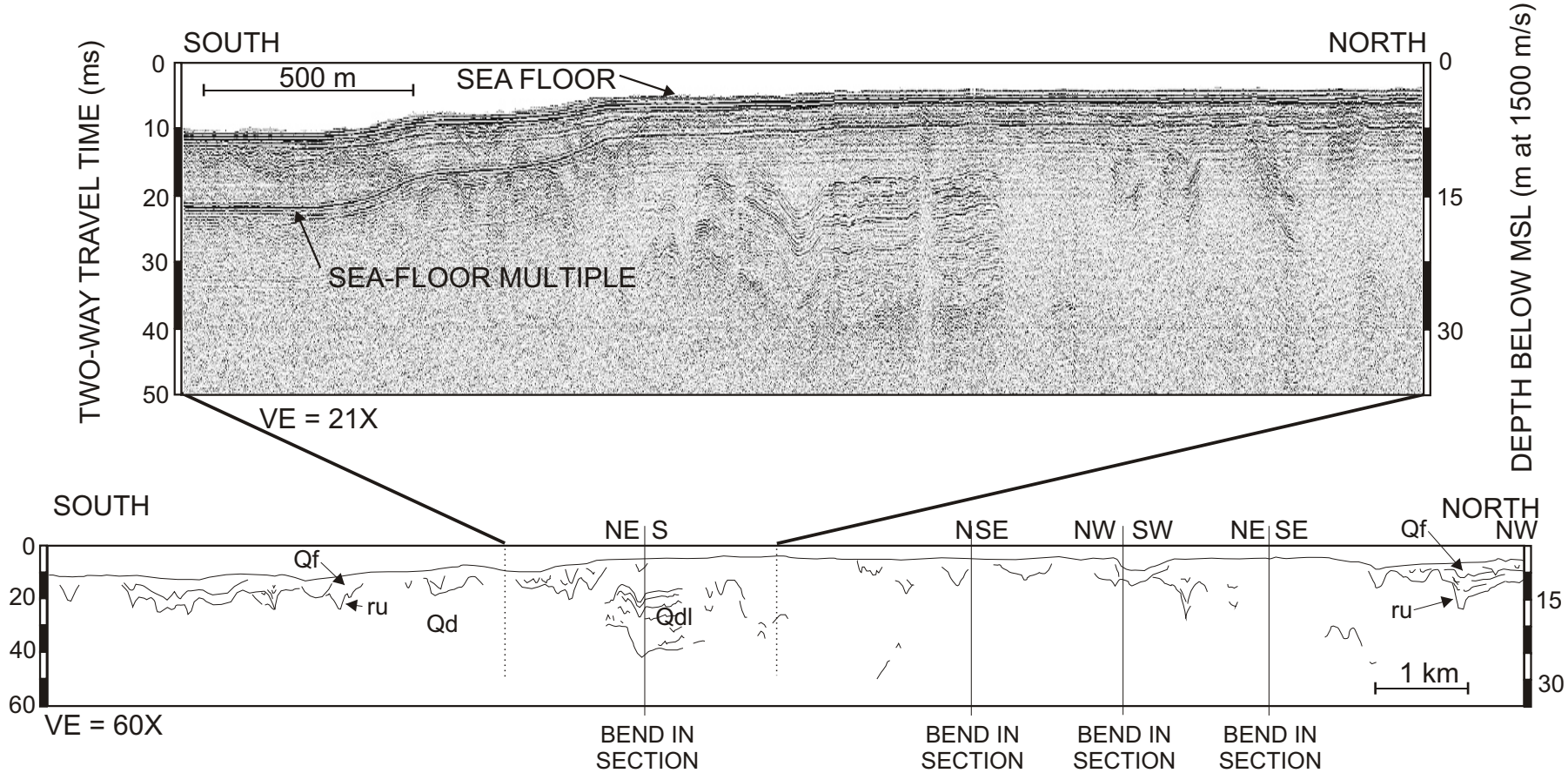


Figure 11. Interpretive cross section and section of a Boomer profile showing glacial lacustrine (Qdl) withing glacial drift (Qd). A sharp facies change on the northern boundary of Qdl and deformed reflectors suggest deposition near glacial ice. The regressive unconformity, ru, marks the base of erosional channels cut into glacial drift (Qd). Channel fill likely consists of fluvial deposits (Qf). However, postglacial marine deposits may in part fill channels. See figure 4 for location of cross section.

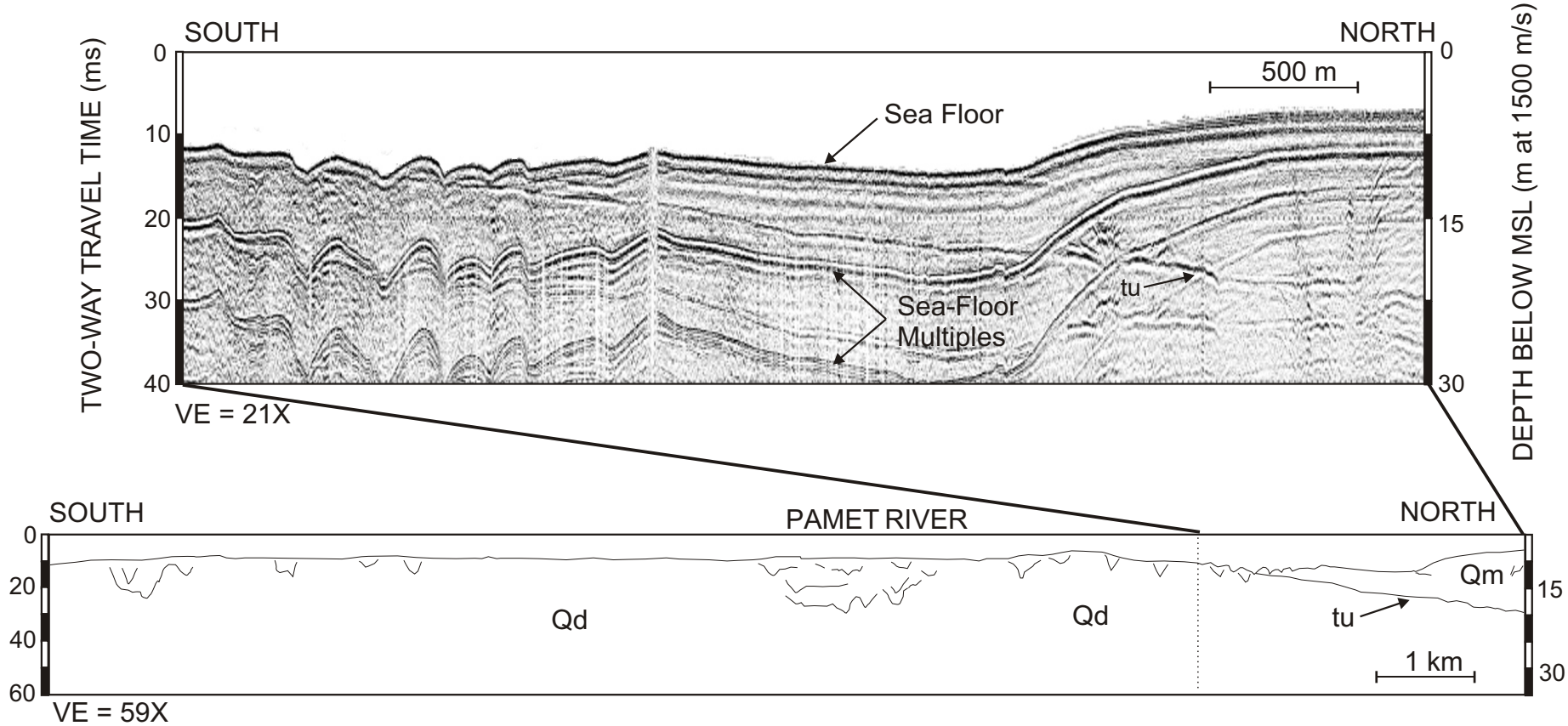


Figure 12. Interpretive cross section and section of a Boomer profile showing glacial drift (Qd) and the erosional Holocene transgressive unconformity (tu). Holocene progradation deposits of Provincetown Hook overlies glacial drift. See figure 4 for location of cross section.

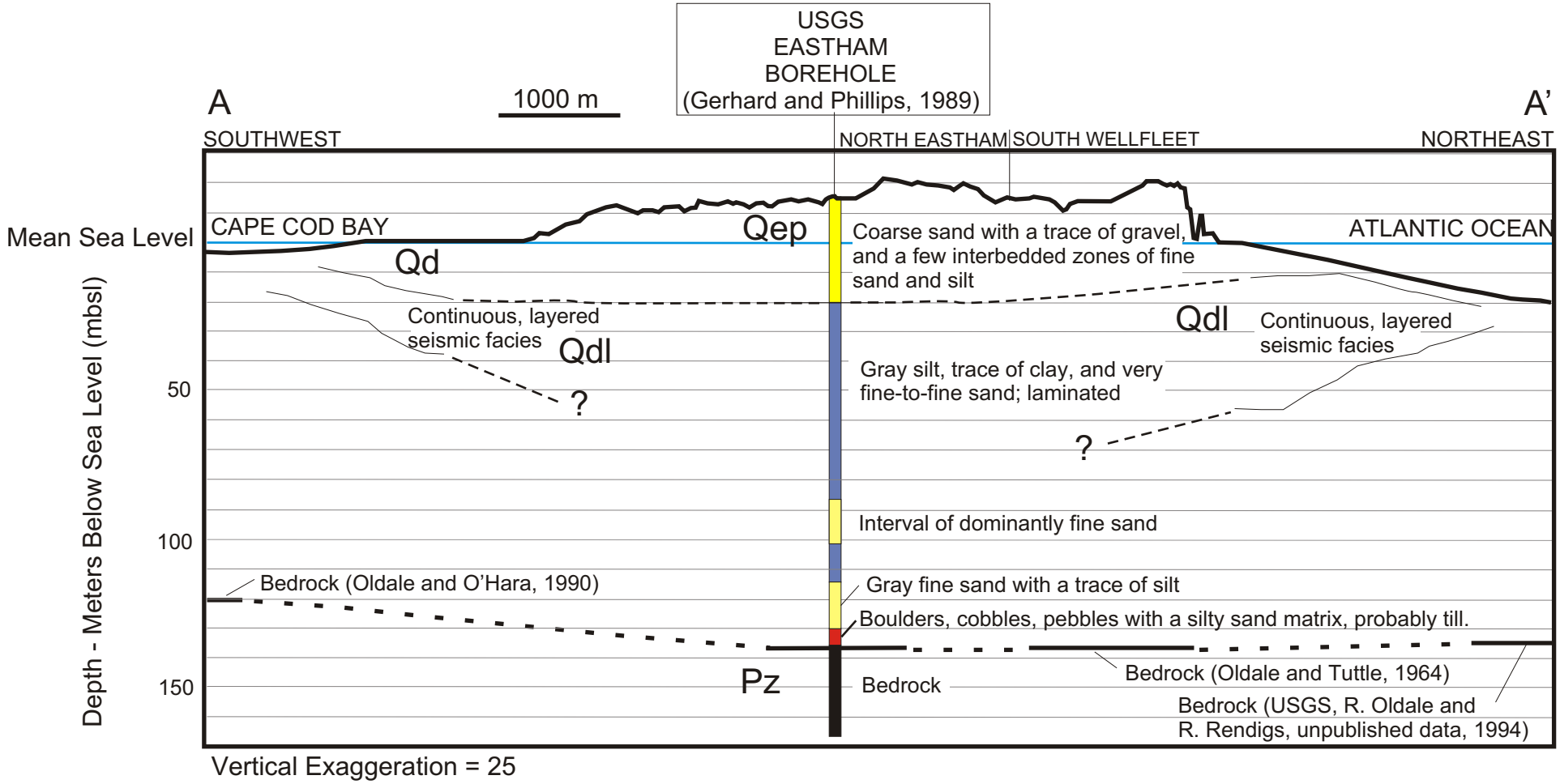


Figure 13. Geologic cross section constructed from nearshore seismic profile interpretation (Oldale and O'Hara, 1990; USGS, R. Oldale and R. Rendigs, unpublished data; This Study) , a USGS deep borehole (Gerhard and Phillips, 1989), and seismic refraction data (Oldale and Tuttle, 1964). Offshore units, glacial drift (Qd), glaciolacustrine (Qdl), and Paleozoic bedrock (Pz) refer to those mapped by Oldale and O'Hara (1990). The Eastahm plain deposit (Qep) is mapped on the surface by Oldale and Barlow (1986). See figures 8,9, and 10 for cross-section location.