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Surficial geology and features of the inner shelf of eastern shore, offshore Nova Scotia

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ABSTRACT

The report describes the Quaternary geology across the inner continental shelf of the Eastern Shore of Nova Scotia, stretching about 70 km from Clam Bay to Moosehead and from the coast to about 40 km offshore. A surficial geology map was constructed from a mosaic of seabed topography images from water depth soundings gridded at spatial resolutions ranging from high (5 m) to low (500 m), supplemented with a sparse network of acoustic geophysical transects and limited sample data. The coast and inner shelf morphology, to about 120 m water depth, is primarily governed by bedrock and has a far more rugged topography than the offshore. Hard meta-sedimentary rocks comprising slates and meta-sandstones of the Lower Paleozoic age Meguma Supergroup present bedding and cleavage at the seabed which impart a rough ridge and trough morphology trending parallel to the coast. The glacial depositional and erosional imprint is strong in the area; numerous broad fjord-like channels oriented normal to the coastline cut deep into bedrock and were largely mud-filled during deglaciation. Different ice flow phases are recognized from striae, drumlins and moraines. Bedrock is locally covered by ground moraine, drumlins and moraines or their erosional remnants. Outcrops with little sediment cover dominate the seabed from 70 m water depth to the headlands except where the broad channels and shallow basins developed a sand and gravel lag during the sea-level transgression. The precise low-stand of sea-level on this part of the inner shelf is not clear but has been reported as >-50 m (Forbes et al. 1991) immediately east of Halifax, and -65 to -70 m (Stea et.al. 1992b, 1994, 1995). Based on near-complete littoral washing of sediments from the bedrock surface as represented in the multibeam bathymetric images, a -70 m elevation is suggested but the shallower low-stand allows for greater sub-littoral wave-erosion action and is likely no less valid. Post-glacial marine mud, largely derived from the reworking of glacigenic sediments during transgression, dominates the offshore, below about 120 m and in harbours and near-shore basins that are relatively sheltered from storm action.

Glacial reconstruction was largely established before this mapping exercise but the improved characterization of features and spatial patterns contributes further detail. Regional ice flow phases established are successfully correlated to the offshore. All but the latest (Chignecto) phase are represented by one or several glacial elements including deep mud-filled bedrock channels, drumlin, moraine and striae. There is no clear pattern as to which flow phases preferentially create or preserve glacial features. The last offshore imprint was during the Scotian Phase, nearly normal to the coastline. If a later glacial phase extended into the offshore, its margin was likely farther east.

BACKGROUND, DRIVERS AND OBJECTIVES

The offshore Atlantic coast of Nova Scotia, from its harbours to approximate 100 m water depth, is generally poorly mapped in terms of surficial geology. This is in part because it is complex and spatially variable and because much remains un-surveyed to today's standards. The bedrock is hard and highly undulating, making for horizontal variability of sediment type and distribution that largely precludes mapping without a dense survey network. Multibeam bathymetric sonar, with upwards of 100% spatial coverage, often collected with associated sub-bottom profiler data is growing in coverage but still limited, especially east of Halifax. When offshore maps of the Scotian Shelf were in compilation (L.H. King and co-workers, in the 1970s, c.f King, 1970) the survey technology did not permit either the spatial or vertical penetration at suitable coverage or resolution necessary. Nevertheless, conceptual advances were made in understanding the surficial geology, but this focused on the South Shore of Nova Scotia (Piper et al. 1986). These maps were quite representative of the actual seabed sediment distribution in basins and harbours but where bedrock or till outcrop covered vast areas, generally seaward of such basins, mapping approach was necessarily degraded or map units amalgamated, or considered only the uppermost sediment textures.

An assessment of seabed resources on the inner shelf (aggregate and resource minerals) in the late 1980s and early 1990s drove offshore surveys of this poorly mapped zone by the Geological Survey of Canada (GSC) but marine mining prospects waned in lieu of a clear federal policy. A multibeam survey was conducted by the GSC in 2003 offshore Sheet Harbour (herein termed the Sheet Harbour survey) to address the lack of survey coverage and to better characterize this broad zone of the inner shelf. This project was in alignment with a broader initiative of the ESSIM Fourm Secretariat (Eastern Scotian Shelf Integrated Management), a collaborative offshore planning process led by Oceans Coastal and Marine Division (OCMD) and Fisheries and Oceans Canada, Maritimes Region. This was directed to ocean resource management and seabed habitat but the mapping initiative also had the potential to address the "difficult terrain" that potential utilities corridors from the offshore to land would encounter.
The area is now considered for designation as an Area of Interest (AOI), an initial, investigative step towards possible marine protection (MPA) under Canada's *Oceans Act* and administered by Fisheries and Oceans Canada. Furthermore, the offshore map area adjoins or overlaps the coast and islands where there is an ongoing initiative for land conservation, driven by Nova Scotia Nature Trust.

The geological rationale for selection of this area for a multibeam bathymetric survey lies partly in knowledge of the geology from previous studies. These indicated that it is largely typical of other parts of the Eastern Shore in most aspects, and so a representative of an inner shelf area. However, there is some uniqueness in that a greater degree of surficial cover is present. Work by Fader, et al. (1993) and Stea et al. (1992, 1993, 1994, 1996, 1998) and Stea (1995) has established a widely-spaced geophysics grid covering parts of the Halifax to Country Harbour area. The impetus for these studies was federal and provincial interest in defining offshore mineral resources. The 2003 survey did not benefit from simultaneous 3.5kHz sub-bottom profiler data collection so the pre-existing geophysical and sample data are critical while the multibeam data presented the opportunity for high-grading present geological understanding.

PREVIOUS STUDY

The 1990s saw abundant survey, analysis and conceptual mapping in the area largely under the direction of R. Stea as part of PhD studies and later following both provincial and federal mandates, with GSC direction from G. Fader. A major driver was the need to define offshore mineral resources, especially seabed-mining related resources such as sand and gravel for aggregate, high purity silica sand, gold and other heavy minerals.

Their terrain zonation delineates a wide zone off Sheet Harbour to Ship Harbour where the bedrock outcrop zone, which is otherwise dominant along the whole area, becomes largely covered with till (blanket, drumlinized and small moraines). The onshore surficial geology map of Stea et al. (1992) indicates a greater density of drumlins near the shoreline along a 100 km stretch from Clam Bay to Liscomb.

The broad geological aspects, including glacial and sea-level framework, identified in these earlier studies, include:

- identification of local glacial deposits generally previously thought to have been destroyed with the post-glacial transgression;
- identification of a shallower sea-level low-stand, at about 65 m present water depth as opposed to the more universal 100 to 110 m in most of the outer shelf;
- identification paleo-coastal deposits (and therefore aggregate) including some assessment of engineering quality;
- confirmation, through provenance studies (Stea 1995) that the latest till, the generally locally-derived Beaver River Till, extended to the Scotian Shelf end moraine complex. This till is auriferous, including a high >250 ppb assay off the Eastern Shore.
- confirmation that difficult terrain with respect to utilities corridors is ubiquitous

The two latter points, ubiquity of high relief terrain and latest phase offshore till, are reconsidered in the discussion.

DATASETS AND METHODS

Multibeam Bathymetric Data Collection

Multibeam bathymetric data present a detailed seabed topography and are generally displayed as a hill-shade (sun-illuminated topography or shade relief image). Seabed morphology forms the basis for surficial geology interpretation. Nevertheless, samples and sub-bottom profiler data are critical for understanding the stratigraphy and its relation to morphology. The survey was conducted from the CCGS Frederick G. Creed, a 20 m long, 10m wide, SWATH (Small Water Area Twin Hull) survey and sounding vessel. She is equipped with a Simrad EM 1000 multibeam bathymetry system and can survey at speeds up to 12 knots (22 km/hr). The Creed navigation system was comprised of two Magnavox 12 channel Differential Global Positioning Systems (DGPS). The GPS signals from the Canadian Coast Guard station at Western Head, NS, were received via the MBX Beacon receiver located on the ship's bridge. This information was passed to a POSMV system (corrects for vessel attitude) which used a gyro accelerometer package to provide sub-meter accuracy real-time positions to the SIMRAD sounders. No patch test was performed although a sound velocity profile (SVP) was measured using the Brook Ocean Technology Ltd. Moving Vessel Sound Velocity Profiler (MVSVP). Generally only one cast was performed per day. Tidal corrections were by predicted tides only. A total of four days (ca 46 hours) surveying in 2003 produced 69 lines in an offshore grid, amounting to about 230 km^2 multibeam coverage. In addition, six traverses in or out of the wharf in Sheet Harbour (ca. 20 km^2) and a small supplementary survey comprising five traverses in/out of Shoal Harbour (ca. 4 km^2) completed the survey with about 255 km^2 total. Data cleaning was performed via a CARIS HIPS and SIPS Microsoft Windows-based program while at sea.

Supplemental Data

Supplementing the multibeam data are pre-existing bathymetric, geophysical, limited sample and earlier map and profile compilations interpretations. These provided sufficient information for a new synthesis of surficial geology. Geologic data came from several sources:

- Canadian Hydrographic Service (CHS) field sheet (unpublished spot depth data, also known as “boat-board” charts) bathymetric information and bottom-type qualifiers (sediment type). As outlined below, the spot depths were processed to digital elevation models from which shaded relief images were generated. Similar to the multibeam-based images but at one to two orders of magnitude diminished resolution, such compilations were already shown (King and Hynes 2003) to significantly improve recognition of bedrock terrane, moraines, and sediment basin fill. Further, the field sheets contain substrate type indicators derived from grab samples and/or tallow samples.
- GSC-A sediment grab and short core (piston or gravity) samples.
- GSC-A high resolution reflection seismic (boomer, sparker and air gun) profiles and high resolution sidescan images.
- a surficial geology map compiled by Stea (1995) from the above GSC-A data set.
- a new CHS LiDAR image and associated photographs, including the non-light spectrum, not fully processed. This is entirely under-utilized in the present map, only made available after mapping was complete.

Figure 1 shows location of the datasets contributing to the map and report.

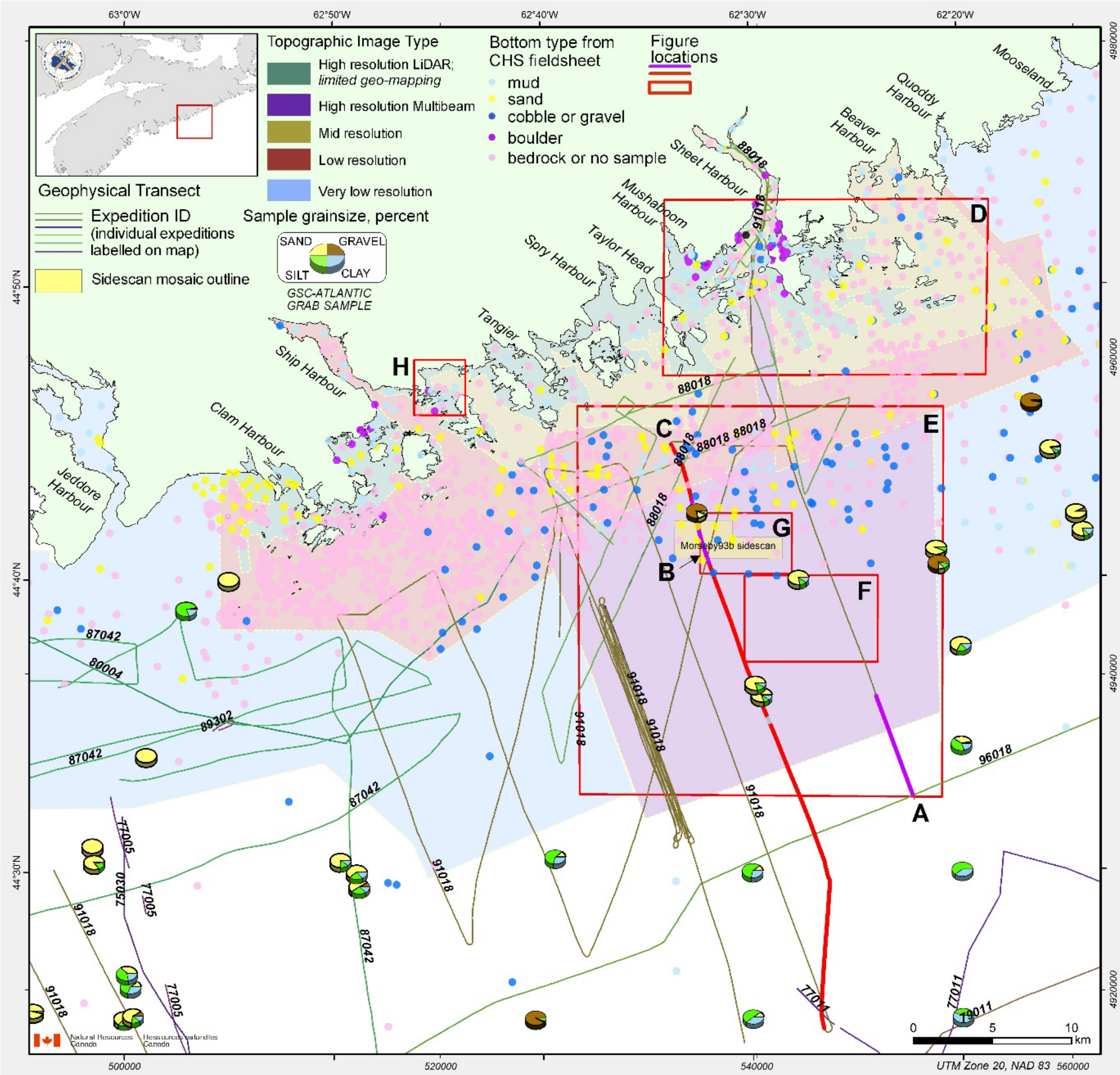


Figure 1. Sample, bathymetric, geophysical, LiDAR, and multibeam bathymetry data control for map compilation. Illustration locations in red and mauve.

CHS Field Sheet Data and Derived Shaded Relief Images

CHS field sheets are essentially hand-drawn spot depth maps. Spot depth data were supplied digitally by CHS for FS 1386 but, at the time of post-multibeam survey analysis, the other relevant sheets were only available as scans. Scanned field sheets were 1: 12 000 and 1: 36 000 scale. These include field sheet numbers 4421, 4185, 4013 and 4279, 3047, 3050, 3279, and 1000256, covering harbours, headlands and beyond. Depth binning on the original field sheets was generally in fathoms, except in areas shallower than 20 m, where fathoms (ca 2 m) and feet were registered.

The field sheets were georeferenced in (in the ESRI Arc 8 environment) to a positional accuracy typically within 10 m and always within 15 m. Spot depth placements on the field sheets are typically hand-drawn and the digits cover a diameter typically from 25 to 150 m. Depth points were digitized at the center of every hand-drawn depth sounding., Then, data points of similar depth were selected and assigned the appropriate depth value and converted from fathoms (or feet) to metres (79793 points in total). Better than 50 m resolution (spot point spacing) was available in the headlands and harbour areas. Between five and 15-20 km offshore, point spacing is more typically 100 m and farther offshore it is about 500 m between data points. Any horizontal inaccuracies are likely insignificant in relation their low vertical precision (1 fathom). These points were then gridded, generally with a kriging method and a seabed shaded relief (hillshade) display applied. The images are presented at the same vertical exaggeration of 10 times and with a "sun" illumination angle of 45 degrees from horizontal and from 45 degrees west of north (i.e. from the NE). The low vertical precision induces considerable artifacts in the shaded relief images. This is especially evident across the relatively smooth, flat or gently inclined seabed areas where it imparts an artificial terraced appearance.
Figure 2 shows an example of the nearshore shaded relief image and superimposed bottom type points.

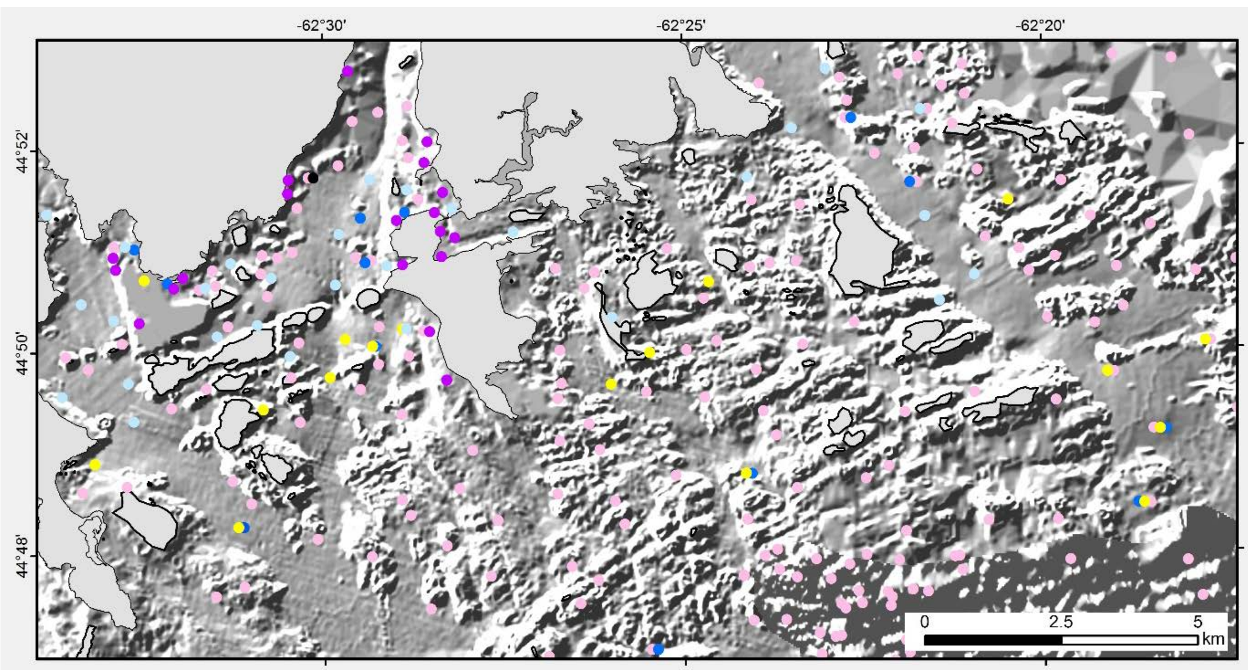


Figure 2. Shaded relief image in the mid-resolution range, offshore Beaver Harbour. Flat areas with sand or mud contrast with high relief bedrock-dominated areas. Bedrock structure is clearly visible. Coloured dots show CHS spot bottom types that help distinguish sand (yellow) from mud (light blue) areas. Legend for dots is included on the Quaternary geology map. Location is shown in Box F in Figs. 1 and 6.

Surficial Geology Mapping from Low-resolution Hillshade Images

The considerable advantage in creating DEMs and hillshade images is in recognizing elements of morphology such as ridges, troughs, channels, and basins; each can be interpreted in a surficial geology context where supplementary information is available. A successful contribution of low-resolution hillshades derived from DHS spot depths for use in geologic mapping was demonstrated by King and Hynes (2003) along the SW shore of Nova Scotia. An effort by DFO to continue this technique was made by M. Greenlaw and M. Doon, DFO, St. Andrew's, NB. Their unpublished map covers most of the NS inner shelf. By the time of their compilation (ca. 2012) the manually-digitized spot data were supplied digitally by CHS. From this, M. Doon produced TIN grids (triangulation-based shaded relief images) and mapped, largely without the aid of supplementary data. More recently the TINs were made available to GSC-A. However, large gaps remained in the Sheet Harbour area. While the TINs were superior in the nearshore area, others areas were lacking in definition compared to the original DEMs from the field sheets. Hence, both sets of shaded relief images were utilized in updating their map. The farthest offshore hillshade image generally has insufficient resolution for feature recognition purposes so mapping relies on trackline data. The nearshore spot depth-based geology map builds on the far better control from the multibeam dataset and the geophysics data. The differentiation of terrain character and stratigraphy within the multibeam area (e.g. bedrock ridge and troughs, incised and sediment filled valleys, sand and mud-covered basins) allowed recognition of similar terrain characters in the low-resolution areas, providing a more confident geological interpretation. The latest composite surficial geology map (*see* accompanying file of_8375_Figure 3) encompasses this multi-resolution aspect, combining interpreted map polygons derived from the full range of hillshade resolutions (low, medium and high). This necessitates a grouping of map units where resolution is insufficient. The till blanket, with moraines and drumlins, was especially difficult to discern from bedrock outcrop and is under-represented in the low-resolution areas. Nevertheless, the sparse geophysical data demonstrate that indeed, the till is very thin or absent across much of the nearshore.

GSCA and CHS Sample Data

GSCA sample data from the area are limited but they supplement numerous bottom type designations digitized from the CHS field sheets. The CHS bottom type points are especially useful for differentiation of mud from sand substrates because both have an indistinguishable smooth topography in the hillshade images. Shortcomings appear to be a lack of differentiation of cobble and boulder texture from bedrock; the post-glacial sea-level transgression likely left a lag over bedrock.

GSC-A Geophysics Data

GSC-A geophysical data collected in the region prior to the 2003095 expedition and utilized in the map compilation are shown in Table 1:

Table 1. Geophysical survey data

Expedition Year	Expedition ID	Data Type	Location relative to Multibeam survey
1965	035	air gun, low resolution	overlaps southern extent
1966	004	sparker	overlaps southern extent
1968	Gold	unknown source	Sheet Harbour and Ship Harbour
1980	004	sparker	single traverse positioned to west
1987	042	sidescan, sparker	traverses well to west
1988	018	GeoPulse sparker, sidescan, bubblepulser	Sheet Harbour and approaches
1993	Moresby93a	sidescan mosaic	area of cocaine dump investigation
1991	018	Huntec boomer and BIO, low res. sidescan	several transects across area
1996	018	3.5kHz sub-bottom profiler	single traverse
2006	048	Sidescan only	eastward

Several traverses of raw seismic profiles and sidescan sonograms from the GSCA 1988-018 expedition were interpreted and incorporated into the map. The 1991-018 tracks interpreted by Stea (1995) were digitized and also contributed significantly to map compilation. He differentiated zones of outcrop, estuarine, moraines, glacimarine mud, truncated and with a lag, basinal muds, and finally, the larger examples of sediment infilled bedrock valleys. The concepts for the new map were largely adopted from the Stea (1995) work.

The CHS and GSC-A bottom type stations, the geophysics tracks (interpreted data not shown) and the composite hillshade images are shown in Figure 1. These represent the bulk of the dataset for map compilation. The boundary between the multibeam-based map polygons and those from the low-resolution bathymetry areas are identified. Also, the area mapped by M. Doon (DFO-St. Andrews), and the original offshore map (King 1970) coverage are shown. Significant modifications to both were made to conform to the more recent dataset.

Shipwrecks

The offshore multibeam survey covered a shipwreck notice posted on the CHS chart (44° 36.55 N, 62° 33.054 W) but preliminary inspection of the multibeam data show no targets here. Much of the local area is bedrock outcrop-dominated such that any shipwreck target not on the relatively flat, sandy seabed could be hidden within the rough bedrock returns. A known wreck (possibly the M/VArctic) immediately south of the Sheet Harbour NE Arm wharf (only 10s of metres) and marked with a bow buoy returned spurious acoustic reflections but no clear anthropogenic characteristics are evident on the processed image.

GEOLOGIC SETTING

Geomorphic Characterization

The geomorphologic characterization of the inner shelf by Forbes et al. (1991), Stea et al. (1994, 1996) and Stea (1995) provides the setting for the Eastern Shore offshore map area. They divided the inner shelf into five morphological terrain zones based on limited multibeam, sidescan and sub-bottom profiler data and multibeam data offshore Halifax (Fig. 4). The four innermost of these zones are covered by the multibeam survey and their descriptions apply, with some exceptions. They classified, from nearshore to offshore a (1) Truncation Zone, (2) Morainal Zone, (3) Outcrop Zone, (4) Basin zone and (5) Scotian Shelf end-moraine complex. The end moraine complex (outermost, Zone 5) lies just seaward of the multibeam survey but is included in the new map. The Basinal Zone (4) which they describe as a glacial-depositional zone, includes glacimarine sediments (Emerald Silt) including biological and mineralologic signatures of the Younger Dryas cooling period (ca. 11 to 10 ka) and overlying Holocene age muds (LaHave Clay). The Morainal Zone, first described by Stea et al. (1992b and 1993) lies just landward of the basins and the type section falls within the map area. They described a crude en-echelon pattern of morainal? ridges from 5 to 20 m height and 200 to 3000 m length, occasionally strewn with boulders and comprising a cobble-rich, matrix-supported diamicton with striated pebbles. The moraine pattern was mapped based on limited geophysical track lines and extrapolation using bathymetric control (Stea 1995). The newer multibeam data allow an improved characterization, spatial delineation and orientation of these moraines. Stea (1995) interpreted these as marginal or subglacial moraines that have always remained submerged and not undergone modification with the post-glacial transgression. This transgression effectively formed the Truncation Zone (3), evident by a major, relatively planar erosional unconformity on glacimarine strata, till, and a muted topography across bedrock in water depth shallower than ~50 m. The surface has rounded, non-striated gravel and cobble clasts constituting a lag overlying bedrock, till and glacimarine clays. Within this zone Stea et.al. (1994) also describe bedrock valleys (their Valley Subzone) up to 1 km across and up to 70 m deep, oriented both coast-parallel and coast-normal, and partially or fully infilled with till, glacimarine and post-glacial sediments, all sub-classified by Stea et. al. (1994). These channels are well delineated in the new map.

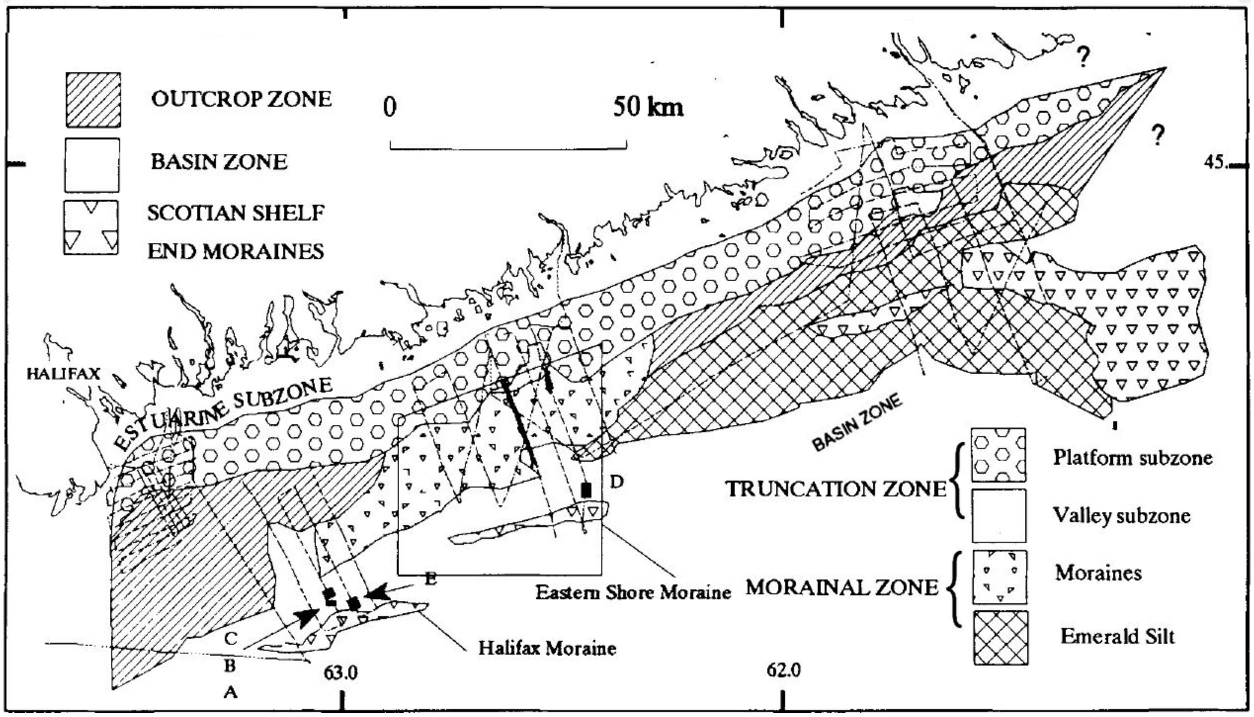


Figure 4. Inner shelf geomorphic zonation modified from Stea et al.1996 (in format only).

Stratigraphy and Depositional Environment

Stratigraphy of the map area was largely derived from the seismic transects; Units 1 to 7 (bottom to top) are differentiated. Figures 5 and 6 provide examples of both the boomer and deeper-penetrating air gun seismic profiles.

The sequence is most complete in the geologic profile, Fig. 7. Developed mainly from sub-bottom profiler data, the concepts generally follow and adopt the work of King and Fader 1986, Forbes et al. 1991, and Stea et al. 1992b and 1996. Table 2 shows approximate unit correlatives and provides a ready means of comparing the studies. The maps and profiles presented in this report differ some in unit sub-division, variously emphasizing deposit and feature types and facies but the unit numbering is consistent.

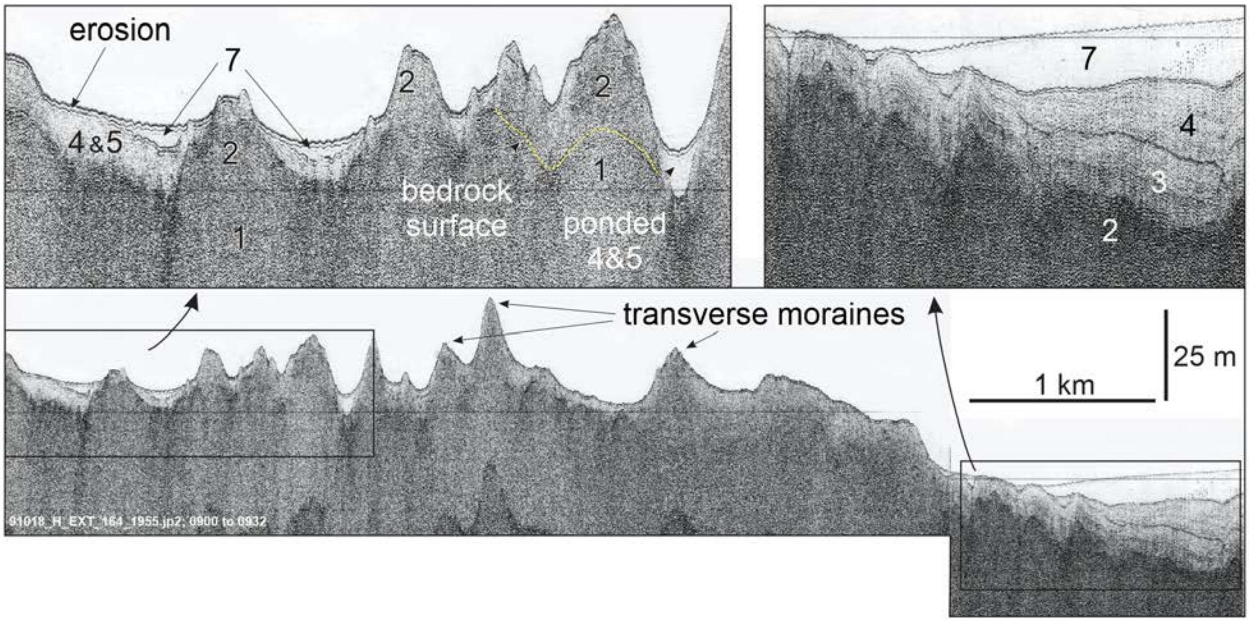


Figure 5. Boomer profile showing some of the stratigraphy of the south-central map area. Numbers correspond to the Quaternary geology map legend. Location is Line A in the maps (Figs. 1 and 8).

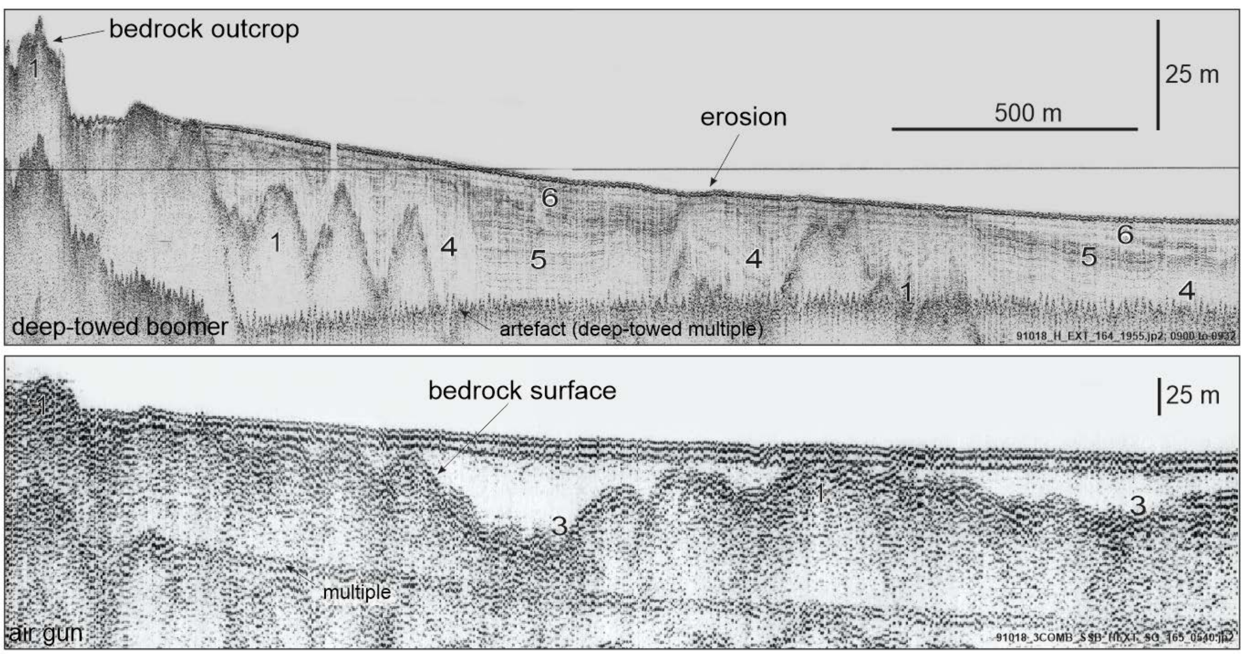


Figure 6. Boomer and airgun profiles showing some of the stratigraphy of the central map area. Numbers correspond to the Quaternary geology map legend. Location is Line B in the maps (Figs. 1 and 8).

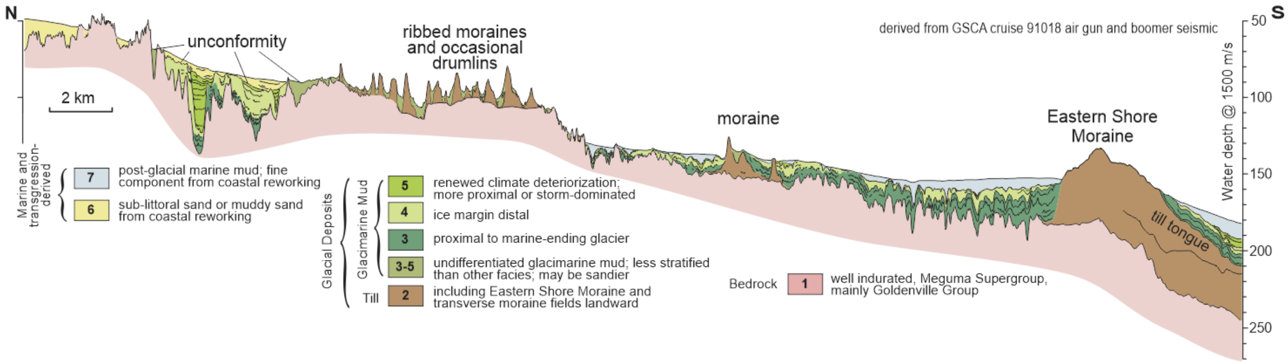


Figure 7. Geologic profile interpreted from deep-towed boomer and small air gun seismic profiles. Bedrock (pink) is hard and undulating metasediments with a general shore-parallel strike and slightly plunging anticlines and synclines. The Eastern Shore Moraine (brown) represents a post mid-shelf Late Wisconsinan marine-ending glacier still-stand and the drumlins and superimposed ribbed moraine on the inner shelf represent the latest marine phase. The stratified glacimarine mud (greens) is sub-divided into three facies, reflecting an evolution from ice proximal to ice distal conditions. The topmost of these bracket the Younger Dryas period with increased storminess and oceanographic current activity and may indicate marine-based ice in the region. Stea and Mott (1989) recognized YD age glacitectonics well to the east in Guysborough County (Colin's Pond). A sea-level low-stand at ~70 m present water depth is marked by a change from sand and gravel-mantled glacial sediments below this depth that was paleo-coastally modified above dominated by bedrock outcrop and a much thinner sediment cover with gravel and sand dominant. Abundant sediment supply with coastal erosion and wave-base smoothing deposited the locally thick sub-littoral sands (yellow), some of which may have enhanced auriferous content. The marine clay (blue) is a distal, low energy equivalent, also derived from the offshore bank transgression. Location, see Profile C on maps (Figs. 1 and 8).

Table 2. Correlation of stratigraphic units and summary of lithology and environmental interpretation

This Study	Stea et al. 1996	Stea et al. 1993	Forbes et al. 1991	King and Fader 1986	Lithology[5] (from all references)	General Environment (from all references)	
7	7	6	G	LaHave Clay	clay and silt, minor sand no gravel, bioturbated	paraglacial basin fill	marine hemipelagic; mainly transgression-derived
			E		thin sand and sandy gravel	post-transgression shoreface & inner-shelf	
6	6	4	D 3 facies	Sable Island Sand and Gravel	basal transgressive sand & gravel, lacustrine mud, estuarine mud & sand, rare tidal-inlet sand and peat	littoral: estuarine, back barrier, tidal	littoral, lacustrine and estuarine; transgressive systems tract
				Sambro Sand			sub-littoral, transgressive systems tract
5	5[4]	5		Emerald Silt, Facies B	massive, stiff mud, minor sand, some bioturbation	distal glacimarine, climate re-deteriorization	
4		1[3]	F		banded grey or brown compact mud, silt, (silty clay and clayey silt) sand and rare ice rafted gravel, some bioturbation	distal glacimarine, ice rafting, more open marine	
4&5							
4	4	3					
	3						
3	2	2	C[2]	Emerald Silt, Facies A	banded grey or brown compact mud, silt, sand and rare ice rafted gravel	ice re-advance (more proximal)	proximal glacimarine, persistent sea-ice, low energy
	1	1				ice retreat	
2	Scotian Shelf Drift	Stony Till[1]	B	Scotian Shelf Drift	clast-dominated; local derivation	Chignecto Glacial Phases 3-4	sub-glacial, time trans-gressive, ground moraine and successive moraines and drumlinization
		Lawerencetown Till			diamict; poorly sorted mixtures of mud to boulder-sized material	Escuminac Glacial Phase, 2	
		Hartlen Till				Caledonia Glacial Phase, 1b	
1	Acoustic Basement		A	Acoustic Basement	metasediment; slate, greywacke, quartzite	bedrock; glacially-sculpted substrate	

[1]*Beaver River till in study area* [2]*assigned a proximal glacial outwash origin; inner shelf area; likely sand and gravel dominated*
[3]*note the assignment of a different stratigraphic order (reassigned in this study)* [4]*Yankee Bank Fm.* [5]*where sparse, samples not necessarily representative*
~~~~~~ *unconformable*
~~~~~~

SURFICIAL GEOLOGY MAP

Figure 8 shows the surficial geology map. A larger (~43 by 68 cm) and higher resolution version is provided in the document enclosure. The digital map is presented with numerous “layers” that can be toggled to display or hide. While primarily a map showing the distribution of Quaternary sediments at the seabed, the large bedrock exposures allow some elements such as jointing, faulting and folding to be recognized. The display-or-hide map elements include the graticules, legends, index map, surround and place names, geophysical tracklines and expedition labels; linear bedrock elements including fold axes, joints, faults and fluting, strike directions (without dip); along-track point data depicting features or seabed texture details which were not possible to extrapolate for lack of resolution in the seabed relief images; pie diagrams depicting grainsize distribution, and finally, the polygon map itself. The large map version has a description of the major map units in addition to what follows.

Two map unit legends are presented; one for the multibeam survey area, where details of features and stratigraphy permit, and the other where the low resolution or sparse geophysical spacing dictates a grouping of map units.

Lithology is included in Table 2, derived largely from other publications. The map depicts both GSC-Atlantic-collected grab sample grainsize distribution summaries and CHS-derived bottom quality, classified to best match the map units. As for many Quaternary geology maps, the uppermost veneer is both difficult to recognize (without a partly calibrated acoustic backscatter image) and not emphasized to the degree that the stratigraphic unit and depositional environment are. Accordingly, sand and gravel are disproportionately represented in the sample designations; they occur as a thin veneer across many of the map units. Till has a greater gravel component while glacimarine has a high sand component in the veneer. The mud map units match the sample grainsize more faithfully.

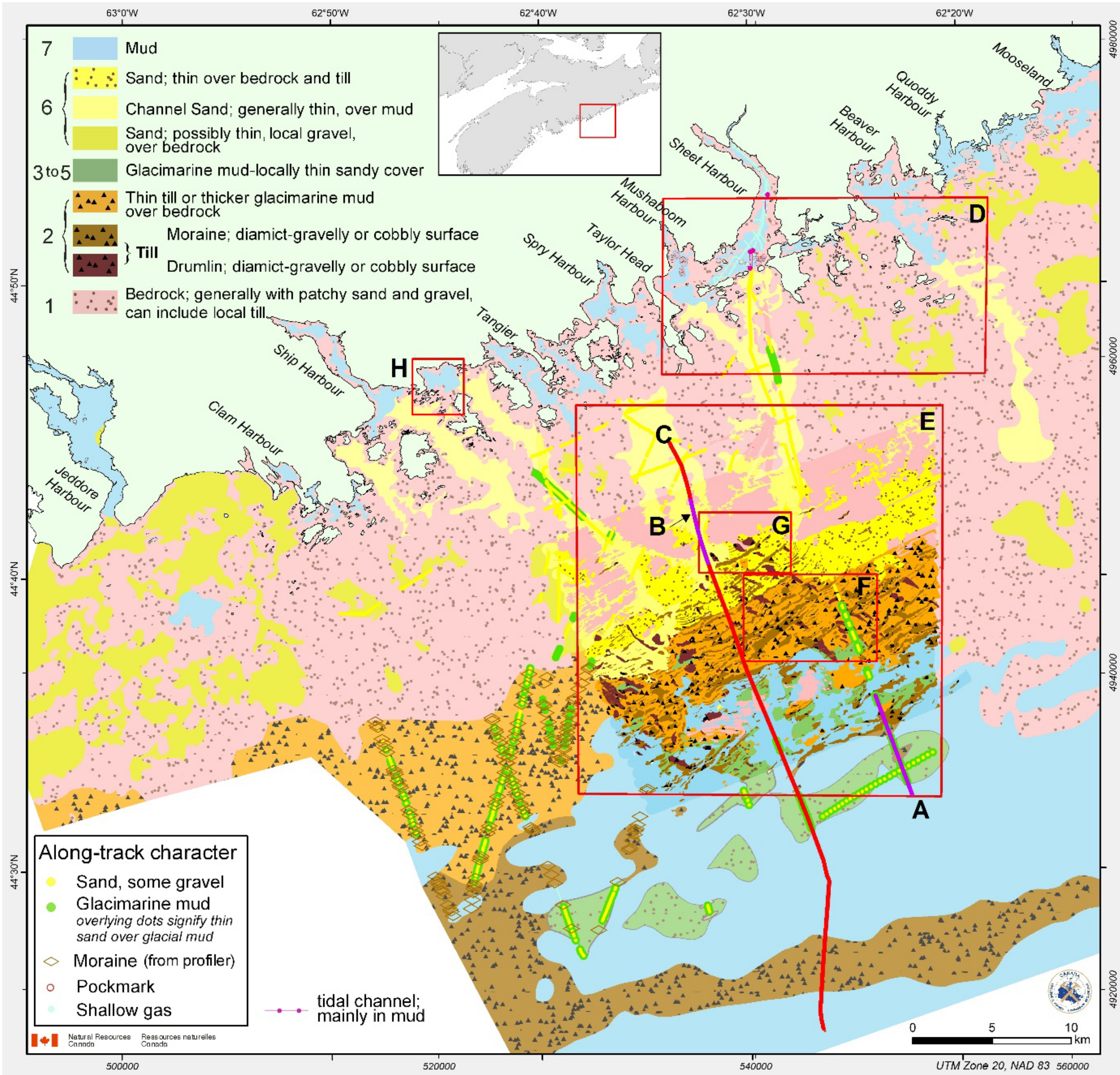


Figure 8. A multi-resolution surficial geology of the area offshore Clam Harbour to Mooseland along the Eastern Shore of Nova Scotia. Data control for the map is shown in the previous illustration. Accompanying illustration locations outlined in Boxes A through H (in red). The multibeam survey area (Box E) serves as an archetype for the broader map area. A broad zone dominated by bedrock outcrop with incised mud and sand filled channels is flanked offshore and landward by thicker and varied sediment types. These include soft mud, gravel and boulder-rich till, bedrock outcrop, and sand and gravel. Spatial variability is high, as illustrated in the central detailed areas, Boxes D, G and F. The document enclosure is a higher resolution version of the map.

Figure 9 is a more detailed map compiled from the higher resolution multibeam bathymetric survey data.

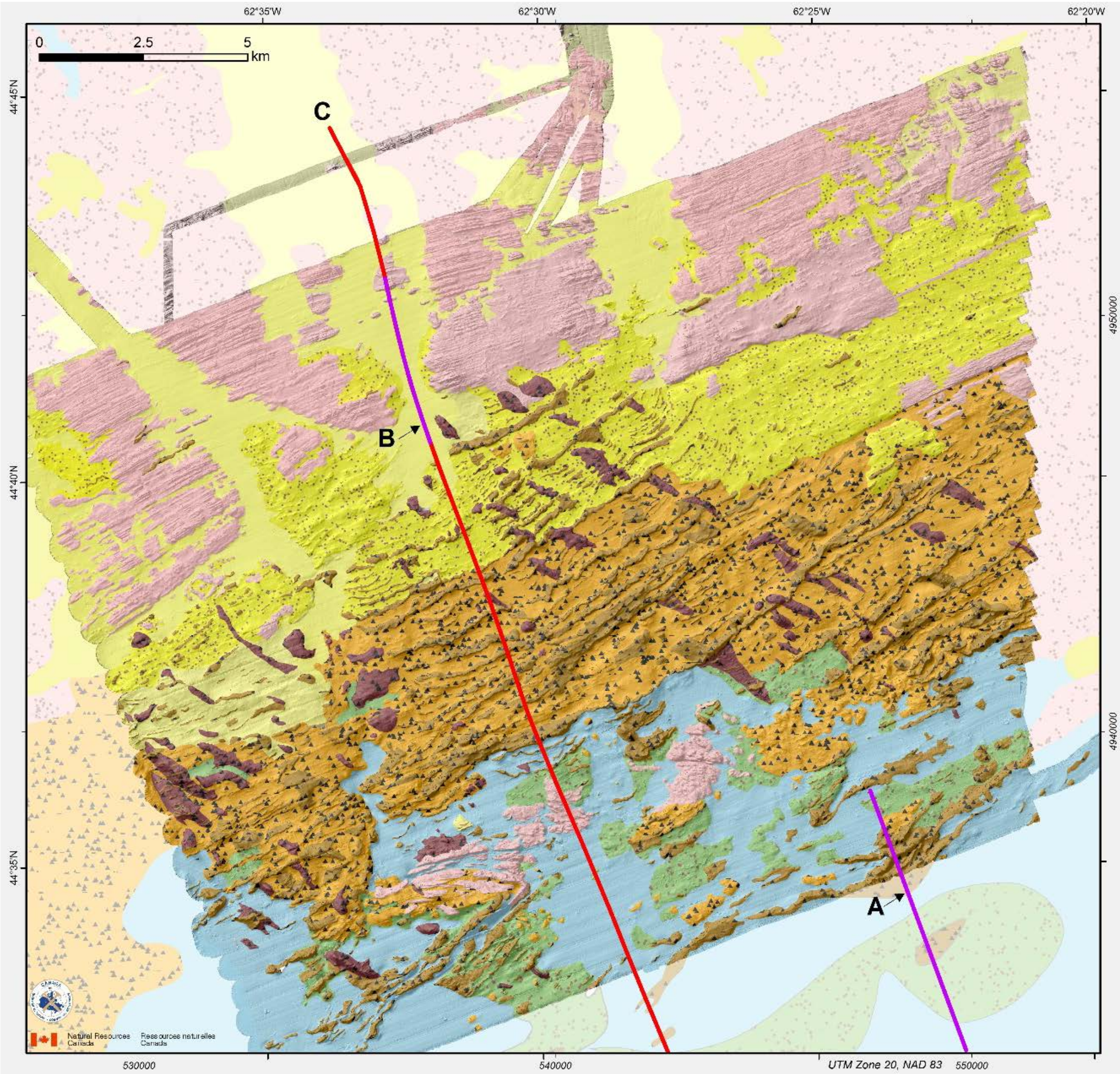


Figure 9. Surficial geology rendered slightly transparent across the multibeam bathymetric shaded relief image with subdued tones in the surrounding low-resolution map area. Location corresponds to Box E in Figs. 1 and 8. Legend as per Fig. 3. Note that there was too little control to extend map unit details along the eastern boundary but this was more successful on the western and northern boundaries. The southern extent is modified after the offshore map (King 1970).

Figure 9 presents details mappable with multibeam survey coverage. Figures 10 and 11 are further detailed views. Fig. 10 highlights the moraines and drumlins and Fig. 11, the bedrock outcrop, washed till and sand units.

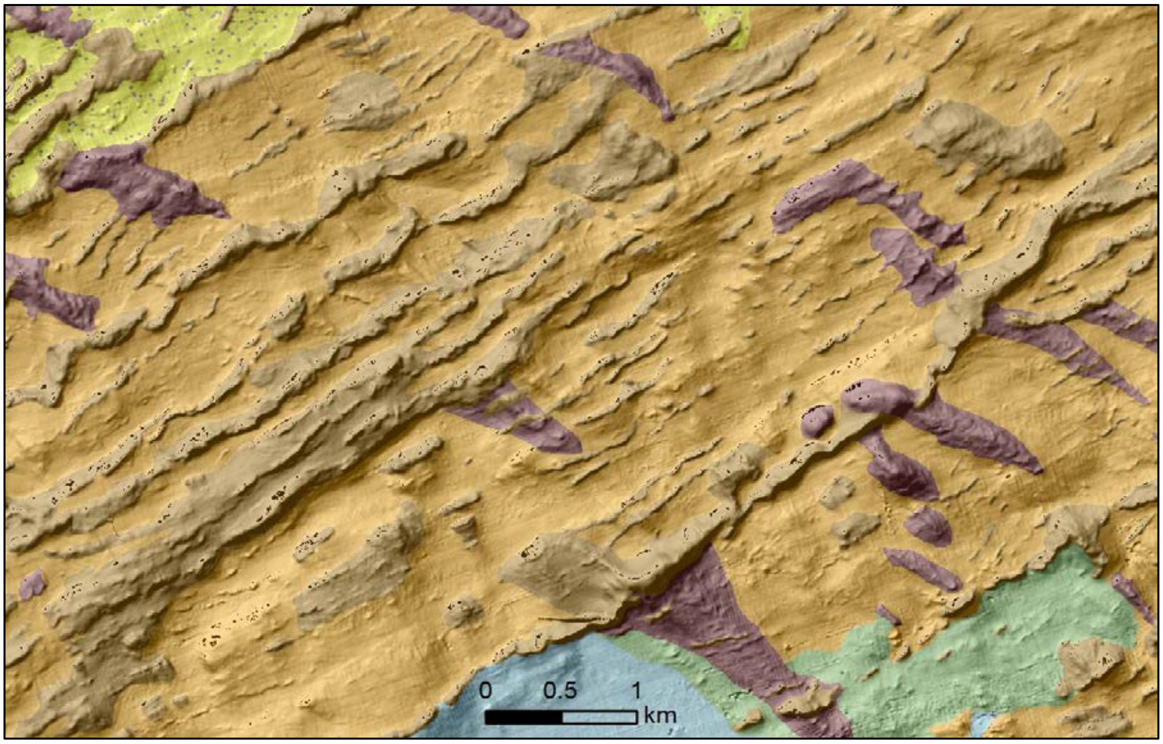


Figure 10. Detail of the Quaternary geology in the area of multibeam bathymetric data. The map is rendered transparent, revealing the topographic expression of the features. See legend in map. Location is Box F of the maps (Figs. 1 and 8).

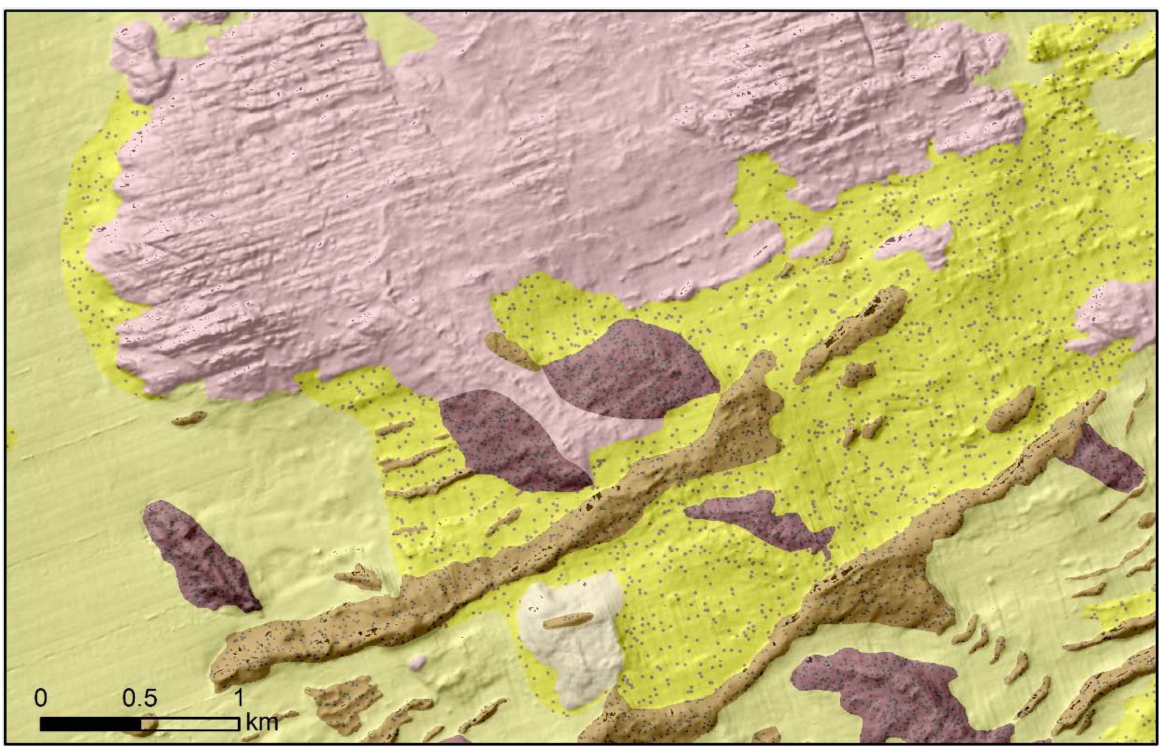


Figure 11. Detail of the Quaternary geology in the area of multibeam bathymetric data. The map is rendered transparent, revealing the topographic expression of the features. See legend in map. Location is Box G of the maps (Figs. 1 and 8).

Bedrock

Seabed character of the inner Scotian Shelf along the open Atlantic coast is primarily governed by the bedrock morphology. The hard meta-sedimentary rocks comprising Meguma Supergroup (~450 to 500 million years before present and older) have undergone a long history of metamorphism, folding and minor faulting.

The bedrock (map unit 1) offshore continues from the adjacent land along the entire Eastern Shore. It comprises metasediments of Lower Paleozoic age belonging to the Goldenville Group, dominated by greywacke and quartzite and overlying slate-dominated rocks of the Halifax Group. A Devonian granitoid batholith crops out about 10 km north of the coast along the western half of the map area. Harder, generally sandier beds stand proud of softer, slate beds with several metres relief, giving a jagged topography with long ridges and valleys. Occasional faults (inactive) and jointing add to this relief. The bedrock type here is recognized from the outcrop morphology alone; samples, other than that transported in overburden, do not exist (King and MacLean 1976). The pattern of these beds includes broad folds with plunging axes at several kilometres spacing, giving rise to a chevron pattern of V-forms in plan view. Sculpting from multiple glaciations adds to the relief.

Landward of about 100 m water depth the relief is quite pronounced. It is sometimes termed the skerry zone, especially where it has a highly undulating relief, as is the case here. This bedrock topography can have a strong influence on the type and distribution and especially the patchiness of surficial deposits where bedrock is not fully buried. The coastline and especially the outer islands are primarily bedrock controlled and this character continues seaward to the paleo-low-stand of sea level at ~70 m where sediment cover thickens.

The deep channels cut in bedrock and largely filled with glacimarine mud and the Channel Sand map unit (6) and the elongated orientation of the inner-shelf mud deposits have a clear relationship with the bedrock topography. They are sub-parallel to the faulting observed both onshore and offshore. The glacier that sculpted these was likely strongly influenced by these bedrock weaknesses as some phases of regional ice flow directions match them (further discussion on flow directions later). Both Ship Harbour and Sheet Harbour have some fjord-like character but display a marked swing in their trends about mid-harbour, further suggesting a structural control.

Glacial deposits

The Scotian Shelf Marine Sciences Papers surficial geology maps of the 1970's by L,H. King and co-workers (c.f. King 1970; digital and shelf-wide version Fader et al. 2004) provided a stratigraphic formational classification of the area. Since then this has been refined, locally subdivided, and assigned basic age constraints. Till or glacimarine sediments lie directly on bedrock in the area seaward of about 70 m water depth.

Till (unit 2): The large end-moraine complex, here termed the Eastern Shore Moraine (King 1970) is a 40 to 50 m thick, slightly convex ridge of over 50 km length flanked on both sides by stratified glacimarine and marine muds (Fig. 8). The seaward side has a 20 m thick till tongue, shown, far right in Figure 7, interfingering with the stratified sediment and representing a minor adjustment of the grounding zone of a floating glacier margin (King 1996). Landward of this, till is generally sparse or absent except for a mid-sized moraine, centrally located on the map. It is over 20 m thick and ~10 km long. In the zone from ~110 m to ~80 m water depth is a 6 to 8 km broad field of smaller ribbed (Rogen or deGeer) moraines, typically 5 to 20 m high, 2 to 5 km long and spaced 500 m. Much smaller examples are interspersed, typically 2 to 5 m high, less than 1 km long, and spaced at under 100 m. They generally express greater sinuosity. The moraines extend both east and west, beyond the multibeam survey area. Though recognized in seismic profiles as extending to the western map limit, only limited sidescan data identify their presence east of the multibeam survey area. The smaller moraines are commonly slightly arcuate, concave down-ice and arranged such that their pattern forms coherent groupings of matched curvature (Figs. 9 and 10). Below the low-stand, where truncation is not readily evident, the till is somewhat continuous as a thin blanket between the moraines. This is designated “thin till or thicker glacimarine mud over bedrock” in the map.

Drumlins or drumlinoid features are also recognized but present a more subtle character. They are only preserved in the moraine field area (Fig. 10). They are recognized by a consistent NNW-SSE orientation (~120 degrees) on ridges only metres high. They are not oriented precisely normal to the moraines; ice flow direction from those is ~150 degrees. Most have superimposed ribbed moraines, indicating their formation at an earlier glacial phase.
The preservation of the moraine fields is related to the ~70 m low-stand. Above this the glacial section that is not buried deeply has been washed and largely destroyed; former extent of the drumlins and moraines is not discernable.

Glacimarine mud (units 3 to 5) crops out in the deeper water on topographic rises where it is lapped by the later marine mud (Figs. 7 and 8). It is usually topped with a thin sandy lag. Otherwise, it sub-crops sand and gravel lag of the Channel Sand facies of unit 6. Here it is up to tens of metres thick (Fig. 7). Locally developed unconformities are evident especially in the deep channels, apparently as multi-generational channel fill, consistent with findings of Forbes et al. (1991) and Stea et al. (1996).

Late and post-glacial deposits

Sand and gravel (unit 6) is mapped as three different sub-units, more based on mapping technique than facies differences. In the multibeam survey area, a washed surface flanking the topographic highs (bedrock and till) is clearly a wave-modified product. Morphology of the till and bedrock remains, indicating a thin sand and gravel veneer. This is designated “Sand; thin over bedrock and till”. Given the source and processes sand is largely inferred with a largely undetermined gravel component. Limited sampling generally shows greater than 75% sand.
The deep channel fill is mud-rich but the transgression has worked it into sand and gravel at its surface. It is locally several metres thick, probably because the channels remain as topographic lows and hence depocentres for the transgressed area. This is designated “Channel Sand; generally thin, over thick mud”.

Where the channel fill topography is not readily evident in the low resolution bathymetry areas, the map unit designation is “Sand; possibly thin, local gravel, over bedrock”, reflecting the more limited information across this area.

Marine mud (unit 7) is the latest major depositional unit, ponded in topographic lows in a much more contiguous deposit than the other map units seaward of the low-stand. It laps both the glacimarine and till units and reaches several metres thickness in the offshore, Fig. 7. In the inner harbours and bays, basinal Holocene marine mud deposits are common. Locally, estuarine or lacustrine and coastal deposits have survived the post-glacial transgression (c.f. Forbes et.al., 1991, Fader et.al. 1993) and are either exposed or slightly buried. It can reach several metres thickness. Tidal channels and meandering channels formed in the mud may have maintained the general pattern of river valleys inherited from the low-stand, for example, throughout Sheet Harbour. However, the relative sea-level may not have allowed much sub-aerial exposure or time to develop river systems. A double (adjacent, parallel) channel at the outermost mouth of Sheet Harbour (see Enclosure) demonstrates tidal influence more than inheritance of a paleo-fluvial system.

Shallow gas (likely methane) is locally pervasive in the harbour settings. The entire mud unit in Sheet Harbour registers shallow gas just below the seabed in sub-bottom profiler data (Enclosure). This is the only harbour locality with such data coverage in the map area. Given this, the ubiquity of shallow gas in most of the harbours can be inferred. Pockmarks, likely from mud erosion with periodic escape of this gas, are only recognized in two of the harbours (from multibeam, profiler and LiDAR data).

Map Limitations

Limited spatial coverage

Given the spatially and thematically diverse dataset, the map product has limitations. Clearly, the multibeam coverage allows a detail not possible from the low resolution and seismic-only areas. This requires an amalgamation of map units which cannot be differentiated here. For example, the “Thin sand with scattered outcrops” unit in the multibeam area is largely recognized by a subdued morphology of the glacigenic units due to the high energy paleo-coastal process to which it was subjected. Also, the drumlins and superimposed moraines can be recognized from seismic traverses but cannot be defined as individual polygons outside the multibeam bathymetry area. The same applies to the channel fill of glacimarine mud; its presence is documented but map contacts are necessarily very generalized or not depicted at all. Accordingly, the “thin sand with scattered outcrops”, the “moraines over drumlins”, the “moraines”, the “thin till or glacimarine mud over bedrock”, the “modified glacimarine mud”, and the “sand cover over modified till and/or glacimarine mud” are all merged into one map unit outside the multibeam coverage. This is termed “glacigenic sediments of variable thickness” recognizing that all elements are present.

To somewhat offset this inability to map units due to insufficient topographic information, the map also includes an along-track characterization compatible with the map units. This is presented with overlapping coloured symbols identifying the surficial texture and the immediately underlying stratigraphic unit type. It imparts a sense of the spatial variability without falsely implying boundaries.

The southwest corner of the map has some geophysical data but inadequate topographic resolution for mapping while the SE map corner suffers from very low resolution topography and a lack of geophysical coverage. As such, this has the lowest level of confidence on the map polygons and boundaries are suspect here.

In the offshore, below about 130 m water depth, the polygons are heavily drawn from the King 1970 map, based on relatively closely-spaced MS26B echosounder transects. The old echosounder records had significant limitations. Accordingly, polygons there have been modified some (contacts adjusted and some reassignment of map unit) based on the 1988 and 1991 geophysical sonar data.

Comparison with video transects

A comparison of map polygons with the Vandermullen (2018) station data provides excellent groundtruth for the mainly morphologically-based surficial geology map. Video transects conducted by DFO in 2017 cover a portion of the innermost shelf and have been compiled for initial benthic species identification (Vandermullen 2018). These summaries are presented at about 600 m spacing camera drops or “stations” along the transects, most of which start or end and radiate from islands or headlands. He also characterized the seabed into four classes, each covering: mud and sand, gravel, cobble and boulder, and ledge (outcrop). Figure 12 shows the transects and substrate summaries.

Note that these data were only available after the map compilation; several polygon contacts were slightly adjusted to better match the video data in the area of lowest resolution data coverage. Spatial diversity of observed classes within each camera “drop” station (multiple classes per drop) precludes direct percentage calculation of individual classes without a normalization.

Video-based identification of stations located within the “mud” polygons, includes 42 of 46 stations with “mud and sand” occurrences, 7 of 46 showing gravel, cobble and/or boulders while 7 of 46 identify bedrock. The bedrock “discrepancy” is simply imprecision in map placement of the contact between the sand or mud and the bedrock polygon; most examples of discrepancy were well within 100 m of this contact. Vandermullen (2018) does not differentiate mud and sand from the video, unlike the GSC map. A significant sand component in the mud is expected at some locations, especially the more seaward. The same boundary proximity error applies to the very coarse sediment component.

Only 15 of 155 bedrock observations on video fall within the “sand” and “channel sand” map polygons with the remainder correctly showing sand and gravel on the video. Again, the polygon boundary proximity positional error explains much of this.

The “bedrock and patchy sand and gravel” map polygon is clearly bedrock-dominated yet, without the video, it was not possible to quantify the proportion of local cover by sand and gravel patches at the seabed. The video results indicate 121 of 265 outcrop observations within the polygon. The bedrock is generally strewn with gravel and cobbles/boulders. Fully 192 of 265 record gravel and/or cobble and boulders in addition to the bedrock.

At 80 of 265 stations, mud and/or sand (likely sand) occurs within the bedrock-dominated polygon, generally confined to the narrow troughs between protruding bedrock ridges. Only 24 of 137 bedrock stations have superimposed sand or mud in the videos (likely sand-dominated). Figure 13 shows a normalized presentation of these values, highlighting the general agreement between the nearshore detail from the video transects and the map unit polygons.

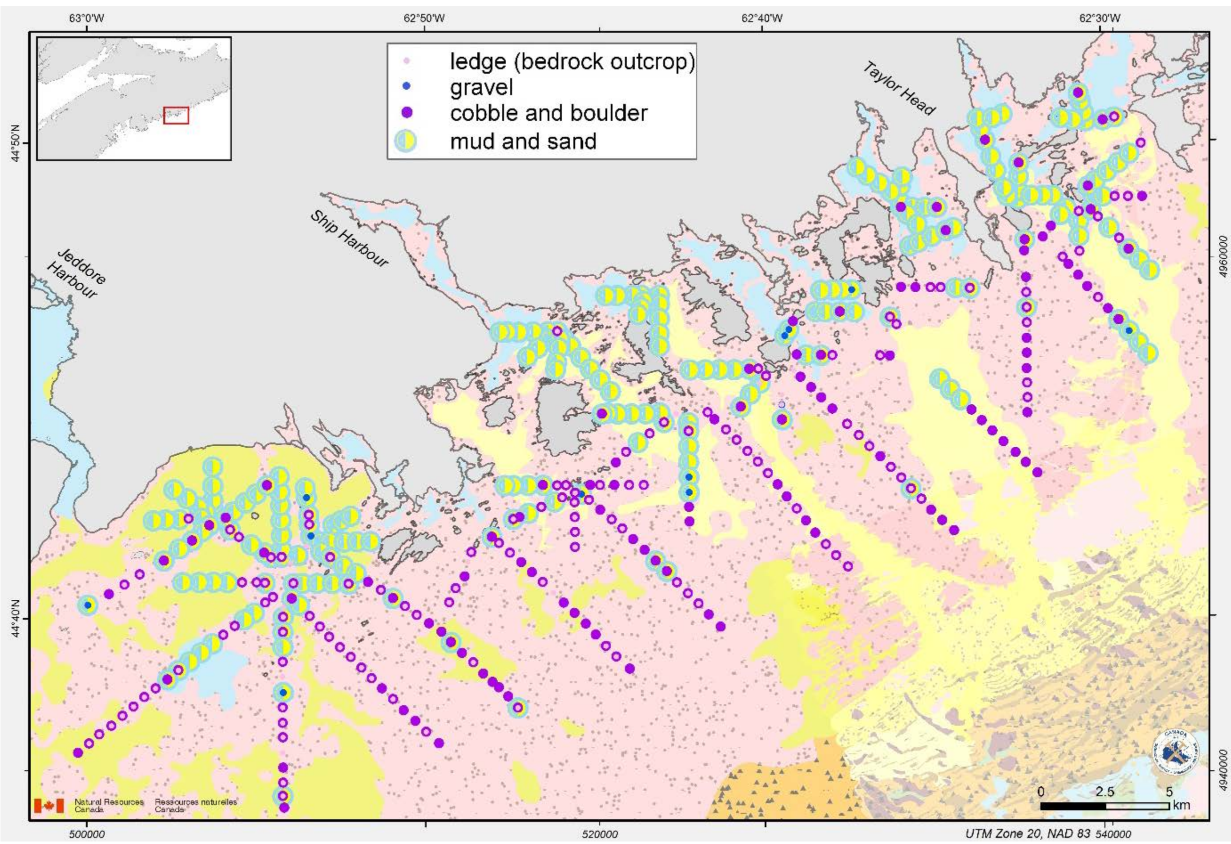


Figure 12. Substrate type from video transect drop stations (dots, from Vandermullen 2018) superimposed on the map showing the general agreement from independant data. Observations of multiple seabed types are overlain, utilizing different symbol sizes.

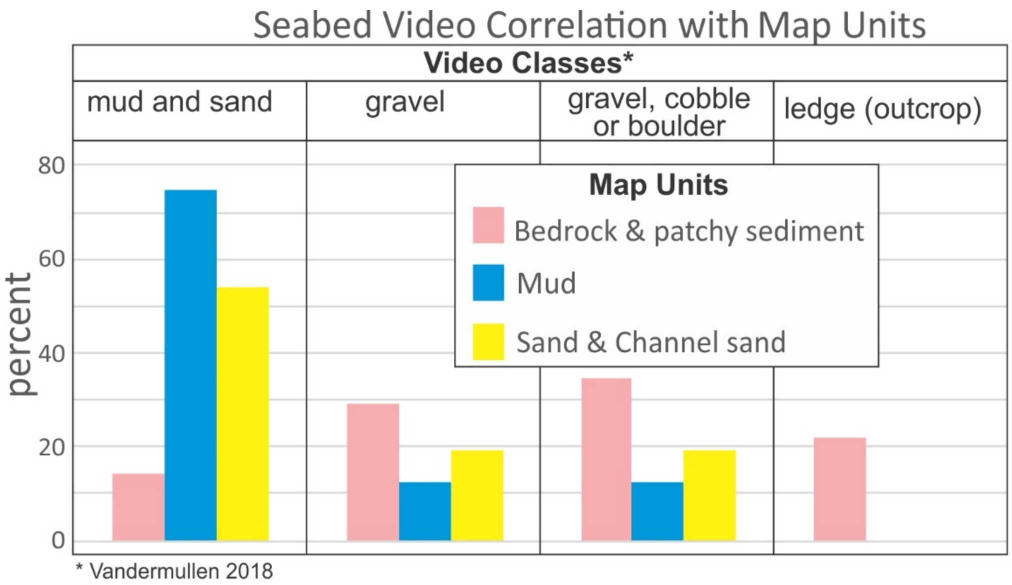


Figure 13. Match between morphology and limited sample based map and video drop classes.

New and underutilized LiDAR bathymetric data

CHS has recently collected airborne based LiDAR data of the area. These data provide better than 5 m resolution (locally far better) in water depths up to 15 m in some areas (depending on water column clarity). This represents an order of magnitude better resolution for the nearshore area, potentially two orders of magnitude in very shallow areas. Non-rigorous examination of derived topographic images shows that the concepts and generalized map unit boundaries are valid but that considerable detail improvement is possible in the zero to 15 m water depth range. Specifically, the present map boundaries commonly do not identify the individual, small bedrock outcrops faithfully. Nor are bedrock-mud and bedrock-sand contacts placed as near to the bedrock contact as is possible with the new dataset. The new data also allow some differentiation of bedrock from till and till-covered bedrock not possible from the low resolution images. Figure 14 compares the map with an update based on the LiDAR, for a small area only. Typically, the map unit contacts are displaced 50 m to 300 m away (deeper) than the actual positions. The LiDAR images also depicts geo-features not discernable from the older data. These include but are not limited to:

- occasional narrow (10 to 25 m wide) current-generated or maintained troughs in mud between islands or submerged outcrops
- submerged coastal features such as bars, spits, beach ridges, sand platforms, wash-over, tidal channels, ice-push ridges
- pockmarks
- moraines and possibly sand dunes;
- collapse or gas escape troughs in mud

Access to (available) higher resolution data will clarify and enhance feature recognition and interpretation.

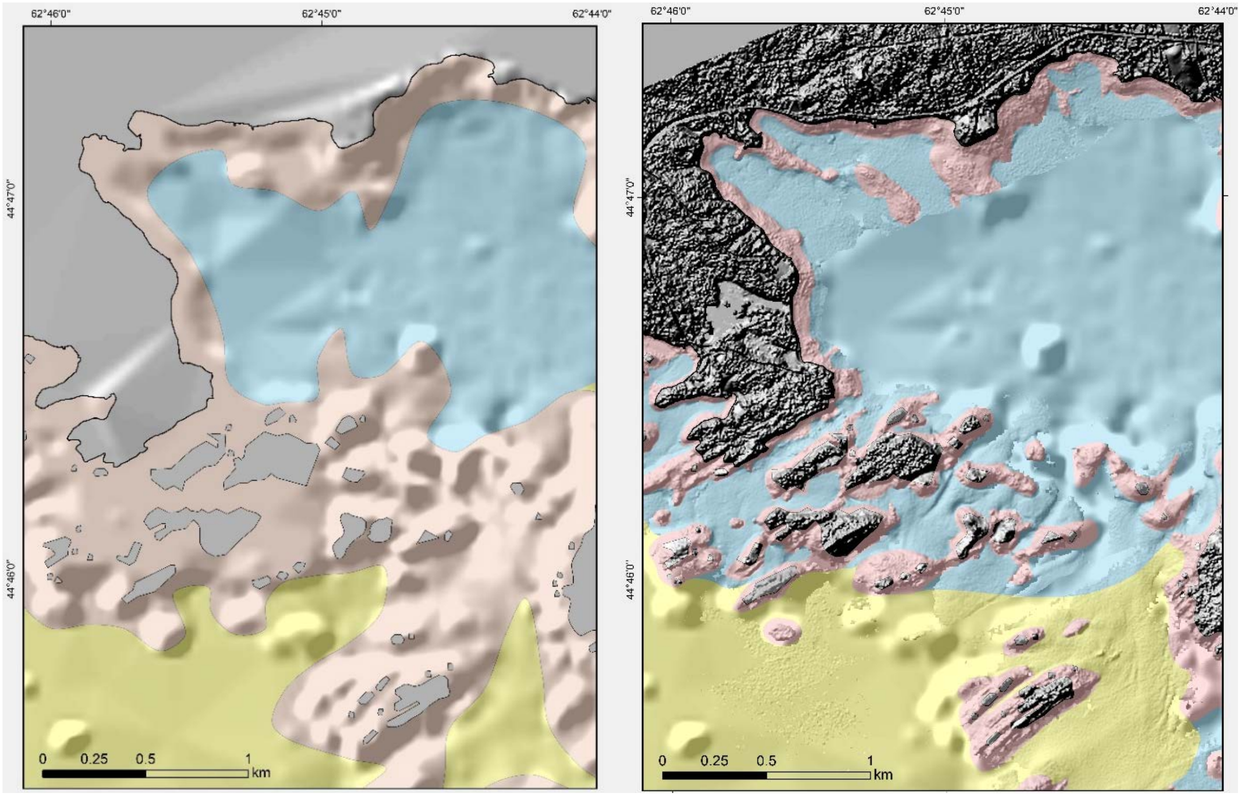


Figure 14. Comparison of detail map boundaries derived from CHS bathymetric LiDAR data versus fieldsheet spot depth data. The extent of the mud is better discerned, including through passages between islands and ledges. Note the current-formed troughs in the mud. The LiDAR also allow some differentiation of bedrock from modified till, for example on the two promontories extending south from the northern bay shoreline. There, the typical ridge and trough of bedrock bedding is absent, displaying a roughness characteristic of beach-modified till, with cobbles and boulders. This differentiation is not depicted in the map unit polygon. Location is Box H of the maps (Figs. 1 and 8).

DISCUSSION: GLACIAL RECONSTRUCTION

Stea et al. (1996) developed a deglaciation model based largely on the map area. With chronology largely based on cores in the area or nearby, they presented a scenario of continuous deglaciation beginning with Eastern Shore Moraine development between 16 and 15 ka (conventional C-14 ages reported) with retreat to an interim moraine by 15 to 14 ka, followed by formation of the ribbed moraine fields by 14 to 12.8 ka. This phase is tied to the Scotian Ice Divide. Sea-level study by Stea et al. 1994 indicates a sea-level lowering as isostatic uplift outpaced eustatic rise and a subsequent relative sea-level lowering and low-stand timing about 11.7 ka. They place glacier retreat to a position near the present coastline between 12.8 to 12 ka. By this time, Stea et al. (1996) recognize a regional ice flow with a strong SW component associated with the Chignecto Phase. Much of the wave-base erosion occurred at this point. The deglaciation was interrupted somewhat by a return to cooler and stormier conditions during the Younger Dryas, correlated to a local unconformity and change in glacimarine mud character.

The present study can contribute to the above glacial reconstruction scenario, primarily through an improved onshore-offshore correlation, presented in the following discussion, based on a better understanding of the flow regimes and flow phases.

Moraine field and ice flow regime

Figure 14 shows the ribbed moraine field with crestline tracings to accentuate their plan geometry. A cuspate character is apparent in many. Cross-cutting of moraines may be present; some ridges intersect others. However, local differentiation of bedrock ridges and moraines can be challenging. Indeed, the bedrock likely pins or nucleates the moraines. Individual zones with as little as 2 km (flow normal) spacing are recognized.

Similar cuspate moraines occur in the Bay of Fundy (Todd and Shaw 2012, Figs. 13 and 14), ranging from 5 km to 300 m spacing. Morphologies off the Eastern Shore are nearly identical to those on German Bank (near the mouth of the Bay of Fundy (Todd et al. 2007, Fig. 6), including scale and nesting of small cuspate zones within larger cuspate morainal zones.
There is longstanding discussion in the literature of the mode of formation of such ribbed moraines. Both sub-glacial and glacier front models are common. Stea et al.'s (1996) glacier reconstruction indicates sub-glacial moraine formation at basal crevasses though without much critical discussion. Todd et al. (2007), in recognizing the nesting of large and smaller moraines and cross-cutting relationships favour the De Geer Moraine school emphasizing near ice-frontal push, generally annual, with progressive retreat such that the features are preserved.
In recognition of the cuspate patterns (Fig. 15), groupings of zones with common patterns has been suggested, separated by the green dashed lines. The grouping attempts to separate zones of the small, arcuate moraine fields, each with independent cuspate plan morphologies. Zones are as little as two km wide, in likeness with the Bay of Fundy and German Bank examples) though narrower flow separations are common on valley glaciers.

The cuspate morphology suggests slightly independent flows such that relatively faster flow in the center bulges the grounding zone (hence the moraine curvature). If so, the green lines would be positions in the glacier subject to some differential longitudinal shear, possibly with associated crevasses. The grouping of some reflects individual glacier lobes. If this reasoning is correct, it favors a near ice-frontal interpretation (similar to De Geer moraines) over the basal crevasse model where feature preservation requires a near vertical lift-off of a floating ice (shelf). Indeed, the Eastern Shore examples exhibit a very similar moraine-crest water depth. Both models point to a floating, near-floating or marine-ending glacier.

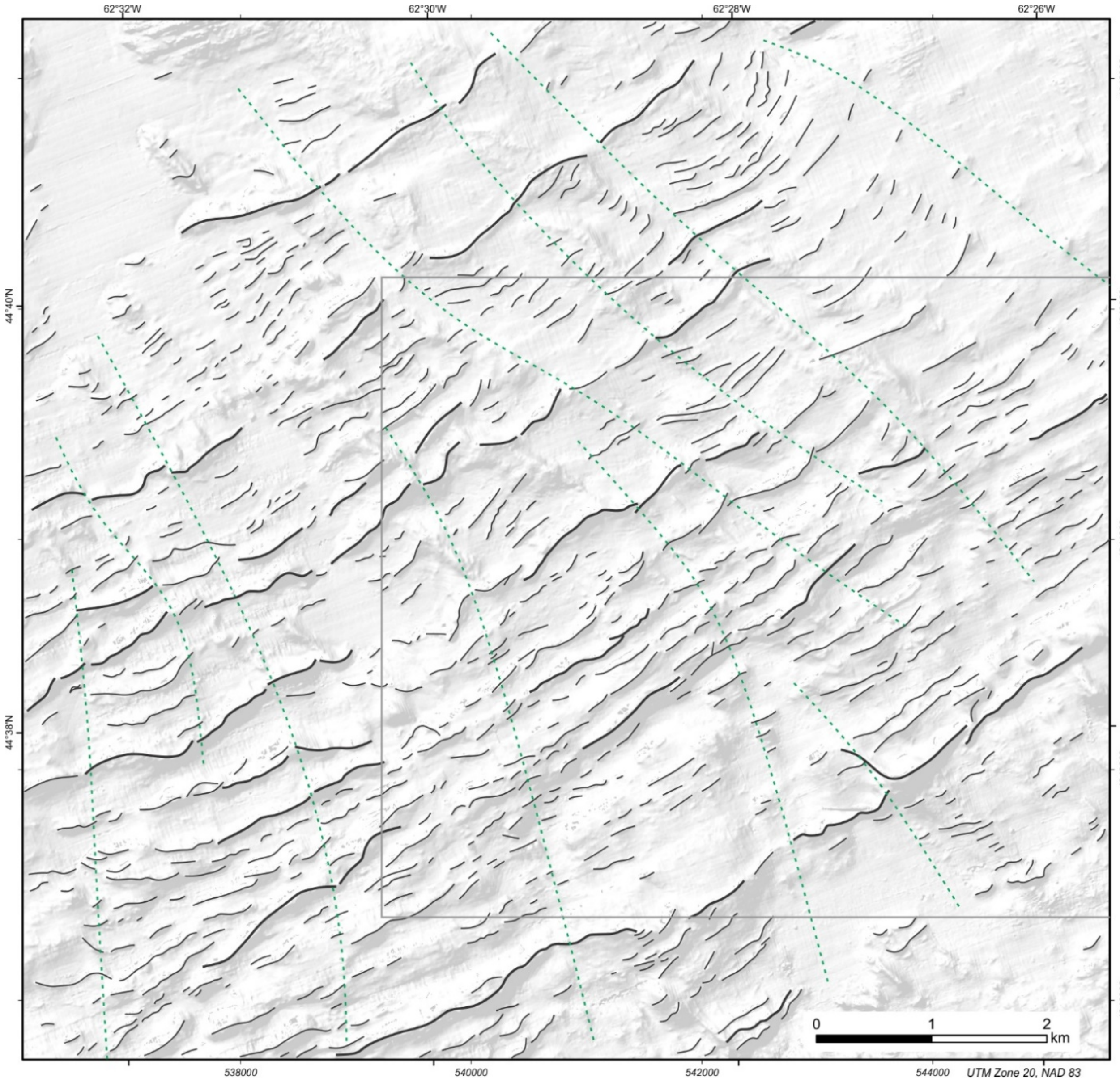


Figure 15. Traces of ribbed moraine crestlines across a portion of the multibeam bathymetry survey. Heavier lines represent the larger moraines. Dashed green lines separate subtle zones of like pattern suggested to mark longitudinal crevasse or flow shear in the glacier. Grey box is location of Fig. 10.

Glacial ice flow directions and relative age

As glaciation retreat progressed, the ice divide migrated from a continental to more local scale, eventually thinning such that local topography directed ice directions. On a regional basis, the evolution of the flow patterns (governed by ice divide migration) has been unravelled by Stea and co-workers (1992a, 1993 and 1996). Their deductions evolved, so multiple versions are in print, but the Stea (1996) work presents the latest, including a tie to the offshore (Fig. 16). Until the multibeam data were collected, orientation of the offshore moraines was unclear and the drumlins were not recognized. The onshore elements include fluting, striae and drumlins; two fields with different orientations are outlined Fig. 17. Further ice flow indicators include striae at Taylor Head (Fig. 18). The new mapping presents the opportunity to compare onshore and offshore elements. The offshore direction indicators include drumlins, moraines, the deep, infilled bedrock channels, and, though not commonly observed, fluting. Only two ice directions are discerned in the offshore, one represented by the drumlins, and a later one that swung more southward, represented by the retreat phase moraine field. Summaries of the regional flow directions and relative timing are shown in Fig. 19. Box “a” includes the directions of regional ice divide phases from Stea et al. (1992a, 1993), box ”b”, the onshore (coastal), and box “c”, the offshore (inner shelf) flow direction indicators, each sub-divided by glacial feature type. Bedrock lineation orientations, box “d” are included for directional comparison. Note that bedrock strata strike and fold axes are omitted; they are generally normal to the ice flow here.

Combined, the flow directions are confusing (Fig 19, box e). However, based on orientation alone, and irrespective of feature type or relative age, three strongly grouped directions emerge, each with elements conforming to within about 3 degrees (Fig. 19 f). In summary, the onshore-offshore record on the Eastern Shore closely matches the (Late Wisconsinan) Caledonia 1b, the Escuminac (2), and the Scotian Phases (3). The final, regional Chignecto Phase (4) is not evident here, offshore or on land.

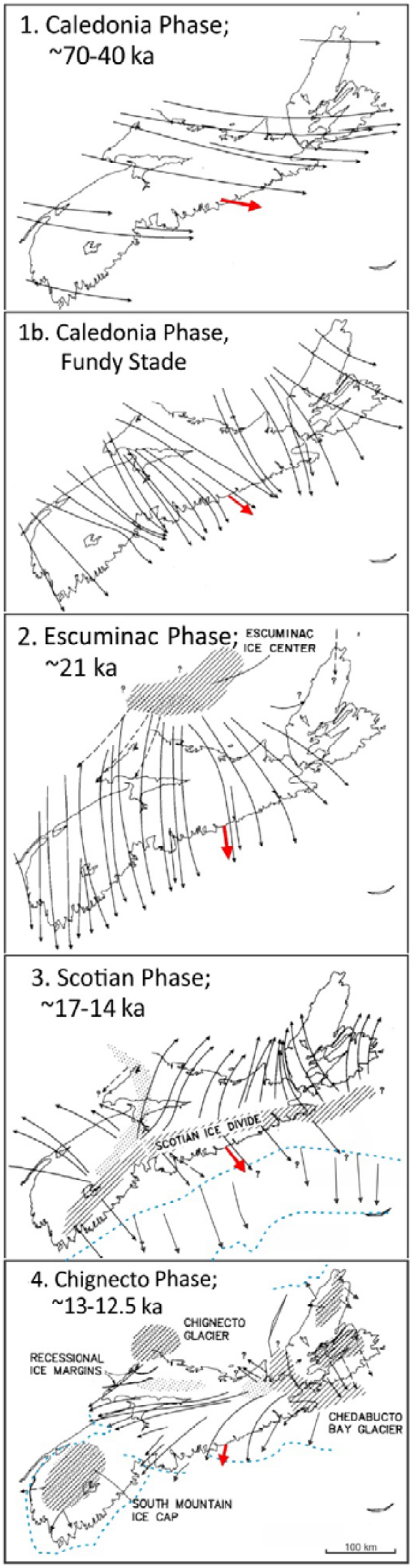


Figure 16. Evolution of glacier phases, divides and direction, modified from Stea et al. (1993 and 1996). Blue dashed lines are offshore glacier margin reconstructions. The red arrows highlight the map area flow directions from which Fig. 18a arrows are derived.

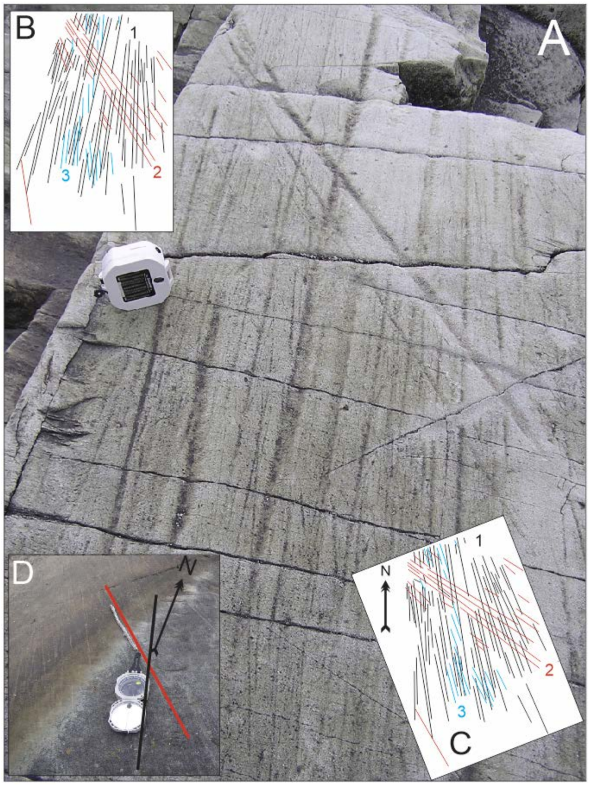
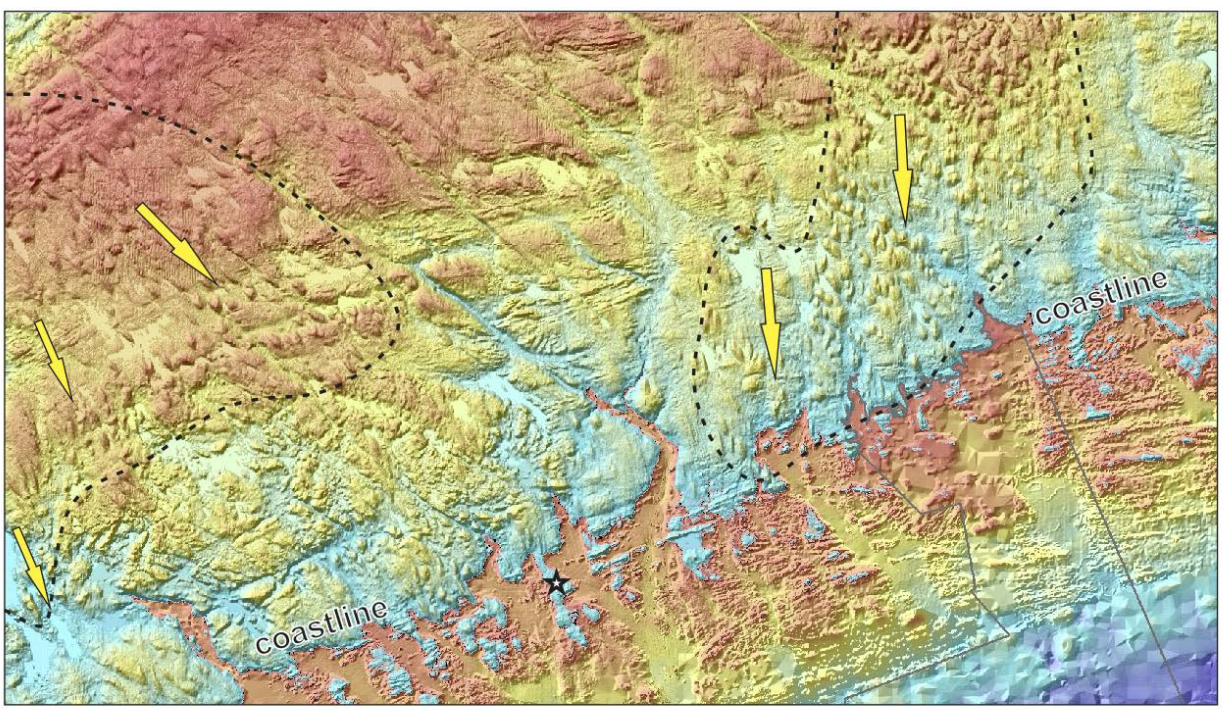


Figure 17. Glacial striae directions at Taylor Head. Boxes B and C are tracings of Box A striae, C is oriented to north. Numbers indicate relative age, with the blue sub-set representing the latest flow. Splay is apparent, due to perspective. D is nearby with lines showing the two main orientations.

Figure 18. Shaded relief of onshore and offshore in the map area. The rainbow colour (red upland, blue lowland) cycles such that the coastline juxtaposes blues on land with reds offshore. Drumlin fields on land are outlined. Star shows location of Taylor Head striae measurements.



There is one enigmatic mis-match between the onshore and offshore glacial directions. The dominant fluting and striae direction at Taylor Head (Figure 19b, direction 1) is mid-way between regional Scotian and Escuminac phases and has no recognized offshore equivalent. It is grouped with the Chignecto direction as ‘not represented” (Fig. 19 f, left side). A local ice steering may be responsible. The bedrock lineations (offshore and onshore, Fig.19 d) span more than the range of the glacier lineations, however, the overlap is strong. It raises the question if the bedrock is governing the ice flow or if the ice flow is accentuating the bedrock lineations through their preferential erosion. The latter seems more plausible; had bedding strike and fold orientations matched ice flow, presumably, those orientations also would be enhanced. The land-based drumlin flow directions match the Escuminac (2) and Scotian (3) Phases closely, reflecting the ice divide migration. Yet in the offshore the drumlins only match the Caledonia 1b phase. The offshore moraines were formed when the ice divide had migrated eastward to flow up to 30 degrees more southerly (Scotian Phase). Stea et al. (1995) demonstrated from till clast lithology that this phase matches the Eastern Shore and later ribbed moraine field and correlates with the Beaver River Till (Stony Till) on land. The two phases represented by these flow directions, Caledonian (1b) and Scotian (3) are not sequential; the Escuminac Phase (2) intervenes. This implies that the offshore drumlins survived erosion during the intervening Escuminac flow. Nevertheless, the offshore bedrock channels match both the Escuminac (2) and Scotian (3) Phases closely.

The lack of any manifestation of the latest, Chignecto (4), ice direction in either the coastal or the offshore suggests this phase did not extend this far west from the . Surely an imprint across the multibeam survey area would reveal this, were it the case that Chignecto ice reached here. Even the very fine-scale moraines conforming in direction to the earlier Scotian Phase are preserved. This indicates that the Chignecto ice margin, if indeed it reached the marine realm, lay landward of the multibeam survey. Apparently, because the features were subsequently destroyed with the transgression, there is no record. The reconstruction of Stea et al. (1996) shows limited offshore ice extent, emanating from Cape Breton, with the margin crossing from offshore to onshore in the vicinity of Jeddore Harbour. The new observations necessitate a (minor) landward shift of this margin about 20 km, or more. This would place the glacial margin shoreline crossing eastward, to at least Taylor Head, but compatible striae were not in evidence there either. If there is, indeed, an offshore Chignecto Phase ice margin, multibeam surveying below the low-stand between the map area and Country Harbour is required to document it.
In summary, reconciling ice flow directions in the map area with the regional ice flow phases confirms a close match on all but one count (one Taylor Head fluting/striation). Accordingly, there is no evidence of independent offshore ice caps or divides, at least across the inner shelf. The ice sheet which produced the last known imprint in the map area was during the Scotian Phase. Its retreat is responsible for the Eastern Shore Moraine and subsequent ribbed moraine field formation. Any subsequent marine-ending glacier, if it existed, grounded in less than about 70 m present water depth. There is no equivalent to the Chignecto Phase preserved unless only its transgression-destroyed remnants exist, unrecognized, above the low-stand. There is no clear pattern as to which flow phases preferentially create or preserve glacial features by feature-type (channel, drumlin, moraine or striae).

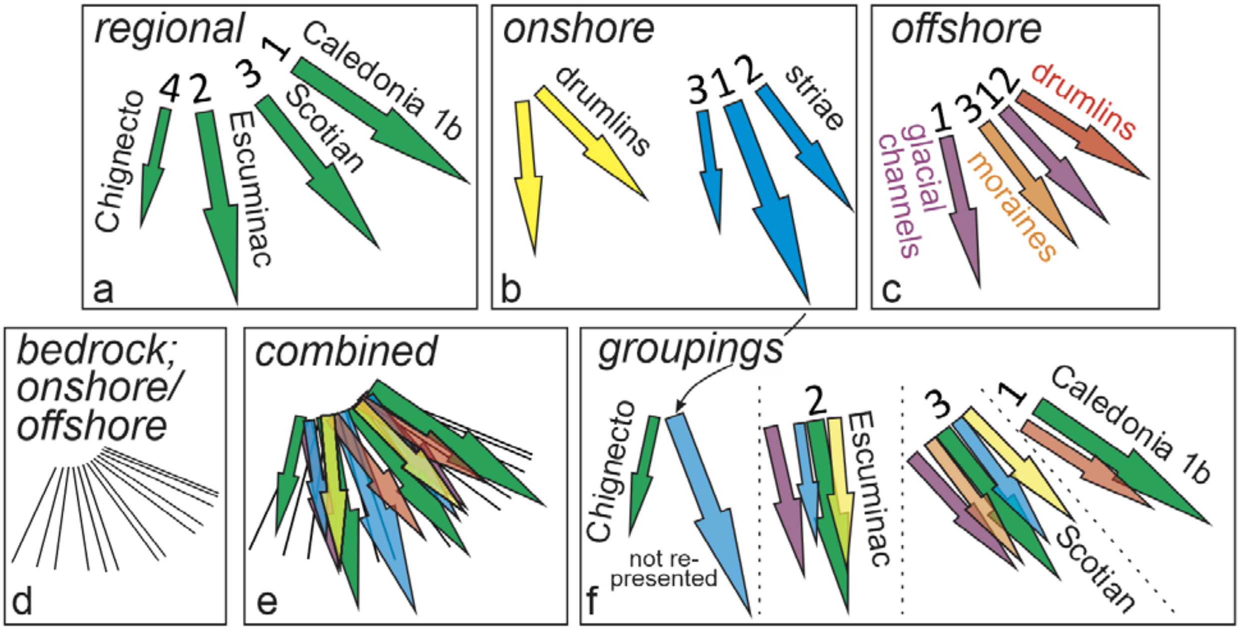


Figure 19. The top row shows glacial flow direction indicators in the offshore and onshore of the map area compared with the regional onshore glacial phases of Stea et al. (1992a and 1993) and Fig. 16. Bedrock lineation orientations (apart from bedding strike and fold axes) are also shown. Glacial feature types are colour-coded. Relative age is numbered and relative magnitude is reflected in arrow size but this is non-rigorous and reflects duration as much as landscape effect. The bottom row combines all (boxes d and e) and then groups like orientations (f). The map area features closely match regional orientations for the Caledonia, Escuminac and the Scotian Phases but there is no close tie with the major fluting and striae at Taylor Head, or for the latest (Chignecto) Phase.

Iceberg scour and glacial limits

Generally the Scotian Shelf Drift (primarily till) was uniquely identified by its rough surface relief (King 1970), later identified as iceberg scour. However, apart from on the Eastern Shore Moraine, only in one small location (a sidescan-only transect west of the multibeam survey) was iceberg scour recognized on the till. While the low-stand would have infilled and destroyed it in areas shallower than ~70 m, the till blanket and moraines in the multibeam survey area are apparently devoid of ice scour.

Early retreat from the Eastern Shore Moraine likely contributed to calving which scoured the moraine crest. However, neither the retreat of the Scotian Phase which formed the moraines, nor any subsequent marine-ending glacier, including those along the Cape Breton or Gulf of St Lawrence, produced icebergs with a keel depth or path capable of seabed impact across the map area.

Ice scour patterns southwest of Cape Breton revealed a late-phase ice scour population post-dating the ubiquitous population during Laurentian Channel ice stream calving. Trajectories of these late iceberg scours indicated they were swept by the proto Nova Scotian Current and thus originated from icebergs from the Gulf of St Lawrence (King 2014). These reached a maximum of 175 m water depth, so fully capable of grounding along the Eastern Shore. Though these latestage occurrences are sparse, even offshore SE Cape Breton, the question arises if there was a barrier to such groundings along the Eastern Shore. Were Chignecto Phase marine-ending glaciers always grounding in less than 70 m water depth or was there an ice shelf or heavy sea-ice presence, for example, which prevented incursion of these or even far-travelled icebergs? Stea and Mott (1989) recognized Younger Dryas age glaci-tectonics well to the east on the northern shoreline of Chedabucto Bay in Guysborough County (Collins Pond). Were no Younger Dryas marine termini capable of the ice scour greater than 70 m (paleo) water depth?

ENGINEERING AND RESOURCE EXTRACTION

The map has some implications for potential future engineering or resource activities in the area. Gold has long been extracted nearby but on land. Extraction has always been from the host rock, both from veins and as disseminated habits. Historically, stamping processes have generally left a contamination legacy and this has been addressed at some Eastern Shore sites (Parsons et al. 2012).

The potential for offshore gold resources in this area was addressed by Stea et al. (1993) and by other workers farther east. This included numerous assays of grab samples, discussion of the placer potential, and some preliminary assessment of monetary value. Typically, assays showed values, primarily in sands, in the low ppb range. One notable exception is a 274 ppb value in a sample that also included a 1 mm gold flake. With a present consideration by both private and government preservation of the area, both on and offshore, an assessment of mineral potential is part of the federal government mandate, and will be conducted shortly.

Part of the original driver for the inner shelf geophysical and sampling surveys in the late 1990s was the potential for offshore aggregate resources. While quality and quantity are not considered here, the map has clear potential in terms of defining location.

Unlike for offshore hydrocarbons, present federal policy has not been established for any seabed mineral resources. The hydrocarbon potential is nil in the map area.

The potential routing of offshore utilities corridors, suitable for communications cables, power cables, pipelines or similar engineering infrastructure, is periodically raised by government and/or industry. The map and supporting data can clearly contribute by affording seabed and immediate sub-seabed geological characterization. It also serves, to some degree, as a template for large areas of the inner shelf which remain sparsely or entirely unmapped.

The glacial mud and sand filled bedrock channels are typically very sparse along the Atlantic coast but the new map delineates several. The adjacent bedrock outcrops present highly varied but juxtaposed foundation conditions and terrain roughness. Generally, a broad geotechnical characterization can be derived from experience and measurements in analogous areas, though this is not presented here. Outcrops may, for example be amenable to any form of infrastructure anchoring. Alternatively thick muds on smooth seabed can provide alternative to “difficult terrain” across bedrock and hummocky till. It may be suitable for pile-type structure support or for cable or pipeline routing, including burial options.

Benthic habitat is presently best determined by sampling and optical techniques (still and video photography). However, on a broad scale, a faithful and independent agreement between video and mapping of substrate is demonstrated. The reverse applies also. As the correlation between the map units and biotic character becomes better established, the surficial geology can contribute to better spatial control on benthic habitat mapping.

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APPENDIX I

Extended summary of this report for purposes of draft review for the Eastern Shore Fisheries and Oceans Canada Area of Interest

GEOLOGIC CHARACTERIZATION OF THE INNERMOST CONTINENTAL SHELF OF THE EASTERN SHORE OF NOVA SCOTIA

As part of Canada's approach to identifying effective area-based marine conservation measures a large area off Nova Scotia's Eastern Shore, encompassed by the map area, is one of the Areas of Interest (AOI), an initial step in considering it for Marine Protected Area status. The following is a summary of findings in this study suitable for characterization of the proposed park area.

Introduction

The nearshore and inner shelf geology is derived largely from interpretations of sparse coverage of seabed-penetrating and seabed sonars, including sparse seismic and local multibeam bathymetric data, topographic relief images generated from Canadian Hydrographic Service spot depths, limited LiDAR bathymetry, grab samples and very limited core samples.
An understanding of the surficial geology has implications for benthic habitat understanding, potential pipeline or cable routing, offshore seabed infrastructure and potential aggregate and/or gold resource development.

Bedrock

Seabed character of the inner Scotian Shelf along the open Atlantic coast is primarily governed by the bedrock morphology. The coastline and especially the outer islands along the entire Eastern Shore are primarily bedrock controlled and this character continues seaward to the paleo-low-stand of sea level at ~70 m where sediment cover thickens. The hard meta-sedimentary rocks comprising Meguma Group (~450 to 500 million year before present, and older) have undergone a long history of metamorphism, folding and minor faulting. It comprises metasediments of Lower Paleozoic age belonging to the Meguma Supergroup, dominated by slate of the Halifax Formation and mainly greywacke and quartzite of the Goldenville Formation. Harder, generally sandier beds stand proud of softer, slate beds with several metres relief, giving a jagged topography with long ridges and valleys. Occasional faults and jointing and sculpting from multiple glaciations add to this relief. The seabed (map) pattern of these beds includes broad folds with plunging axes at several kilometres spacing, giving rise to a chevron pattern of V-forms in plan view. Landward of about 100 m water depth the relief is quite pronounced. It is sometimes termed the skerry zone, especially where it has a highly undulating relief, as is the case here. This bedrock topography can have a strong influence on the type and distribution and especially the patchiness of surficial deposits where bedrock is not sediment-covered.

Glaciation and glacial deposits

The glacial depositional and erosional imprint is strong in the area. The last continental ice sheet covered the entire Scotian Shelf, depositing a sequence of till and glacimarine mud and a series of moraines upon retreat (King 1970, King and Fader 1986). Repeated glaciations have eroded deep channels (tens of metres) that are generally extensions of the main embayments at the coast and the paths of former rivers. Stea et.al. (1994) describe bedrock valleys up to 1 km across and up to 70 m deep, oriented both coast-parallel and coast-normal. They are largely sediment-filled and broad smooth-bottomed valleys now that contrast with their bounding bedrock-dominated flanks.

Glacial deposits take the form of isolated deposits of till (gravelly and cobbly diamict or boulder-clay) in the form of blanket deposits, drumlins, and moraines of various scales, and overlying glacimarine mud deposits infilling bedrock topographic lows (c.f., Fader, et.al. 1990, Stea et. al. 1992b, 1994, 1996). A record of at least two phases of glacier flow direction/timing are preserved in flow-parallel drumlins, hills of till with pear-shaped plan form. These formed under a different (older?) flow phase than those on the adjacent coast. The deposits also include sets of large and small moraines marking short-lived still-stands during overall glacier retreat. The most significant lies beyond the inner shelf, shown in the geologic profile. The 50 m thick Eastern Shore Moraine (King and Fader 1986) extents 70 km parallel to the shore, is 50 m thick, 5 km wide and includes a tongue on its seaward flank representing fluctuations of the ice margin (see geologic profile). Landward of the moraine are thick glacimarine muds that accumulated while the glacier margin was in the marine realm. These are, in turn, capped with a broad continuous soft mud blanket derived from the erosion products of shallower areas partly eroded when sea-level was lower. The Eastern Shore Harbour Moraine was succeeded by deposition of a series of smaller, sub-parallel moraines, again paralleling the coast, formed parallel to the retreating ice margin. They reach 20 m relief, and some form a broad field of boulder and cobble-topped moraines of small and mid-size (profile and detailed map) lying just seaward of the 70 m depth contour. These moraines lie on top of the drumlins, cross-cutting them approximately normally, to create a complex orthogonal pattern of till outcrop. Ponded between them are pockets of glacimarine mud emitted and transported beyond the glacier margin by meltwater plumes. The moraine field was submerged sufficiently to be protected from destruction by processes in the paleo-coastal zone, immediately to the landward.

Post-glacial sea-level rise and resulting deposits

During the latest low-stand of sea-level, when land-based ice sheets stored ocean volumes sufficient to drop global sea level by ~100 m lower than today, and the ice margins had retreated from the continental shelf to the land, the valleys would have maintained rivers. The 100 m deep low-stand on the outer continental shelf becomes shallower in most of the inner shelf zone (Forbes et al. 1991), and more precisely defined locally at about –70 m (Stea et.al. 1994), reflecting a degree of glacio-isostatic crustal rebound and global sea-level rise following glaciation. Stea et. al. (1996) suggested this low-stand dates to ca. 11.6 ka. As sea-level rose and the paleo-coastline moved across the seabed, the sediment overlying bedrock were subject to high energy shoreline and shallow water processes. As a result, this -65 m water depth marks a change in the seabed sediments; a relatively continuous blanket of glacial and post-glacial sediments below this contrasts with much more bedrock outcrop in shallower areas, with patchy sediment collected or preserved from erosion in the topographic lows. This transgression “washed” at least the top portions of the glacial deposits, concentrating sand and gravel lag deposits across much of the seabed, modifying the texture of immediately underlying diamicts and muds only cm or dm below. The glacial mud-filled channels contain a significant sand and a small gravel component, so developed a thin sand and gravel lag at the seabed. Locally the bedrock surface was “cleaned” of the fines, leaving a boulder-gravel-strewn surface while depositing the finer products in the pockets between bedrock ridges. Neither the absolute or relative timing of glacier retreat and sea-level rise is precisely known older than ~11 ka but the seabed erosion is strong evidence for subaerial exposure. However, there are no indications of a fluvial system, which, had they evolved, would be cut into the channel sands. Such fluvial systems would also have been confined to a narrow zone between the retreating ice margin and the sea and so confined to limited watersheds encompassing the numerous divides between broad channels. Of course, they would also have been subject to the coastal processes and potential destruction. The lack of evidence for paleo-rivers is consistent with a low preservation potential and with a similar lack of evidence for drowned coastal features such as beach ridges, bars and tidal channels. A meandering channel emanating from Sheet Harbour, appears to be maintained by present-day currents in these mud-dominated deposits. Such features are registered by the LiDAR data but only in very shallow areas and coupled with the present coastal deposit regime. Auriferous tills, also known on land, when subject to erosion during low stands can concentrate the gold. Indeed a nugget was recovered in one grab sample (Stea et al. 1993).

Post-glacial deposition in bays and inner harbours

The effects of sea level rise continue at the coastline even today, albeit at a slower rate. Therefore, in the inner harbours and bays the coastal deposits (primarily tills) are progressively removed, or partly so. Much of the finer component of the erosional products is transported landward to collect in the basinal areas of sheltered harbours and bays. The offshore extensions of these inlets are generally more sandy and the sand and gravel beaches reflect a balance between longshore, offshore and onshore transport in a continuing sea-level rise scenario. The sandier inlets reflect a greater present day influence by currents than the mud-dominated inlets.

Comparison with the Atlantic innermost shelf

The Eastern Shore inner shelf is characterized by extensive bedrock with patchy till and glacimarine mud. Sand and gravel generally overlies the bedrock, till and mud, occasionally dissected by glacially cut channels filled with sand and glacially-derived mud. offshore muds occur below 100 m),and more recent muds derived from coastal erosion are deposited in harbours. , Where not destroyed erosion processes, a record of deglaciation is preserved in a complex series of moraines and drumlins, partly modified on their surface by paleo-coastal processes. This map area is relatively representative of the morphologic and geologic character of the innermost shelf along the Atlantic shoreline of Nova Scotia, having a similar process history (Piper et al. 1986, Forbes et al. 1991, Stea et al. 1994).
Along the entire Atlantic coast bedrock ranges in age, structure and rock type but comprises, almost without exception, well indurated (hard) bedrock with moderate to high relief, not unlike on the adjacent land. The seaward limit of this bedrock marks the greatest morphologic change, where they become buried under younger and less indurated (generally Cretaceous age, ~150 Ma) sedimentary strata that have a much smoother relief, partly in response to sea-level erosion

episodes and partly to a smoothing affect by glacial erosion. The contact with the younger Cretaceous rock varies from 30 to 60 km distance from the coastline, 45 to 55 km off the map area; Another major morphologic change is where the thick, continuous glacial and post-glacial sediment package which infills and smooths underlying bedrock topography thins landward to expose more of the bedrock (skeery zone). This is about 25 km offshore from Shelburne to Halifax Counties, slightly less to the east but less than 10 km off Cape Breton.

Glaciations effected planation, general smoothing, local sculpting and plucking. Glacial deposits are similar along the entire coast; an end moraine system marks stepwise, non-synchronous still-stands (King 1996) of the retreating ice sheet of which the Country Harbour Moraine, continuing offshore Sheet Harbour, is part. This region of the coast is typical of the Atlantic coast with some exception. The glacial deposit thickness and continuity contrasts from east to west in the map area; 5 to 20 m thickness is typical in the west (below the low-stand position) and much thinner in the multibeam survey area. The dominant morphological influence by the glaciation(s) is the carving of broad valleys emanating from the larger bays and inlets into shallow drowned fjord-like topography. A similar fjord-like topography typifies the Atlantic coast of Yarmouth and Shelburne counties but the Eastern Shore examples extend far further across the inner shelf, a trait extending east as far as Country Harbour. The bays are much broader across Queens, Lunenburg (except the La Have River valley) and Halifax counties, to St Margaret's Bay. Nearly all the South Shore inlets have mud dominant in their sheltered, shallow upper reaches only. However, mud distribution in the Eastern Shore inlets generally floors both the harbour basin and extends seaward to the basins adjacent headlands. Another contrast is the presence of barrier beaches of sand, gravel and cobble to the westward of the map area and not eastward. At the mouths of Cow Bay, Cole Harbour and eastward to and including Musquodoboit Harbour the barrier beaches reduce storm wave energy behind them, permitting mud preservation. This contrasts with Jeddore, Ship, Tangier, Spry, Sheet, Mushaboom and Beaver Harbours, which lack such barrier beaches. Here, the offshore bedrock islands are far more common and apparently provide shelter, permitting mud deposition outside the harbours. Fewer beach barriers here might also reflect a general paucity of thick tills on land and immediately offshore, leading to a greater sand and gravel deficit in the budget supplying such beaches. Another contributing factor to the barrier beaches may be that the thicker glacial sediment blanket west of Jeddore Harbour supplied more sand and gravel there to the sediment budget during post-glacial transgression. Recognition of this contrast corroborates concepts of cumulative sediment reworking and low feature preservation potential introduced by Forbes et al. 2008 for the area offshore Halifax.