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GEOLOGICAL SURVEY OF CANADA
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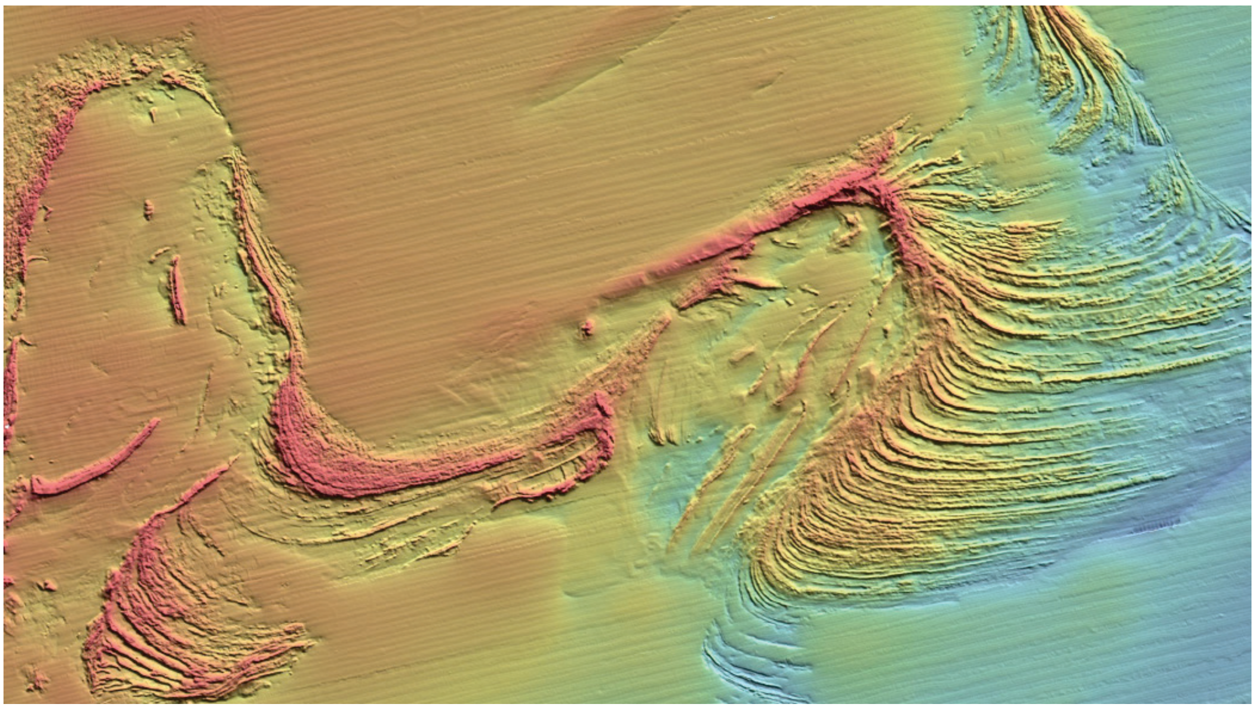

J.B.R. Eamer, J. Shaw, E.L. King, and K. MacKillop

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This report benefitted from the processing and rectification of many scanned seismic profiles by students, particularly Ryan Taylor and Andrey Kostylev. Reviews by Gary Sonnichsen and Vladimir Kostylev were very helpful and greatly improved the report.

Cover illustration: A shaded relief multibeam bathymetric map of the inner shelf near the Magdalen Islands in the Gulf of St. Lawrence provides a good example of the seabed complexity found with high resolution data. The region hosts several outcrops of Carboniferous and Permian bedrock that are deformed by salt tectonism, as well as smooth areas representing metres-thick sheets of sand.

Summary

- ***The shallow seafloor of Atlantic Canada (<100 m) displays a great diversity of conditions, necessitating a subdivision into 23 unique regions.***

- ***For each region we summarize the combinations of bedrock type, seafloor morphology, and surficial sediments as they are relevant to the emplacement of offshore infrastructure (e.g. piles, anchors, cables, pipelines).***

- ***The surficial sediment (overburden) found throughout the 23 regions comprises combinations of glacial diamict (ice-contact sediment or till), glaciomarine mud, postglacial mud, and postglacial sand and gravel, each unit having differing geotechnical properties.***

- ***Because of resistance and boulder content, till presents the greatest challenge to the emplacement of monopiles. The distribution and thickness of the remaining surficial units varies across the regions. Relatively thick deposits of postglacial mud and glaciomarine mud are found in parts of regions 1, 5, 8, and 11.***

- ***The most extensive area of shallow water, low relief, and very thin overburden (e.g., suitable for gravity-based development) is the southern Gulf of St. Lawrence and off northeast Cape Breton (regions 2, 3, 4 and 6). Smaller areas of similar character exist off the Newfoundland coast (regions 16, 18, and 21).***

- ***Widespread thick (>25 m) overburden suitable for pile installation is only present in one large area: Region 12, Sable Island – on the outer continental shelf.***

- ***Factors that may present difficulties to development include: a) Seafloor scour and bedform migration (regions 2 – 6, 11, 12, 16, 18, and 21); b) pervasive sea ice and icebergs (regions 16 – 20); c) incised submarine valleys (regions 1, 2, 3, 5, 7, 23); d) extensive gas in sediments (regions 1, 9, 12, 21, 22); e) salt diapirs (regions 4, 6, 22); and f) seafloor collapse due to mining (region 7). See Introduction Figure 7 for map of regions.***

Glossary

Bedform – Features that deviate from a flat seafloor that form as the result of a combination of different processes – sea level history, geological context, river inputs, waves, tides, and bottom currents.

Borehole – A hole drilled into the subsurface for collecting contextual geologic or geotechnical information.

Cone Penetration Test - The cone penetration test (CPT) is a method used to determine the *in-situ* geotechnical engineering properties of soils and delineating soil stratigraphy. In the CPT a cone on the end of a series of rods is pushed into the substrate where cone sensors measure tip resistance, sleeve friction, and pore pressure.

Cone resistance – The cone resistance, (q_c) is a direct measure of the resistance of the soil during a CPT test and is measured with a load cell attached to the penetration cone tip.

Consolidation – The process by which the sediment volume is reduced and the sediment density increased through loading (e.g. via ice or sedimentation) and compaction of the sediments. The reduction in volume results in an increase in sediment strength. The sediment is considered to be overconsolidated if the existing effective overburden pressure is less than the maximum effective pressure the soil has been subjected to in the past.

Continental shelf – The area of the seabed that extends from the coastline to the shelf break. This region is shallower (on the order of a few hundred metres water depth) than the broader ocean basin and has a minimal slope. It is underlain by continental crust (as opposed to oceanic crust in the deep ocean basins).

Diapir – A geologic intrusion where a more fluid, plastically deformed material is injected into brittle overlying rocks. In the context of this report, diapirs almost exclusively refer to salt that is injected into the upper bedrock forming the seabed, usually resulting in visible deformation.

Dropstone – A large clast (stone) of pebble to boulder size that is lodged in finer, water deposited (laminated) sediment. Typically the result of the clast melting out of entrainment in floating sea ice or an iceberg, where it drops into an otherwise fine bed of sediments on the seabed. Indicates sediments that are glacially influenced (glaciomarine).

Drumlin – A streamlined oval hill, elongate in the ice flow direction, of sediment that varies in composition from till to stratified sand and gravel with sizes that range from 10s of m to kms in length and width.

Esker – A long, narrow, sinuous ridge of stratified glacifluvial (glacial meltwater) material (generally sand and gravel) deposited by a stream normally flowing beneath or at the margin of a stagnant or retreating glacier in an ice tunnel or subglacial stream bed.

Flute – A narrow, elongate ridge aligned parallel to ice movement generally composed of till that typically will only achieve heights of a few metres. Rarely composed of silt and clay and all involve an upstream "obstruction" such as a boulder. *Megaflutes* are larger than flutes but smaller than *Mega-Scale Glacial Lineations* (see below).

Furrow – A large trench eroded into the seabed that is elongate parallel to the erosive source (e.g. iceberg movement, glacier flow, or current direction). In this report, furrows most commonly refer to erosion via iceberg grounding and dragging, which often has berms (raised ridges) on either side of the furrow parallel to the long axis.

Glacial landforms – Features found on the seafloor that are formed under the influence of glacial ice. For landforms referred to in this report, see *moraine, drumlin, esker, flute, and mega-scale glacial lineation.*

Holocene – The period of time following the previous ice age from 11 700 years ago to present.

Lag (surface) – Residual coarse sediments left behind after some erosive force (e.g. currents, waves, sea level *transgression* (see below)) removed the finer sediments from a deposit. When laterally extensive is referred to as a lag surface.

Littoral – Depending on context, the definition of this zone is variable – in this report the littoral zone is the shallow submerged seabed from the coastline to depths where the seabed is still influenced by wave action (e.g. including both the eulittoral and sublittoral zones). This definition can, for the most part, be extended to all shallow shelf areas covered by this report.

Mega-Scale Glacial Lineation – An elongate, sub-parallel to glacial flow, subglacial landform generally thought to be indicative of ice streaming (rapid, concentrated flows of ice). Characteristically have length:width ratios of 15:1.

Moraine – A mound, ridge or other distinct accumulation of generally unsorted, unstratified sediment, predominantly till, transported and deposited chiefly by direct contact with glacier ice and commonly from underneath glacial ice.

Multibeam echosounder (MBES) surveying – An acoustic surveying technique where multiple acoustic pulses are sent from a source (most commonly a surface surveying vessel) and reflected off the seabed, providing accurate water depths and a detailed map of seabed bathymetry. MBES maps of bathymetry can be combined with coregistered backscatter intensity to infer seabed texture.

Overburden (and basement) – Unconsolidated sediments, usually of Quaternary age, that overly more consolidated (often older) sediments and bedrock (termed basement). Can be defined by acoustic properties, whereby high-resolution systems cease penetration at the basement.

Paraglacial – Non-glacial processes that are directly influenced by glaciation, for example local changes in sea level due to retreating ice (see *relative sea level*, below).

Piston core – A device for obtaining a core sample of the subsurface that works best in fine-grained unconsolidated sediments. *Borehole* drilling (above) is used for bedrock and consolidated materials, and *vibrocoring* (below) for sands (un- and semi-consolidated).

Pockmark – A concave crater-like depression in the seabed on the order of 10s of metres formed from fluid escape (e.g. groundwater, hydrocarbons, gasses).

Prograding – Refers to an actively depositing body of sediment that is unidirectionally traversing the seabed or coastline. Examples include deltaic sediments prograding further seaward into a lake/ocean, and beach-dune systems prograding further seaward into the nearshore.

Quaternary – The most recent geologic Period, covering the past 2.58 million years. When referring to sedimentation, Quaternary sediments (see *overburden*) are the most recently deposited, most likely to be at the seafloor, and typically least consolidated.

Relative sea level – The sea level as observed relative to the modern coastline in a specific region. In Atlantic Canada, relative sea level is mostly governed by global changes in sea level combined with isostatic effects relating to adjustments to the crust as the large weight of ice was removed following the last ice age.

Sand dune – In a marine context, a dune is a bedform typically composed of sand (in rare cases gravel) where flow depth, current speed, and grain size control the size and shape of the dune.

Sand ridge – A somewhat generic term that refers to elongate, large-scale ridges (up to 40m tall) of sand that typically have an asymmetric transverse (short edge) profile. They can be shoreface-connected or offshore (both are prominent in the Sable Island Bank region).

Sand wave – Compound sand dunes typically formed by tidal currents.

Scour – Localised erosional features produced over a surface of unconsolidated sediment by turbulent water flow or direct contact with ice.

Sub-bottom seismic surveying – A suite of surveying techniques that image the subsurface at varying resolutions depending on sound source. Systems referred to in this report that are relevant for shallow sediment depths include: shallow high-resolution systems such as chirp systems/3.5khz subbottom profilers; and intermediate depth and resolution systems such as sparkers and boomers of which the widely used Geoforce Huntec Deep Tow System (DTS) utilizes.

Shear strength – The resistance of a material to applied stress, provided by the cohesion (bonding strength of fine grained soils) and the frictional resistance of the soil grains.

Sidescan sonar – An acoustic surveying technique that uses return backscatter to create a high-resolution "picture" of the seabed. High- and low-backscatter returns generally indicate hard (e.g. bedrock, gravel) or soft (e.g. fine sand, mud) seabed compositions, respectively, similar to multibeam backscatter intensity mapping. Sidescan is effective at imaging seafloor relief and differentiating a smooth and rough seabed texture.

Strandplain – A broad coastal landscape consisting of alternating ridges and swales (topographic highs and lows) consisting of sand and gravel often related to *prograding* (see above) coastlines with high sediment supply (e.g. at a rivermouth).

Subsidence – The reduction in height of a surface relative to some datum, most commonly relative to sea level. An example is land subsidence under the weight of large volumes of glacial ice.

Surficial geology – In this report, surficial geology refers to the collection of landforms and surficial sediments (or *overburden*, see above) that makes up the seabed or land surface. Surficial sediments are simplified into broad categories of till, glaciomarine, sand and gravel, and postglacial mud, described in the introduction below.

Tectonism – Deformation of existing landforms or beds. A term often applied to large-scale crustal plate movement and deformation (plate tectonics), but can also refer other deformation processes such as bedrock deformation from salt diapir intrusion (salt tectonism) or glacial modification of existing landforms (glaciotectonism).

Tombolo – A type of shoreline barrier, usually composed of sand or gravel, which links islands to each other or to a mainland coast. Formed by wave refraction and diffraction around the island.

Transgression – A process that occurs at the shoreline during sea level rise, where the high energy zone of sediment erosion and transport near the coast traverses landward at the rate of sea level rise. Often results in glacial sediments being reworked by waves and currents into better sorted sand and gravel, and erosion and removal of large amounts of sediment.

Triaxial tests – A laboratory test to determine the strength and stress-strain relationships of a cylindrical soil sample. The results are useful in determining strength and deformation properties of cohesive soils using Mohr-Coulomb strength criterion (cohesion and friction angle) and Young's modulus.

Vibrocorer (or vibracorer) – A subsurface sampler for obtaining a core in coarse grained or more consolidated sediments.

Winnowing – The selective erosion and transport of finer grained sediments from a deposit of mixed grain sizes by currents, leaving a *lag* (see above) remaining on the seabed.

Data

Current GSC holdings for marine and coastal radiocarbon dates, seabed photos, grain size distributions, multibeam bathymetry coverage, and seismic profiles are indexed in the following spatial database:

http://ftp.maps.canada.ca/pub/nrcan_rncan/raster/marine_geoscience/Seismic_Reflection_Scanned/NRCan%20Marine%20Data%20Holdings.kmz

This database contains references to most of the data used for interpretation in this study.

For Atlantic Canada-scale bathymetry, GSC-A efforts to develop a seamless raster are ongoing. A comparable product is provided by the Canadian Hydrographic Service NONNA-100 products:

https://open.canada.ca/data/en/dataset/d3881c4c-650d-4070-bf9b-1e00aabf0a1d

For an Atlantic Canada-scale surficial geology classification, GSC-A efforts to update regional mapping to reflect recently collected data and updated mapping standards are ongoing. Previous mapping efforts are referenced throughout this report.

Introduction

The purpose of this report is to describe seabed foundation conditions on the inner shelf of Atlantic Canada as a guide for any future seabed installations. Over the last two decades, seabed conditions as they related to oil and gas exploration and development activities on the outer continental shelf has been a primary focus of the GSC. With increasing global development of the seabed for emerging renewable energy technologies (wind, wave and tidal), it is timely to re-examine the inner continental shelf.

Typical constraints on offshore installations include distance from connected infrastructure (e.g. power grid) and water depth. For example, data on existing offshore renewable energy installations show that the majority are within 100 km of the coast in water depths <50 m, although some are being planned for deeper water particularly as technology develops further (e.g. floating offshore wind). Accordingly, this study focuses on areas shallower than 100 m and within 100 km from the coast (Fig. 1). The largest areas of shallow water are the shelf north of Prince Edward Island, Bay of Fundy, southwest Nova Scotia, northeast of Cape Breton, and western Newfoundland. With several exceptions there is very little shallow coastal fringe off Newfoundland.

RECENT GEOLOGICAL HISTORY

The surficial geology of the inner continental shelves of Atlantic Canada is a result of:

Repeated Quaternary glaciations Throughout the region, glacial diamict (till) deposited in contact with ice overlies bedrock. This is commonly overlain by a drape of glaciomarine mud deposited by meltwater plumes from the retreating ice. A key summary of the glacial history of Atlantic Canada can be found in Shaw et al. (2006a).

Changes in relative sea level Relative sea level changes resulted from the interplay between changing levels of the world's oceans and crustal motions. Large areas of the inner shelves (e.g., Northumberland Strait) were dry land during the postglacial period and were subsequently drowned in the Holocene transgression. In these areas the older glacial sediments have been extensively re-worked, generally resulting in a higher proportion of sand and gravel. A key summary of sea level changes and paleogeography in Atlantic Canada can be found in Shaw et al. (2002a).

Modern processes Postglacial mud is accumulating in sheltered basins and harbours, and postglacial sand and gravel are present and commonly reworked in shallow areas impacted by waves and strong currents.

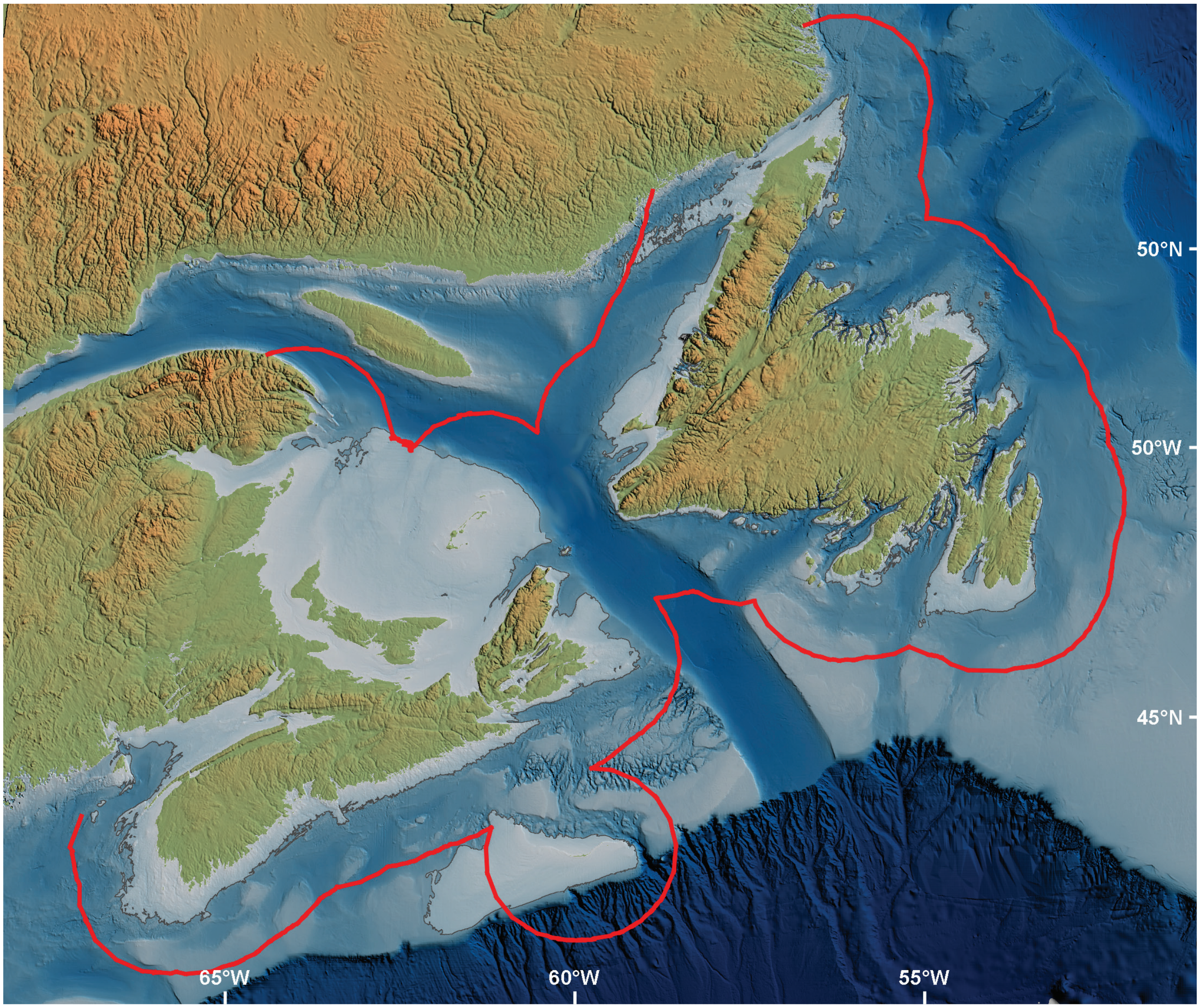


Fig. 1: *Bathymetry of Atlantic Canada with the 100 km coastal buffer (red line) and shallow shelf (lighter colour and outlined by the grey 100m depth isobath) within that buffer, indicating the area of interest for this study.*

OVERVIEW OF SURFICIAL SEDIMENTS

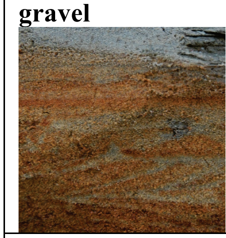
Sediment type	Materials	Backscatter	Sub-bottom acoustic signature	Generalized geotechnical properties
Postglacial sand and gravel 	Sand and gravel derived from reworked glacial sediments; often mobile with bedforms	Low (sand), high (gravel)	Range of acoustic signatures	**Non cohesive** Cone resistance 5 – 20 MPa
Postglacial mud 	Mud derived from reworked glacial sediments with weak stratification; may be gas-charged; very low relief	Low	Transparent	**Low shear strength** Up to 20 kPa
Glaciomarine mud 	Gravelly sandy mud with dropstones deposited from glacial meltwater; draped over earlier sediments; stratified	Low (muds), high (gravel lag at seabed)	Strong stratification	**Moderate shear strength** 15 - 70 kPa, increasing with burial depth
Till (glacial diamict) 	Mixture of boulders, gravel, sand and mud; deposited directly by glacial ice; "till" can be dense sand on outer banks (e.g. Sable Island Bank)	High	Incoherent	**High shear strength** Typically 210 – 240 kPa, range 120 – 460 kPa

Table 1: *Quick reference for surficial sediment types in Atlantic Canada. Shear strength values are for undrained samples. Geotechnical properties from Table 2 – an expanded table of sediment and bedrock properties for Atlantic Canada found at the end of this section.*

The limited range of surficial sediment types found in Atlantic Canada (Table 1) are presented in stratigraphic order according to age, with age increasing downwards in the table and with depth under the seabed. In the past these surficial sediment types have been ascribed formation names, but generic names are applied in this report to emphasize their depositional process or environment. Geotechnical properties have been measured over the years and a more rigorous compilation of properties linked to bottom types is sorely needed beyond that which is reported in unpublished documents (e.g. King et al., 2002a, Sonnichsen and King 2004) and compiled here. Accordingly, a summary of geotechnical properties includes specific measurements drawn from distant locations (Table 2), and further work (ongoing) will expand the number of samples these values are drawn from.

A simplified classification of surficial sediments overlying bedrock in shallow water is, in chronologic order (decreasing sediment depth): 1) till; 2) glaciomarine mud; 3) postglacial mud; and 4) postglacial sand and gravel.

- *Bedrock* Three main types can be differentiated based on the degree of consolidation and/or density: crystalline and metasedimentary, consolidated sedimentary, and cohesive to friable claystone, mudstone, and sandstone (semi-consolidated).

- *Till* Ice-contact sediment (also referred to as glacial diamict or till, the latter of which is used throughout this document) consists of a wide range of grainsizes, but of significance is the fact that boulders and cobbles are commonly found. This unit therefore is a major barrier to emplacement of, for example, monopiles. Till samples are found to have very high undrained shear strengths, particularly where till has been overconsolidated by overriding glacial ice after deposition. Conversely, some marine tills have low strengths, reflecting deposition from a near-floating glacier margin (e.g. in linear and arcuate moraines). Drilling in offshore tills has been highly problematic in some cases, likely because of loose cobbles, and commonly a gravel to boulder lag occurs in a higher concentration on the upper surface where modified by seabed processes.

- *Glaciomarine sediment* Glaciomarine muds are composed of a matrix-dominated silty clay, with varying proportions of sand and gravel. Clasts are commonly pebble-sized dropstones. Piston coring operations in this unit have been successful as a rule, with good penetrations being achieved, but a thin, post-glacial sand cover or cobble–sized clasts have stopped penetration in some instances. Glaciomarine muds typically have a lower undrained shear strength when compared with till.

- *Postglacial mud* This consists of varying proportions of silt and clay, with lesser amounts of fine sand. Found only in sheltered basins on the inner shelf, this unit exhibits low undrained shear strengths. Coring operations in this unit always achieve success as gravel clasts and resistant layers are rarely present.

- *Postglacial sand and gravel* This unit is non cohesive. Reliable strength measurements are derived mainly from full-scale in-situ cone penetrometer tests (CPTs) and appreciably thick accumulations (e.g. generally only found at Sable Island Bank) have been ideal substrate for the establishment of piles.

DISTRIBUTION OF BOTTOM TYPES

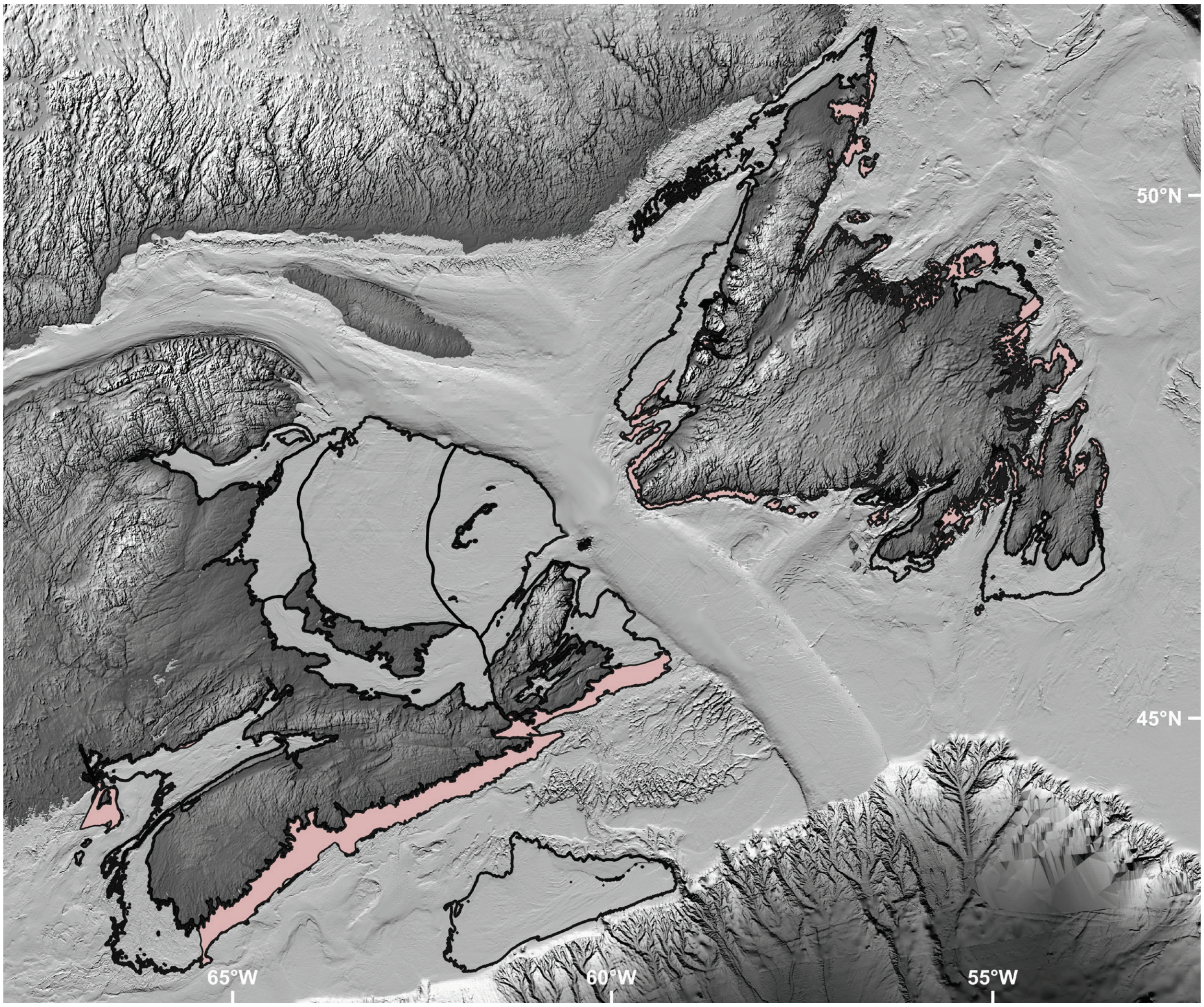


Fig. 2: *Distribution of areas that are bedrock-dominated.*

Figure 2 is a depiction of bedrock dominated areas. Actual exposed outcrops are often rare. By bedrock dominated it is implied that the seafloor is irregular, with areas of rugged relief alternating with deeper areas in which sand and gravel have accumulated overlying earlier sediments, including estuarine sediments. Furthermore, fields of glacial landforms such as drumlins are found in places, truncated by wave action during the postglacial sea level lowstand. This bedrock dominated zone includes large estuaries such as Halifax Harbour, within which postglacial muds have accumulated. Highly detailed maps are available for only small areas, such as Lunenburg Bay (King et al., 2017; region 9 – Figure 7), offshore Sheet Harbour (King, 2018, 2019; region 9) Halifax Harbour (Fader and Miller, 2008; region 9), and Placentia Bay (Shaw et al., 2011; region 15). Although it's not immediately obvious as the shallow shelf is so narrow, the majority of the area off of Newfoundland is considered to be bedrock-dominated, with some exceptions.

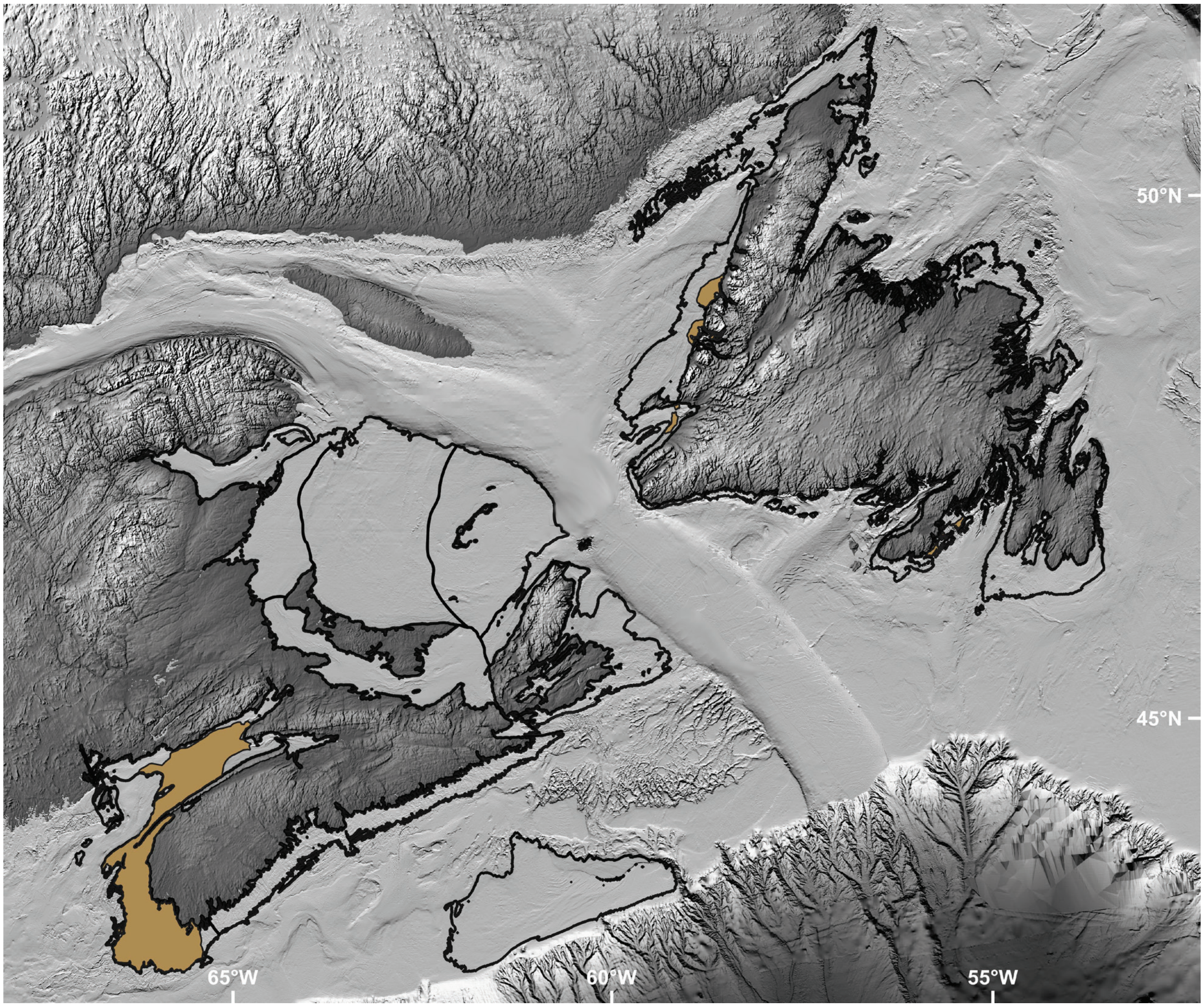


Figure 3: *Shallow areas in which till predominates at the seafloor.*

Figure 3 shows that till is predominant in the Bay of Fundy and offshore from southwest Nova Scotia. The character of the till differs in the two areas: in the Bay of Fundy a complete cover of till is present, with morainal ridges. By contrast, off southwest Nova Scotia systematic mapping reveals that till is organized into narrow morainal ridges, with intervening bedrock outcrops. In both areas the till has a high boulder content. The till off western Newfoundland occurs in thick morainal ridges off Bonne Bay, Bay of Islands (region 21), and St. George's Bay (region 22), and in smaller fields of glacial landforms in Placentia Bay (region 15).

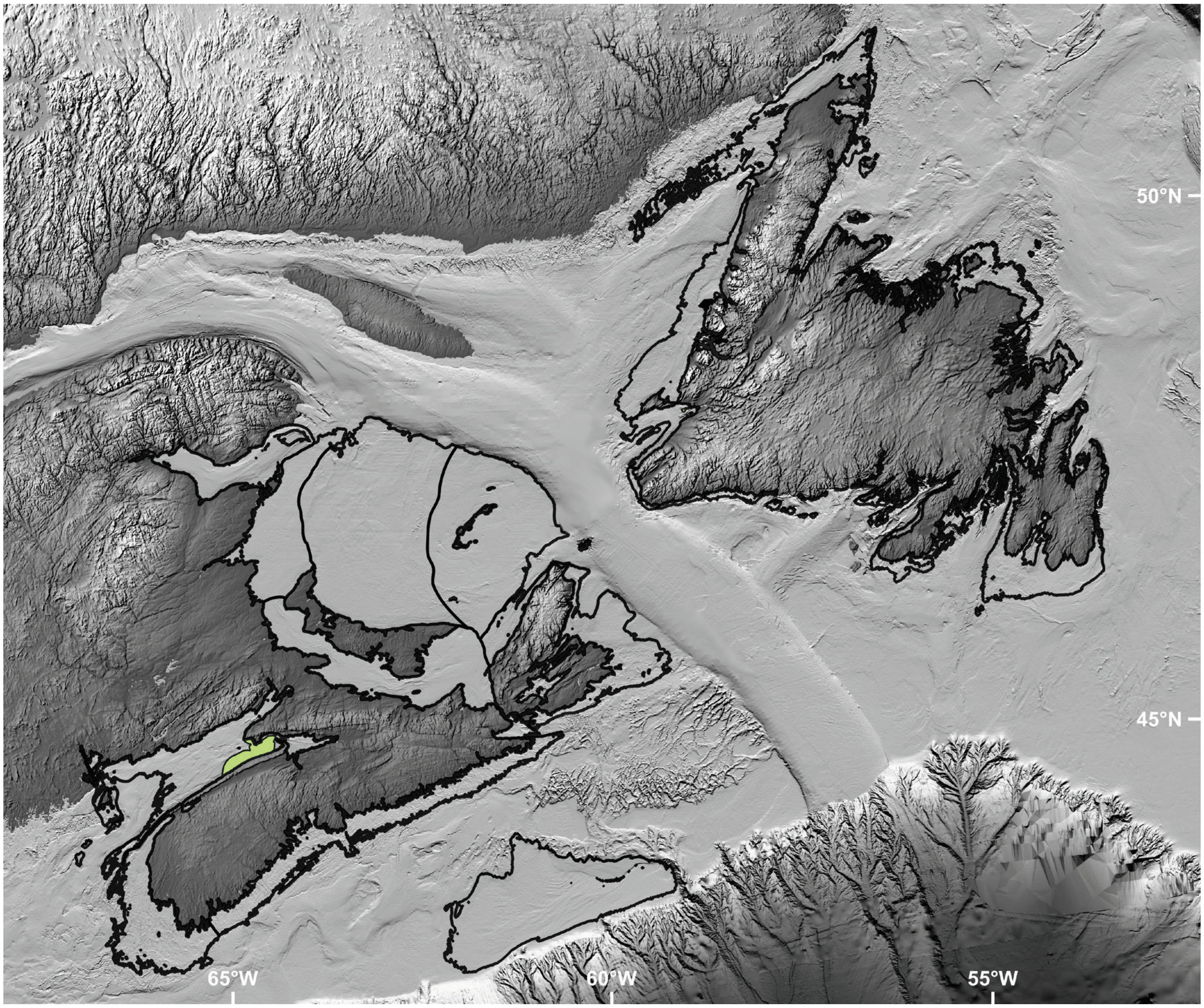


Figure 4: *Shallow areas in which glaciomarine sediment predominates at the seafloor.*

Seabed cores throughout the region are likely to intersect glaciomarine sediment, sandwiched between the underlying till and the overlying postglacial sediments. Seabed exposures over large areas are not common in shallow waters. The largest area (Fig. 4) is in the upper Bay of Fundy (region 11). A small area of exposed glaciomarine sediments mapped in Shaw et al. (2006b) in St. George's Bay, Newfoundland (region 22) is barely resolved in Figure 4. Larger areas of mapped glaciomarine sedimentation found in Placentia Bay are deeper than 100 m and out of the scope of this study.

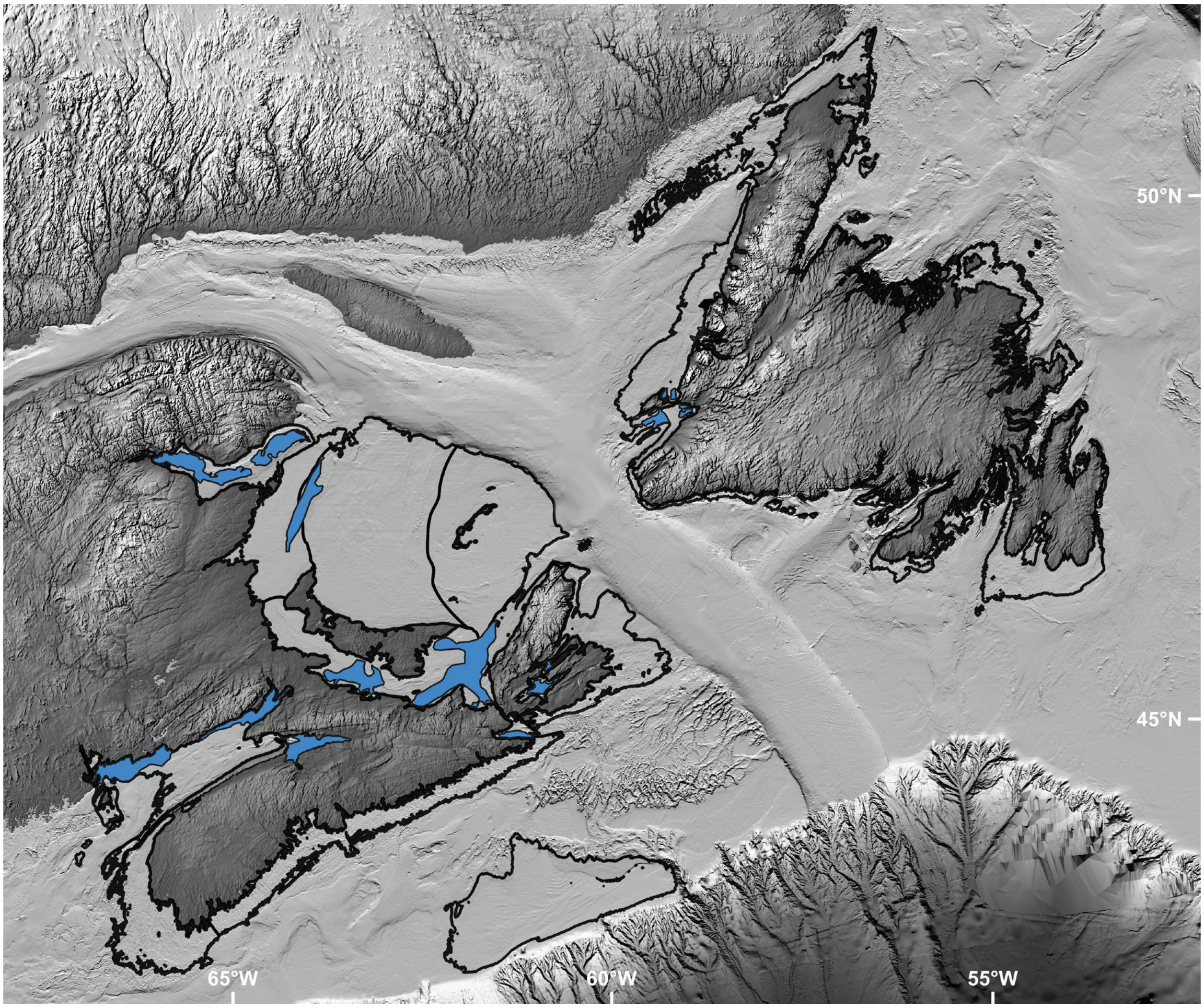


Figure 5: *Areas of shallow water in which postglacial mud predominates at the seafloor.*

The largest areas of postglacial mud in waters shallower than 100 m (Fig. 5) are in Baie de Chaleurs, offshore New Brunswick (region 1), Northumberland Strait (region 5), Bras d'Or Lakes (region 8), and Chedabucto Bay (region 9), and offshore from St. John's, New Brunswick (region 11). Smaller pockets are found in St. George's Bay (region 22) and Port au Port Bay (region 21) in southwest Newfoundland. Yet smaller areas not shown on this map include Halifax Harbour and most fjords found along the Newfoundland coast (the latter for which nearly all basins are deeper than 100m water depth). The areas depicted as mud in the inner Bay of Fundy in fact have a rather complex sediment distribution, with a full range of sediments types including areas of sandy bedforms (see Shaw et al. 2012).

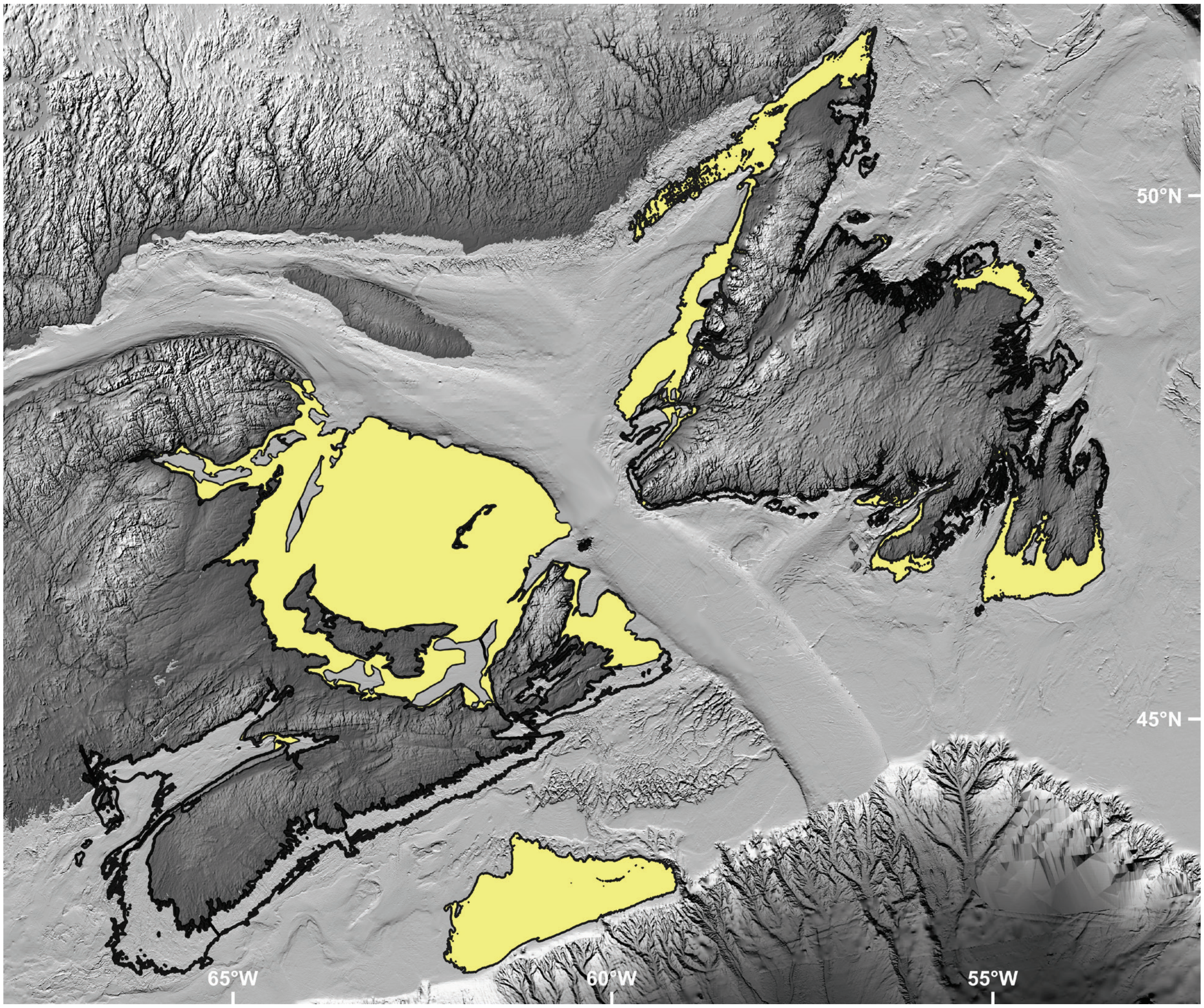


Figure 6: *Areas of shallow water in which postglacial sand and gravel predominate at the seafloor.*

The largest area of postglacial sand and gravel (Fig. 6) is the Magdalen Plateau in the southern Gulf of St. Lawrence**.** Smaller areas are depicted around Newfoundland, however minimal data exists to support some of the broader defined areas (except perhaps the Straight Shore (Shaw et al., 1999), region 18). While the sand and gravel in southern Gulf of St. Lawrence and surrounding Newfoundland is mostly a thin veneer and/or isolated pockets of deeper sedimentation, the sand around Sable Island is tens of metres thick. What is not shown here are, firstly, the numerous sandy bedform fields in the upper Bay of Fundy (see Shaw et al., 2012; region 11), and secondly the extensive areas of sand and gravel found on the irregular topography with bedrock and glacial landforms along the coast of Nova Scotia, from southwest Nova Scotia to the eastern tip of Cape Breton Island (see Fader and Miller, 2008; King et al., 2017; regions 7, 9, 10). Nor does the large area of delineated sand and gravel off western Newfoundland show the true complexity of this region (21), including large bedrock ridges and multiple large linear moraines in the south and a series of moraines in the Strait of Belle Isle in the north (Shaw and Potter, 2015).

CLASSIFICATION INTO SUB-REGIONS

For this study, the shallow inner shelf of Atlantic Canada is subdivided into 23 regions (Fig. 7) with similar properties of geomorphology, surficial geology, and modern processes (wave and current impact, exposure to sea-ice, and iceberg disturbance). For each segment we summarize the geomorphology and surficial geology. We delineate important constraints, such as seafloor scour due to ice or currents, slope instability, large bedform fields, shallow gas and pockmarks, salt tectonism, and seafloor subsidence due to mining. For each segment we provide one or more vignettes, where data is available, to provide a representative sample of surficial geology for that segment.

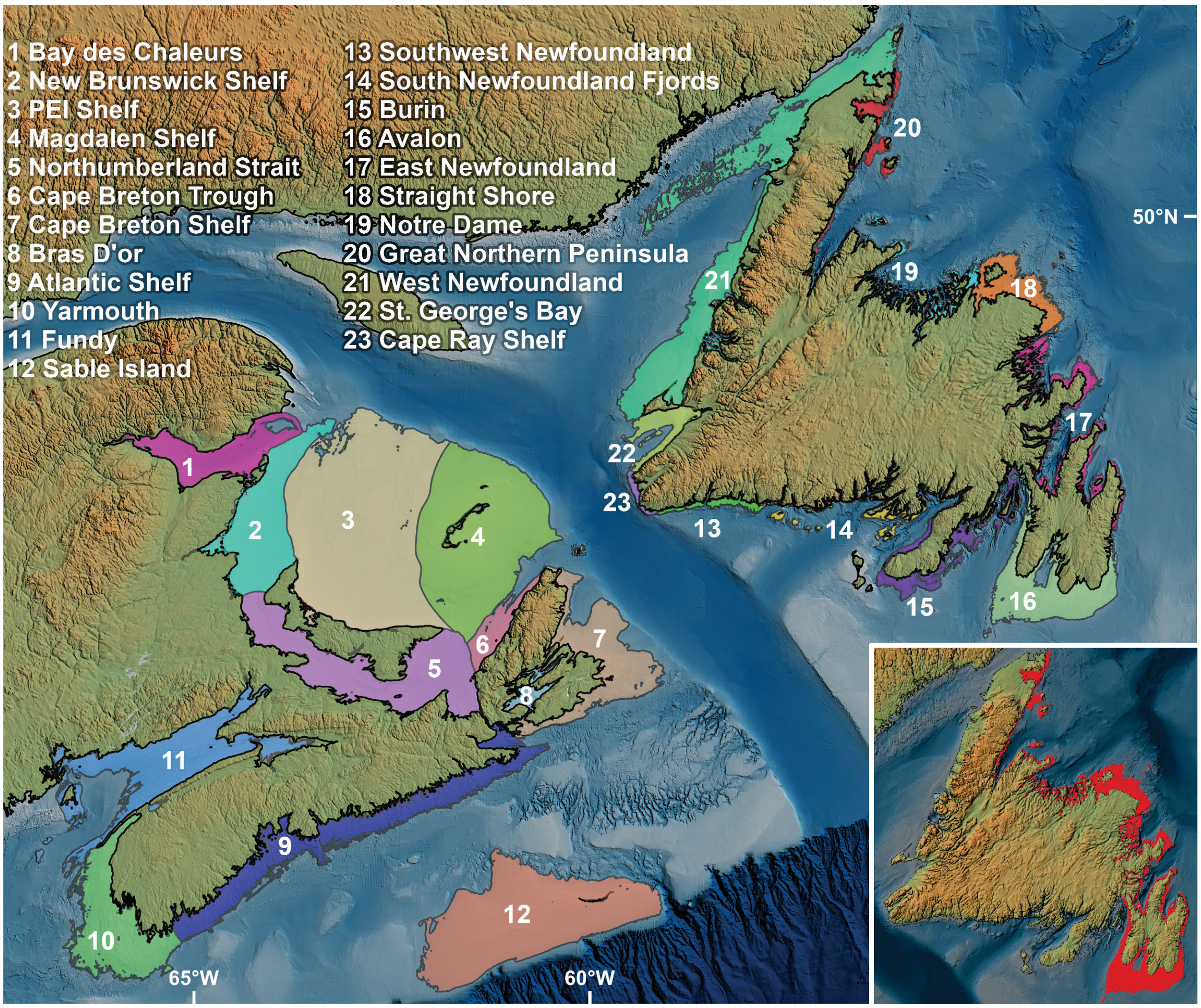


Fig. 7: *Inner shelf segments, Atlantic Canada. Inset (bottom right) highlights the regions (16-20, eastern Newfoundland) where the seabed shows clear geomorphic evidence of modern iceberg and sea ice impacts – an important constraint on offshore infrastructure development.*

Bottom Type	Simplified Lithology	Spatial Attributes	Geographic Applicability	Available Geotechnical Data	Unit Weight (kN/m3)	Undrained Shear Strength	Moisture Content (%)	Plasticity Index	Cohesion	Internal Friction Angle (°)	Cone Resistance (Mpa)	Foundation Constraints
"hard" bedrock	crystalline and metasedimentary, minor volcanics; mid to high-level metamorphism		Limited electric drill cores; correlations inferred from land in King and MacLean (1976)	General Literature (Zhang 2005; Pariseau 2007)	26 - 30	10 - 241 Mpa			Intact: 14.8 - 70.3 MPa (Ave. 45.7), Jointed: 0 - 2.7 Mpa	Intact: 15 - 47 (Ave. 27), Jointed: 19 - 56		Hard; tight folding; paleo-faults; high relief with slopes locally over 20 degrees; local corridors known or inferred with sediment cover (limited or no outcrop)
"soft" bedrock	cohesive to friable semi-consolidated claystones, mudstones, sandstones		Limited electric drill cores; correlations inferred from land in King and MacLean (1976)	General Literature (Wyllie and Norrish 1996; Zhang 2005)	19.0 - 21.5				20-200 kPa	12-17		Stratigraphic variability in physical properties; requires geotechnicall engineering for large structures (e.g. drilling rig)
"consolidated" sedimentary	limestone, sandstone, shale, conglomerate		most rock types represented on land; large data set for fix PEI link project in Permian rocks (not accessed), mining operations in Cape Breton (Carboniferous rocks) (Sanford 1998).	General Literature (Wyllie and Norrish 1996; Zhang 2005)	23 - 27				50-120 kPa	10-17		Variable hardness, lighology-dependant; locally jointed and faulted
till	Cohesive clay and gravel to large (> 1m) boulders in matrix; often loose gravel to boulders in greater concentration if exposed at seafloor. Note that ice-contact sediments can be very sandy e.g. on outer continental shelf.	Generally 1 - 12m thick, rarely 10s of m thick, gravel lag can be metres thick. Widespread distribution owed to broad deposition patterns and resilience to erosion.	Outside reported regions. **GSC piston core (2003030)** Laurentian Channel **Industry boreholes and CPTs** (Avalon Channel, Jeanne d'Arc Basin, Halibut Channel).	Index properties, Atterbeg limits, mini-vane shear strength, triaxial tests and CPT data. Highly variable dependant on location, depositional and stress history.	16.0 - 22.5	50 - 500 kPa	11 - 62	7 - 38	25-35 kPa	32-46	6-60	Boulders on upper surface and in cohesive matrix; challenging trenching; heterogenities and winnowing can concentrate large clasts
glacimarine mud	gravelly sandy cohesive mud with drop stones; gravel or sand lag at seabed is common; can be laminated (finely bedded)	Rarely exposed on inner shelf, generally 1 - 10m thick in subsurface, locally thicker. Widespread in the subsurface.	7 **GSC piston cores** (cruise 2009044) in close proximity to NFLD coast Regions 17 and 18. **One GSC piston core** 20030330030 in Laurentian channel. **Two GSC piston cores** (cruise 79011) Scotia Slope. **One Industry** borehole (87B2, Halibut channel).	Index properties, Atterberg limits, shear strength for upper 7 meters from piston cores and 8 to 20 m from the borehole. Highly variable dependant on location, depth below seafloor, depositional and stress history.	13.5- 27.5	2-70 kPa	11-95	10-25				Can be appropriate for trenching and piles; can lie in broad channelized corridors providing pipe or cable routes; can have thin coarse cap
post-glacial mud	soft marine silt and clay with minimal structure	Only in sheltered basins on the inner shelf, otherwise typically in deeper waters. Generally 1 - 5m thick, but can be 10s of m (e.g. Baie de Chaleur). Widespread as thin blanket on low energy seabed	2 **GSC piston cores** (cruise 2009044) in close proximity to NFLD coast Regions 17 and 18. **One GSC piston core** 20030330030 in Laurentian channel.	Index properties, shear strength for upper 5 meters from piston cores	13.5- 22.6	1-6 kPa	47-62					Low strength; generally offshore in deep water (>75 m) and in harbours
post-glacial sand and gravel	cohesionless sand and gravel, likely cobbles and boulders; often local erosional remnants of till beneath gravels; well sorted when reworked during sea level transgression	Only widespread thick (>20m) accumulations found on outer banks (e.g. Sable Island), otherwise widespread on shallow inner shelf in thin (<1m) sheets and patchy deeper accumulations (>10m)	Outside reported regions. **GSC grab samples. Industry boreholes and CPTs** (Avalon Channel, Jeanne d'Arc Basin, Halibut Channel).	Index properties, shear strength and CPT data	15.7-19.6	18-22.5 kPa	10-55		cohesionless	36-45	5-20	Locally unknown distribution and thickness; patchyness; low repose angles; small bedforms assumed and minor to moderate periodic sand mobility in storm-influenced water depths and areas

Table 2: More detailed descriptions of geotechnical properties of generalized seabed types encountered in Atlantic Canada.

Region 1: Baie des Chaleurs

SUMMARY

Coastlines in the Baie des Chaleurs range from eroding bluffs and large boulder, gravel and cobble reflective beaches to sandy spits and tidal inlets. This large bay is shallow, with low relief, and contains a range of relatively thick surficial sediments (glacial and postglacial) overlying sedimentary rocks. Irregular terrains are found in a moraine across the inner bay, and in parts of the outer bay that have been scoured by ice.

Favourable factors for foundation emplacement include a shallow bay (mostly <100m depth); low relief; thick Quaternary sedimentation

Constraints for foundation emplacement include irregular terrain in areas of high quality data; channelized erosion and variable subsurface geology; gas masking in postglacial muds; mobile sediments in littoral

A GSC map series (Syvitski et al., 1987) and a paper (Syvitski, 1992) provide a comprehensive source of information.

GEOLOGY

Geomorphology The inner bay is generally shallower than 50 m, while most of the outer bay is shallower than 100 m (Fig. 8). The floor is smooth and low relief. As elsewhere in Atlantic Canada, there are no data for areas shallower than 20 m. Relative sea level fell to 45 m below the present level in the early Holocene, before rising once more to present levels.

Bedrock Inner Baie de Chaleurs is underlain by Carboniferous rock (Visean to Westphalian) while the outer bay is underlain by upper Carboniferous to Permian rocks. Bedrock is gently deformed sedimentary strata dipping less than 3°. The bedrock surface is 30–100 m below modern sea level, and is incised by channels associated with a pre-glacial drainage system.

Surficial materials Bedrock is overlain by up to 10 m of till. Above this, glaciomarine sediments are up to 20 m thick. Paraglacial sediments, formed when ice was nearby and/or when relative sea level was falling, overlie the glaciomarine sediments in places. Postglacial mud, the uppermost unit, exceeds 10 m thickness in the inner bay, and reaches a maximum of 34 m in the outer bay. Gravelly sand and sand occurs in shallow water (<20 m deep) where modern processes inhibit sedimentation and winnow glacial and paraglacial sediments. A representative seismic profile is shown in Fig. 9.

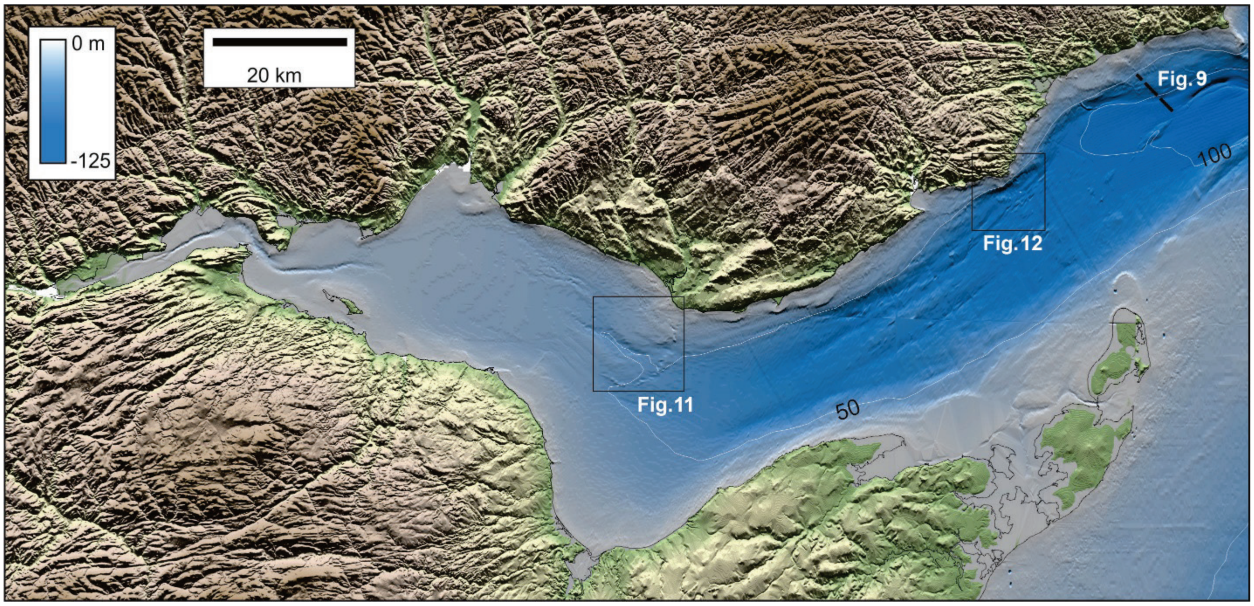


Fig. 8: *Bathymetry, Baie des Chaleurs, with 50 m and 100 m isobaths. Also showing locations of Figs. 9, 11 and 12.*

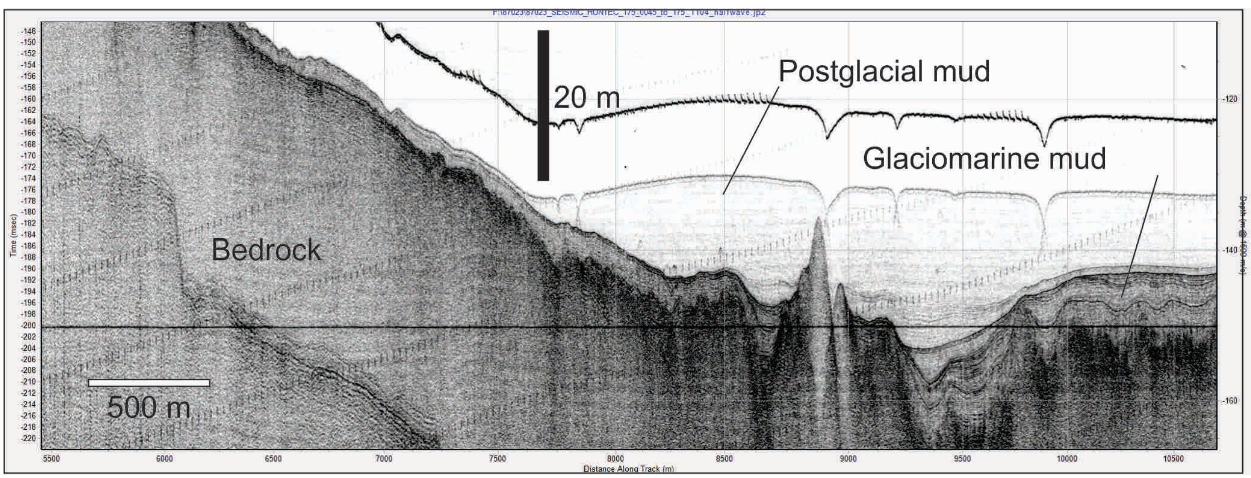


Fig. 9: *Representative seismic profile, outer Baie de Chaleurs. Thick postglacial mud overlies glaciomarine sediments in the deeper water, whereas glaciomarine mud is exposed in the shallows, i.e., above 120 m water depth. The 'v' shaped depressions at the seafloor are likely sedimentary furrows generated by tidal currents. Huntec DTS seismic data from survey 87023, day 175.*

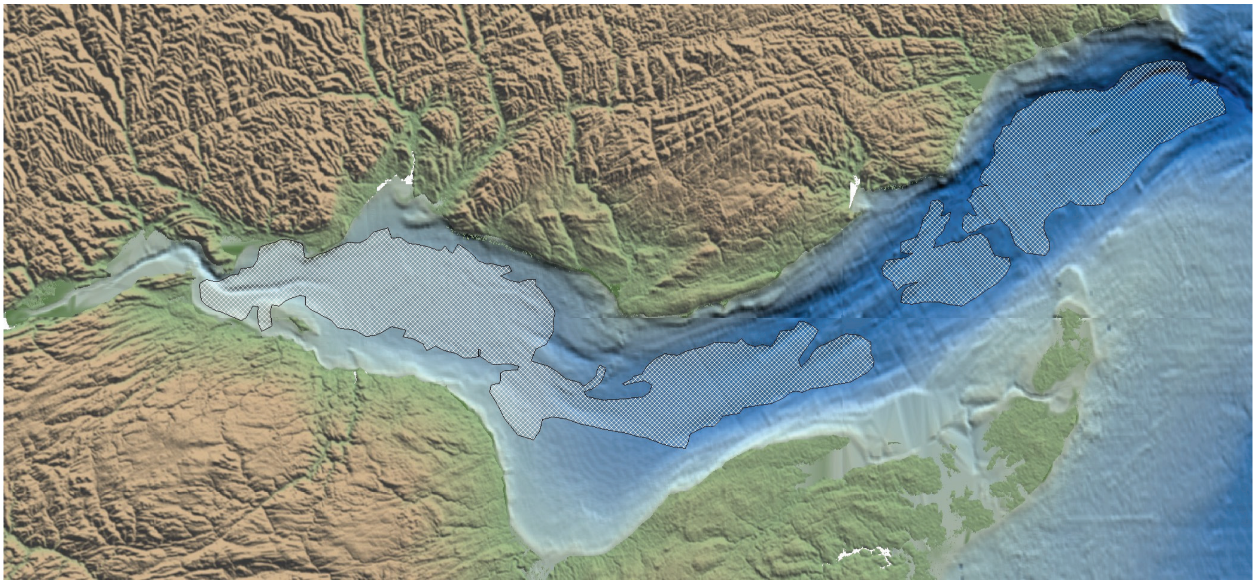


Fig. 10: *Hatched area indicates the location of postglacial mud thicker than 2 m in Baie de Chaleurs, from Sheet 3, Syvitski et al. (1987). Outside this boundary, glaciomarine and paraglacial sediments occur at the sea floor, below a coarse surface veneer (muddy sandy gravel).*

PRINCIPAL GEOMORPHIC REGIONS

The bay is divided into four geomorphic regions, each with a unique morphology, stratigraphy, and surface texture:

- *Shallow coastal zone off the north and south coasts* In shallow water near both coasts the thick postglacial muds of the deeper-water depocentres are absent. Total thickness of Quaternary sediments is less than 20 m. The terrain is irregular in places.
- *Inner bay depocentre* The sea floor is smooth with low relief, with extensive areas of postglacial mud. Gas masking is common. A single channel in the inner bay is a continuation of the Restigouche River. Below the postglacial mud a series of sub-parallel channels were formed during the early postglacial period of lowered relative sea level.
- *Outer bay depocentres* Thick deposits of postglacial mud (see Figs. 9 and 10) are found in the middle of the outer bay, in three principal depocentres. Gas masking is common, and gas escape structures (pockmarks) have been mapped. The glacial sediments under the postglacial mud have an eroded surface with sub-parallel lineations. These are a continuation of lineations on the northeast coast described in the second vignette (below).
- *Bonaventure Moraine* At the eastern boundary of the inner bay an arcuate moraine system extends out from the north shore (Fig. 11).

VIGNETTES

1. Submarine moraine off Pointe Bonaventure

Multibeam imagery (Fig. 11) reveals a submarine moraine (A) that formed when retreating glaciers halted. It is arcuate in form and rises 8 m above the surrounding terrain (see Fig. 12A in Syvitski, 1992). The surface is truncated in places due to lowered sea level in the early Holocene. It is surrounded by the postglacial mud unit (B), generally smooth but with gentle relief likely due to tidal currents. In shallow water near the coast the terrain is much more irregular (e.g., C) likely due to the presence of glacial or paraglacial sediments; bedforms about 1 m high are found at D, in a depth of 17 m.

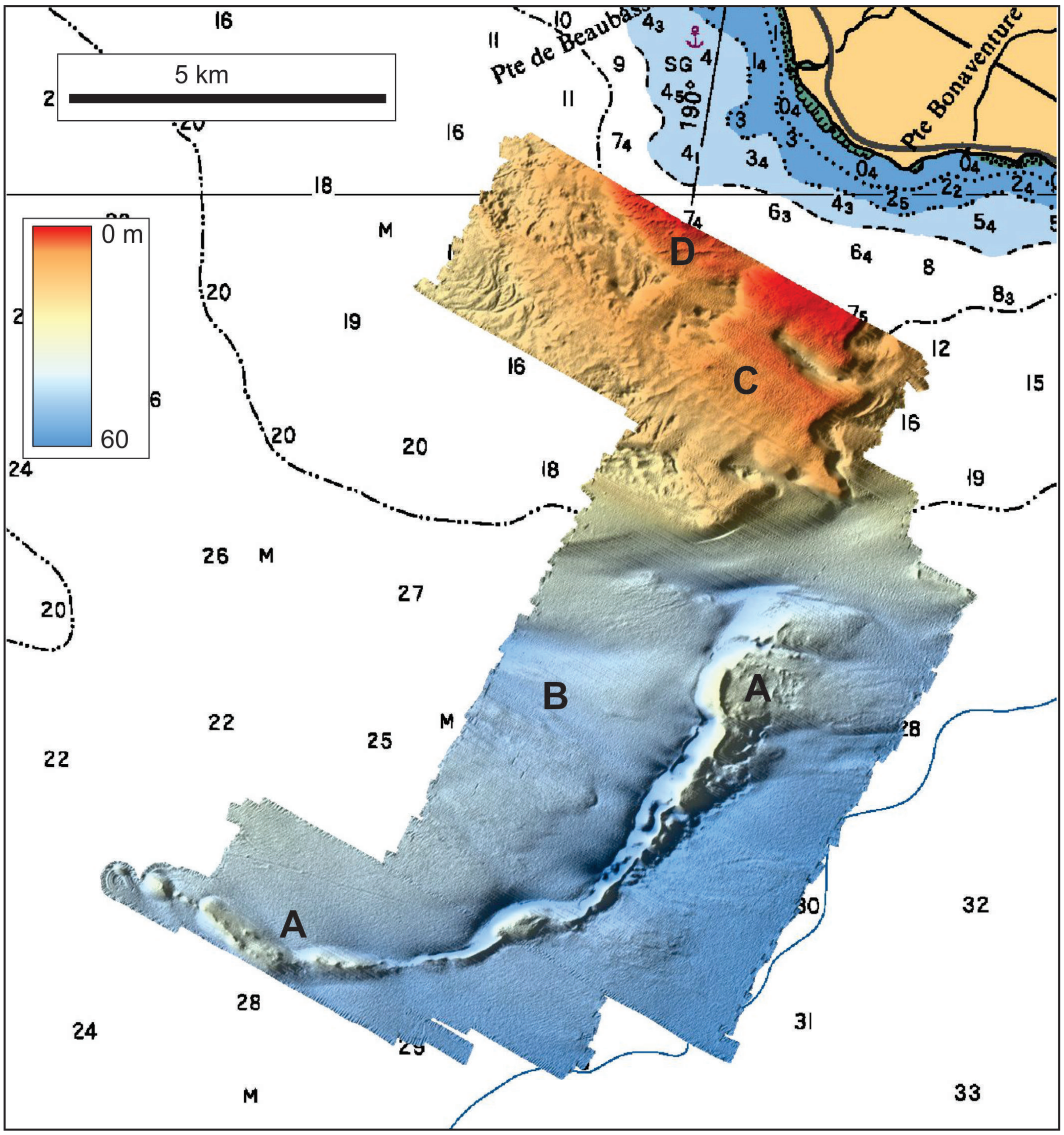


Fig. 11: *Arcuate submarine moraine (A) in the inner bay, with postglacial sediments (B), glacial sediments in shallow water near the coast (C) and modern bedforms (D).*

2. Irregular seafloor in the outer bay

Near Pointe Noire (Fig. 12) glaciomarine sediments are incised by fluted grooves up to 3 m deep (A), producing an irregular seafloor. The erosion was caused by lightly grounded ice readvancing out of the bay, following earlier retreat. A meandering furrow (B) was likely created by an iceberg. Erosion also created a 10 m high escarpment (C), south of which the seafloor is highly irregular (D), with relief of 5 m. The flute at E is a current-formed feature, developed in a patch of postglacial mud.

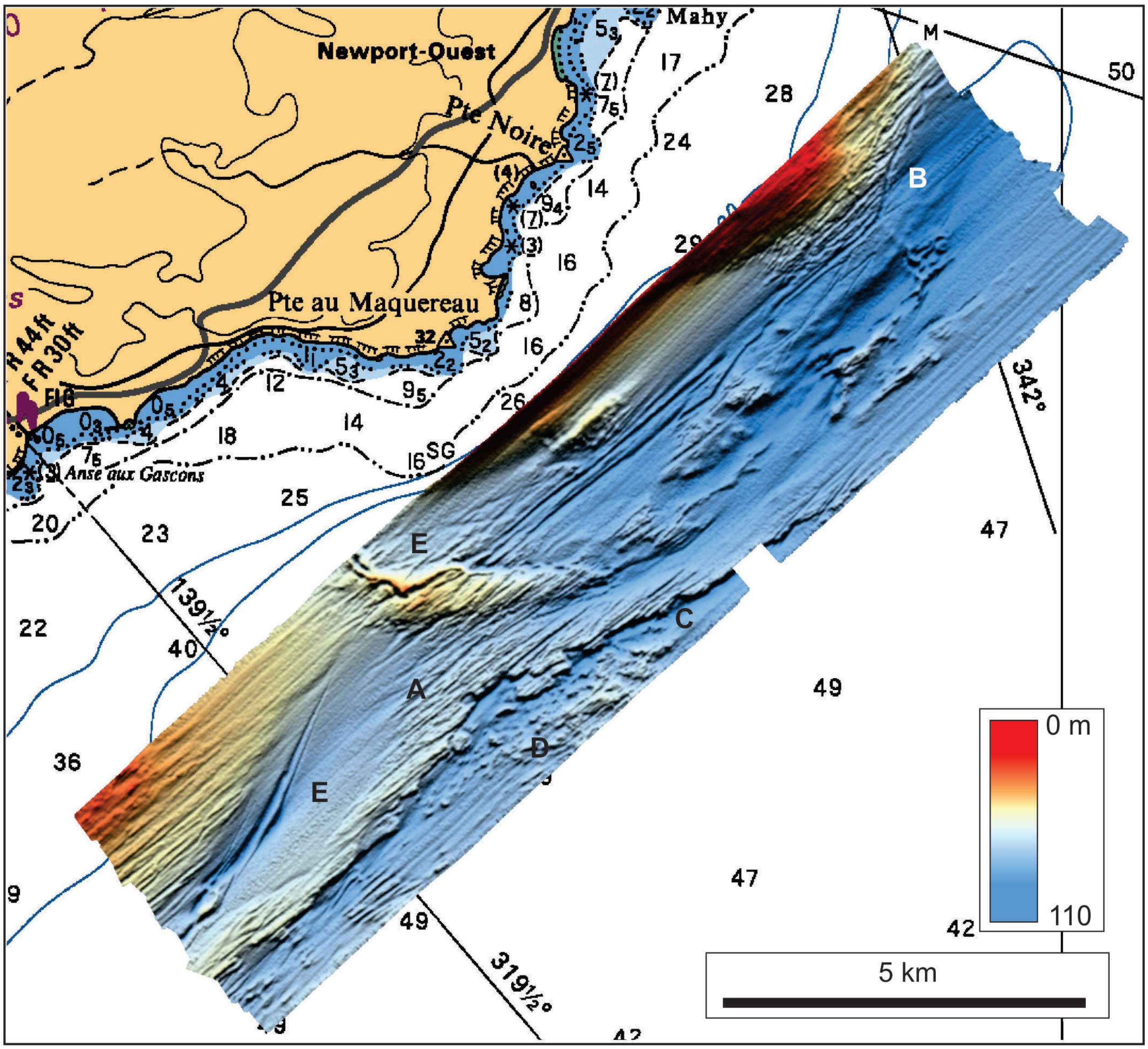


Fig. 12: Irregular topography in the outer bay, to depth of 90 m.

FAVOURABLE FACTORS, POTENTIAL CONSTRAINTS, AND HAZARDS

- The comprehensive 1987 map series depicting, among other aspects, postglacial mud thickness and depth to bedrock, together with the archived seismic data upon which it was based, provide a good basis for planning.
- The bay is shallow (nearly all <100 m water depth), with low relief and roughness.
- Multibeam surveys reveal irregular terrain in places, for example the large submarine moraine north of Belledune. The glacially-fluted glacimarine sediments near Pointe Noire may occur elsewhere, and the flutes and escarpments likely occur over a much wider area, under the blanket of postglacial mud.
- An irregular channel system exists below the postglacial mud blanket of the inner bay.
- The postglacial mud unit contains gas, and gas escape structures (pockmarks) occur in the outer bay.
- In the littoral and nearshore fringes (depth <30 m) fine sediments are absent and glacial, glacimarine and postglacial sand and gravel are winnowed by currents and waves and reworked extensively.

Region 2: New Brunswick Shelf

SUMMARY

New Brunswick's gulf coast shows a variety of generally low-relief coastlines, with sandy spits, lagoons, and barrier islands forming the majority of the coastal fringe. The shelf is wide and shallow, with a central trough (Shediac Trough) extending to the northeast. This results in one of the largest areas of shallow water in Atlantic Canada. Relative sea level fell to -45 m in the early Holocene, so much of the area has experienced sub-aerial exposure and consequent reworking of glacial sediments. Relatively thick sand bodies exist adjacent to the barrier island coastline of New Brunswick.

<u>Favourable</u> factors for foundation emplacement include a large, low relief shallow shelf; bedrock incisions contain thicker sediments; the coastline and nearshore likely hosts large deposits of sand and gravel

<u>Constraints</u> for foundation emplacement include very little existing data; Quaternary sediment cover is generally thin; bedrock is friable

Systematic mapping by Loring and Nota (1973) shows that generally thin, mobile sand and gravel overlie carboniferous to Permian sedimentary bedrock, with up to 25 m of unconsolidated sediments in bedrock channels.

GEOLOGY

Geomorphology The shelf is wide and shallow (Fig. 13), with a central trough (Shediac Trough) extending to the northeast. Relative sea level fell to 45 m below the present level in the early Holocene, before rising once more, so much of the area has experienced sub-aerial exposure. Seabed relief is very subdued throughout the area.

Bedrock The gently sloping (<1 degree) seabed is underlain by Upper Carboniferous to Permian sedimentary rocks, generally friable reddish brown sandstones. Bedrock is gently deformed sedimentary strata dipping less than 3° (see cross sections in Loring and Nota, 1973).

Surficial sediments Bedrock is overlain by a veneer of Quaternary sediments, with thicker deposits in incised channels. The Loring and Nota map of surficial materials shows gravelly sand near the coast, and finer sand in deeper water, particularly in the Shediac Trough. Thicker deposits are found locally in sand bodies at the seafloor and sediment in bedrock incisions. The bedrock channel on Fig. 14 extends to 60 m below modern sea level.

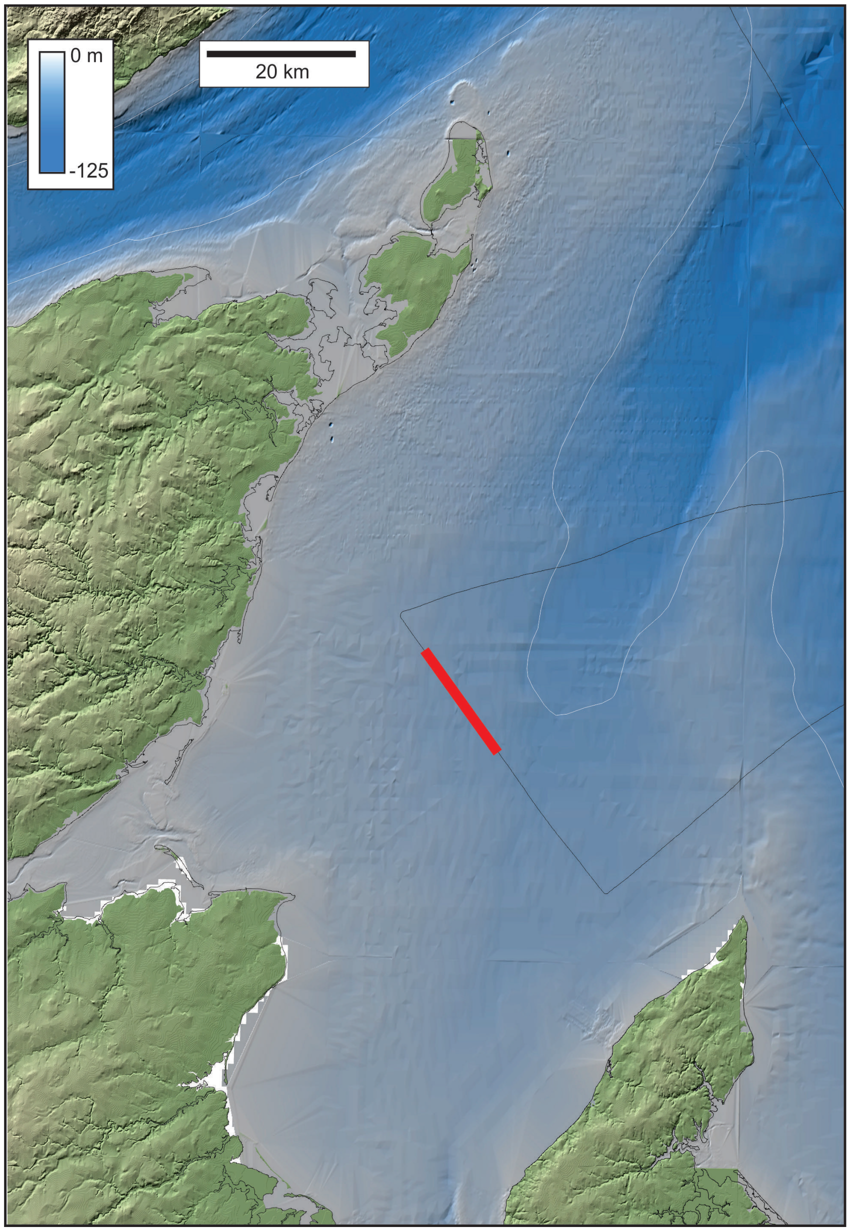


Figure 13: *Bathymetry, off northeast New Brunswick, also showing 50 m isobath (white line), track of cruise 89008 (black line), and location of seismic records of Fig. 14 (red line).*

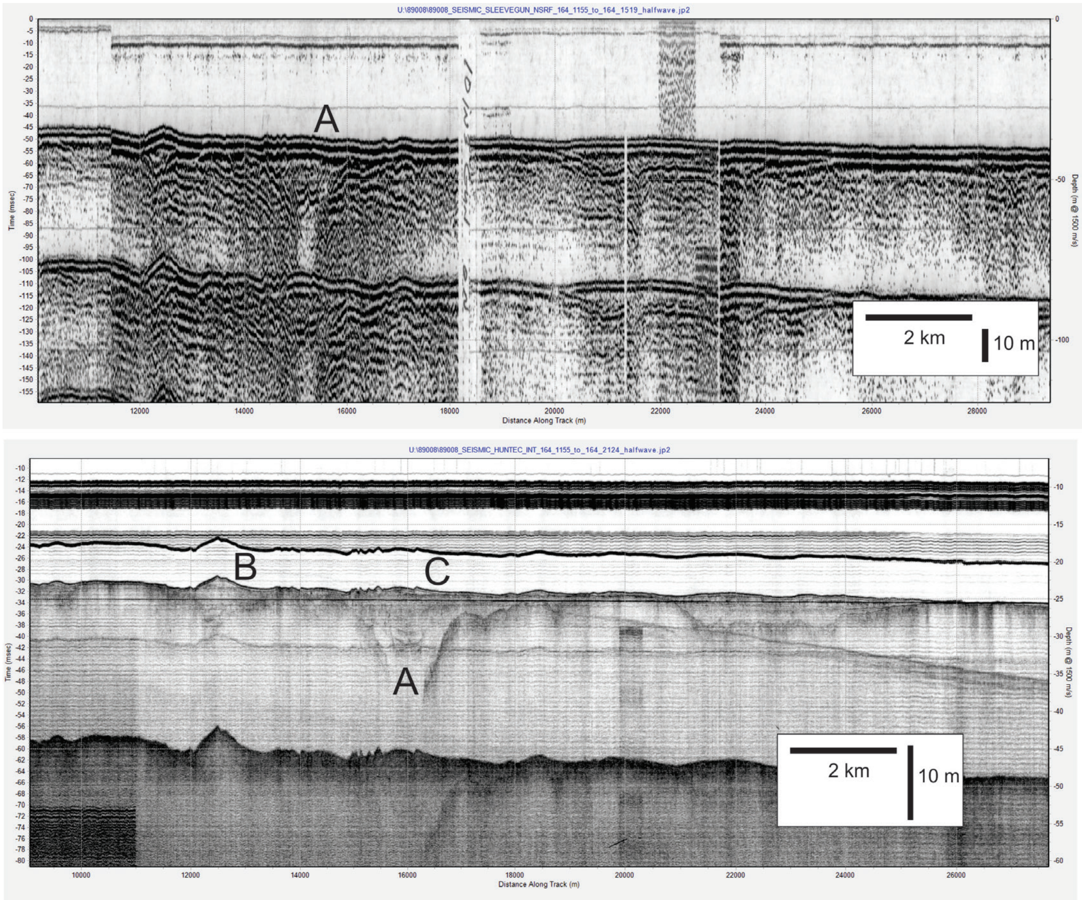


Figure 14: *Representative seismic profiles, offshore from the New Brunswick shelf in the Gulf of St. Lawrence. a) sleeve gun record from cruise 89008 showing thin sediment over bedrock, except where bedrock channels exist, e.g. at A. b) Huntec DTS seismic data from the same area showing that sand bodies several m thick form a veneer over bedrock, with some larger bodies, e.g at B and C.*

PRINCIPAL GEOMORPHIC REGIONS

The bay is divided into two geomorphic regions, each with a unique morphology, stratigraphy, and surface texture:

- *Shallow inner zone* In shallow water a series of tidal inlets are protected by barrier beaches and nearshore bars (Reinson, 1980). Multibeam sonar surveys are not available, and, as with Prince Edward Island and the Northumberland Strait, it is likely that sand bodies with bedforms occur near the coast.

- *Deeper water* The sea floor is smooth with low relief, and thin (several metres) sand and gravelly sand overlie bedrock, with finer sand in the deeper parts of Shediac Trough. In Loring and Nota (1973), profiles 7 and 8 across Shediac Trough show sediment infill of up to 25 m. Narrow, incised valleys are found scattered across the region, and are infilled with sediment. Larger sand accumulations form bedforms, but their exact distribution is unknown.

FAVOURABLE FACTORS, POTENTIAL CONSTRAINTS, AND HAZARDS

- The region has one of the largest areas of shallow water in Atlantic Canada, with low relief and roughness.
- Bedrock consisting of Carboniferous to Permian sandstone lies just below the seabed, under a veneer of gravelly sand; thicker sand deposits are found in Shediac Trough.
- Bedrock is incised by narrow, sediment-filled valleys.
- At the coast numerous tidal inlets are protected by barrier beaches and nearshore bars. The largest inlet is that of the Miramichi River.
- Multibeam sonar data are not available but it is speculated that thicker sand bodies may be located in the littoral zone and nearshore, as elsewhere in the Gulf and Northumberland Strait, and also offshore.

Region 3: Prince Edward Island Platform

SUMMARY

Coastlines of the North side of Prince Edward Island are typified by the National Park along its shores, with sandy beach dune systems, spits, barrier islands and sedimentary coastlines interspersed with loosely consolidated sandstone bluffs. The shelf north of the island is wide and shallow. The gently sloping (<1 degree) seabed is underlain by Upper Carboniferous to Permian sedimentary rocks—generally friable reddish brown sandstones—with a veneer of sand and gravel. Thicker deposits of unconsolidated sediments infill relict valleys.

Favourable factors for foundation emplacement include this being the largest shallow water region in Atlantic Canada; the shelf is low relief; bedrock incisions are filled with thicker packages of sands; nearshore sand prisms are connected to the coast by bar systems

Constraints for foundation emplacement include generally thin Quaternary sedimentation; bedrock is generally friable and rough

GEOLOGY

Geomorphology Very gentle slopes prevail (Fig. 15), except in several areas and close to the coast, where old river valleys exist that were active when relative sea level was lower in the early Holocene (Fig. 3).

Geology The gently sloping (<1 degree) seabed is underlain by Upper Carboniferous to Permian sedimentary rocks, which are generally composed of friable reddish brown sandstones. Bedrock is gently deformed sedimentary strata dipping less than 3° (see cross sections in Loring and Nota, 1973).

Surficial sediments Bedrock is overlain by a veneer of Quaternary sediments, with thicker deposits in incised channels (Fig. 16). The maximum Quaternary sediment thickness is ~ 40 m on the shallow inner shelf. The Loring and Nota map of surficial materials shows a mosaic of gravel, gravelly sand, and sand. Thicker deposits are found locally in: 1) sand bodies at the seafloor; and 2) sediment in bedrock incisions. Unconsolidated sediments more than 50 m thick are also found in the deep, narrow troughs between Prince Edward Island and the Magdalen Islands.

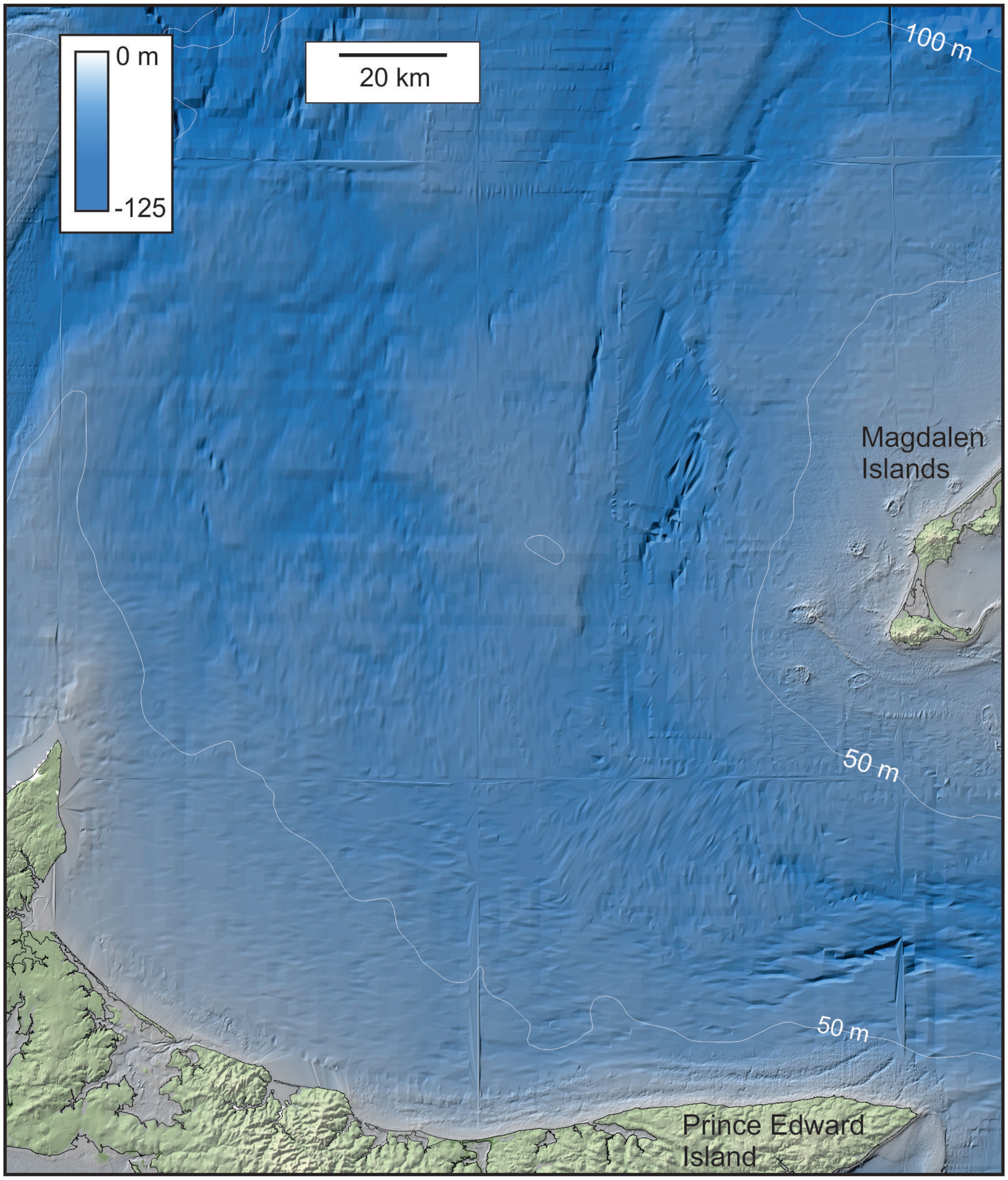


Figure 15: *Bathymetry of Gulf of St. Lawrence, off Prince Edward Island, also showing 50 m and 100 m isobaths. Bedrock ridges parallel the eastern part of the coast.*

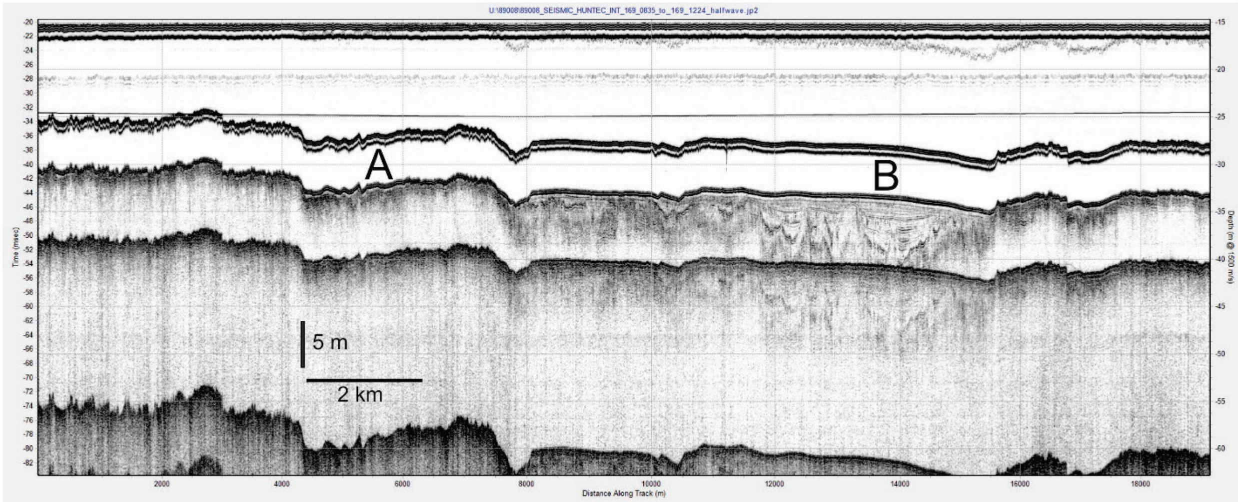


Figure 16: *Representative Huntec DTS seismic profile offshore from Prince Edward Island showing bedrock with a sediment veneer (A) that characterizes much of the region, and up to 15 m of sediment in a depression (B). Cruise 89008 day 169.*

PRINCIPAL GEOMORPHIC REGIONS

The region is divided into two geomorphic regions, each with a unique morphology, stratigraphy, and surface texture:

- *Shallow inner zone* At the coast tidal inlets are protected by barrier beaches and nearshore bars (e.g., Armon, 1980). As described in the vignette (Fig. 17) nearshore bars systems connect with sand prisms in shallow water immediately offshore. Bedrock predominates, with numerous fluvial channels (perhaps formed during the postglacial sea level lowstand).

- *Deeper water* The sea floor is smooth with low relief, and thin (several metres) gravelly sand and sand overlie bedrock, with thicker deposits in several areas.

VIGNETTES

1. Innermost shelf, Rustico area

Multibeam coverage extends from a few metres depth at the coast to a maximum depth of 44 m. Large sand prisms found near the coast (A) average 1 m in thickness, thickening towards the coast where multiple shore-parallel nearshore bars are developed (B). The sand bodies extends farther offshore in places (e.g., C) and link with deeper sand bodies (D). The sand body at E is more than 3 m in thickness, and supports sand ridges ~1 m high. Large areas of bedrock (F) may have a very thin veneers of gravel and sand between outcrops. River valleys (G) that dissect the bedrock are typically 3-4 m deep and ~100 m wide.

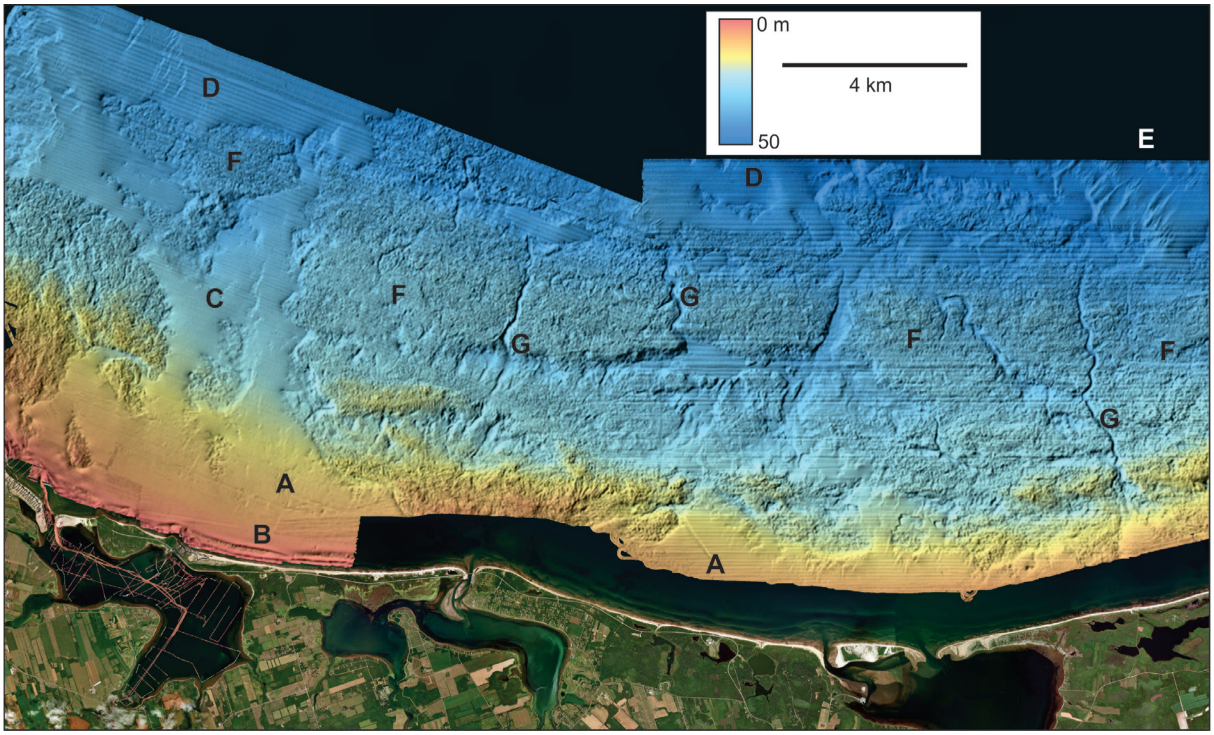


Figure 17: *Innermost shelf Rustico area, Prince Edward Island.*

FAVOURABLE FACTORS, POTENTIAL CONSTRAINTS, AND HAZARDS

- The region has the largest area of shallow water in Atlantic Canada, with low relief and roughness.
- Bedrock consisting of Carboniferous to Permian sandstone lies just below the seabed, under a veneer of gravelly sand; thicker sand deposits are found in some depressions.
- Bedrock is incised by narrow, sediment-filled valleys in places, particularly near the coast.
- Numerous tidal inlets are protected by barrier beaches and nearshore bars. The bars connect with relatively thick nearshore sand prisms.

Region 4: Magdalen Shelf

SUMMARY

Coastlines on the Magdalen Islands are generally low relief and sedimentary, with areas of low bluff erosion common. They are surrounded by a shallow, gently sloping shelf. A cluster of narrow channels up to 144 m deep is found in the southwest, between the islands and Prince Edward Island. Surficial sediments consist of a veneer of sand over bedrock, with thicker accumulations in bedrock valleys. Near the islands the sands are organized into trains of sand waves, with thicker deposits of sand accumulating in several places near the east-facing coasts. The extent and origin of a large sand wave field to the south of the islands are unknown. The notable aspect of the islands is the presence of numerous irregular exposures of bedrock deformed by salt diapirism.

<u>Favourable</u> factors for foundation emplacement include a large shallow seabed with low relief and roughness; sands organized into locally thicker deposits; nearshore accumulations of sand connect with offshore prisms

<u>Constraints</u> for foundation emplacement include generally thin surficial sediments; bedforms indicate sand mobility; salt tectonism leads to seabed and bedrock distortion

Key sources of information include Howie (1988) for a discussion of regional salt diapirism and Rémillard et al. (2016) for postglacial evolution of the islands.

GEOLOGY

Geomorphology The Magdalen Islands (Fig. 18) are surrounded by a shallow, gently sloping shelf, bounded in the east by the Cape Breton Trough. A cluster of narrow channels up to 144 m deep is found in the southwest, between the islands and Prince Edward Island. The seafloor has low relief except in the vicinity of the islands, where irregularity is due to either sandy bedform fields or contorted bedrock exposures. Maximum lowering of relative sea level below modern in the early postglacial period was >60 m at 9 ka BP (Shaw et al., 2002).

Bedrock The gently sloping (<1 degree) seabed is underlain by Upper Carboniferous to Permian sedimentary rocks, generally composed of friable reddish brown sandstones that are organized into gently deformed sedimentary strata (Figs. 19, 21). However, large areas have been deformed by salt tectonics (see Howie, 1998).

Surficial materials Bedrock is overlain by a veneer of Quaternary sediments, with possibly thicker deposits in incised channels. The Loring and Nota (1973) map of surficial materials shows a mosaic of gravel, gravelly sand, and sand. Areas immediately west of the island are non-depositional, with lag deposits, whereas a large area of sand occurs to the east. Near the islands relatively thick sand deposits occur as linear bedform trains (D, E and G, Fig. 18). Thicker deposits of sand have accumulated in several places in the lee of the islands (A,B, G and F, Fig. 18), as a result of net sediment transport from west to east. An area of large sandy bedforms is located south of the islands (southern white rectangle, Fig. 1). The areas of sandy bedforms in the north and south of the islands coincide with areas of maximum modeled tidal currents.

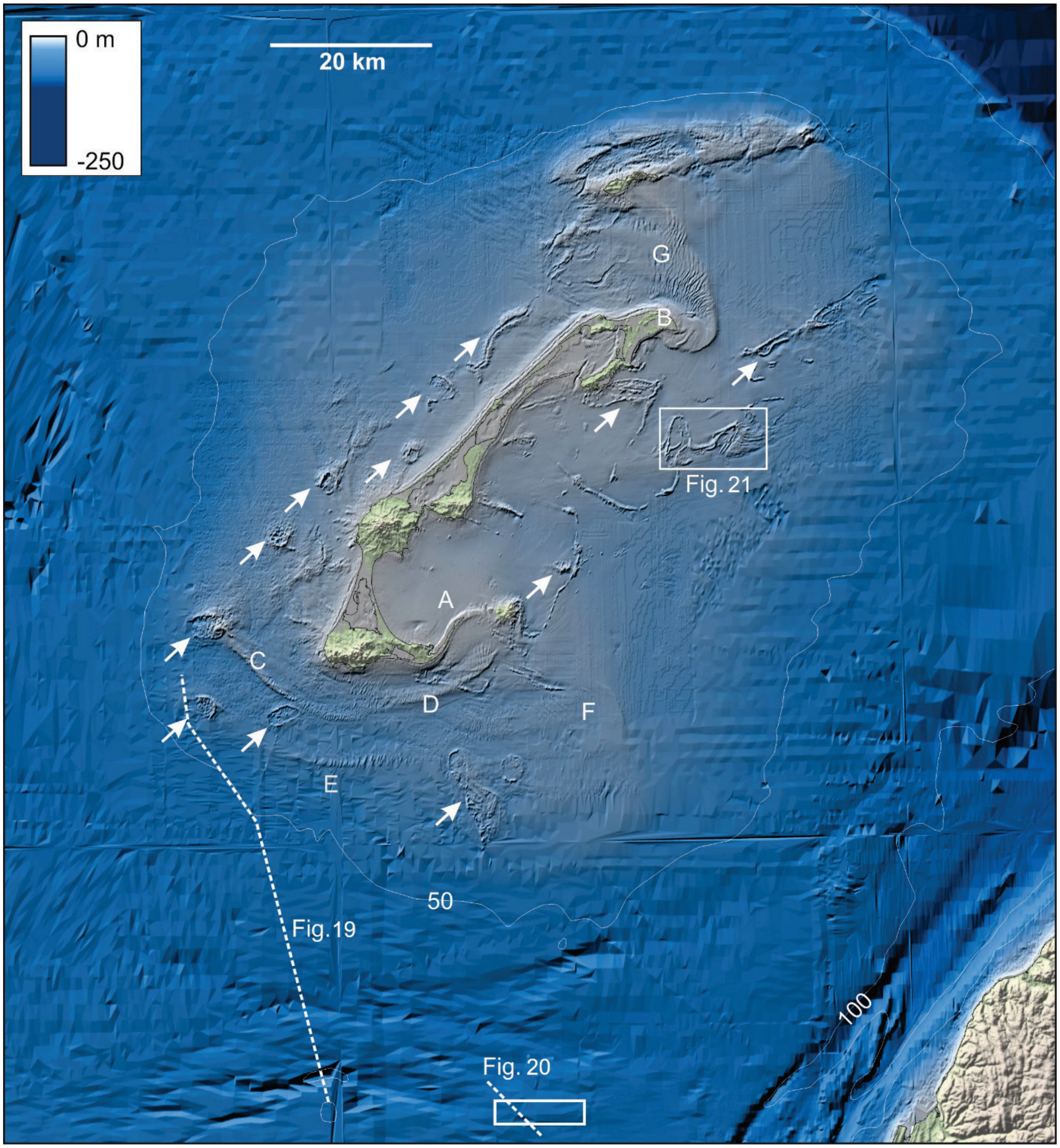


__Fig. 18:__ Bathymetry off the Magdalen Islands, Gulf of St. Lawrence. Irregular features in the otherwise smooth offshore plateau are sandy bedform fields (A to G). The curving deposit at C is in the lee of an outcrop of tectonised bedrock. Bedrock deformed by salt tectonism is arrowed. Also showing location of profiles, Figs. 19 and 20, and Fig. 21. White rectangle at bottom indicates approximate position of a large sand bedform field.

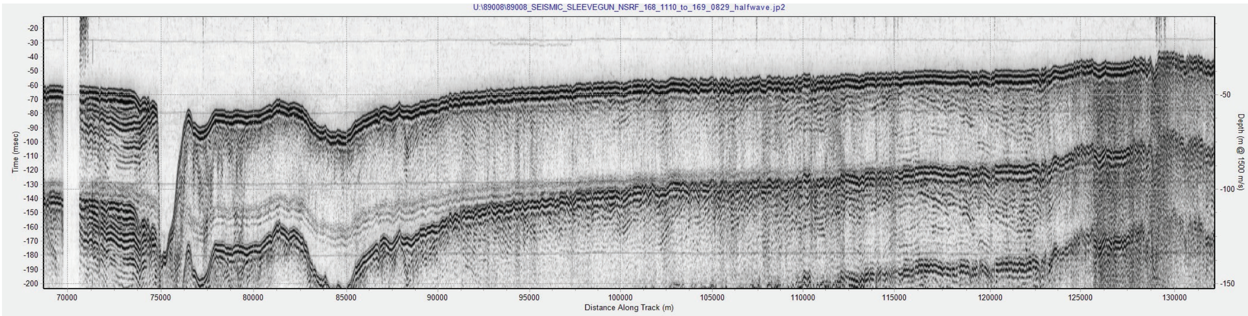


Fig. 19: *Representative Sleevegun profile (cruise 89008, day 168) from south of the Magdalen Islands (location on Fig. 18). The two troughs at extreme left are incised into bedrock. The record shows bedrock, with negligible surficial sediment cover. The shallow area at the extreme right corresponds with a tectonised bedrock outcrop on the coarse-scale bathymetric data.*

PRINCIPAL GEOMORPHIC REGIONS

The region is divided into two geomorphic regions, each with a unique morphology, stratigraphy, and surface texture:

- *Shallow inner zone* As described by Owens and McCann (1982) the islands are a series of rock outcrops linked together by a double tombolo system. The west coast beaches experience sediment bypassing, and sediment is accumulating at two terminal spits in the north and south (A and B. Fig. 18). Both spits are located on sandy platforms. These two areas coincide with areas of maximum tidal currents according to oceanographic models.

- *Deeper water* While gravel lag surfaces predominate in the west, areas of relatively thick sand are present, organized into arcuate bedform fields (Fig. 18, C, D, and E) in water depths of 20–30 m. Thicker sand sheets are present in the south (F) (~ 10 m thickness) and north (G). The former includes fields of sand waves, 4 m in height. The latter forms a ramp-like wedge, sloping upwards from the west, with a thickness of ~ 10 m, and containing 5 m-high sand waves. Both these sediment accumulations agree well with the Owens and McCann findings that sediment is accumulating on the east side of the islands.

  The approximate location of a large area of sandy bedforms about 3 m high, in water depths of 60 m, is shown by the dashed box on Fig. 18. It is unknown whether these are: 1) active bedforms, formed by strong tidal currents east of the cluster of deep channels mid-way between the Magdalens and Prince Edward Island; or 2) relict bedforms that were active when tidal flows between Prince Edward Island and the Magdalen Islands operated when relative sea level was at least 60 m lower than today, 9000 years ago. A seismic profile of the bedform field (Fig. 20) shows that it overlies sediment-filled valleys.

Irregular bedrock outcrops with relief up to 10 m are found around the islands, in water depths down to 40 m. These bedrock areas are highly deformed as a result of salt tectonism. Their distribution is shown in map form on Fig. 77 of Howie (1988), whose cross-sections (Fig. 76) show salt diapirs reaching the surface on the islands.

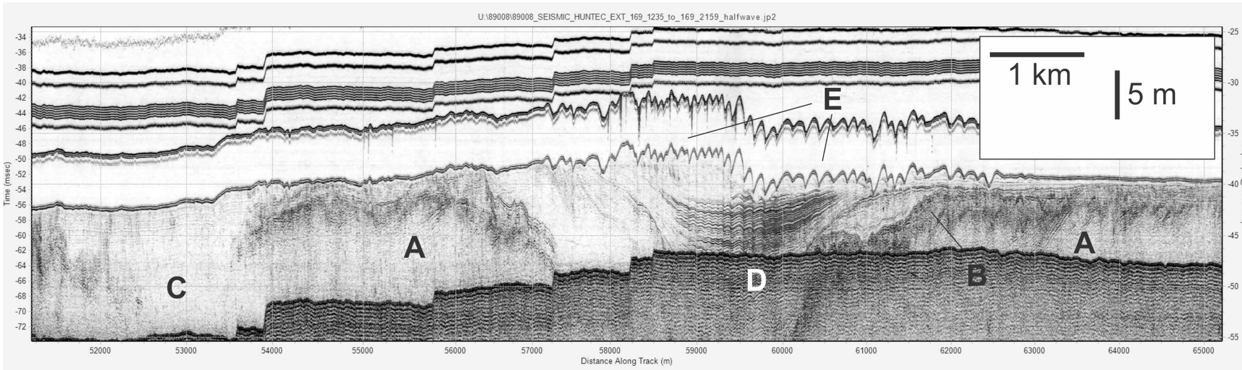


Fig. 20: *Huntec DTS profile (cruise 89008, day 169) from an area of large bedforms south of the Magdalen Islands. Location on Fig. 18. The profile shows bedrock (A), with a cover of till (B). Several valleys incised into bedrock (C and D) contain an infill of stratified sediment. The bedform field is at E.*

VIGNETTES

1. Salt tectonism

Imagery from east of the islands in water depths down to ~ 30 reveals highly contorted bedrock ridges with average relief of 5 m, ranging up to 13 m (Fig. 21). The bedrock has high backscatter. It is surrounded by a narrow fringe of high backscatter interpreted as gravel. Everywhere else, the smooth seabed is sand, 2-3 m thick and overlying a gravel lag. The contortion of bedrock strata is evidence of the salt tectonism in the southern Gulf of St. Lawrence (Howie, 1984; Waldron and Rygel, 2005). Areas showing evidence of extensional stress, e.g., the outer rim of curved features, convex shaped, will undoubtedly have extensional fracturing. Similarly areas of compressional stress will also be fractured but in an antithetic fashion. Both cases will diminish the structural strength of the host bedrock. Additionally, the action of drilling footings into these same bedrocks may allow water to penetrate deeper, possibly coming into contact with shallow evaporitic rocks which would then be at risk of dissolution with further structural complications.

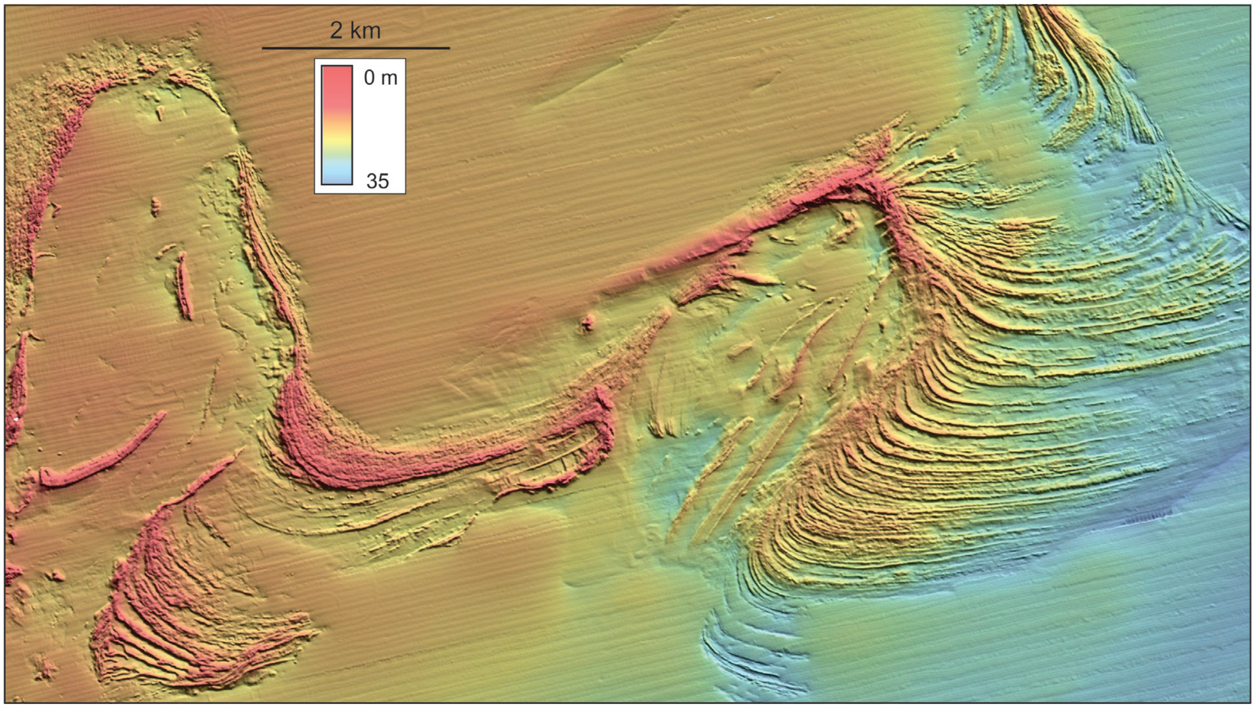


Fig. 21: *Carboniferous/Permian bedrock deformed by salt tectonism. Smooth areas are sand sheets several metres in thickness.*

FAVOURABLE FACTORS, POTENTIAL CONSTRAINTS, AND HAZARDS

- The region has a large area of shallow water, with low relief and roughness, except for scattered large outcrops of bedrock. The exception is the deep trench in the south.
- Surficial materials are thin, and predominantly gravel and sand, with sand predominating east of the islands. Sand sheets are a few metres in thickness, overlying gravel lags and bedrock.
- Sand is also organized into larger and thicker accumulations in places.
- The coast is characterized by barrier beaches, back-barrier lagoons and nearshore bars. The bars connect with nearshore sand prisms.
- As a result of salt tectonics, numerous areas of bedrock outcrop on the seafloor have been distorted, likely compromising their structural integrity.

Region 5: Northumberland Strait

SUMMARY

Coastlines in this region are low relief and sedimentary, and the shallow seabed in the strait is generally low relief. Sea level fell after deglaciation but rose once more, so that by 6000 years ago much of the bay had drowned and Prince Edward Island was disconnected from the mainland. A network of old river channels incised in bedrock contains till. In several areas thick postglacial muds overlie thin glacial sediments; elsewhere thin postglacial sand and gravel overlie a veneer of glacial sediments. As a result of tidal scour, a network of ancient lakes and rivers is preserved near the Fixed Link bridge crossing (Abegweit Passage). Sandy bedform fields are found near coasts, notably the large accumulation at East Point.

<u>Favourable</u> factors for foundation emplacement include a low relief seabed; areas of thick Quaternary sedimentation, including sands

<u>Constraints</u> for foundation emplacement include strong currents causing scour; mobile bedform fields; broad areas of till surficial cover; variable thicknesses of Quaternary cover

Krank (1971) provides a good starting point for understanding the surficial geology of this region, and Shaw et al. (2008) give in-depth discussion of the Milne Bank using high-resolution data.

GEOLOGY

Geomorphology Northumberland Strait is shallowest in the west and middle, and deepens in the east towards the Laurentian Channel (Fig. 22). Pre-glacial river channels incised in bedrock and extending east and west are found along its axis (Kranck, 1975). Following deglaciation, Northumberland Strait was entirely exposed when relative sea level dropped in the early Holocene. During the postglacial period, relative sea level dropped, reaching -45 m in the east at c. 8000 BP, but shallower than this in the west (perhaps -20 m near West Point). In the late Holocene, relative sea level rose, and the Prince Edward Island was disconnected from the mainland c. 6000 BP. The main consequences of changing sea level were: 1) drowned river valleys, some of them reoccupying pre-glacial river valleys; 2) drowned lakes; and 3) reworking of glacial sediments during the transgression.

Bedrock The region is underlain by Upper Carboniferous to Permian sedimentary rocks, except in the extreme east where Ordovician to Permian rocks are found.

Surficial sediments Kranck (1971) mapped the Quaternary sediments that overlie bedrock in the region. Overburden thickness is generally 5-10 m, with thicker deposits in the channels, up to a maximum of 35 m. The lowest unit is till and is absent from some areas, forms a veneer elsewhere, and is up to 25 m thick in the channels southwest of West Point. Where exposed it comprises poorly sorted sandy gravel. It is overlain in places by stratified pro-glacial sediments. Early postglacial sediments include widespread sands and muds. The main postglacial to modern sediment units are sand and gravel, which occurs as a veneer off East Point and as a 20 m thick deposit off West Point, and postglacial mud. The latter predominates in the east of the strait and also in the central area, just east of Abbegeweith Strait.

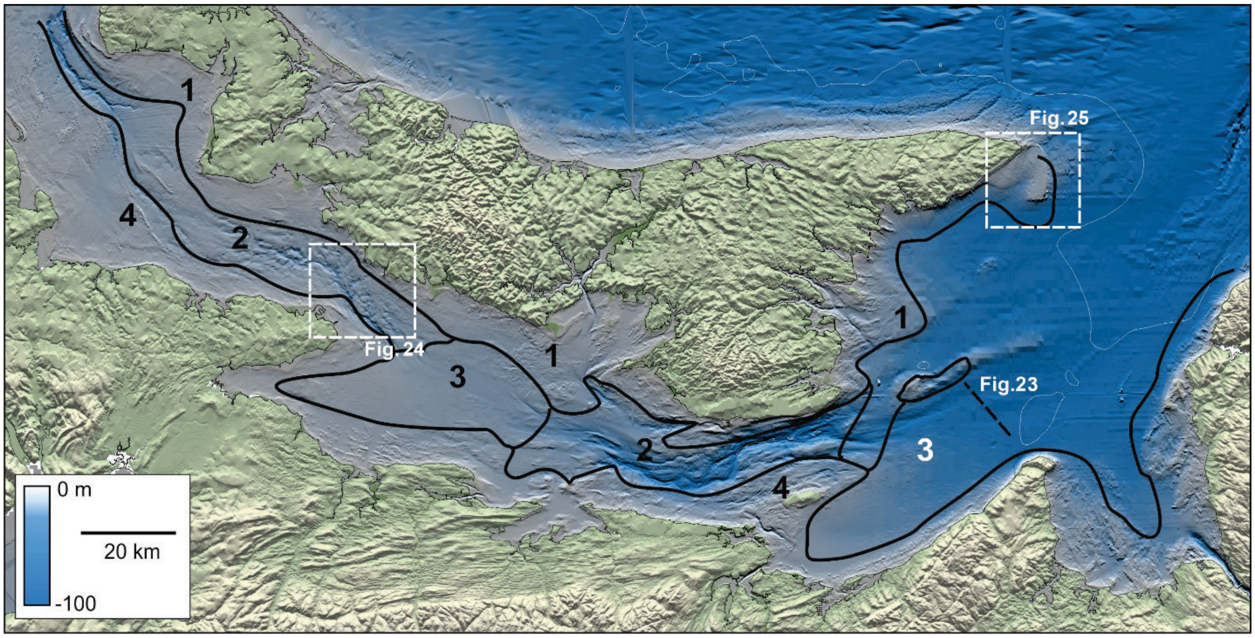


Fig. 22: *Bathymetry of Northumberland Strait, also showing geomorphic regions: 1) northern coastal zone; 2) channel zone; 3) major depocentres; and 4) southern coastal zone. Boxes show positions of Figs. 24 and 25, and the dashed black line indicates location of the seismic profile of Fig. 23.*

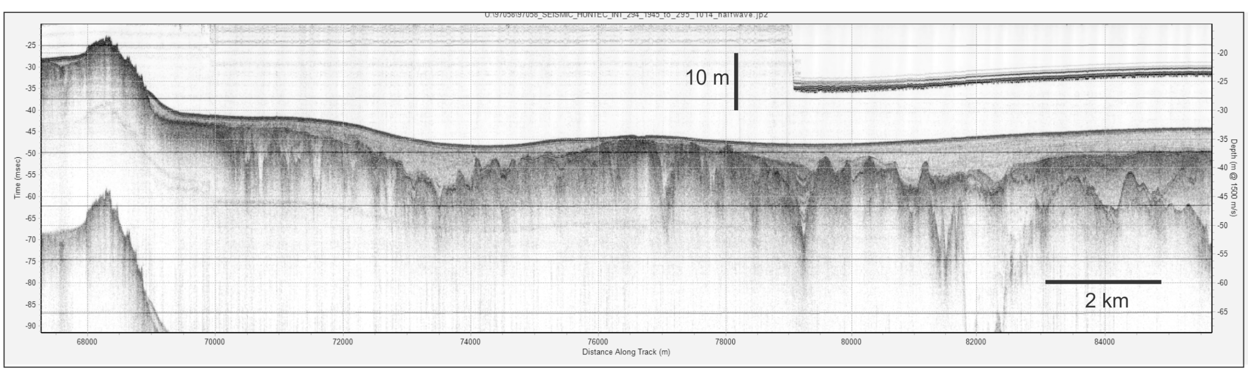


Fig. 23. *Huntec DTS seismic profile from the east of Northumberland Strait (location on Fig. 22). The uppermost postglacial mud unit (Pugwash Mud) averages 5 m in thickness. It overlies an acoustically stratified unit that infills the irregular bedrock surface. Gas masks the stratigraphy at the right hand side of the section. Maximum overburden is 15 m.*

PRINCIPAL GEOMORPHIC REGIONS

The strait is divided into four geomorphic regions (Fig. 22), each with distinct morphologic and textural properties.

- ***Northern coastal zone.*** Bedrock ridges with relief up to 10 m extend out from the coast in places, notably at Hillsborough Bay. Overburden is relatively thin, and consists of veneers of sand, organized into mobile bedform fields in places. Very large sand accumulations with bedforms, fed by littoral drift (Shaw and Taylor, 2001), are found at West Point, and notably at East Point (see below). The latter is located under a tidal gyre, is >40 m thick, and is actively prograding, with migratory bedforms several metres in height.

- ***The channel zone.*** Channels oriented along the east-west axis of Northumberland Strait are developed in bedrock to a maximum depth of 70 m below modern sea level. The channel zone can be seen on the slope map (Fig. 23). They are not evident east of Abegweit passage, only because they have been buried by Quaternary sediments. The same applies in the east of the strait. They are likely of pre-glacial origin, but are also likely to have functioned during the postglacial sea level lowstand when the strait was largely dry land. Channels drained west and east from a divide in Abegweit Passage. The channels contain deposits of till up to 35 m in thickness termed the Northumberland Drift. Areas between channels are bedrock with 2-5 m of sand and gravel. Thicker sand deposits form ridges with superimposed bedforms, notable southwest of Cape Egmont. The Abegweit Passage zone is swept by strong currents (Fader and Pecore, 1989), the evidence of which includes sand ribbons, megaripples, sand waves, and comet marks (obstacle-induced scour depressions). Other seabed features include zones of boulders, dredge spoils, ice scours, and scallop fishing gear marks.

- ***Major depocentres.*** Two principal areas of modern sediment accumulation coincide with areas of reduced maximum bottom current in oceanographic models. These areas have very low relief, and consist of mud, sandy mud, and muddy sand termed the Egmont Formation. These fine-grained postglacial sediments average 10-20 m in thickness, and overlie variable thicknesses of till, generally <5 m. The eastern depocenter occupies the strait west of Cape George, and extends into St. George' Bay. The western depocenter lies east and south of Cape Tormentine. The westernmost part of the latter is a fan shaped deposit of muddy sand incised by radiating channels. It is interpreted as a tidal delta, formed where the strong tidal currents of Abbegweith Strait drop in velocity where the strait widens.

- ***Southern coastal zone.*** This extends along the entire south, and is characterized by a mosaic of bedrock outcrops and thin overburden (0-5 m). Bedrock relief is generally subdued except off New Glasgow (relief up to 10 m) and the fringes of St. Georges Bay (relief up to 20 m). Even where relief is low, bedrock surface is rough, with ridges and troughs up to 2 m (e.g., off Buctouch Spit). The scattered patches of multibeam sonar coverage reveal trains of sand waves in shallow water (<10 m) with relief up to 2 m (offshore from Shemogue and Buctouche spit, for example). Elsewhere off the New

Brunswick coast, sand ridges up to 10 m in elevation are found, with superimposed sand bedforms. The fragmentary multibeam evidence suggests that sand-wave fields are common through the western part of this zone.

VIGNETTES

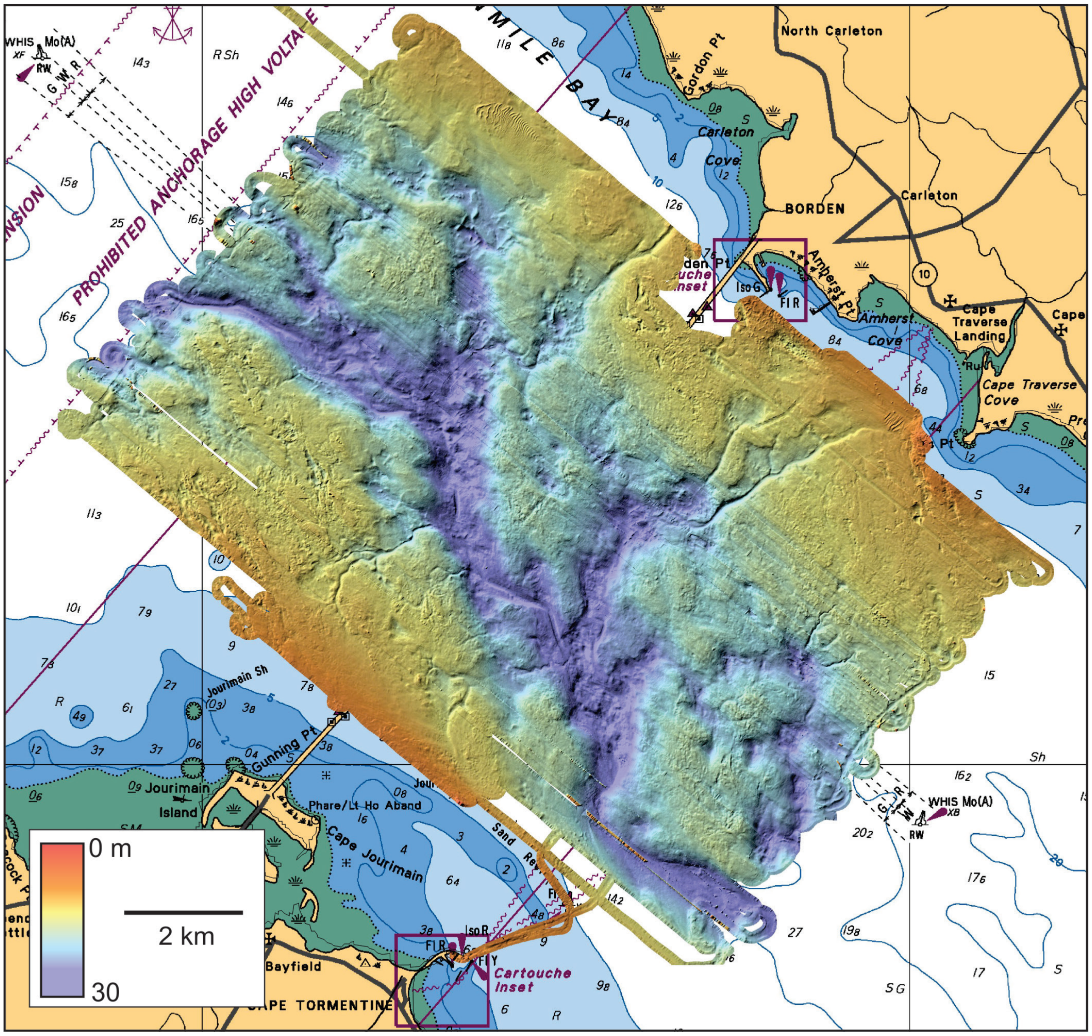


__Fig. 24:__ Sun-illuminated seafloor topography in the vicinity of the Fixed Link, Abegweit Passage. Location on Fig. 22.

1. Abegweit Passage.

Several small areas of multibeam coverage shed light on the true complexity of Northumberland Strait. At the Fixed Link crossing site in Abegweit Passage (Fig. 24) the multibeam sonar data show the irregular terrain typical of the channel zone, notably a series of depressions and channels with relief of up to 10 m; these would have been occupied by rivers and lakes in the early Holocene, when the entire strait was sub-aerial (Shaw et al., 2002; McCulloch et al., 2002). The lake basins are connected by channels suggestive of drainage to the southeast, in agreement with the earlier interpretation of Kranck (1975). Narrow (100 m) incised drainage channels commonly 1–2 m deep connect with this system from both PEI and Nova Scotia, and likely formed during the postglacial relative sea level lowstand. As noted above, this entire area is strongly current-swept, with thin sand streamers in places. This builds on earlier mapping by Fader and Pecore (1989) who identified a highly dynamic seabed with fields of sand ribbons, waves, and megaripples.

Subsequent multibeam mapping reveals that southeast of the current-swept Fixed Link area the seafloor has the form of a lobate sediment body (composed of the sandy facies of the Pugwash Mud) incised by channels fanning out to the southeast. This is interpreted as a tidal delta, formed by flow from the west.

2. Milne Bank

The large sand deposit at Milne Bank (Fig. 25) is unique in the region, and illustrates the variability in seafloor conditions within the physiographic regions of Atlantic Canada. It also represents an area which for various reasons would pose problems for infrastructrure emplacement. Milne Bank is a submarine bank at East Point, the eastern tip of the island. The disturbing effect of East Point on the hydrodynamic regime controls sediment transport (Shaw et al. 2008). The northern boundary of the bank is a steep sand wave located where southward tidal and wave-driven currents rounding East Point suddenly decelerate. Sand from the north coast enters Milne Bank and is carried south in a field of migrating sand waves that are shed from the northern bounding sand wave, towards the prograding end of the bank. Milne Bank is a major sediment sink, rather than a link between the eroding north coast and the sediment-rich south-facing coast. It contains >40 m of sand (Frobel 1990). Longshore transport in nearshore bars is more likely to be responsible for continued sediment accumulation on the south coast. Embayments on the south coast have filled up in a cascading fashion, each one facilitating sediment bypassing when it has reached full capacity.

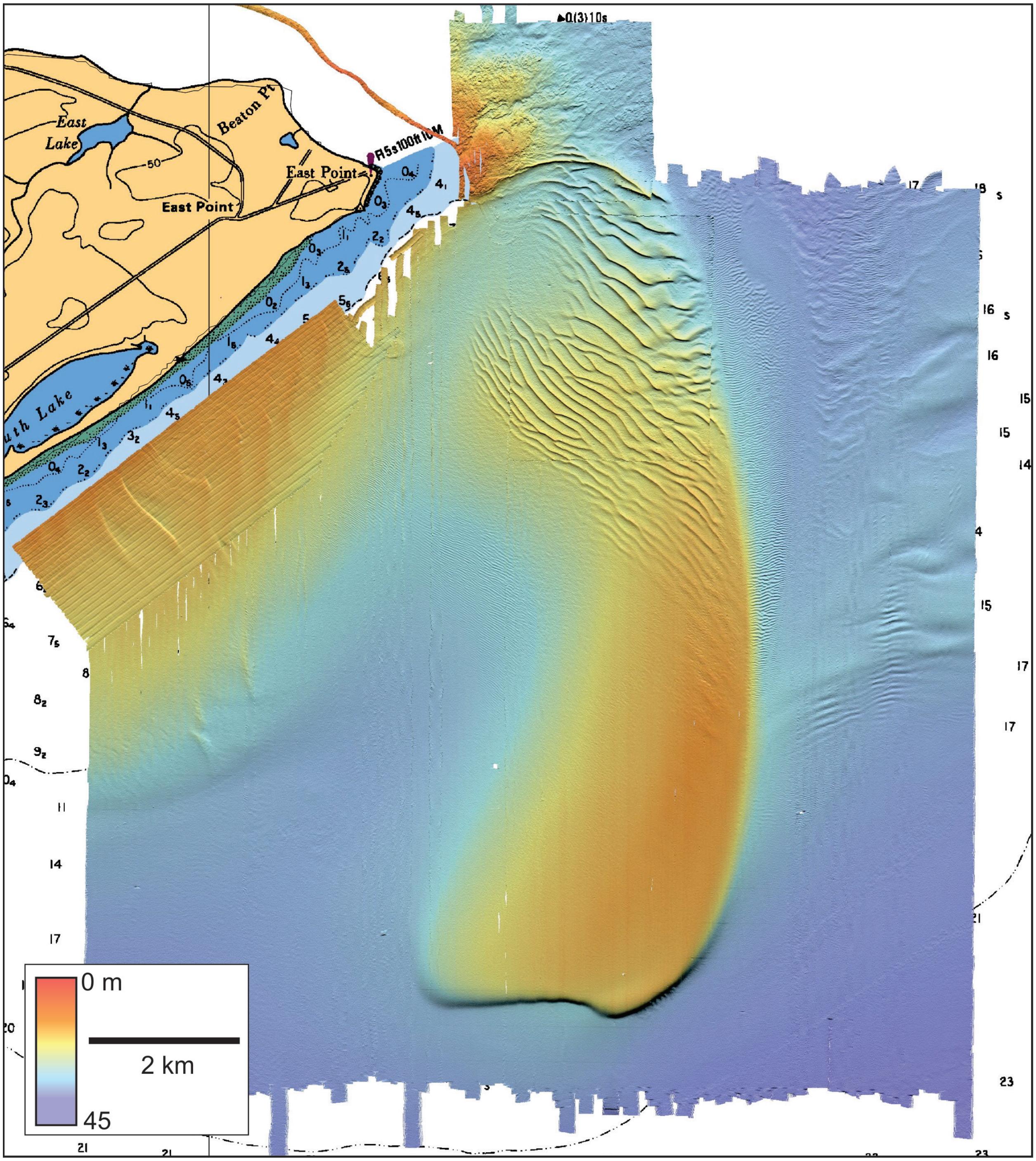


Fig. 25. *Sun-illuminated seafloor topography, Milne Bank, eastern Prince Edward Island. Location on Fig. 22.*

FAVOURABLE FACTORS, POTENTIAL CONSTRAINTS, AND HAZARDS

- Low relief and low roughness prevail across much of the region.
- Quaternary sediments have been mapped by Kranck (1971), who provides useful cross-sections; the seismic data used for the mapping are not available.
- Highly variable thickness of the overburden, with evidence of exposed bedrock in many areas, particularly west of Abbegweith Strait and in the coastal zones.
- Exposed surface of the Pomquet drift (till) may be very coarse according to Kranck (1971).
- Bedrock surface is irregular in the central zone (ancient river channels).
- Multibeam surveys of the Fixed Link area show more recent channel systems incised during the postglacial relative-sea level lowering in the region.
- Tidal scour in Abbegweith Strait; tidal gyres elsewhere, e.g., East Point.
- Mobile bedform fields are found throughout the region. A few have been mapped and described, notably the huge sand deposit at Milne Bank, but the small patches of multibeam sonar data suggest that mobile sand wave fields, and perhaps large sand ridges, may be present throughout the region, away from the depocentres, particularly west of Abegweit Passage.
- Seafloor relief is more variable in the shallow fringes to the north and south, in St. George's Bay, for example, or on the flanks of Hillsborough Bay

Region 6: Cape Breton Trough

SUMMARY

The deep (>100 m) Cape Breton Trough contains thick Quaternary sediments, but thinner Quaternary sediments overlie bedrock to either side of the trough. Coastlines are steep and rugged in the north and lower relief in the south. Following deglaciation, areas shallower than 50 m were sub-aerially exposed when relative sea level dropped in the early Holocene. Because of strong tidal currents with a net residual to the northeast, fields of large mobile sandy bedforms are found off the coast of Cape Breton Islands, as well as areas of seafloor erosion. Salt diapirs are found in this region.

***Favourable** factors for foundation emplacement include a low relief, shallow coastal platform along the coast*

***Constraints** for foundation emplacement include shallow sediment depths outside of the deep (>100m) trough; active seabed erosion and bedforms indicate sediment mobility; salt diapers common; irregular bedrock outcrops*

GEOLOGY

Geomorphology The deep (>100 m) Cape Breton Trough extends to the northeast; to its west and south large areas of seafloor within this region are shallower than 100 m (Fig. 26). A narrow (2-10 km wide) platform along the west coast of Cape Breton Island is shallower than 50 m. Following deglaciation, areas shallower than 50 m were sub-aerially exposed when relative sea level dropped in the early Holocene. Strong tidal currents (0-20 m depth averaged) have a net residual to the northeast, parallel to the coast.

Bedrock The Cape Breton Trough hosts a major fault, west of which the Carboniferous/Permian rocks that characterize most of the southern Gulf of St. Lawrence are present. East of the fault, Upper Carboniferous rocks lie offshore. Salt diapirs are scattered across the region.

Surficial materials In comparison with other southern Gulf of St. Lawrence regions (2-5) the surficial sediments are complex. Northwest of the trough, bedrock is near the surface, overlain by a sandy veneer. In the west a field of sand waves is present (black rectangle, Fig. 26). The trough contains relatively thick Quaternary sediments of unknown origin. The platform at the coast of Cape Breton Island is largely bedrock, with a drape of glaciomarine sediments. This being eroded to form pits and a scalloped surface. Large mobile sandy bedforms are common on the platform. Figure 27 shows a cross section from the coastal platform and across the trough.

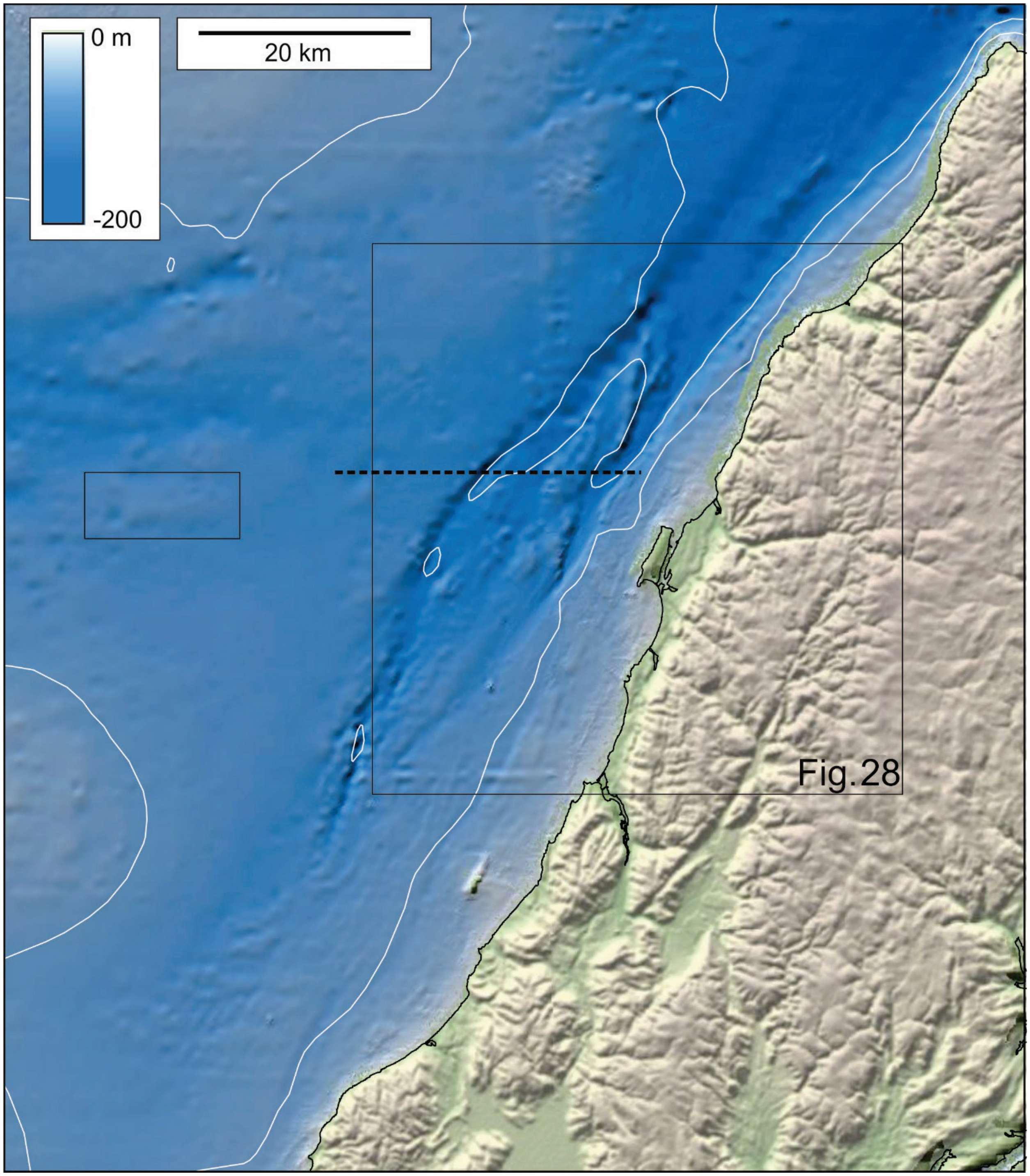


Figure 26: *Bathymetry off western cape Breton Island, also showing the location of a major bedform field (black rectangle) west of the Cape Breton Trough.*

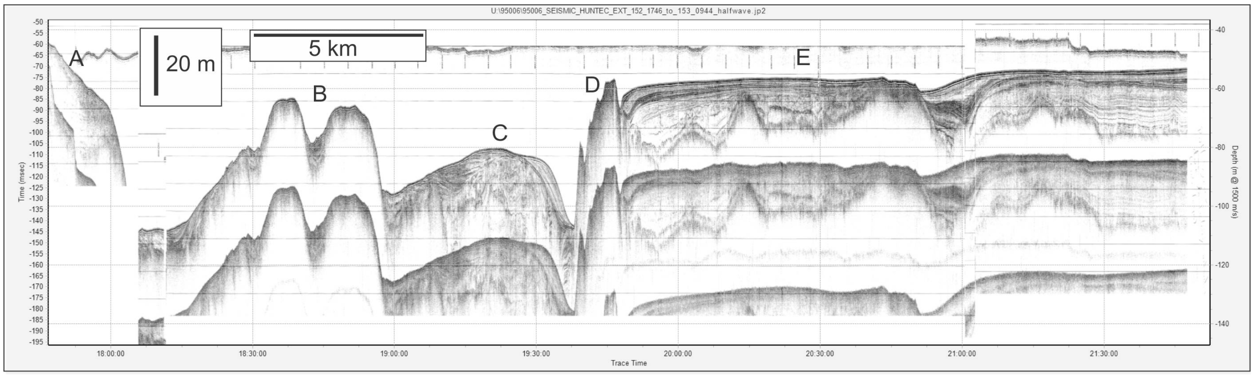


Fig. 27. *Huntec DTS seismic profile across Cape Breton Trough, from east to west (location on Fig. 26). Features include: A) slope upwards to the shallow platform off Cape Breton coast; B) several bedrock ridges); C) Quaternary unconsolidated sediments up to 20 m thick overlying an irregular bedrock surface; D) bedrock ridge, (perhaps relating to salt diapirism: and E) Quaternary sediments overlying bedrock. The Quaternary sediments have very complex internal stratification, perhaps caused by changes in ocean circulation induced by changing water depths during the postglacial lowstand and the subsequent transgression. Cruise 95006, day 152, Huntec DTS external.*

PRINCIPAL GEOMORPHIC REGIONS

The strait is divided into three geomorphic regions, each with a unique morphology, stratigraphy, and surface texture:

- ***North and west of Cape Breton Trough*** Low-relief seafloor with bedrock near the seabed, under a veneer of Quaternary sediments. A large bedform field (see Fig 26 for location), with individual ridges up to 8 m-high, may be modern and mobile, or may be relict. It lies east of the troughs between the Magdalen Islands and Prince Edward Island. If the bedforms are relict, they may have been active when sea level was lower about 9000 years ago.

- ***Cape Breton Trough*** In the trough bedrock ridges extend to the northeast. In the deepest areas Quaternary sediments are up to 20 m thick, and have complex acoustic structure. Some irregular areas of high relief my be caused by salt diapirism.

- ***Coastal platform off western Cape Breton Island.*** The platform is gently sloping, with a break of slope on the flank of Cape Breton Trough at depths of 60 to 70 m. The seafloor is a mosaic of: 1) bedrock outcrops; 2) glaciomarine sediments undergoing erosion; and 3) sandy bedform fields (see vignette).

VIGNETTES

1. Coastal platform off western Cape Breton Island

The multibeam imagery (Fig. 28) shows the platform. Areas of bedrock (A) are found in depths of 20 to 50 m. Just north of the village of Cheticamp the seafloor consists of glaciomarine sediments undergoing erosion, producing a scalloped seafloor (B), as well as pits up to 12 m deep (see inset 2). Further evidence of strong currents includes bedform fields (C). The northern bedform field (inset map b) includes sandy ridges up to 8 m in height, as well as barchan dunes in deeper water. The Cape Breton Trough contains thick bodies of Quaternary sediments (D) as well as areas of irregular seafloor (perhaps showing evidence of salt diapirism).

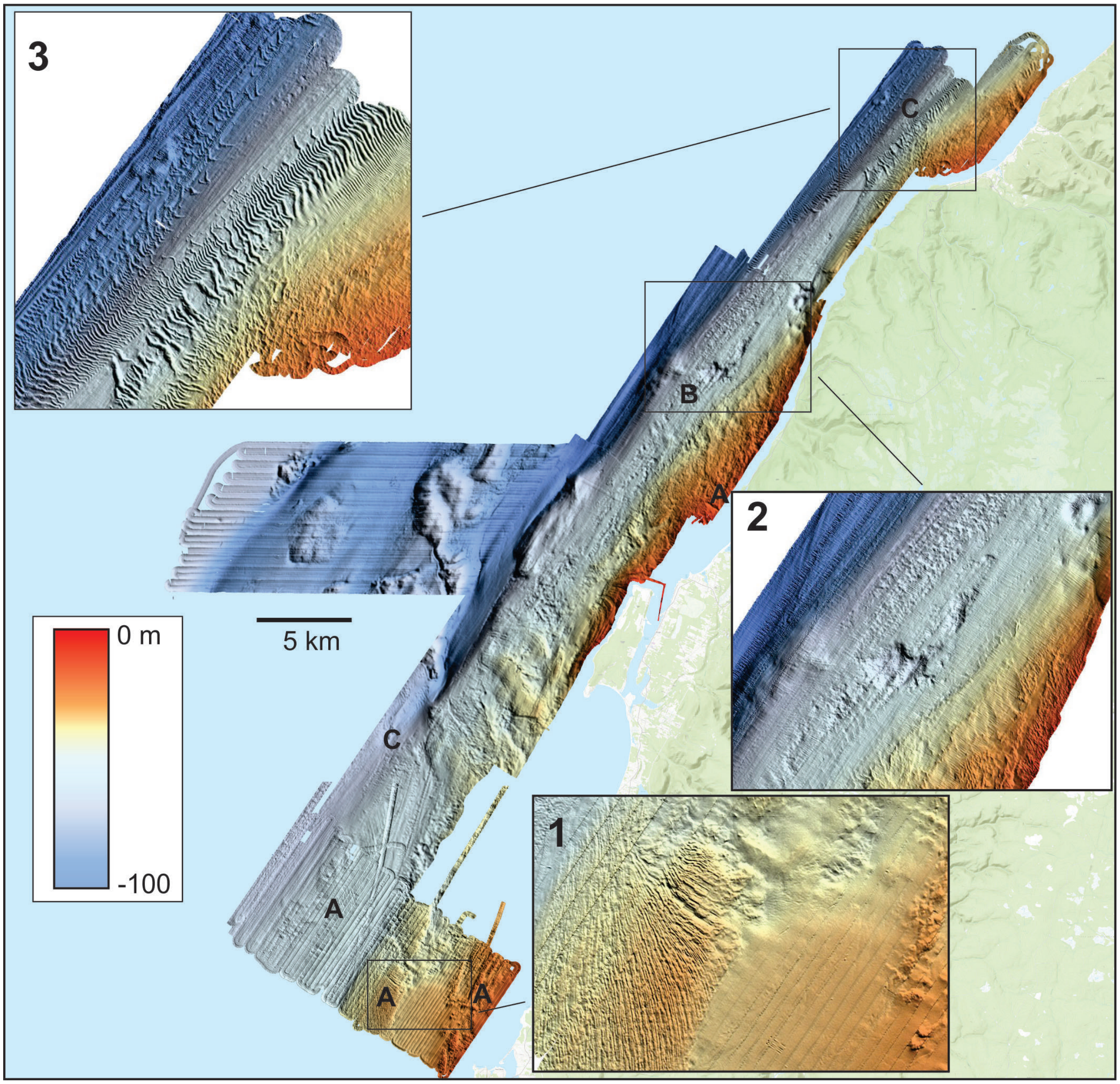


Figure 28 (previous): *Sun-illuminated seafloor topography of the shallow platform off western Cape Breton Island, showing areas of bedrock (A), a zone of seafloor erosion (B), and fields of large mobile, sandy bedforms (C). Inset map 1 shows well-bedded bedrock, inset map 2 shows erosional pits, and map 3 shows the large bedforms of the northermost bedform field.*

FAVOURABLE FACTORS, POTENTIAL CONSTRAINTS, AND HAZARDS

- Low relief and low roughness west of the Cape Breton Trough; irregular relief within the trough, and a low-relief but "rough" seafloor on the coastal platform.
- Thick surficial sediments in the trough, with complex stratigraphy and lithology; thin overburden elsewhere.
- Active seabed erosion on the coastal platform due to strong currents.
- Fields of mobile, sandy bedforms on the coastal platform
- Shallow overburden on the platform, but hard gravelly bottoms, and irregular bedrock outcrops in places.
- Salt diapirs are common in the area.

Region 7: Cape Breton shelf

SUMMARY

Coastlines in this region are generally steep bedrock or eroding bluff with several large low-relief sandy embayments found along its length. The inner shelf contains large areas of shallow, gently sloping seafloor, but relief is more rugged on the St. Annes Bank and elsewhere on the southeast and south-facing coasts. The thin overburden consists of mobile, postglacial sand and gravel, with thicker sand in major embayments. Drowned ancient river channels incised into bedrock are partly filled with sand. Seabed subsidence has been observed where underground mine workings extend offshore. The seafloor on St. Anns Bank and on the inner shelf off the south-facing coasts has irregular bedrock outcrops and glacial landforms, including drumlins.

<u>Favourable</u> factors for foundation emplacement include a gently sloping inner shelf with low relief; sand-infilled paleo-river channels and thick sands in major embayments; large areas of shallow water

<u>Constraints</u> for foundation emplacement include generally thin Quaternary sedimentation; high relief in bedrock exposures and in glacial landforms; seabed subsidence over offshore underground mine workings

In King (2014a), two detailed maps of the St. Annes region of the inner shelf provide a representative example of the seabed found in this region.

GEOLOGY

Geomorphology Large areas of shallow water with generally low relief are located in this region, and the 100 m isobath is 60 km offshore in places (Fig. 29). Relief is more rugged on the St. Anns Bank area that extends eastwards from the southeast corner of the island (Fig. 32). Following deglaciation, areas shallower than 50 m were sub-aerially exposed when relative sea level dropped in the early Holocene, hence bedrock is incised by ancient river channels in places.

Bedrock Upper carboniferous bedrock predominates, although the St. Anns Bank area is characterized by a wide range of rock types, including well-bedded Carboniferous sedimentary rocks and a plateau of early Cretaceous volcanic rocks.

Surficial materials Over much of the region surficial sediments in waters shallower than 100 m are sand and gravel, forming a veneer over bedrock. The sediments are organized into bedforms in places. The map by Fader and Miller (1989) of the inner shelf off the northeast-facing coasts of the island shows that thicker deposits of sand are found in the largest embayments (e.g., northeast of Sydney Harbour). Small areas that have been mapped by multibeam sonar reveal carboniferous bedrock ridges, dissected by sand-filled channels. The St. Anns Bank area is characterised by large areas of thin postglacial sand and gravel overlying bedrock, with muddy sand in deeper areas, and small areas of moraine composed of till.

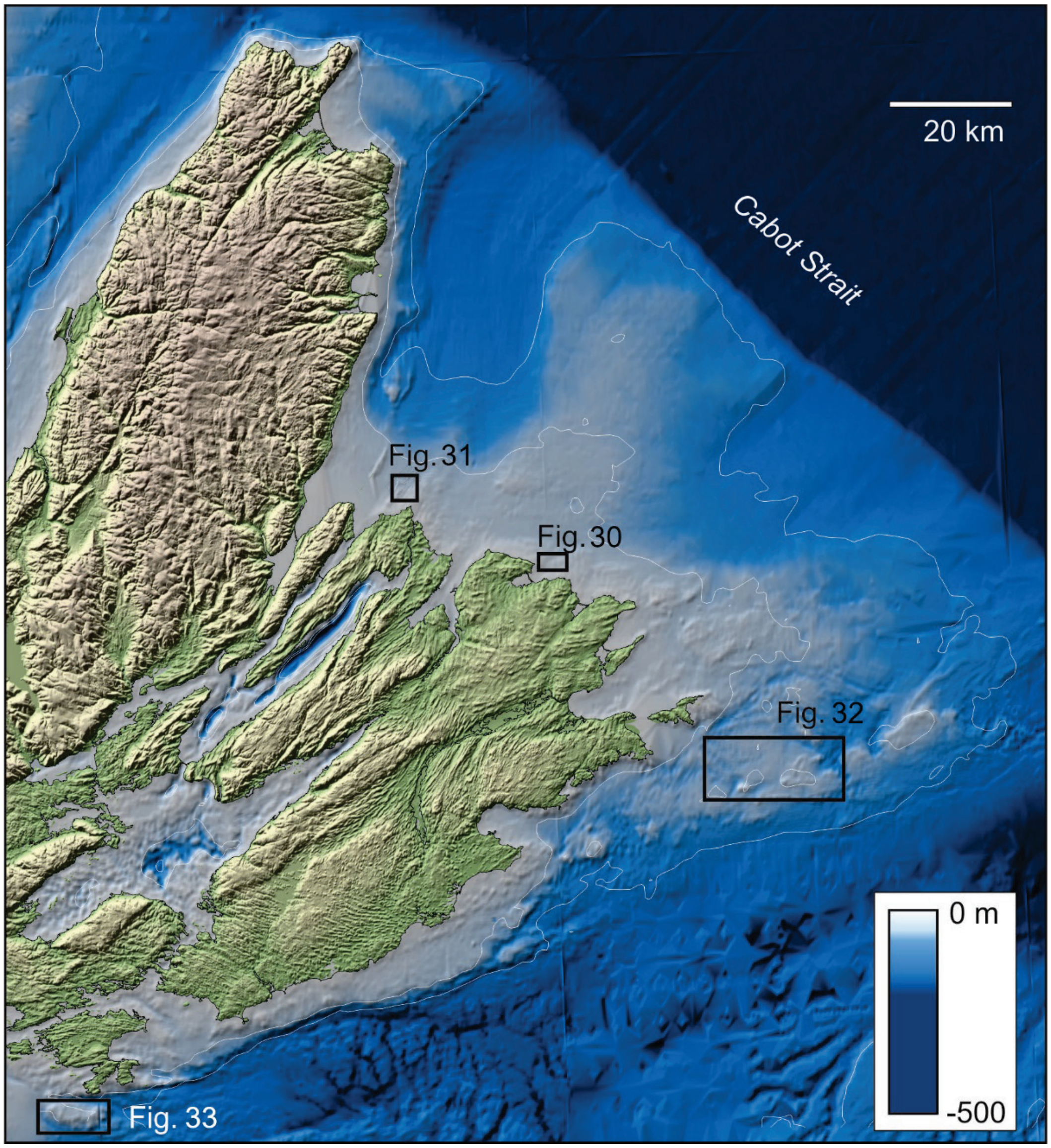


Figure 29: *Bathymetry of the shelf around eastern Cape Breton Island. with the 50 m and 100 m isobaths shown (white lines).*

PRINCIPAL GEOMORPHIC REGIONS

The shelf is divided into two geomorphic regions, each with a unique morphology, stratigraphy, and surface texture:

- ***Inner shelf, northeast coast of the island*** Low-relief seafloor with well-bedded Carboniferous bedrock near the seabed under a veneer of Quaternary sediments (see vignettes 1 and 2). Thicker sediments (postglacial sand) are located seaward of large embayments. Bedrock is incised by ancient river channels that contain sand.

- ***Inner shelf off the southeast coasts*** The inner shelf is wide off the eastern tip of the island and narrows to the southwest. Seafloor morphology is more rugged in the area of St. Anns Bank (see vignette 3) and the narrow inner shelf to the southwest, in the Isle Madame area (see vignette 4).

VIGNETTES

1. New Waterford area - inner shelf off the northeast-facing coast

Figure 30 shows typical conditions on the northeast-facing inner shelf off Cape Breton Island. Gently folded Carboniferous bedrock has bedding planes with relief of 1–2 m. The bedrock is incised by channels extending to the northeast. These may have formed with lower postglacial sea level, but also could have formed under glacial ice. The channels are up to 200 m wide and have a fill of sand, whereas the bedrock areas are strewn with patchy sand and gravel.

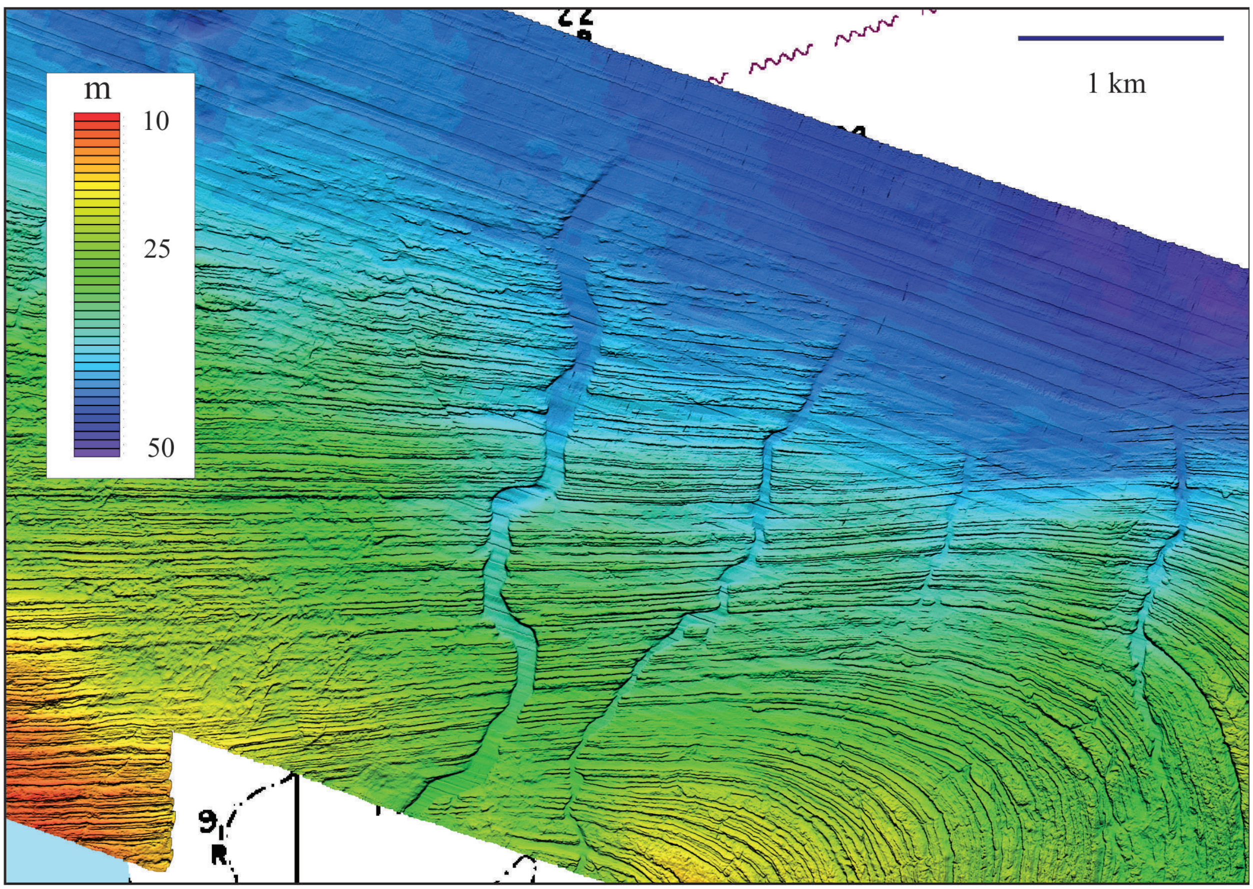


Figure 30: *Sun-illuminated seafloor topography of the shallow platform off New Waterford showing carboniferous bedrock with incised channels.*

2. Seafloor collapse due to mining, Point Aconi area.

Figure 31 also shows typical inner shelf conditions off the northeast coast of Cape Breton Island – the deepest water in this image is 48 m. Near Point Aconi, extensive exposures of Carboniferous bedrock (A) have bedding planes with relief of up to several metres. Thin sand sheets occupy the areas of lesser relief (B). The series of NW to SE trending parallel depressions (e.g., C) are up to 1 m deep and are caused by underground coal mining. Repetitive surveys by the GSC established that the collapse of underground galleries following coal extraction reached the seabed within a month. This mine is no longer in operation but underground mining continues in the Donkin area nearby.

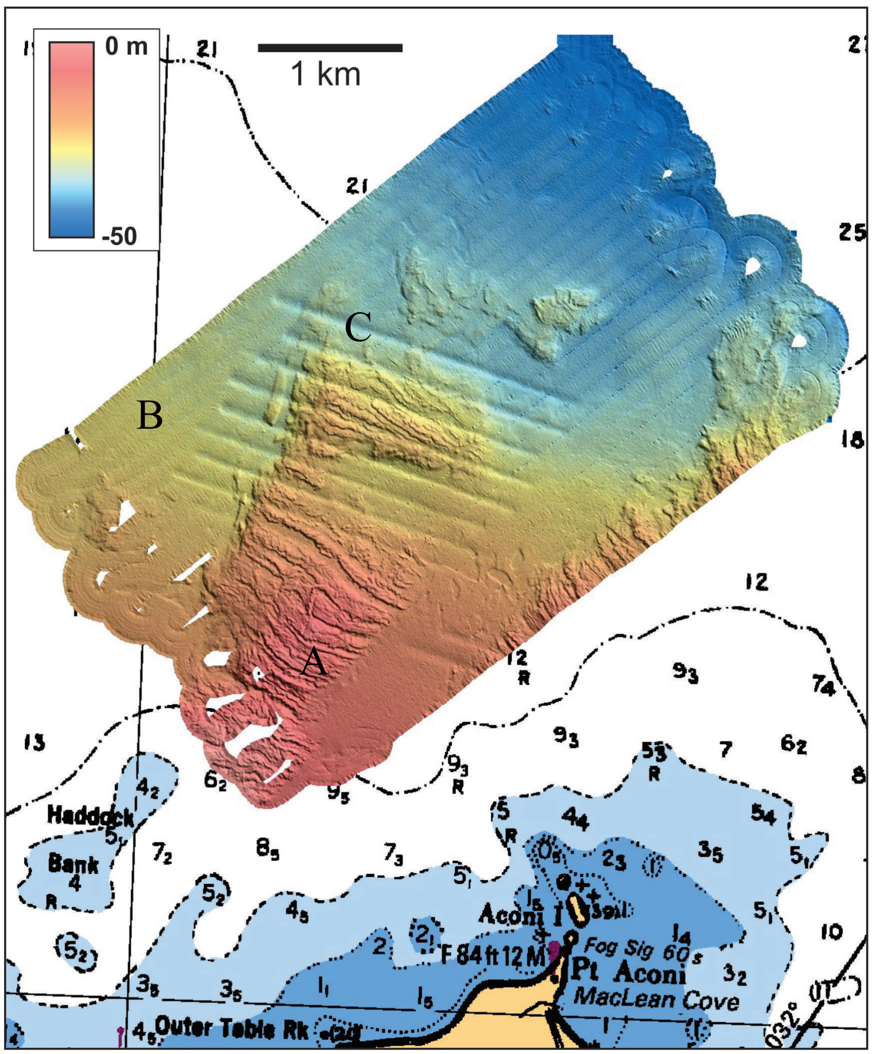


Figure 31: *Sun-illuminated seafloor topography off Point Aconi showing subsidence of the seabed caused by underground mining.*

3. St. Anns Bank

St Anns Bank is a shallow area that extends to the southeast of the island. A large area has been mapped with multibeam sonar and a detailed interpretation is available. As summarized by King (2014a), St. Anns Bank has a diversity of seascapes, similar to geomorphic regions, strongly controlled by bedrock: a ridge and bedrock scarp of Early Cretaceous flow basalts and basic intrusives contrast with Carboniferous folded strata in the north.

The shaded relief image of Fig. 32 shows only the area of the bank shallower than 100 m. Carboniferous bedrock ridges (A) have relief of up to 5 m, while the northeast-trending ridge at B has relief of 15 m. The major bedrock escarpment (C) rises 40 m above the seabed to the north. Smooth areas (D) have sand veneer while sandy mud is found in several deeper basins (E).

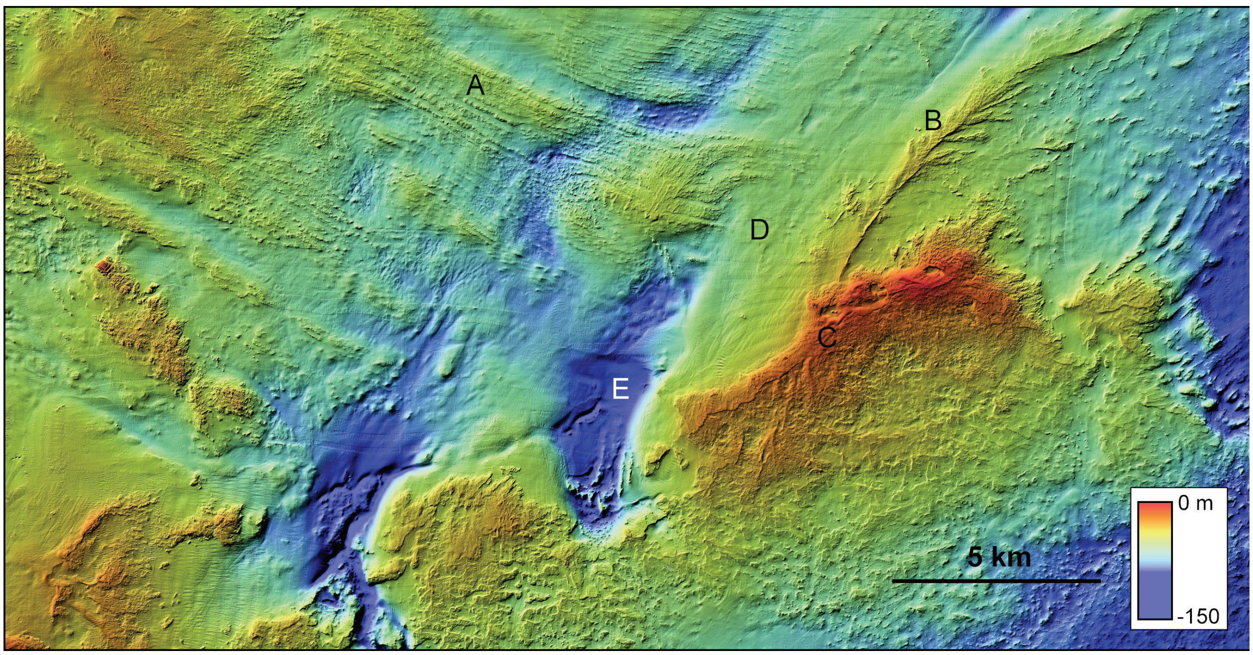


Figure 32: *Sun-illuminated seafloor topography of the shallow (<100 m) portion of St. Anne Bank. Location on Fig. 1.*

4. Irregular terrain, southern Cape Breton. This final example serves to illustrate the variability of the terrain in the southern part of the Cape Breton inner shelf. Taylor et al. (1989) reported channels incised to about 30 m below sea level, and filled with 15 m of sediment, in St. Peter's Bay, near Isle Madame, on the southwest coast of Cape Breton Island. The multibeam imagery of a shoal 10 km south of Isle Madame reveals drumlins on both north and south sides with NW-SE alignments similar to those onshore (Fig. 33). They are unmodified below depths of 55 m. Above this depth the terrain is rocky, with a cluster of truncated drumlins ('scars') at a depth of about 35 m.

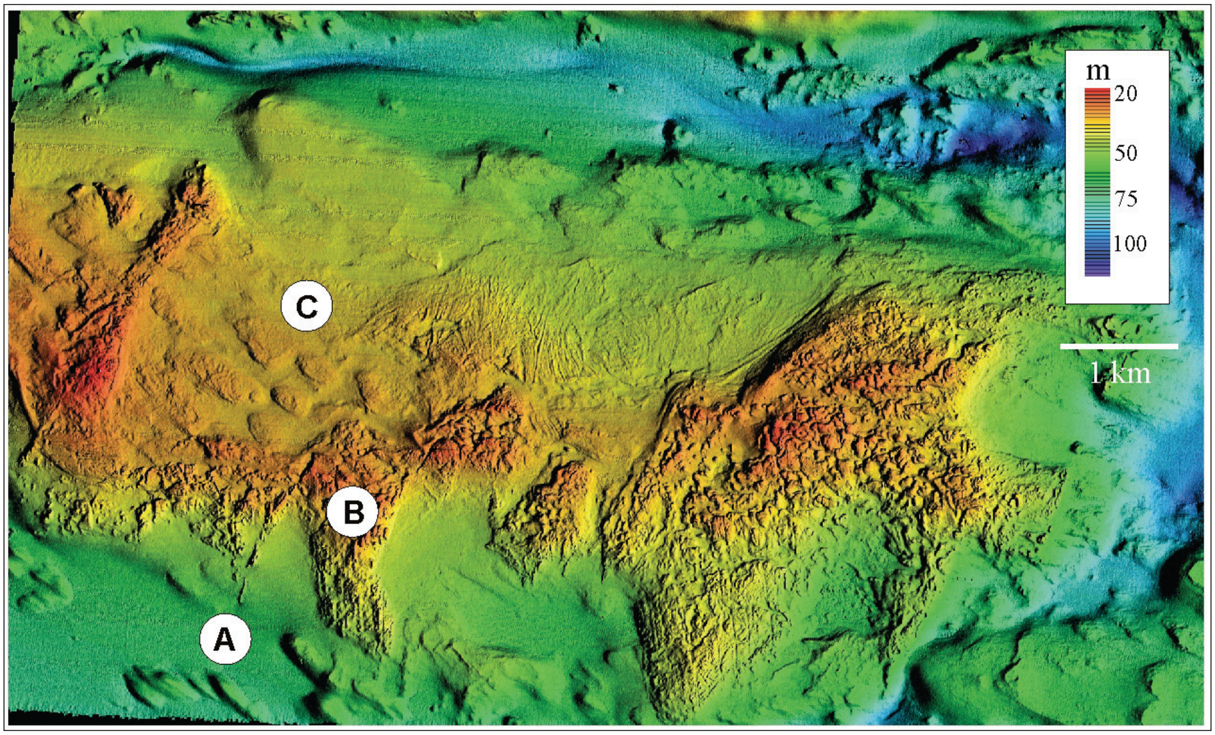


Fig. 33. *Coloured shaded-relief multibeam image of sea floor showing unmodified drumlins (A), rocky terrain (B) and truncated drumlins (C) in the Isle Madame area. Location on Fig. 1.*

FAVOURABLE FACTORS, POTENTIAL CONSTRAINTS, AND HAZARDS

- Gently sloping inner shelf with low relief off the northeast-facing coasts, with minor roughness (several metres) due to bedrock ridges.
- Thin overburden, consisting of patchy sand and gravel, with thicker sand in major embayments.
- Numerous drowned ancient river channels incised into bedrock and partly filled with sand.
- Seabed subsidence where underground mine workings extend offshore.
- Highly irregular seafloor on St. Anns Bank, with bedrock predominant; irregular rocky seafloor with drumlins off Isle Madame.

Region 8: Bras d'Or Lakes

SUMMARY

Canada's inland sea has a highly irregular seafloor encompassing submerged drumlin fields, submerged ancient coastlines, deep basins, gypsum sinkholes, and bedform fields. Modern coastlines are generally low relief and sedimentary in the southern and central portions of the lake, with steeper bedrock coastlines dominating in the northern reaches.

<u>Favourable</u> factors for foundation emplacement include Quaternary sediments dominated by low-relief mud; generally shallow bathymetry; little to no outcropping bedrock; sediments are thick (10s of m) in places

<u>Constraints</u> for foundation emplacement include complex relief in areas with drumlins, submerged coastlines; sinkholes; organic layers (and other heterogeneities) in the subsurface

The entire area has been surveyed with multibeam sonar and ground-truthed with seismic surveys, with maps of bathymetry, backscatter, and surficial geology available (e.g. series of Shaw and Potter, 2007; 2008; Shaw et al. 2002b; 2006c; 2009a).

GEOLOGY

Geomorphology The lake system today is Canada's largest inland sea, but was a freshwater lake until it connected with the ocean ~6000 years ago due to rising sea level. Accordingly, former river channels appear at the seafloor in places, and ancient beaches are found at a depth of 25 m. The morphology is highly irregular (Fig. 34), and includes deep basins that owe their origin to dissolution of salt in salt diapirs. Thick deposits of postglacial mud are found in some areas, while elsewhere the seafloor is marked by deep sinkholes associated with gypsum deposits. Backscatter maps reveal that seafloor texture is highly variable.

Bedrock Windsor Group Carboniferous bedrock underlies most of the Bras d'Or Lakes. They are notable for containing evaporites, including gypsum and anhydrite. Sinkholes are common in the lakes, as they are on the surrounding land.

Surficial materials The series of backscatter and interpretative maps for this area shows a mosaic of sediment textures at the seafloor. Mud predominates, with sandier sediments near the connection with the ocean. The surficial geology map (Shaw and Potter, 2008) shows two types of glacial deposits: till overlain by glaciomarine and glaciolacustrine sediments. Five types of postglacial sediments were identified: lacustrine mud, fluvial deposits, littoral deposits, undifferentiated muddy sandy gravel, and anthropogenic deposits (mainly dredge spoil).

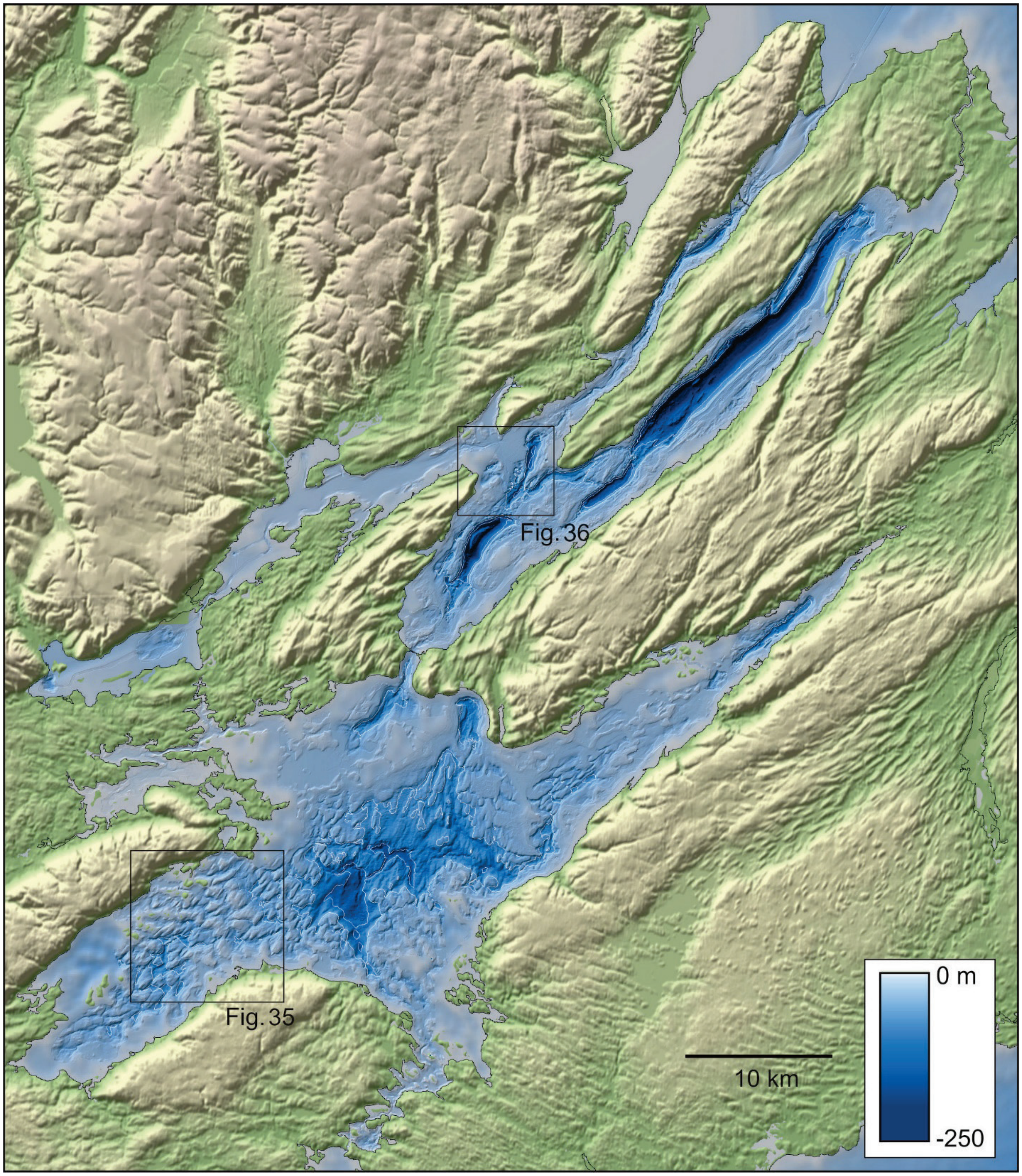


Figure 34: *Bathymetry of the Bras d'Or Lakes, Nova Scotia, with the 50 m and 100 m isobaths shown (white lines).*

PRINCIPAL GEOMORPHIC REGIONS

The lakes are divisible into two geomorphic regions, each with a unique morphology, stratigraphy, and surface texture:

- ***Great Bras d'Or*** Backscatter and surficial geology maps reveal a mosaic of textures at the sea floor, with lacustrine and marine mud predominant and large areas of bedrock and till. The northern part of the lakes contains several relatively deep, steep-sided basins caused by dissolution of evaporite deposits. The deepest basin, St. Andrews Channel, attains a maximum depth of 263 m. It contains thick mud, overlying mass transport deposits, over glaciomarine mud. The basins are surrounded by extensive shallow areas where bedrock or till occur at the seafloor. The shallows vary, and include: 1) an area southeast of Baddeck where the seafloor is pitted by 25 m-deep sink holes caused by gypsum solution; 2) The floor of St. Patricks Channel near Baddeck has old river channels from the lake phase, and early- to mid-Holocene organic deposits (peat and woody remains) lie just below the modern mud; 3) Near the connection with the ocean in Great Bras d'Or (sensu stricto), sandy tidal delta deposits occur at the seafloor.

- ***Bras d'Or Lake*** In the southern part of the lakes the seafloor is highly irregular due to the presence of fields of drumlins and also to a wide variety of ancient coastal deposits, formed during the many thousands of years when the area was a freshwater lake, located 25 m below modern sea level. The backscatter and surficial geology maps reveal a patchwork of glacial and beach deposits, characterised by positive relief and gravel at the sea floor, surrounded by deeper, low-relief areas characterized by marine and lacustrine mud.

VIGNETTES

1. Drumlin terrain in the southern lakes (Bras d'Or Lake)

Very irregular terrain with relief of up to 40 m is found in the drumlin fields West Bay, Bras d'Or Lake (Fig. 35). These glacial landforms are composed of till, and formed under slow-moving ice during the last glaciation. They are common on land throughout much of southeastern Cape Breton Island. When the area was a freshwater lake (after deglaciation and before ~6000 years ago) the drumlins were islands, and careful examination of the drumlins here reveals that many are connected with drowned beaches (e.g., see arrows). Much more substantial beaches are found in East Arm (see figures in Shaw et al., 2006c).

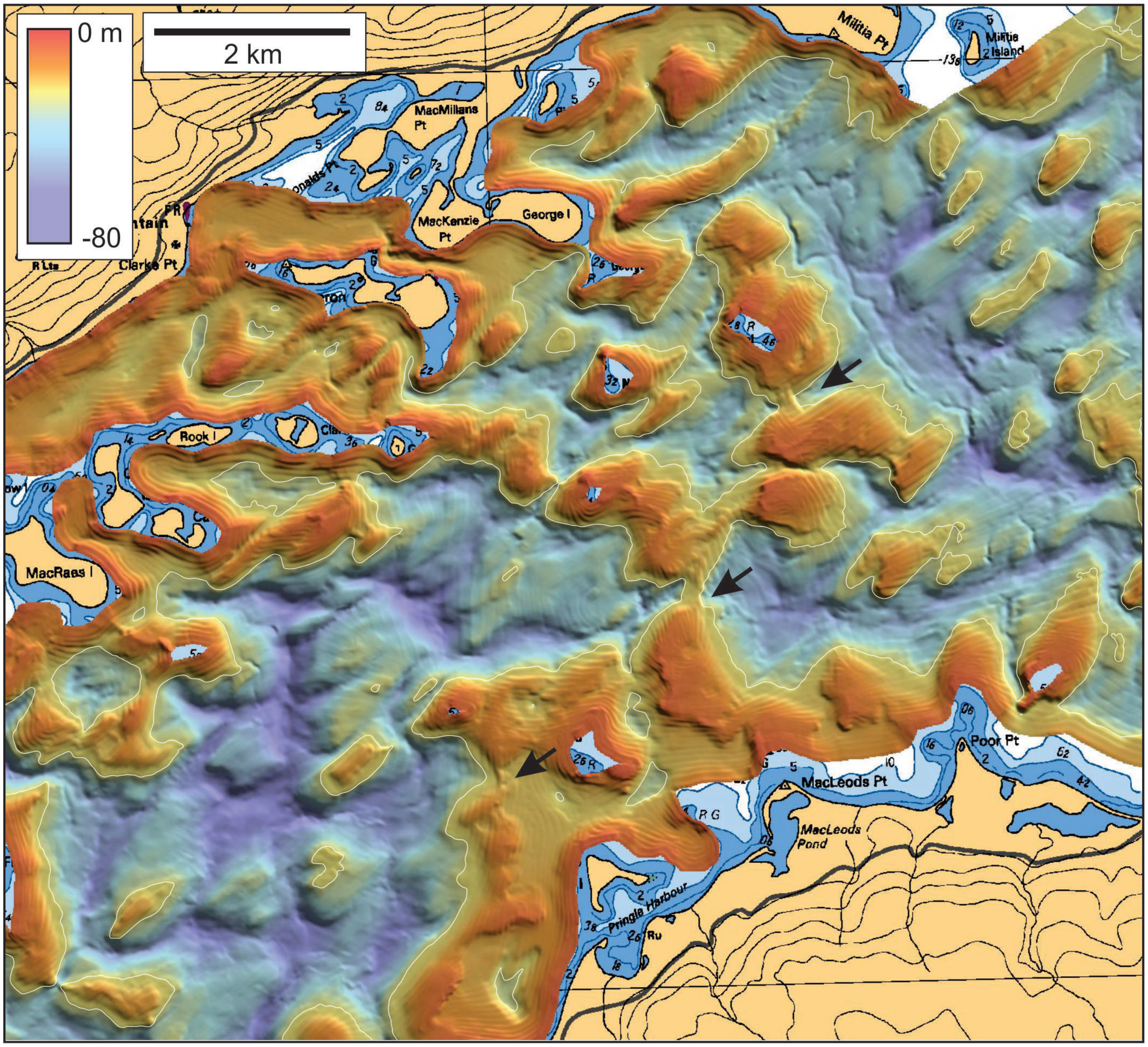


Figure 35. *Drumlin topography in West Bay, Bras d'Or Lake, arrows indicate drowned beaches.*

2. Sinkholes in the northern part of the lakes

Figure 36 shows the seafloor in the northern part of the lakes, near Baddeck. The numerous circular pits (arrowed) are sink holes caused by gypsum dissolution. They range up to 40 m deep. The flat area (A) is a former delta, formed when the area was a lake. The channel west of the delta (B) is a relict of that period.

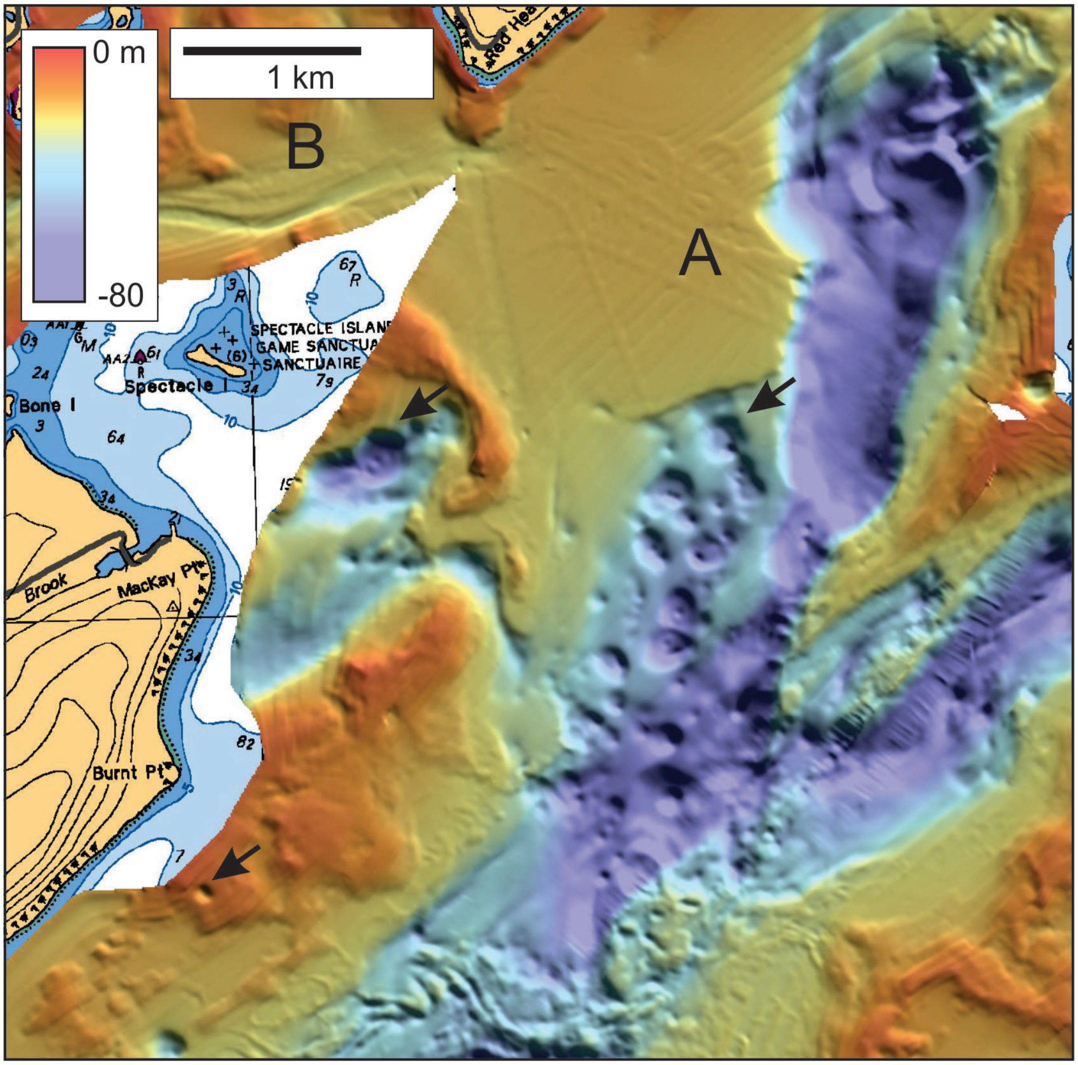


***Figure 36:** Irregular seafloor topography in Great Bras d'Or.*

FAVOURABLE FACTORS, POTENTIAL CONSTRAINTS, AND HAZARDS

- Relief, surficial geology, and seafloor texture are highly variable
- Areas with complex relief include drumlin fields, overdeepened evaporite basins, submerged coastlines.
- Sinkholes present an unusual problem. Unpublished observations suggest that some may be active conduits for groundwater.
- Organic layers exist directly under mud in St. Patricks Channel.
- Denys Basin contains partly buried old river channels and fields of circular oysters beds.
- Comprehensive maps of bathymetry, backscatter, and surficial geology exist, together with shallow seismic information.

Region 9: Atlantic Shelf of Nova Scotia

SUMMARY

Coastlines in this region are varied, with large, low relief sandy beach-dune systems, rugged, steep bedrock coastlines, eroding bluff headlands, and deep estuarine inlets found along the coast. The large inner shelf averages 70 km in width and is highly variable. It has been divided into several zones. In an inner zone (shallower than 50 m), rugged Meguma (Cambrian-Devonian) bedrock is overlain by glacial deposits. Valleys with mobile sand and gravel at the seafloor may be underlain by estuarine deposits, including salt-marsh peat. Fields of drumlins result in rugged topography in some areas. Near the coast, drumlins have been truncated during the postglacial transgressions, resulting in bouldery surficial lag gravels. In outer zones irregular Meguma bedrock terrain predominates.

Favourable factors for foundation emplacement include seabed valleys that can be filled with thick accumulations of sand; thick deposits of postglacial sands and muds found in larger embayments

Constraints for foundation emplacement include pockets of estuarine organic-rich (compressible) sediments; a high-relief seabed either where till is arranged into landforms (moraines, drumlines) or where bedrock dominates

A wide range of materials provide important context for this region, and recent assessments of high-quality data (e.g. Loncarevic et al., 1994; Shaw 1999; King and Beaver, 2017; King, 2018) are especially useful for determining the character of the inner shelf.

GEOLOGY

Geomorphology The inner shelf averages 70 km in width (Fig. 37). The terrain is rugged, with NW-trending bedrock ridges separated by shallow valleys containing unconsolidated sediments, giving relief variations that average 30 m but reach 60 m. Large embayments such as Chedabucto Bay (Fig. 43), Halifax Harbour (Fig. 40), and St. Margaret's Bay (Figs. 41, 42) contain thicker unconsolidated sediments.

Bedrock Bedrock is a seaward continuation of the onshore geology (Piper et al., 1986), and the entire region comprises Cambrian-Devonian rocks of the Meguma Group, primarily turbidites (Goldenville Formation), slates and sandstones (Halifax Formation). Large areas of granitic intrusion occur also (see vignette 1).

Surficial materials In contrast with the mid-and outer shelf (e.g. Sable Island Bank), the overburden on the inner shelf is generally thin, and confined to depressions between the bedrock ridges. Thickest deposits include the till found in drumlin fields generally located near the coast (e.g., Mahone Bay, Piper et al., 1986) and lacustrine and estuarine deposits found in coastal basins such as Halifax Harbour (Fader and Miller, 2008). Fields of bedforms such as gravel ripples are found throughout the region. The unpublished report on the crash of Swissair Flight 111 (Shaw et al., 1999) showed that in the crash areas, south of St. Margaret's Bay, bedrock in depths less than 50 was strewn with boulders, with sand and gravel in joints and faults. In depths exceeding 50 m bedrock had a patch cover of glacial sediments.

A map series for Lunenburg Bay and Harbour characterizes the bedrock and surficial sediments and their evolution with post-glacial sea level rise (King et al. 2017), present day sediment mobility, and anthropogenic influences (King and Beaver 2019a) and basic relationships with oceanographic conditions under storm conditions in the inner bay (King and Beaver 2017b). Combined, these help document details of the seabed and immediate sub-seabed relevant to foundation conditions.

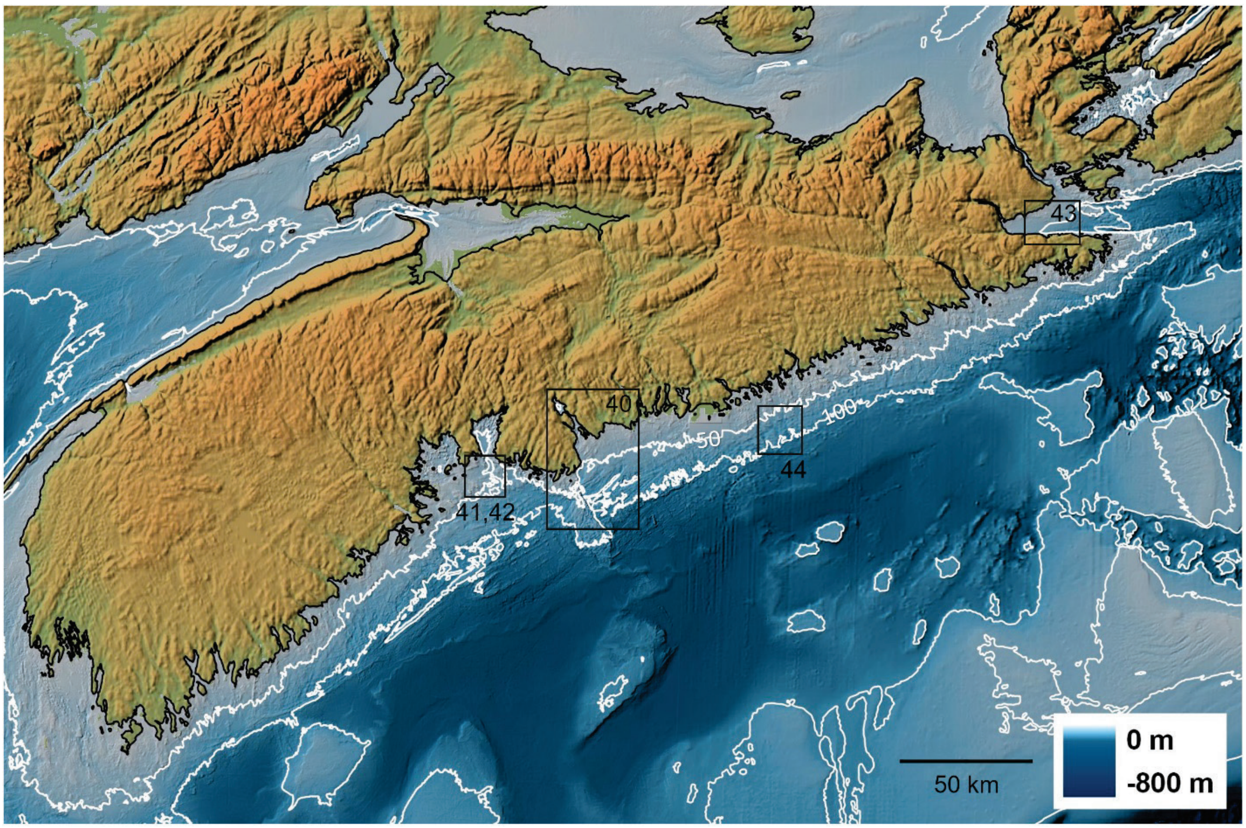


Figure 37: *Bathymetry of the Atlantic Shelf, Nova Scotia, with figure locations and 50 and 100m isobaths shown.*

PRINCIPAL GEOMORPHIC REGIONS

The Atlantic Shelf has been divided into coast-parallel zones by various authors (e.g. Stea et al., 1996; King, 2018). The tripartite scheme described here is that of Forbes et al. (1991), which was based on a survey area just east of Halifax. These zones reflect the fact that: 1) the entire region was glaciated by ice moving from land; and 2) the area shallower than ~60 m was sub-aerially exposed by postglacial sea level lowering and was then submerged during the Holocene transgression. Submergence continues today. The classification below follows this pattern and also includes a description of some of the major embayments.

- ***Inner shelf zone*** In areas shallower than -50 m acoustic basement (Meguma metasediments) is overlain by till and glacial outwash, predominantly sand and gravel (Figs. 38, 39). In seaward-trending valleys the glacial sediments may be overlain by valley-fill deposits consisting of estuarine and lacustrine muds, salt-marsh peats, and freshwater peats. Much of the area has a veneer of mobile sand about 1 m in thickness except for bedrock highs. The unpublished report on the crash of Swissair Flight 111 (Shaw 1999) showed that extensive areas of mobile gravel ripples were present around the crash site (depth 50 m). The map series by King and Beaver (2017a,b) and King et al. (2017) is based on multibeam bathymetry data and extensive ground truth data, and reveals the complexity of the innermost zone near the coast. The map shows Meguma Group bedrock ridges predominate to either side of a sediment filled valley.
- ***Intermediate zone*** In this zone the seafloor is an erosional unconformity that truncates acoustic units; lag deposits of sand an gravel occur as patches.
- ***Outer (outcrop) zone*** This zone extends to just beyond the 100 m isobath and is characterized by rugged outcrops of acoustic basement (Meguma bedrock) with limited surficial sediment cover.
- ***Major embayments*** Chedabucto Bay at the east of the region contains thick postglacial mud, but on the north side of the bay the seafloor consists of glacial deposits with surficial veneers of sand, gravel, and boulder size gravel. Halifax Harbour is a major embayment that includes Bedford Basin. Like the Bras d'Or Lakes, Bedford Basin was a freshwater lake until it connected to the ocean about 6000 years ago. St. Margaret's Bay and Mahone Bay contain fields of drumlins.

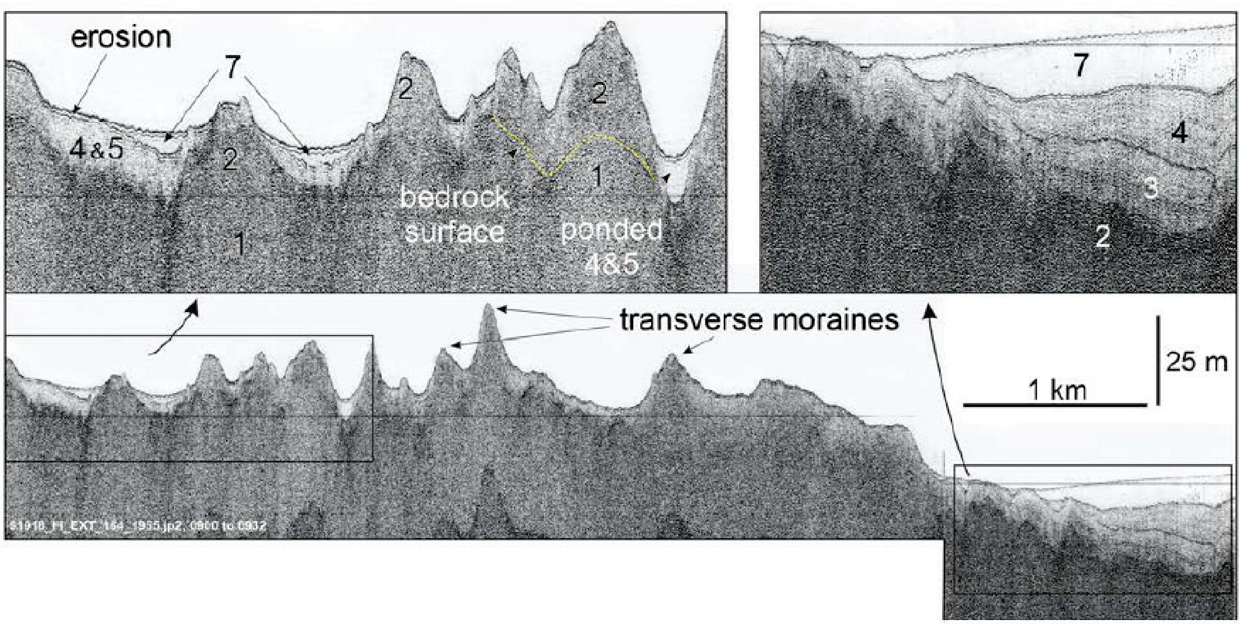


Figure 38: *Boomer profile off the Eastern Shore, location Figure 44 (Line A). Numbers correspond to geologic units in Figure 44. From King (2018).*

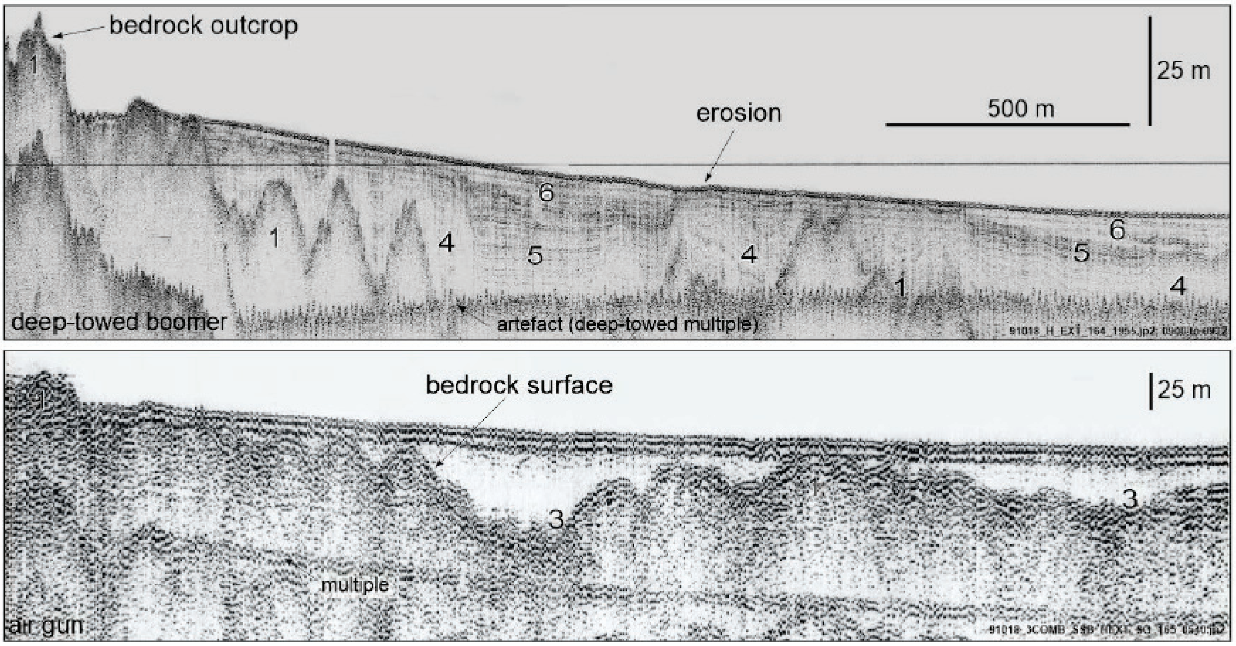


Figure 39: *Boomer and airgun profile off the Eastern Shore, location Figure 44 (Line A). Numbers correspond to geologic units in Figure 44. From King (2018).*

VIGNETTES

1. Inner shelf cross-section off Halifax

The area off Halifax was one of the first areas in Canada for which multibeam sonar data provided a basis for a geological interpretation (Loncarevic et al., 1994). Subsequent surveys extended north and included all of Halifax Harbour (Fig. 4), providing a cross-section of the innermost shelf offshore from Nova Scotia. Much of the seabed in Fig. 40 is bedrock with a patchy veneer of boulders, sand, and gravel similar to what was observed south of St. Margaret's Bay in the Swissair Flight 111 crash area (Shaw 1999).

The strong northeast structural trends of the Cambrian-Ordovician Meguma group are evident (A). Relief in these areas is up to 20 m. The large shallow area at B is the offshore extension of the Devonian South Mountain batholith. Relief on the rugged bedrock surface is up to 20 m.

In much of the image surficial sediments are thin, and limited to infilling depressions between bedrock high. However, fields of glacial drumlins are present, as well fields of linear glacial ridges (moraines) oriented northeast to southwest (see inset, Fig. 40). These glacial ridges are commonly 2-3 m high, and range up to 10 m. Note that the inset on Fig. 40 shows not only the moraines, but Meguma's metasediments with a similar orientation (bottom right of inset).

In the north of the image thicker postglacial sand deposits (C) infill the channel leading towards Halifax Harbour. As described by Fader and Miller (2008), thin mobile sand and gravel at the harbour mouth overlie earlier sediments (including estuarine deposits) and transition to muddier sediments farther north. The innermost part of the harbour is Bedford Basin (D), containing thick deposits of lacustrine and marine mud. In large areas of the basin as well as Halifax Harbour to the south the postglacial muddy sediments are gas-charged.

On the coast east of Halifax, a series of estuaries is fronted by sand and gravel beaches linking drumlins. The coast has been retreating under the impact of ongoing sea level rise, leaving behind a series of drumlin shoals that alternate with bodies of sand just offshore from the beaches (Shaw et al., 1993).

In summary the cross section (Fig. 40) reveals the rugged terrains that are likely to be encountered on the inner shelf off Nova Scotia. Similar mosaics of bedrock and thin surficial sediments in depressions are found, for example, in Lunenberg Bay (King and Beaver, 2017a,b), and St. Margaret's Bay (Piper, 1976). In the latter, as well as Mahone Bay, drumlin fields are a dominant field of the innermost shelf.

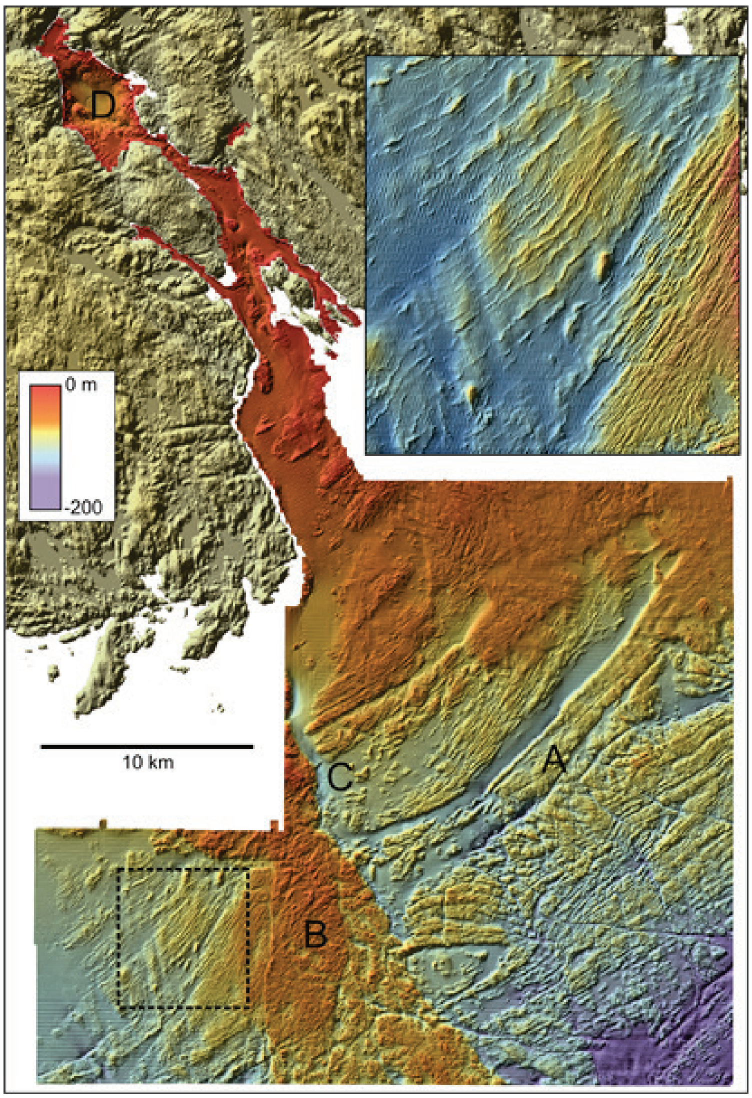


Figure 40: *Shaded relief image of the terrain from Halifax southward. The inset shows glacial landforms (moraines) trending SW to NE.*

2. Seabed south of St. Margaret's Bay.

Following the tragic crash of Swissair Flight 111, surveys with multibeam sonar and sidescan sonar were conducted in an area due south of St. Margaret's Bay. This region provides another view of the "typical" geological setting of the Atlantic shelf off Nova Scotia. Figure 41 is an extract from the unpublished report by GSC (Shaw 1999). This area averages 50 m water depth, but the area coloured yellow in the bottom left of the image is mostly shallower than 15 m. The map shows northeast-trending bedrock ridges, mostly shallower than 50 m water depth. On sidescan sonar the bedrock has a "polished" appearance and is strewn with boulders. Deeper areas have a smooth appearance, and consist of large areas of immobile fine gravel that is a lag over sand. Large areas of mobile gravel ripples are also present in shallower waters.

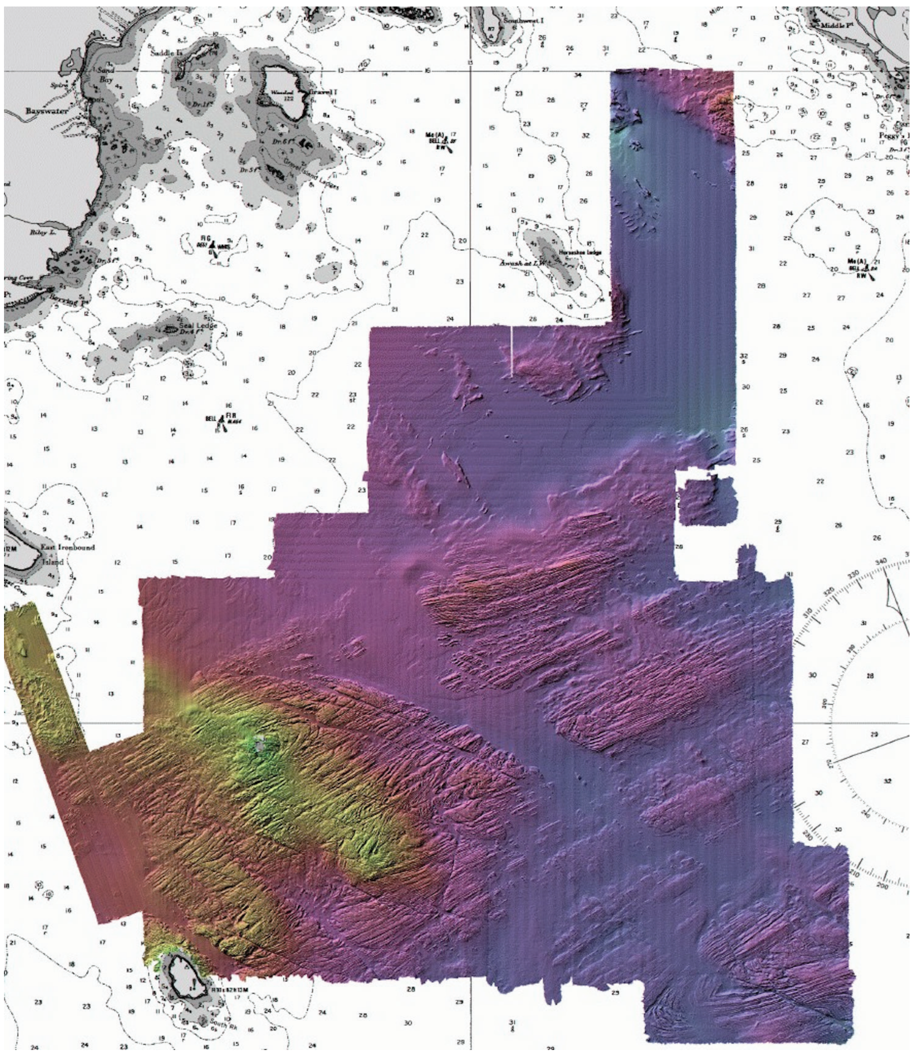


Figure 41: *Shaded relief multibeam imagery of the seafloor south of St. Margaret's Bay. The deepest areas are dark blue, and shallowest areas are coloured yellow. Extract from unpublished report (Shaw 1999).*

The backscatter analysis of the area (Fig. 42) nicely reveals the variations in seafloor morphology and texture in this part of the shelf. The very dark tone delineates areas in which depressions are filled with relatively thick Quaternary sediments, and seafloor is sand or muddy sand. The northeast-trending bedrock ridges have an intermediate tone, and the light tone between the bedrock areas is associated with thin gravel lag deposits overlying sand.

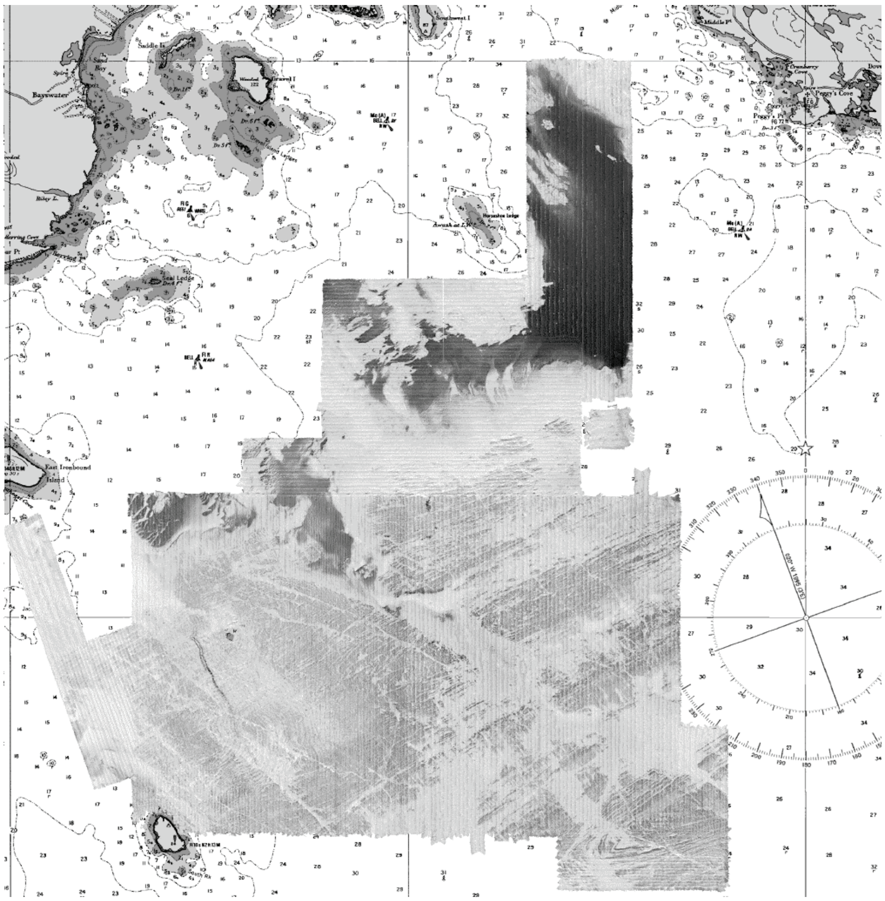


Figure 42: *Backscatter is the Swissair Flight 111 crash area, south of St. Margaret's Bay. Extract from unpublished report (Shaw 1999).*

3. A major embayment: Chedabucto Bay

Chedabucto Bay (Fig. 43) differs from the inner shelf elsewhere in several respects. The southern two thirds of the bay (A) contains postglacial mud averaging 15 m in thickness and containing gas masking in places. In northern areas (e.g., B) the shallower terrain is highly irregular, with relief of several metres. This region consists of glacial deposits, primarily till, that were reworked when relative sea level rose after the early Holocene sea level lowstand. The seabed consists of gravel, mobile rippled gravel (including boulders), and scattered bedrock outcrops. The large feature at C is comprised of prograded sediments, and is interpreted as a former gravel and sand foreland that developed during the sea level lowstand. Other features that rise above the mud (e.g., at D) are also remains of the former coastline, developed at a depth of 36 m at c. 9000 years ago. Just a few kilometres east of the imagery depicted here the seabed hosts a series of drumlins composed of till, yet again illustrating the great variability displayed within even small parts of the continental shelf off eastern Canada. These drumlins are at depths of 65 m, and because they lie below postglacial lowstand depth, are unmodified by wave processes and retain their smooth, streamlined profiles. Figure 43b is a previously unpublished interpretation of the area, based not only on the multibeam but also extensive surveys with seismic systems and sidescan sonar, as well as grab sampling.

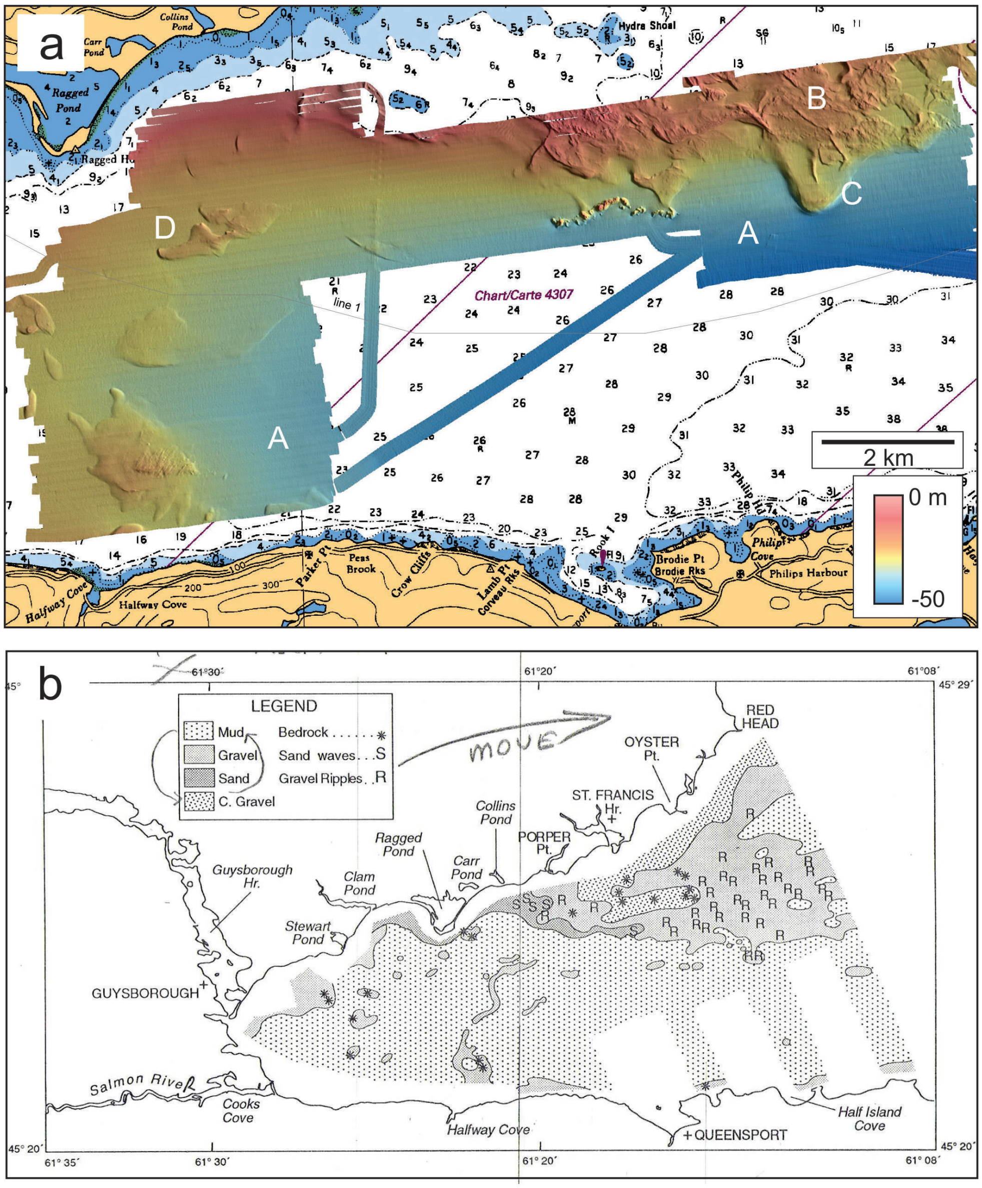


Figure 43. *a) Shaded relief, Chedabucto Bay. Background is CHS chart 4335. b) Previously unpublished interpretation of the seafloor terrain in Chedabucto Bay, showing the contrast between the north and south sides of the bay.*

4. Eastern Shore

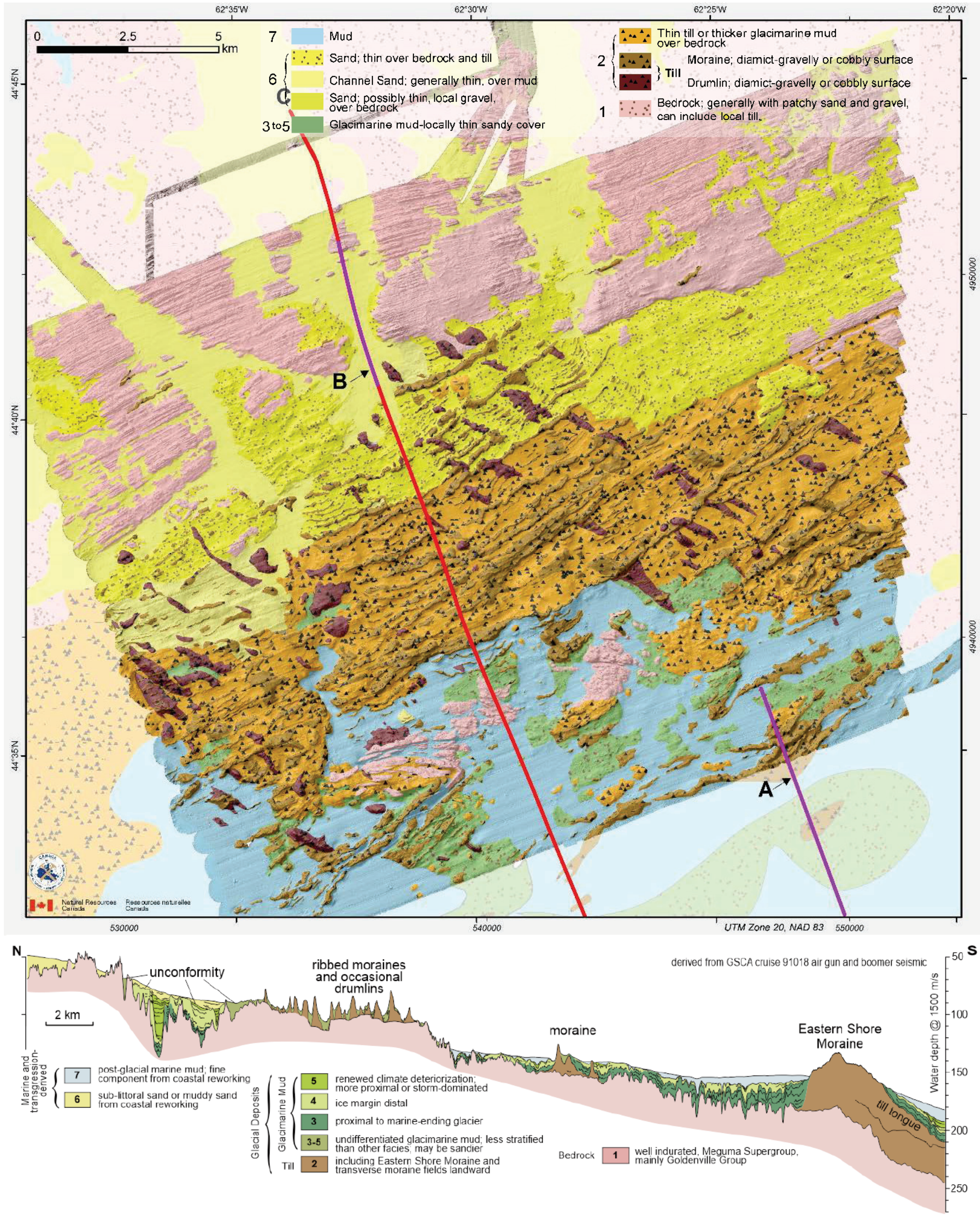


Figure 44: *(Top) Multibeam bathymetric shaded relief model with surficial geology overlain. Locations for figures 38 (A, purple) and 39 (B, purple) shown. (Bottom) Geologic profile interpreted from subsurface data, location shown in top map (C, red, note that profile extends beyond the image). Modified from King (2018).*

In King (2018), the zonation promoted by Stea et al. (1996) and Forbes et al. (1991) is generally represented in the mapped area on the central, mid-inner shelf, with the bedrock and morainal zone clearly delineated (Fig. 44). However, large packages of channel sands, a series of recessional moraines, and areas of muds and glaciomarine sediments in the morainal zone are delineated and indicate the complexity observable with higher resolution data. Subsurface data (e.g., figures 38, 39) also lead to unit-depth relationships, and highlight the shallow nature of much of the Quaternary sedimentation in this region, particularly on the shallow inner shelf. Relief is high, particularly in the regions of bedrock and moraines, and unconformities would reflect either a) rapid changes in geophysical properties where the sea level transgression eroded previously deposited glaciogenic materials and littoral sand and gravel were deposited on top, or b) previously deeper and possibly more consolidated glaciogenic materials that are now exposed at the seabed.

FAVOURABLE FACTORS, POTENTIAL CONSTRAINTS, AND HAZARDS

- Relief, surficial geology, and seafloor texture are highly variable, with bedrock areas alternating with sediment-filled valleys.
- Very extensive areas consist of bedrock of the Meguma Group. These areas have irregular morphology due to the presence of faults, joints, and beds of differing lithology.
- Fields of drumlins composed of till are found in some areas (Mahone Bay, St. Margaret's Bay).
- The innermost shelf area hosts estuarine deposits with high organic content (and hence compressible).
- Larger embayments contain relatively thick deposits of postglacial sand, mud.

Region 10: Atlantic Shelf off southwest Nova Scotia (Yarmouth area)

SUMMARY

The coastline in this region is highly indented with spits, tombolos, and sandy embayments common amongst the steep bedrock coastline. The inner shelf here has a maximum width of 80 km. The seabed is not rugged, but is irregular due to the presence of bedrock exposures and arrays of submarine morainal ridges. Surficial materials are generally coarse grained till or lag and not thick except where found in moraines and in deeper water.

<u>Favourable</u> factors for foundation emplacement include low overall relief; thick Quaternary sedimentation in deeper waters

<u>Constraints</u> for foundation emplacement include most sediments are till; locally highly irregular seabed; surficial sediments are thin at shallow depths

Multibeam sonar and ground-truthing surveys, to a minimum depth of 30 m, provided the basis for detailed mapping of surficial geology and habitat (Todd and Valentine, 2010). The maps reveal a mosaic of seafloor morphologies and textures.

GEOLOGY

Geomorphology The inner shelf (shallower than 100 m) has a maximum width of 80 km (Fig. 45). The terrain is not rugged, but is irregular due to the presence of bedrock exposures and arrays of submarine moraines. As a result there is a broad mosaic of seafloor morphologies.

Bedrock Bedrock is Cambrian-Devonian rocks of the Meguma Group, primarily turbidites (Goldenville Formation), slates and sandstones (Halifax Formation). The extreme southwest is mapped as Palaeozoic and younger.

Surficial materials As shown on the backscatter map (Todd and Valentine, 2010, Sheet 2) most of the seafloor has high backscatter, indicating the presence of either bedrock or coarse grained sediments. The latter are generally thin, except: 1) till in numerous morainal ridges; and 2: thick (>60 m) till in the west of the area, in predominantly deep (> 80 m) water.

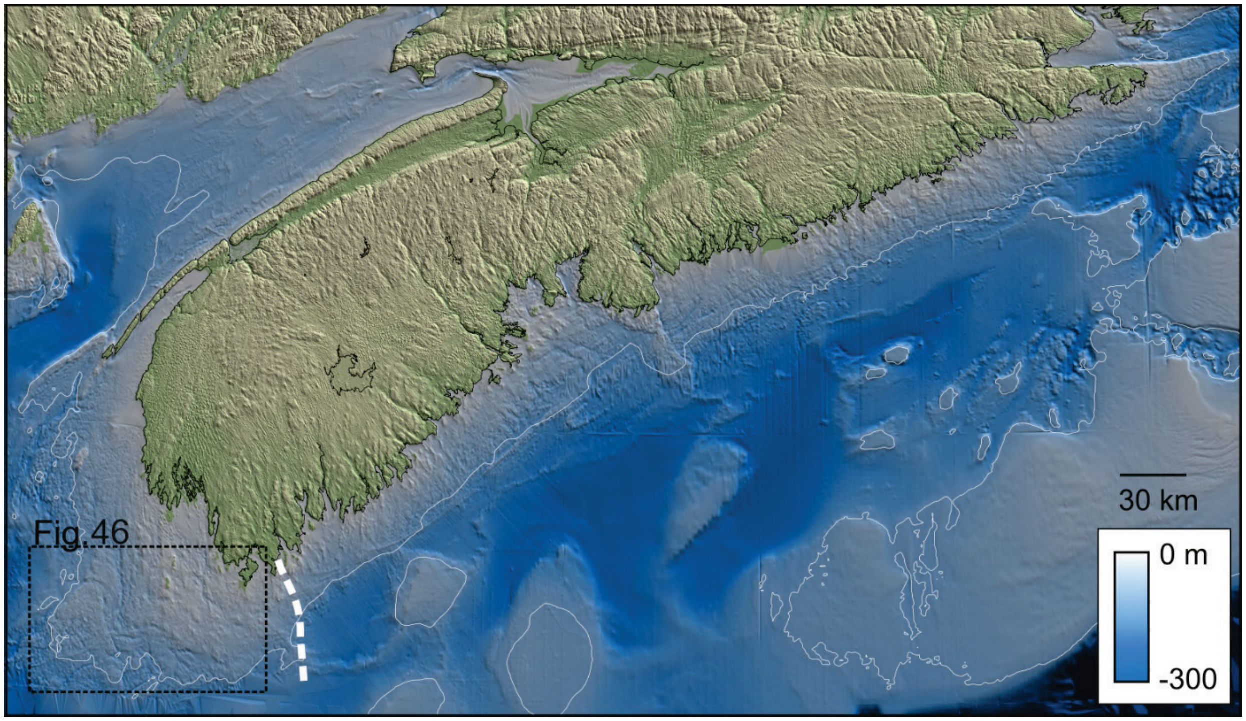


Figure 45: *Bathymetry of the Atlantic Shelf, Nova Scotia, with the 100 m isobath shown (white lines). This region lies west of the dashed white line.*

PRINCIPAL GEOMORPHIC REGIONS

This region has been divided into two geomorphic regions, each with a unique morphology, stratigraphy, and surface texture:

- ***Innermost shelf zone*** In areas shallower than 30 m there is little or no information. Bathymetric maps (e.g. CHS NONNA 100 compilation and OLEX) reveal in a general sense the presence of fields of drumlins that likely have been eroded to greater or lesser degrees during the Holocene transgression.
- ***Inner shelf deeper than 30 m*** In this zone the GSC seafloor mapping shows a mosaic of seafloor textures (Fig. 46). The morainal ridges are up to 20 m high, and record the retreat of former ice margins towards the northwest.

VIGNETTES

1. Inner shelf off southwest Nova Scotia

The German Bank area off southwest Nova Scotia has been mapped by the GSC and various types of maps have been created (Todd 2009; Todd and Valentine 2010; Kostylev and Todd, 2010). The relief of the area is not great, but the seabed is highly irregular. This is due to the presence of exposed bedrock, areas of till, and numerous regularly-spaced arcuate ridges. The latter are submarine moraines formed during retreat of the last ice sheet. They are composed of coarse-grained till. They vary in width from ~ 50 m to more than 500 m, and the largest ridges (A) are 20 m high. For a detailed discussion of the morainal ridges on German Bank see Todd (2016).

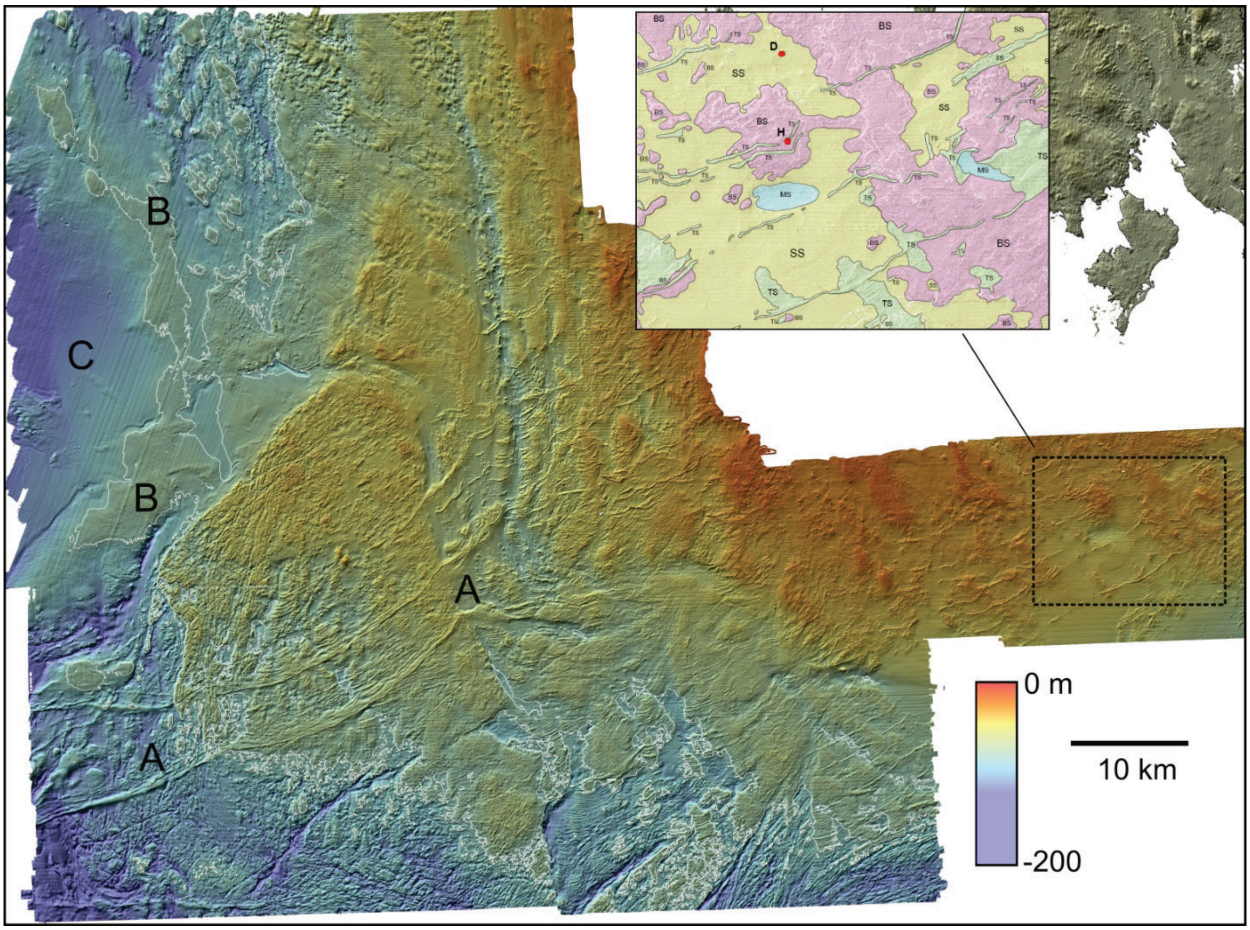


Figure 46: *Shaded relief image of a large portion of the region, with the 100 m isobath shown (white line). Letters discussed in text.*

Large areas of till (B) up to 60 m thick are found in the west, in relatively deep water (Fig. 3 in Todd and Valentine, 2010). The backscatter map (Todd and Valentine, 2010, sheet 2) shows that coarse-grained deposits predominate on Browns Bank. In shallow water (<50 m) sand is found in linear bodies. In deeper parts of the western bank sand has been deposited in broad sheets (C).

The insert on Figure 46 is an extract from the Browns Bank habitat map (Kostylev and Todd, 2010), and shows part of the geomorphic mosaic, in this case thin sheets of sand, bedrock, and numerous morainal ridges running NE to SW.

FAVOURABLE FACTORS, POTENTIAL CONSTRAINTS, AND HAZARDS

- While the seafloor has relatively low relief overall, it is nevertheless very irregular, with relief up to 20 m associated with morainal ridges.
- A mosaic of thin surficial sediments is present, with gravel predominating.
- Parallel sets of morainal ridges are found throughout much of the area.
- Large areas in the northwest of Fig. 46, in depths of 80 m and more, are underlain by thick till.

Region 11: Bay of Fundy

SUMMARY

This large embayment is subject to strong tidal energy levels, with the world's highest tidal range occurring at the head of the bay. Coastlines range from dissipative mud flats through sand and cobble embayments to high relief steep bedrock. The innermost bay contains deep (170 m) tidal scour troughs incised into Quaternary sediments, adjacent to large fields of mobile sand and gravel. Landward of the scour troughs, Minas Basin hosts thick Quaternary sediments with fields of mobile bedforms. Quaternary sediment thickness is highly variable, with greatest thicknesses in the outer bay, and near Minas Passage in the north. Large areas of seafloor have high backscatter due to the presence of: 1) lag gravels on top of glaciomarine sediments, and 2) bouldery gravels where till is present. The till is organized into numerous arcuate moraines. Areas with low backscatter consist of either mobile sand organized into bedforms, or thick postglacial mud with gas masking (south of Saint John). The great diversity of seabed conditions is demonstrated by the presence of elongated horsemussel reefs in the central bay, sandy "banner banks' along the north coast, and the large area of "trapped" sand dunes off Margaretsville, Nova Scotia.

Favourable factors for foundation emplacement include a very detailed mapset and high resolution data covering the entire region; banks of sandy sediments can be thick (up to 30 m mapped); areas with bedforms may not include mobile sediments

Constraints for foundation emplacement include mobile sandy sediments throughout; Quaternary sedimentation is predominantly till; erosion of the seabed has been strong and is ongoing in certain locations; postglacial mud can be gas-charged

The bay has been mapped by the GSC in several phases, resulting in a wealth of information. The most recent mapping phases resulted in a comprehensive series of 17 maps of bathymetry and backscatter (Todd et al. 2011). A seascape map of the bay effectively summarizes geomorphology, texture, and the associated biota (Shaw et al. 2012a).

GEOLOGY

Geomorphology More than the other regions in this report, the Bay of Fundy reveals a great diversity of geomorphology (Fig. 47): low relief muddy basins in the outer bay, large areas of irregular and complex morainal ridges, fields of bedforms, deep tidal scour troughs, banner banks (trains of sandy bedforms near modern coasts), as well as highly unusual large sandy bedforms trapped due to incision in underlying glaciomarine sediments.

Bedrock Bedrock is Triassic sedimentary rocks, with older bedrock types being found along the New Brunswick coast.

Surficial materials A wide variety of surficial materials is found, reflecting: 1) glacial history; 2) changes in relative sea level; and 3) the onset and development of very high tidal ranges (linked to the postglacial transgression). The surficial geology map of Fader et al. (1977) shows sand and gravelly sand in the upper bay, till in the central area, and postglacial mud in the deeper water in the west. Subsequent multibeam sonar mapping (Todd et al. 2011) reveal the true complexity of the seafloor textures. This variability is illustrated by Figure 48.

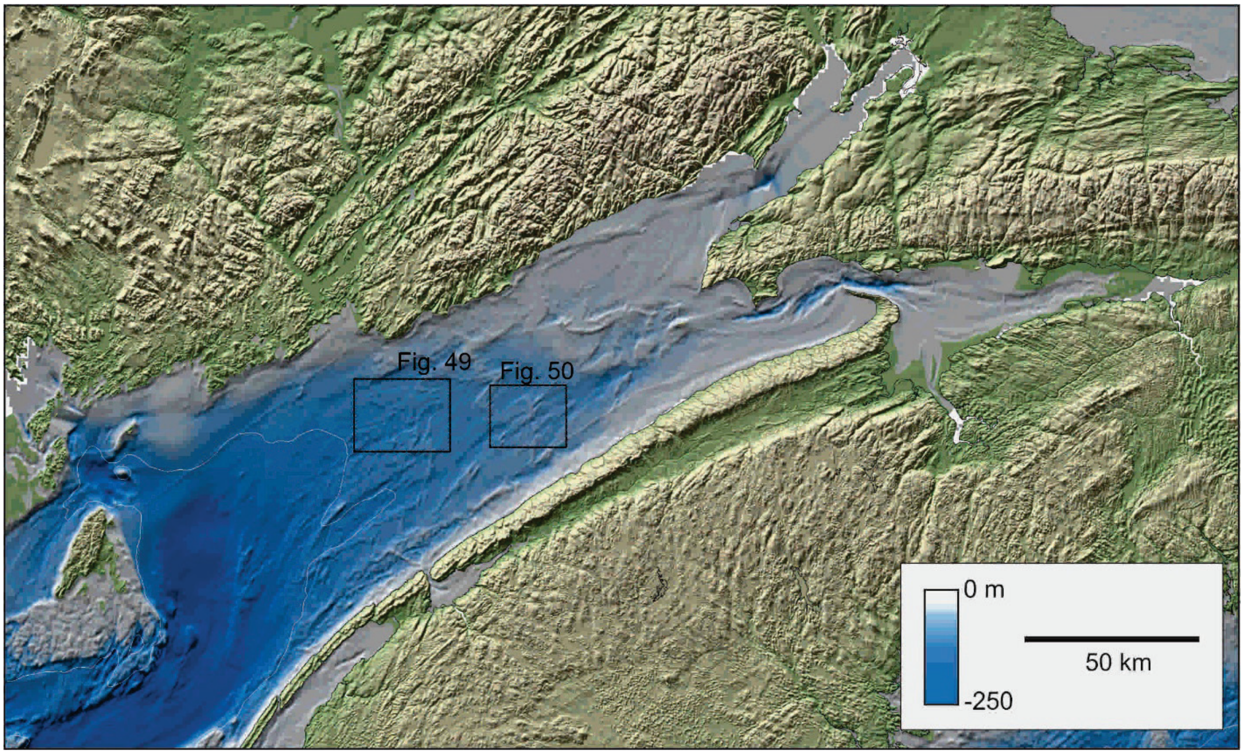


Figure 47: *Bathymetry of the The Bay of Fundy, with the 100 m isobath shown (white lines).*

PRINCIPAL GEOMORPHIC REGIONS

Based on the multibeam sonar mapping, Shaw et al. (2012) divided the entire bay into seascapes: 1) bedrock; 2) glacial; 3) glaciomarine; 4) muddy; 5) scoured; 6) sandy; 7) bioherms; and 6) anthropogenic. They defined seascapes as recurring underwater landscapes with recurring patterns of geomorphology, texture, and biota.

For purposes of description the bay is sub-divided into two geomorphic regions, following the seascape approach of Shaw et al. (2012a):

- ***Innermost zone*** In the inner bay deep tidal scour troughs have formed in areas where the strong tidal flows are constricted. The trough at Minas Passage is 70 m deep, and is incised into glaciomarine sediments (Shaw et al., 2010). In association with the main trough and subsidiary trough are large bedform fields, as described by Shaw et al. (2012b). Further landward of Minas Passage, Minas Basin contains thick surficial sediments, including sand and muddy sand bedform fields.

- ***Middle and outer bay*** Away from the tidal constrictions of the upper bay, the Bay of Fundy contains a vast array of seafloor types: moraines, bedform fields of various types, areas of erosion, banner banks at the coast, a large muddy depocentre in the outer bay (most of it deeper than 100 m), and fields of drumlins. Most of this is described on the seascape map of Shaw et al. (2012a).

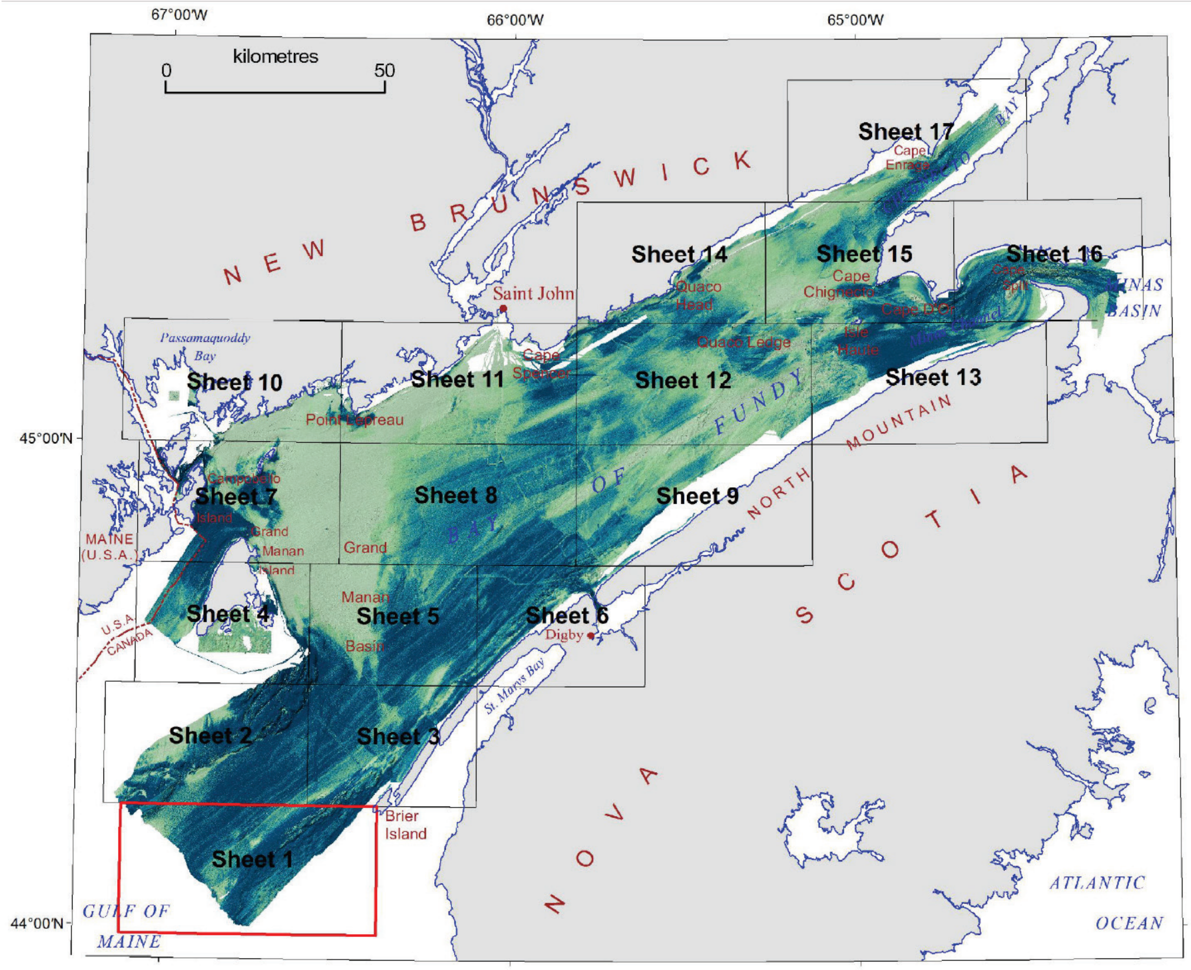


Fig. 48. *An index map from the series of 17 backscatter maps of the Bay of Fundy by Todd et al. (2011). High backscatter (coarse materials such as bedrock, and gravel) have dark tones, while sand and mud have light tones.*

VIGNETTES

1. Fields of moraines in the middle bay

- The most extensive seascape unit on the map by Shaw et al. (2012a) is the moraine seascape, which occupies large tracts of the mid- to upper-bay. An example of this region (Figure 49) comprises numerous low-relief, lobate ridges, 5 to 20 m high, many superimposed upon one another in a splayed pattern. The ridges consist of till up to 40 m in thickness overlying triassic bedrock. The spatial pattern of the moraines shows that they formed when a thin and steadily depleting grounded ice sheet retreated northeast up the bay. Much of the terrain is marked by iceberg plough marks and iceberg grounding pits that have been preserved intact since ice retreat.

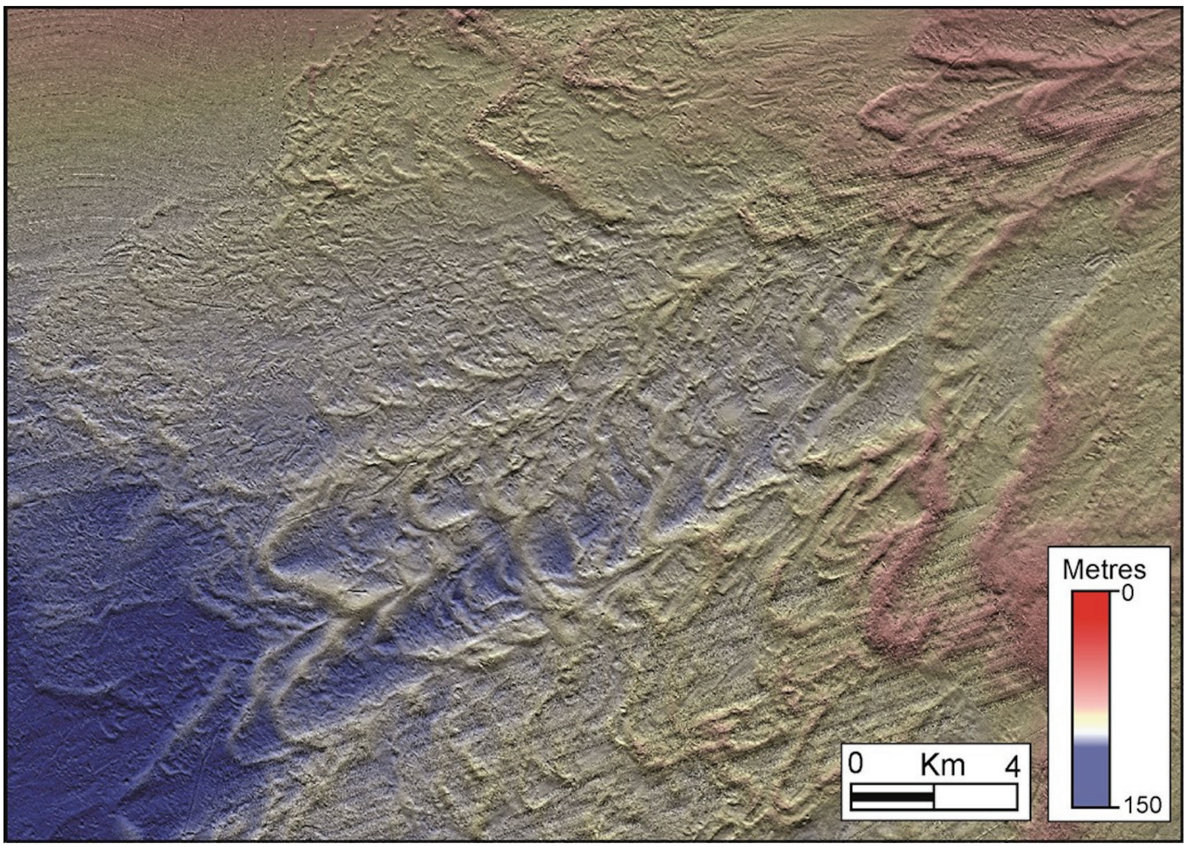


Figure 49: *Shaded relief image of an area of the middle bay, in water depths of 60 to 80 m. The heights of the moraines range from 5 m to 20 m. The entire area has high backscatter, with boulder gravel at the seafloor.*

2. Dune fields off Margaretsville, Nova Scotia.

The area depicted on Figure 50 is the subject of the unpublished maps and interpreted acoustic profiles by Fader et al. In this part of the bay, 10 m of glaciomarine silt overlies 10 m of till resting on Triassic sedimentary bedrock. A large number of sand dunes up to 20 m high rest on the glaciomarine surface, which is characterized by a surface gravel lag (high backscatter). Some of the large dunes are surrounded by depressions up to 6 m deep, and have thus become "embedded" in the underlying glaciomarine sediments. The seafloor is very complex, and in addition to the large sand bedforms, ribbons of sand extending SW to NE host sandy bedforms 1 to 2 m in height, and areas of seafloor scour are present throughout the area, resulting in pits up top 10 m deep.

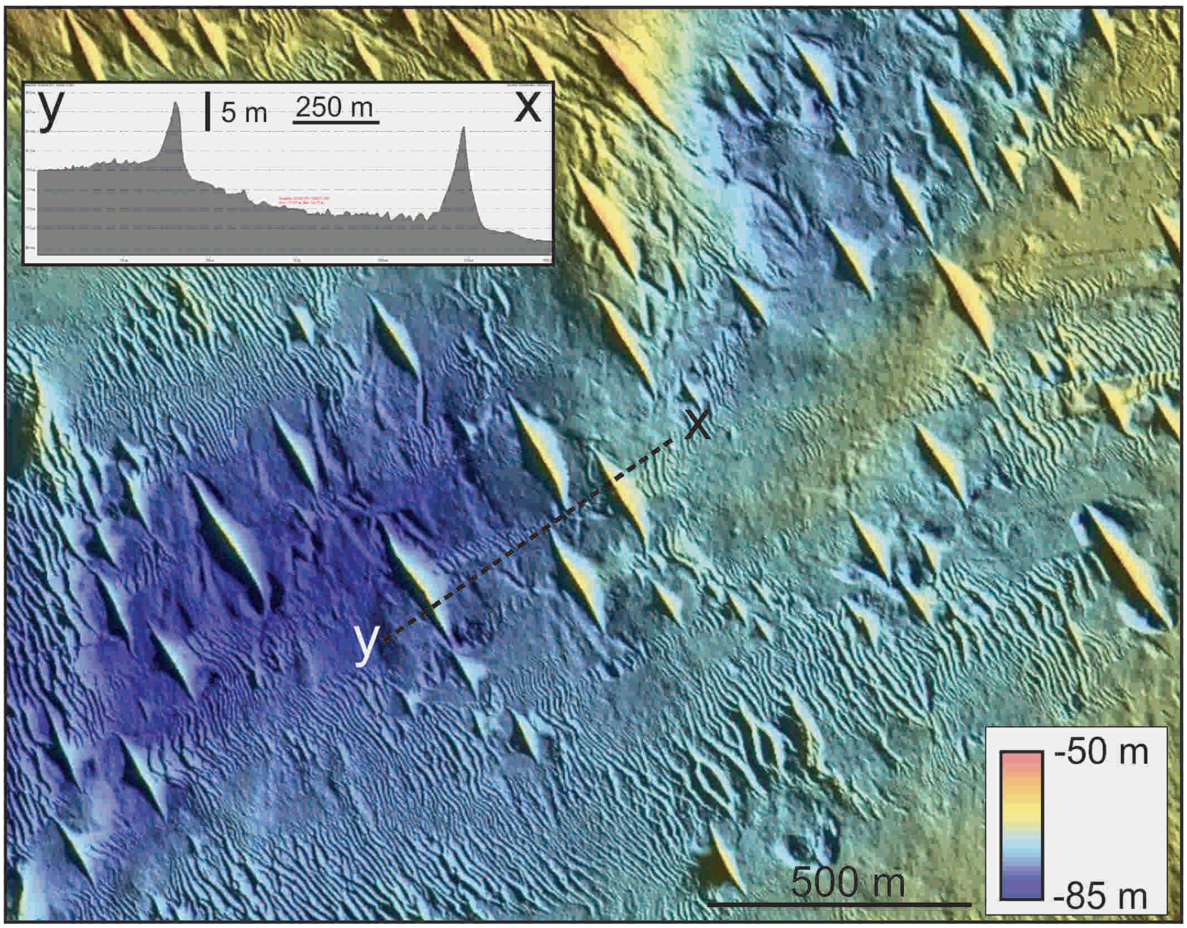


Figure 50: *Shaded relief image of the dune field offshore from Margaretsville, Nova Scotia, in water depths of 60 to 80 m. The large dunes are commonly 10 to 15 m high. The smaller sand bedforms average 1 to 2 m in height, and are arranged in trains that extend from SW to NE.*

FAVOURABLE FACTORS, POTENTIAL CONSTRAINTS, AND HAZARDS

- The comprehensive series of 17 maps showing bathymetry and backscatter provide an excellent database with which to understand the surficial geology of the bay. The seascape map summarizes morphology, texture, and biota. These maps reveal a great diversity of seafloor morphologies.
- The outer bay contains thick deposits of gas-charged postglacial mud. Elsewhere bouldery till predominates at the seafloor.
- In much of the middle and upper bay bedform fields at the sea floor result from the very strong tidal current regime.
- Deep tidal scour troughs at Minas Passage are linked with series of large bedform fields.
- Large bedforms known as banner banks are found near the New Brunswick coasts and Cape Split.
- Large fields of trapped sand dunes are found along parts of the Nova Scotia coast.
- As shown on the seascape map, linear horse mussel reefs occur in the central bay.

Region 12: Sable Island

SUMMARY

This region has relatively thick sandy Quaternary sediments and no bedrock exposures. Previous workers report sand thickness to a maximum of 55 m. Thus, conditions are highly favourable for pile installation, unlike almost everywhere else in Atlantic Canada. The bank has been intensively investigated because of hydrocarbon exploration and extraction: a range of offshore platforms and pipeline infrastructure is located here, south of Sable Island. As a result of the mobile sandy bedforms in the region, scour has been reported, and free spans have developed in pipelines, although these issues have not been considered serious (M. Li., pers. comm., 2019). Because of the unique nature of the surficial sediments, location, and existing infrastructure, this region will include a detailed subsurface analysis as one of the vignettes.

***Favourable** factors for foundation emplacement include thick Quaternary materials, predominantly sand; generally low relief bank; sediment mobility limited to the surface at depth.*

***Constraints** for foundation emplacement include broad sediment and bedform mobility; some heterogeneity in the subsurface sediment; locally high relief where sand ridges are present.*

Li et al. (2009) and King et al. (2004) provide good context for sediment and bedform mobility on the bank, while King (2001, 2002a,b) provide the subsurface stratigraphic framework and broader geologic context.

GEOLOGY

Geomorphology The area around Sable Island is a vast submarine bank, with an average depth of only ~ 30 m (Figure 51). The bank was emergent after deglaciation and has been submerging for many thousand of years, so that Sable Island is a small residual of a formerly much larger island. A large, sandy body over 40 m thick was deposited during a glacial readvance to the bank and then the material was highly redistributed during subsequent sea level rise. While this region has very low relief, the seabed is highly irregular due to the presence of large shoreface-attached sand ridges. Boczar-Karakiewicz (1991) summarizes the sand ridges thus: in depths less that 40 m are shoreface-connected sand ridges, mean height 5 m and wavelength 1600 m. From 40 m to 80 m are offshore ridges with heights of 10 m and wavelengths of 3000 m. This morphology is evident in Figs. 51 and 52.

Bedrock Bedrock is Upper Cretaceous and Tertiary age sedimentary rock. There are no bedrock exposures in the area.

Surficial materials Unlike almost everywhere else described in this report, Sable Island Bank has a thick blanket of unconsolidated sediments overlying relatively unconsolidated bedrock, recognized by Amos and Miller (1990) in seismic data and boreholes. They showed that the bank comprises thick post-glacial sand over glacigenic deposits. King (2001, 2002a) mapped deeply buried (tens to hundreds of metres), glacially-cut valleys with inhomogeneous fill including clay which dissect all but the outer bank, some cutting to over 250 m below sea level. Unconformable horizons in the region stem from low-stands of sea level bounding sandy glacial tills and are generally recognized across the region. Numerous layers of sandy till are topped with buried sand ridges. A sandy moraine and associated outwash apron, typically 10s m thick, buried the sand ridges with a re-advance following the initial glacier retreat, thus building the proto-Sable Island.

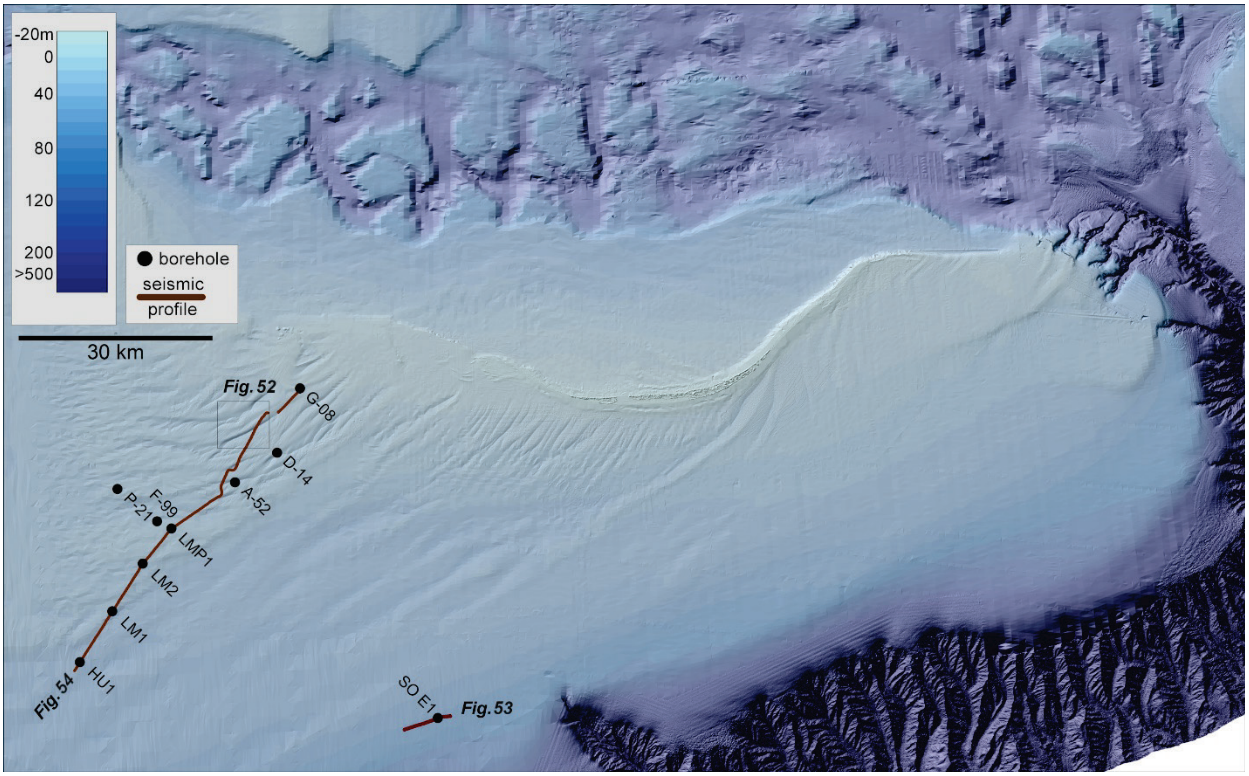


Figure 51: *Bathymetry of Sable Island Bank, with the location of Figure 52 shown as well as the transects from Figures 53 and 54. Boreholes from Figure 55 are also located at the south end of the transect for Figure 54.*

PRINCIPAL GEOMORPHIC REGIONS

For simplicity, the bank is described as a single geomorphic region. Seismic surveys, augmented in recent years by multibeam sonar surveys, show that while the bank has low relief, it is nevertheless topographically complex. Low-stand reworking of the sandy moraine and outwash has reorganized it into a series of shoreface-connected and offshore sand ridges (Fig. 52). Their overall distribution is shown on Fig. 2 B of Li et al. (2012). The average height and wavelength of the larger sand ridges on Sable Island Bank are 12 m and 6.4 km respectively. Sand waves and other bedforms are superimposed on the sand ridges. A thin mobile layer comprising ripples and megaripples is periodically active in the shallow reaches, resulting in a dynamic bedform migration. In general, below about 20 m water depth, only the largest storms have significant effect, reworking to depths of decimetres (Godfrey-Smith et. al. 2003, King 2004, Li et. al. 2009).

The large ridges on the south face of Sable Island have maintained their form largely since their inception at a much lower sea level. The troughs evolved to cut into underlying substrate as transgression evolved (King 2002a). This demonstrates that only a surface skin is dynamic. On a broad scale and long term, migration of sand is eastward and has swept most of Western Bank clean to a transgressive lag surface, leaving periodically active but very thin bedforms. Throughout the Holocene, this has been responsible for building numerous terraces east of the island, and bypassing these to spill into and develop a series of bank-edge canyons. Flux to the side canyons of the Gully (large canyon to the east in Fig. 51) is still largely unknown.

VIGNETTES

1. Sand ridges south of Sable Island.

Figure 52 shows the seabed off in the Cohassett-Panuke hydrocarbon development area, "Copan", off the southwest coast of the island, in water depths of 15 to 45 m, and illustrates the complexity of seabed terrain on Sable Island Bank. The largest sand ridge here has a height of 18 m. Li and King (2007) show that in the long term the upper surface of these ridges is activated and transported to the east. Superimposed on the sand ridges is a hierarchy of mobile sandy bedforms: large wave ripples and megaripples (Fig. 7, Li et al., 2012). Li et al. (2012) also show that portions of the sand ridges can migrate up to 40 m annually but the feature as a whole is dynamically stable.

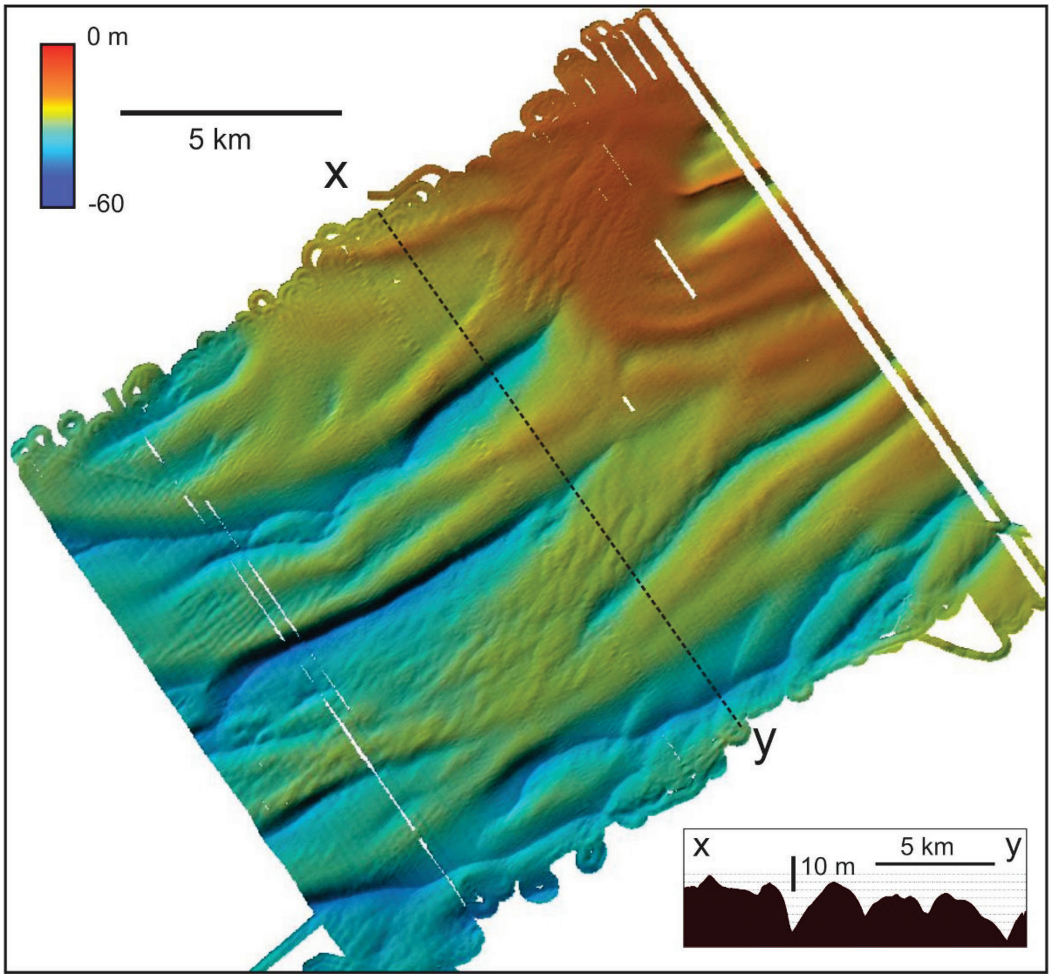


Figure 52. *Shaded relief of the sand ridges in the Cohasset-Panuke area, southwest of Sable Island. Also showing cross section XY. A gas pipeline runs across the ridges, as shown on Fig. 2 in Li and King (2007).*

2. Lithologic characterization of the thick bank deposits south of Sable Island.

Figure 53 shows a correlation between a borehole and high resolution seismic transect, largely anchored by the unconformity horizons represented by continuous gravel (upper) and clay-rich (lower) lithologies. Figure 54 shows a combined seismic and borehole correlation transect extending from the CoPan area in Vignette 1, southwestward to near the shelf break. The boreholes penetrate generations of surficial sand ridges (Units 2SR and 3SS, upper panel), the thick sandy glacial outwash apron (Unit 4DA) and through stiff clay and further down into pre-last glacial dense sands and clays. The upper unconformity has shallow channeling with variable infill sediment types. As noted above, the surficial sands can be periodically mobile but only on the order of tens of cm depth. Figure 55 shows further details of several of the boreholes, including shear strengths and grainsize. Both the sands and the clays are competent and suitable for monopoles.

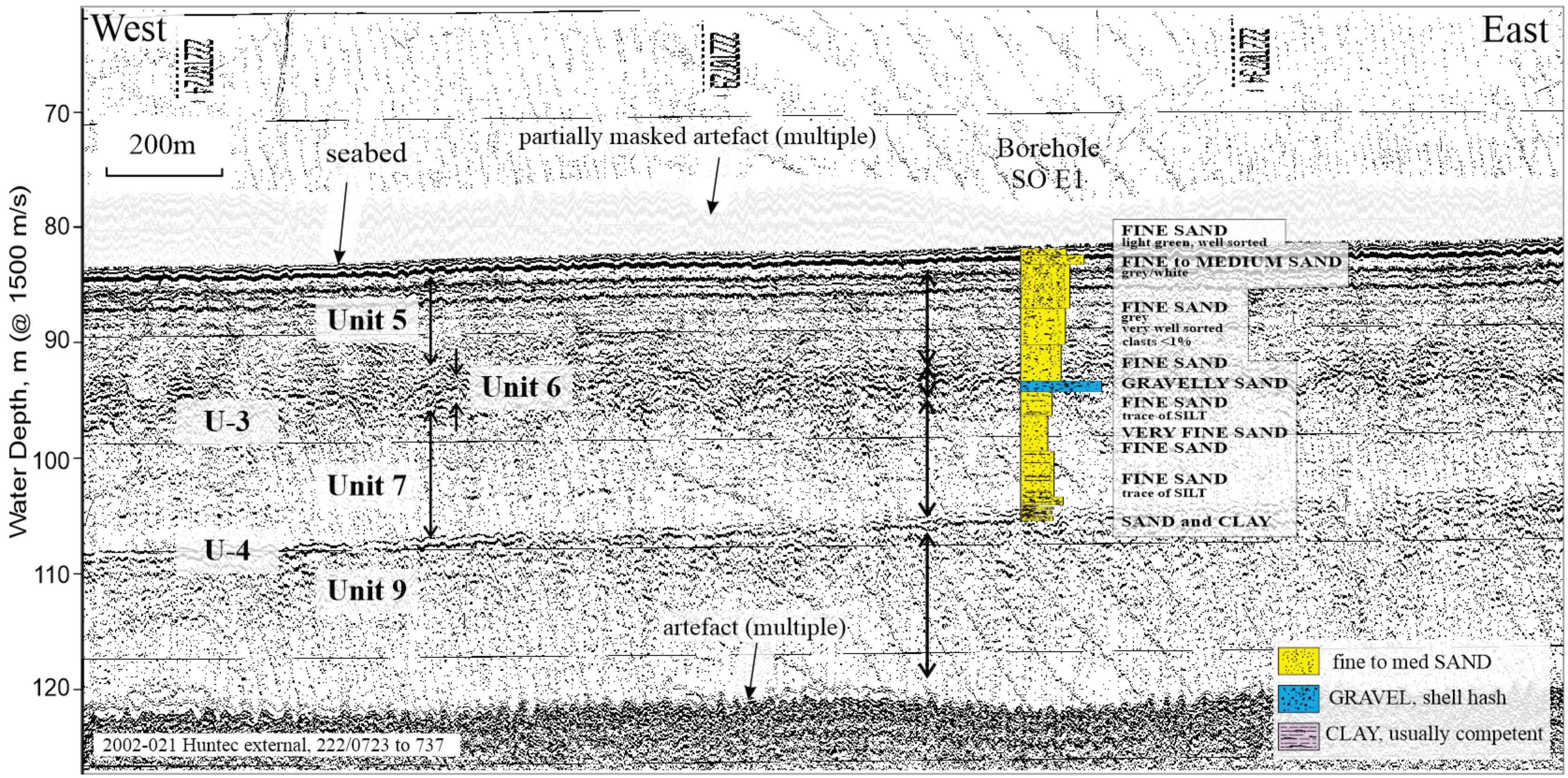


Figure 53. *Deep-towed sparker (sub-bottom profiler) image from outer Sable Island Bank showing projected borehole lithologies through glacigenic sands (bulk corrected for velocities). Location on Figure 51.*

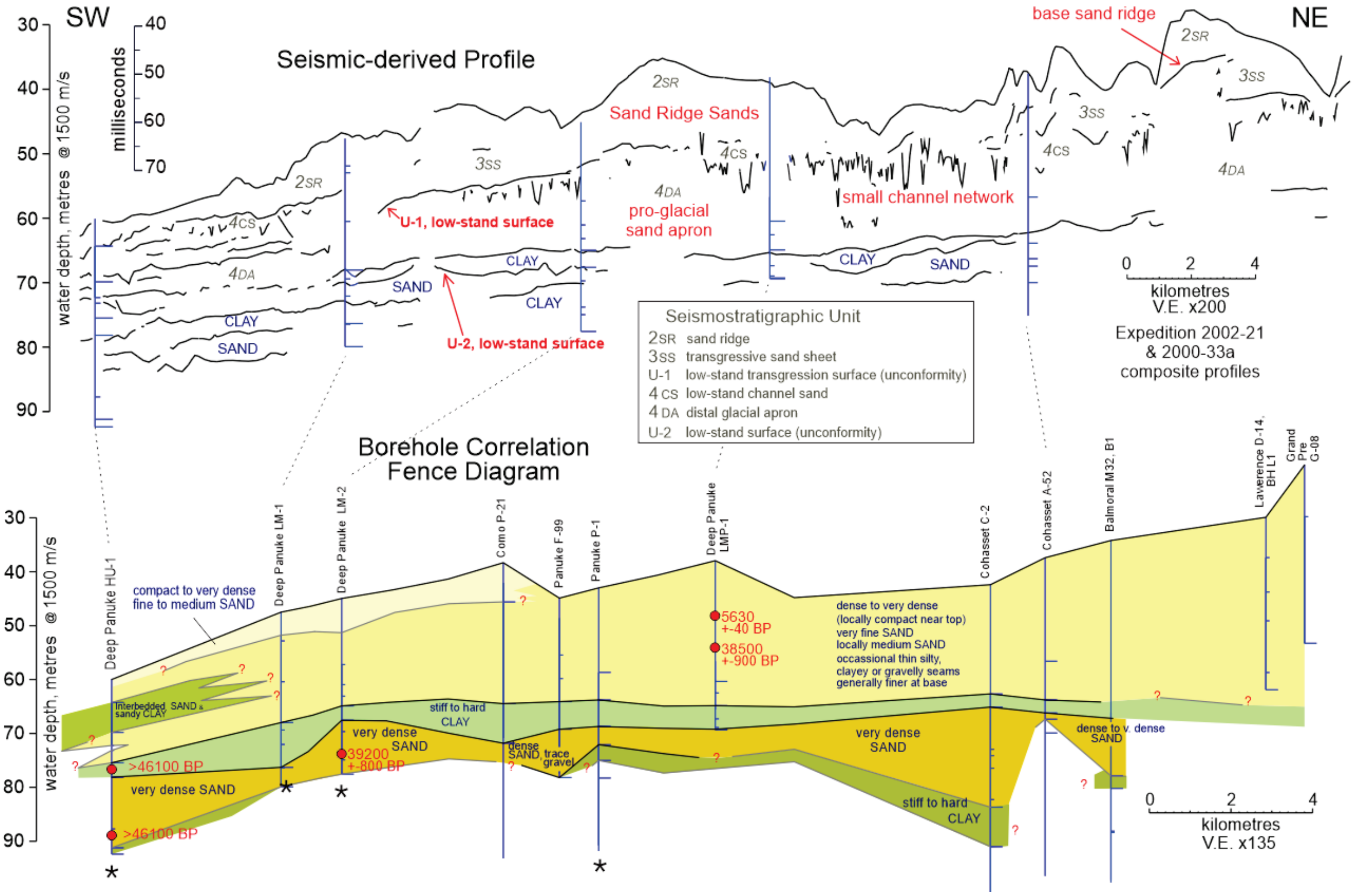


***Figure 54**. Seismic (deep-towed boomer and small air gun, composite) line interpretation (upper panel) from outer Sable Island Bank (location Fig. 51). Seismic unit classification from King (2001; 2002a). The lower panel shows the corresponding correlation of lithologic units derived from numerous industry-collected borehole data, including cone penetrometer, discrete strength measurements, grainsize, and radiocarbon dating. A series of alternating dense sand and stiff clay layers predating the last glacial maximum (LGM) at the base are relatively continuous over many kilometres. An overconsolidated clay overlying the U-2 unconformity is intersected in most boreholes which reach to this depth. The overlying sands derive from a glacial outwash apron (Unit 4), deposited by a glacial readvance following the LGM and forming the proto-Sable Island. They are relatively homogeneous across the area but become finer toward the SW. Locations with an asterix * have more detailed descriptions in Fig. 55. Seismic units and profiles modified from King (2001; 2002a).*

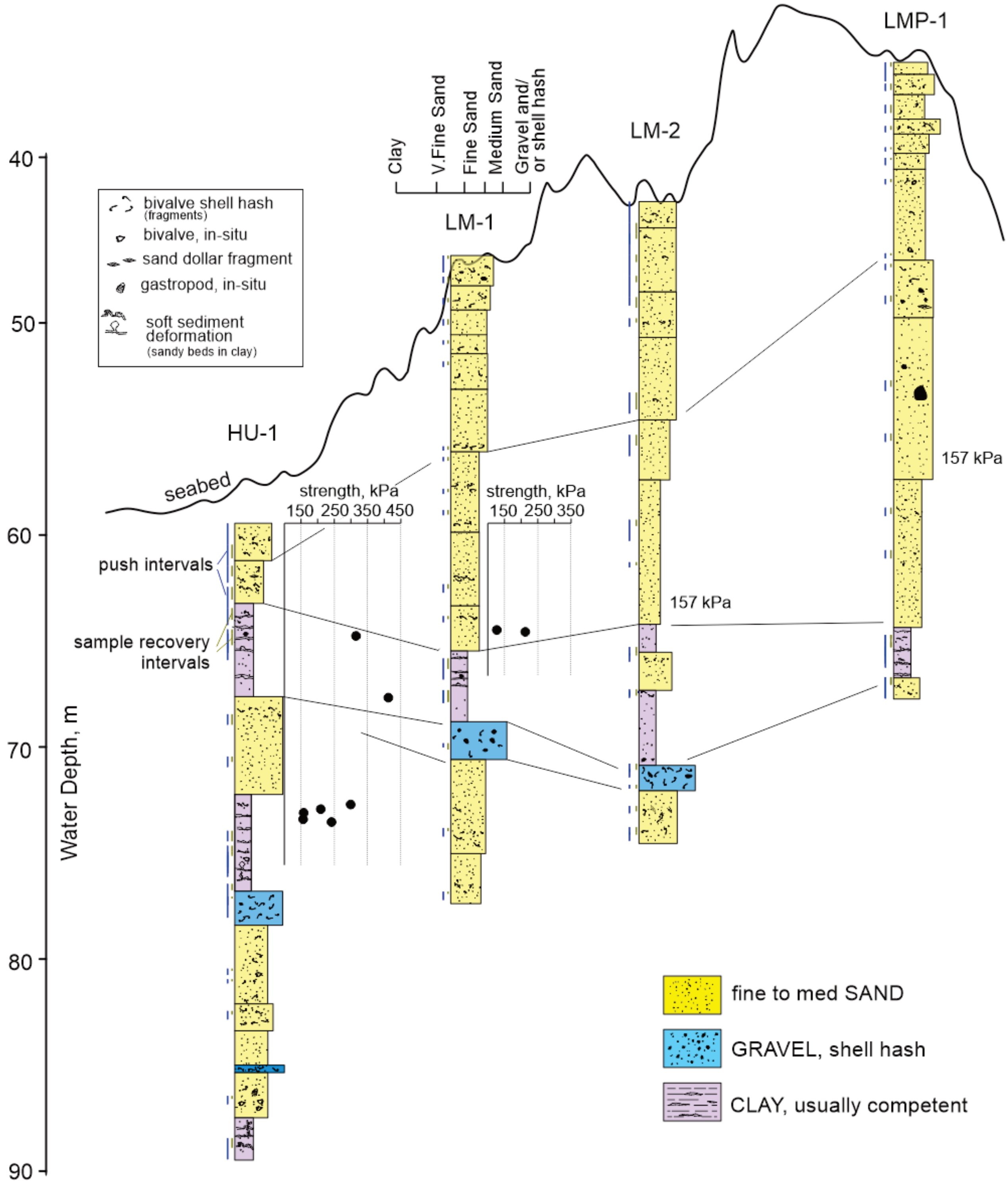


***Figure 55**. Selected borehole logs (locations Fig. 51) projected and correlated on a seabed profile. Sample intervals are shown as are shear strength measurements, both from pocket penetrometer and triaxial tests. Grainsize, basic structure, and shell content are symbolized. Modified from King, 2002b.*

FAVOURABLE FACTORS, POTENTIAL CONSTRAINTS, AND HAZARDS

- The only region in this report with no outcropping bedrock and thick Quaternary materials, as much as 55m of sand.
- Unconformities, clays, and gravel/shell beds introduce subsurface geotechnical variability.
- Areas with heterogeneous subsurface fill (e.g. clays) are well mapped as subsurface channels and easily detected in seismic data.
- Sediments and bedforms are mobile, but generally as a surficial skin and to a lesser extent in deeper (> 20m) water.
- High wind, wave, and current activity experienced as a shelf-edge bank in the North Atlantic.

Region 13: Southwest Newfoundland

SUMMARY

Coastlines in this region are steep and rocky, and the inner shelf is dominated by shallowly dipping irregular bedrock. Small areas of sediments occur at Connoire Bay and in fiords crossing the inner shelf. Thick (~70m of sand and gravel) sediments exist at Connoire Bay.

Favourable factors for foundation emplacement include isolated thick packages of Quaternary sedimentation; a low slope, shallow bedrock platform forms the inner shelf

Constraints for foundation emplacement include a broader lack of Quaternary sedimentation; unstable sediments on slopes and at the mouths of inlets; most prominent Quaternary landform (moraines) in this region composed of till

Shaw and Potter (2015) provide the best summary of the existing data for this region. Existing high-quality MBES data highlights irregular bedrock, moraines, and some of the late Quaternary sedimentation at Connoire Bay.

GEOLOGY

Geomorphology The coastline of this region is generally steep, rocky and east-west oriented (Fig. 56). It is intersected by several fiords along its length. The inner shelf forms a relatively flat, mostly <100m deep, rocky platform that hosts a continuous, shore parallel moraine with typical crest depths of 150m. Relative sea level were similar to modern immediately following deglaciation but dropped to a low of ~ -30m by ca. 10ka BP, gradually rising to present levels (Shaw et al. 2002a).

Bedrock A shallow, irregular (relief of 20m in some places), wave dominated rocky platform exists here that extends up to 8km offshore with irregular sand and gravel deposits between outcrops. This region lies in the Gander tectonic zone, including the boundary between basement (altered volcanic, metasedimentary and granitic intrusive) rock and Carboniferous sediments that predominate further offshore (not observed in the multibeam coverage).

Surficial sediments Bedrock is overlain by acoustically incoherent till, that averages 20m thick, in the moraine belt near the seaward margin of the inner shelf region. Glaciomarine and/or postglacial muds are largely absent above 100 m depth. Isolated pockets of sand and gravel occur in bedrock depressions, except for at Connoire Bay (Figs. 57, 58), where a thick (as much as 70 m), low relief, shallow sequence of sand and gravel are found offshore of a sandy barrier beach found on the coast.

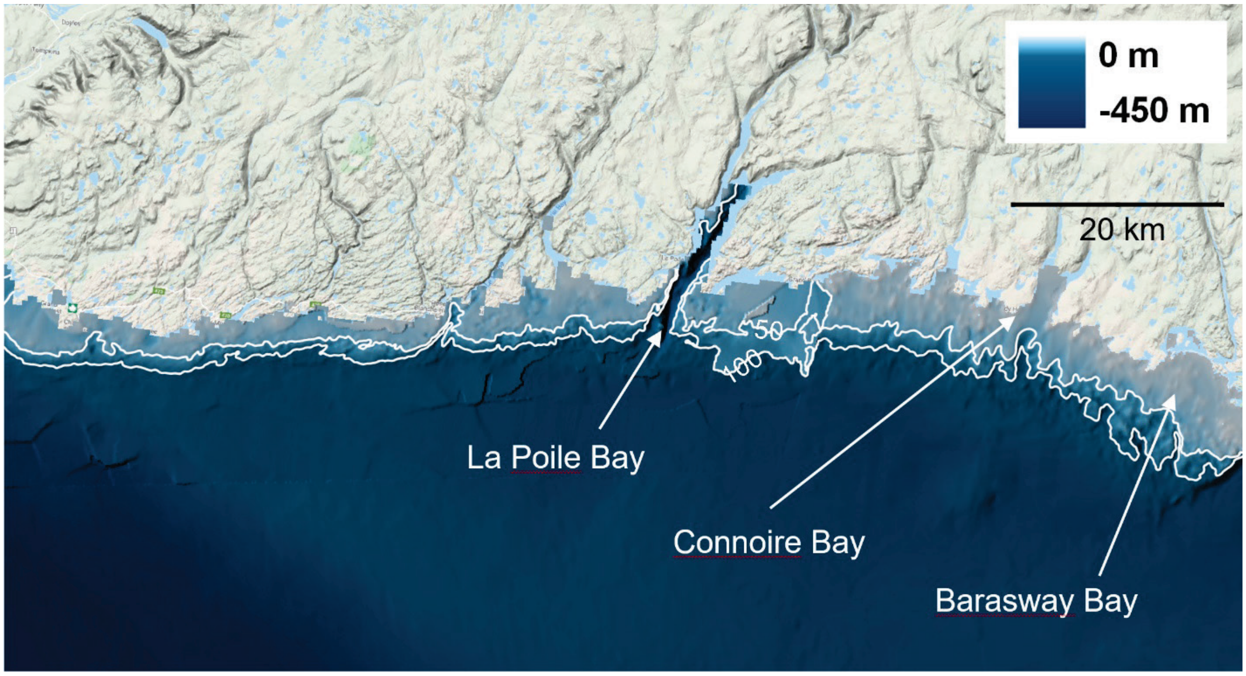


Figure 56. *Bathymetry, Southwest Newfoundland, with 50 and 100m isobaths shown. Background map data: Google.*

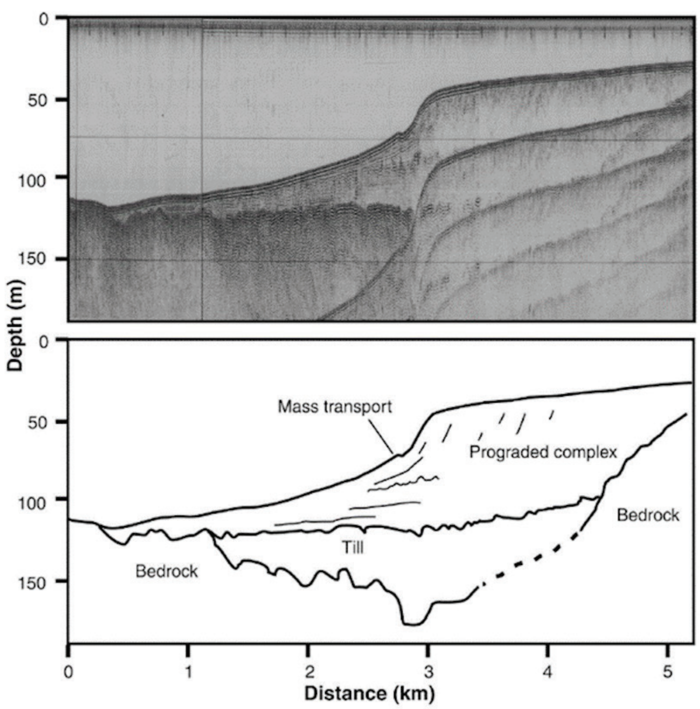


Figure 57: *Huntec DTS seismic-reflection profile and interpretation of the mouth of Connoire Bay, from Shaw and Potter (2015). This is the largest deposit of sand and gravel found on the inner shelf of this region. The profile also illustrates the high relief bedrock surface that is exposed elsewhere. Location indicated on Figure 3.*

PRINCIPAL GEOMORPHIC REGIONS

This region is divided into four geomorphic regions, each with a unique morphology, stratigraphy, and surface texture:

- *Bedrock shelf:* Dominates the inner shelf and is characterized by a shallowly dipping, irregular (relief ~20 m) bedrock seafloor, with minor shallow pockets of sand and gravel found in fracture surfaces.
- *Inner shelf-edge moraines:* As slope and depth increases around the 100 m isobath, till shaped into recessional, coast-parallel moraines reach ~ 20m up from the seafloor.
- *Fjord depocentres:* La Poile Bay is the largest fiord in the region (depths up to 358 m near its mouth) and several others cross the inner shelf. These contain thick sequences of Quaternary sediments, such as the 160m of glaciomarine and post-glacial mud in the basin, interbedded with debris flows, in addition to several metres of acoustically stratified glaciomarine sediment in perched basins in shallower areas along the slopes of the fiord. Nearer to the head of the bay, several submerged terraces of medium to coarse well sorted sand shoal landward to depths of 27-30 m.
- *Connoire Bay depocentre:* A prism of sediment extends ~4 km seaward from its mouth with bedrock overlain by at most 60 m of acoustically incoherent sediments (likely till) which is in turn overlain by as much as 74 m of acoustically stratified sediments associated with a sandy barrier and shoreface that formed when sea level dropped from the highstand to lowstand (Figures 57, 58).

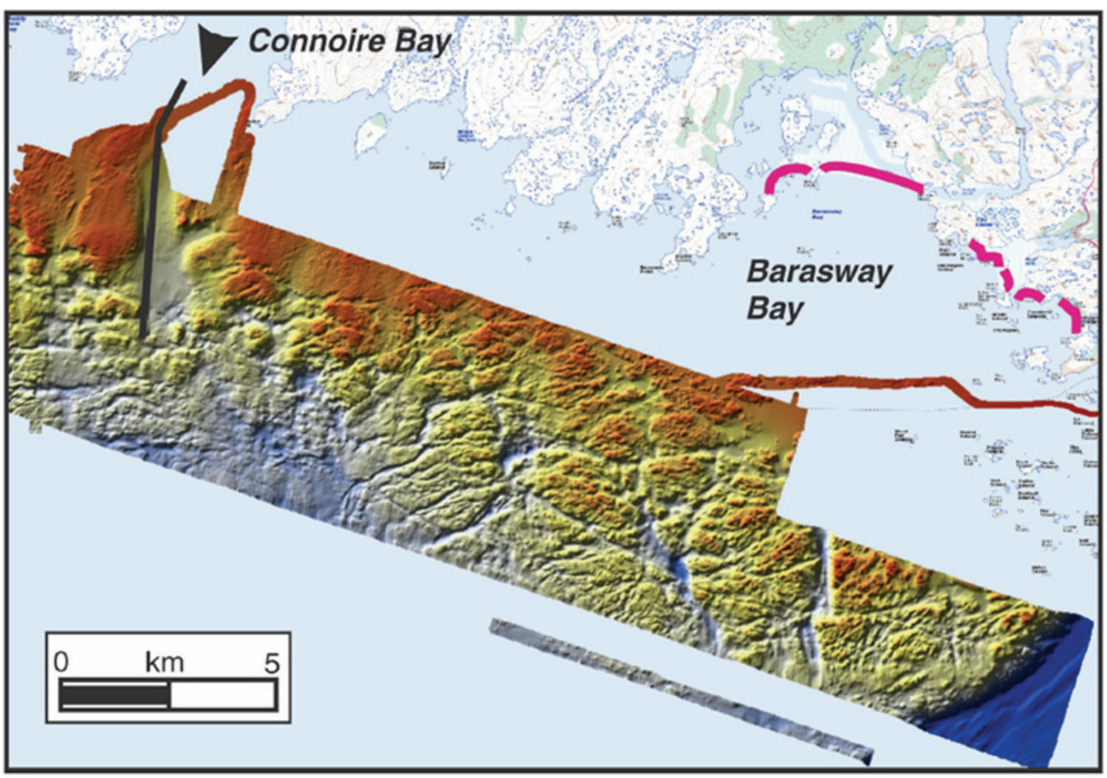


Figure 58 (previous). *Multibeam data showing the sediment prism at the mouth of Connoire Bay(from Shaw and Potter, 2015) and the profile from Figure 2 (black line) overlying the prism.*

VIGNETTES

1. Submarine inner shelf-edge moraines

Multibeam imagery (Figure 59) reveals laterally extensive submarine moraines (black arrows) that formed when retreating glaciers temporarily halted in the shallower water, discussed in Shaw (2003). Close investigation of the area covered by moraines reveals that much of the area is grooved by grounded ice, producing flute-like ridges that are perpendicular to the coast and that exhibit up to 20 m of relief (white box, Figure 4).

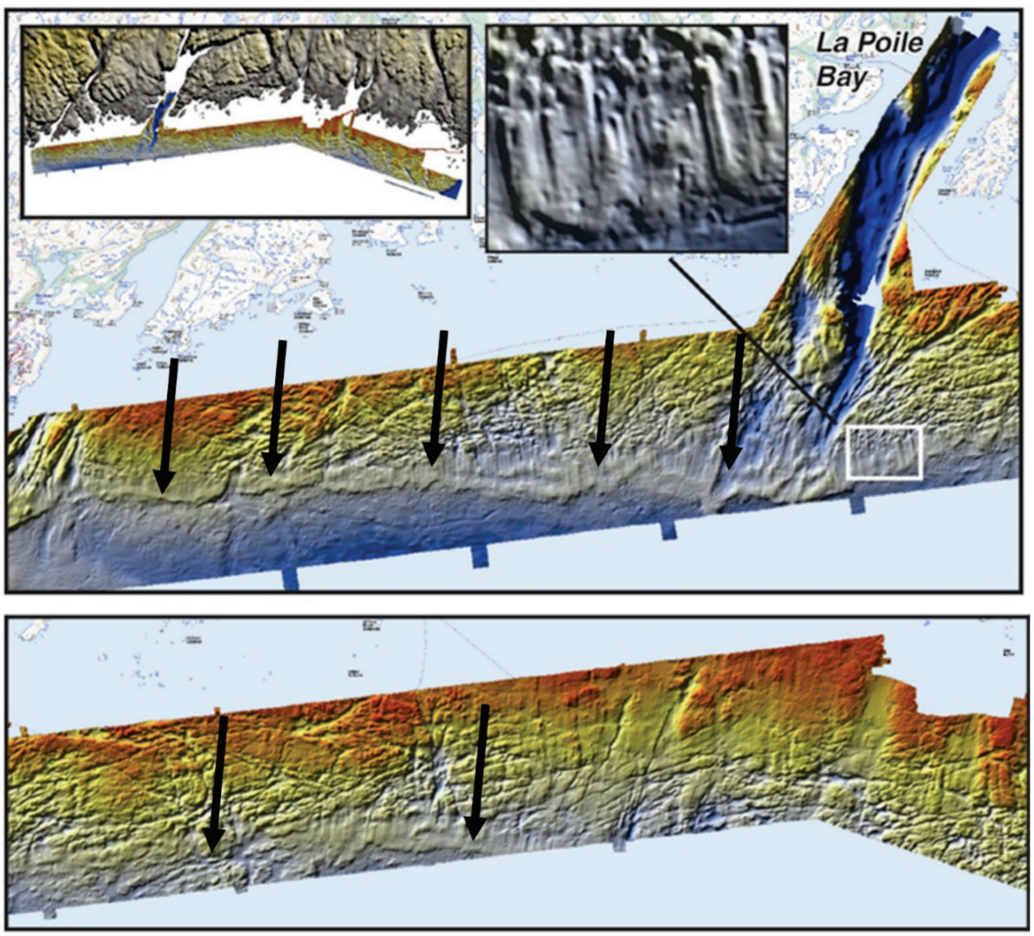


Figure 59. *Multibeam coverage from the region (adapted from Shaw and Potter 2015). Inset in top left shows full area of coverage, white box shows fluted till. Black arrows show distinct moraines.*

FAVOURABLE FACTORS, POTENTIAL CONSTRAINTS, AND HAZARDS

- Bedrock is irregular and high-relief, but of low slope and shallow (< 50m depth).
- Sediments associated with deeper fiords (e.g. La Poile Bay) are unstable, with turbidity currents common and steep slopes prevailing in shallower, terraced areas.
- A thick, flat sequence of sediments is found in Connoire Bay, and more may be elsewhere (e.g. Barasway Bay).
- Sediments associated with the shallow bank at the mouth of Connoire Bay are unstable, with mass wasting prevalent (see Shaw and Potter, 2015, Figure 43).
- Moraines form a shallow ridge of Quaternary sediments, however, are composed of till and unlikely to be ideal for foundations.

Region 14: South Newfoundland Fiords

SUMMARY

This region is dominated by a steep, narrow bedrock coastline and inner shelf, with very little area of the inner shelf occurring above 100 m depth. The exception is at the eastern end of the region and at the heads of inlets, where several flat, shallow, sand and gravel paraglacial deltas occur with a lack of active bedforms.

<u>Favourable</u> factors for foundation emplacement include paraglacial deltas that are flat, shallow, and consist of ideal substrate

<u>Constraints</u> for foundation emplacement include a narrow, steep, irregular bedrock inner shelf; unstable (gas charged) muds in basins; little Quaternary sedimentation

Existing high-quality MBES data highlights trough-mouth moraines, mid-Holocene deltas, cold-seep pockmarks, and evidence of mass wasting. Shaw and Forbes (1995) provide good context for mid-Holocene deltas and Shaw and Potter (2015) provide regional interpretation.

GEOLOGY

Geomorphology Most of this region's coast is steep, rocky and oriented in an east-west direction. The exception is the eastern end, around the Hermitage Peninsula (Fig. 60), where a broader shallow area exists and glacial deposits, pocket gravel beaches, and raised marine terraces can be found. Several fiords also intersect the coastline, incising down through a deep plateau (200 – 300 m). The boundary between basement and younger rocks is at the shore, rather than km offshore, meaning this region lacks the shallow bedrock shelf found in region 12. Because of the deeper inner shelf, glaciers experienced a still-stand in the many fiords in this region, rather than at the edge of the bedrock shelf; moraines here are thus fiord-mouth rather than linear features at the slope break. Sea level were high (as much as 50 m above present) following deglaciation, fell to a lowstand in the early Holocene (between -30 and -15 m) and rose to present (Shaw et al., 2002).

Bedrock West of the Hermitage Peninsula, the contact between basement (volcanic, metasedimentary and intrusive rock) and Carboniferous sedimentary rocks occurs closer to the shore, so there are steep rocky coasts largely devoid of beaches that quickly (mostly within 1 km) drop below 100 m depth away from the coast. Bedrock dominates in the region in areas shallower than 100 m due to steep slopes and a lack of basins for sediment accumulation. Around the Hermitage Peninsula, the bedrock geology is more complicated. It includes rocks with ages ranging from Cambrian to Carboniferous.

Surficial sediments Bedrock can be overlain by acoustically stratified glaciomarine mud**,** which can be interfingered with acoustically transparent debris flow deposits particularly in deep fjords. Postglacial muds that are acoustically transparent are banked in locations, indicating recent reworking by currents. Sand and gravel occur at fiord heads, where internal reflections trend upwards into early Holocene deltas, forming shallow, thick deposits (e.g. >100m, Figure 61). At fiord mouths, acoustically incoherent till is found in moraines deposited either on bedrock or interfingered with glaciomarine mud (Figure 63). A regional complication of unconsolidated sediment thickness (King 2014b) suggests that thick (10-50m) packages of sediment lie offshore in this region, however due to the narrow inner shelf most of this sediment is likely deeper than 100m water depth.

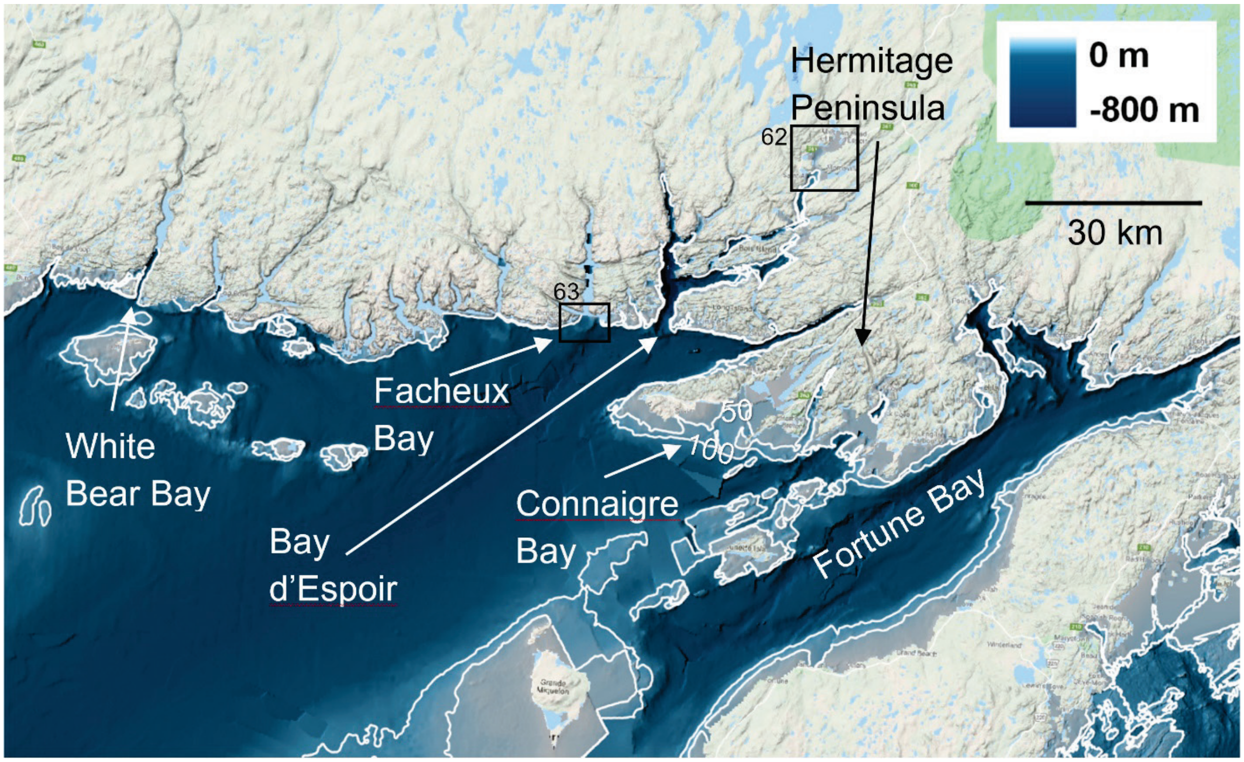


***Figure 60**. Bathymetry, Southwest Newfoundland, with 50 m and 100 m isobaths and figure locations. Background map data: Google.*

PRINCIPAL GEOMORPHIC REGIONS

This region is divided into four geomorphic regions, each with a unique morphology, stratigraphy, and surface texture:

- *Bedrock coast:* Steep, irregular, and generally with little area shallower than 100 m depth.
- *Fiord-head drowned deltas:* Flat topped, shallow (16 m depth to 30 m depth from east to west) wedges of thick sediment with prograded, seaward-dipping internal reflectors are found at the mouths of several fiords such as White Bear Bay (Figure 61), and Bay D'Espoir (Figure 62). Sediment is likely predominantly sands, with minor gravels higher in the sequence and finer sediments lower (cf. Shaw and Forbes 1995).
- *Deep fiord depocentres:* Quaternary infill in several of the fiords in this region is thick (e.g. 180m in White Bear Bay), and fiord depths vary greatly, from Grey River (68 m) to the deepest fiord in Newfoundland in Bay D'Espoir (790 m), however the majority are

deeper than 100m. Fill is mostly glaciomarine and postglacial mud interfingered with debris flow deposits. At the mouth of many of the fiords is a ridge of till in the form of fiord-mouth moraines (e.g. Figure 63).

- *Connaigre Bay mouth:* The largest area of shallow shelf in this region has limited data coverage, however a broad sill exists at 98m depth and mass transport processes are evident in large slide scars and depositional lobes found in glaciomarine sediments. A grab sample in the central portion of the bay (Cruise 73006 sample 7753) yielded predominantly sand.

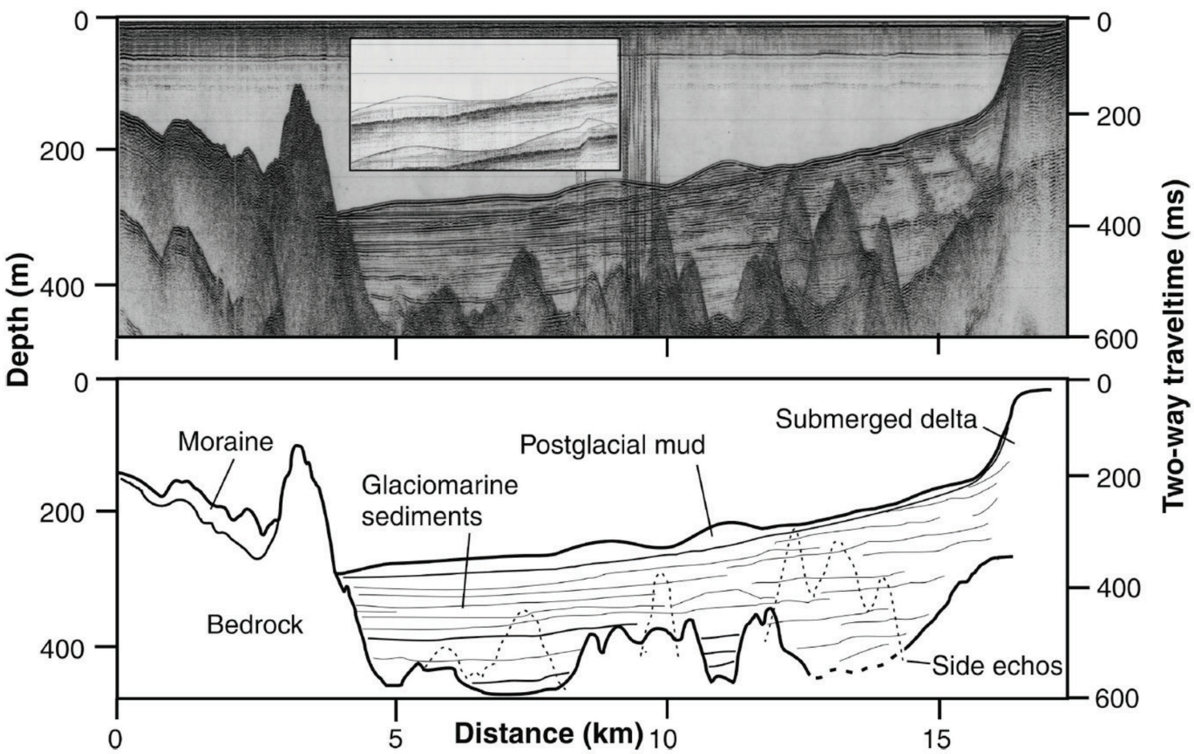


Figure 61. *Huntec DTS seismic-reflection profile and interpretation for White Bear Bay, head to mouth, from Shaw and Potter (2015). Note the shallow, flat submerged delta on the right consisting of a thick (>100m) package of sediment.*

VIGNETTES

1. Mid-Holocene deltas in Bay D'Espoir:

Deltas form flat-topped, fine-to-coarse grained fan-shaped deposits in shallow water. Figure 62 shows several deltas that formed in the Mid-Holocene, when sea level were about 10 m lower in this area (-30m further west in La Poile Bay, Region 12). Figure 62 also shows pockmarks, or features that form when fluids trapped in sediments below migrate upwards and release into the water column, leaving a depression behind (indicating sediment instability). Bay D'Espoir has been reported to host a rich fauna assemblage (e.g. Gagnon and Haedrich, 2003).

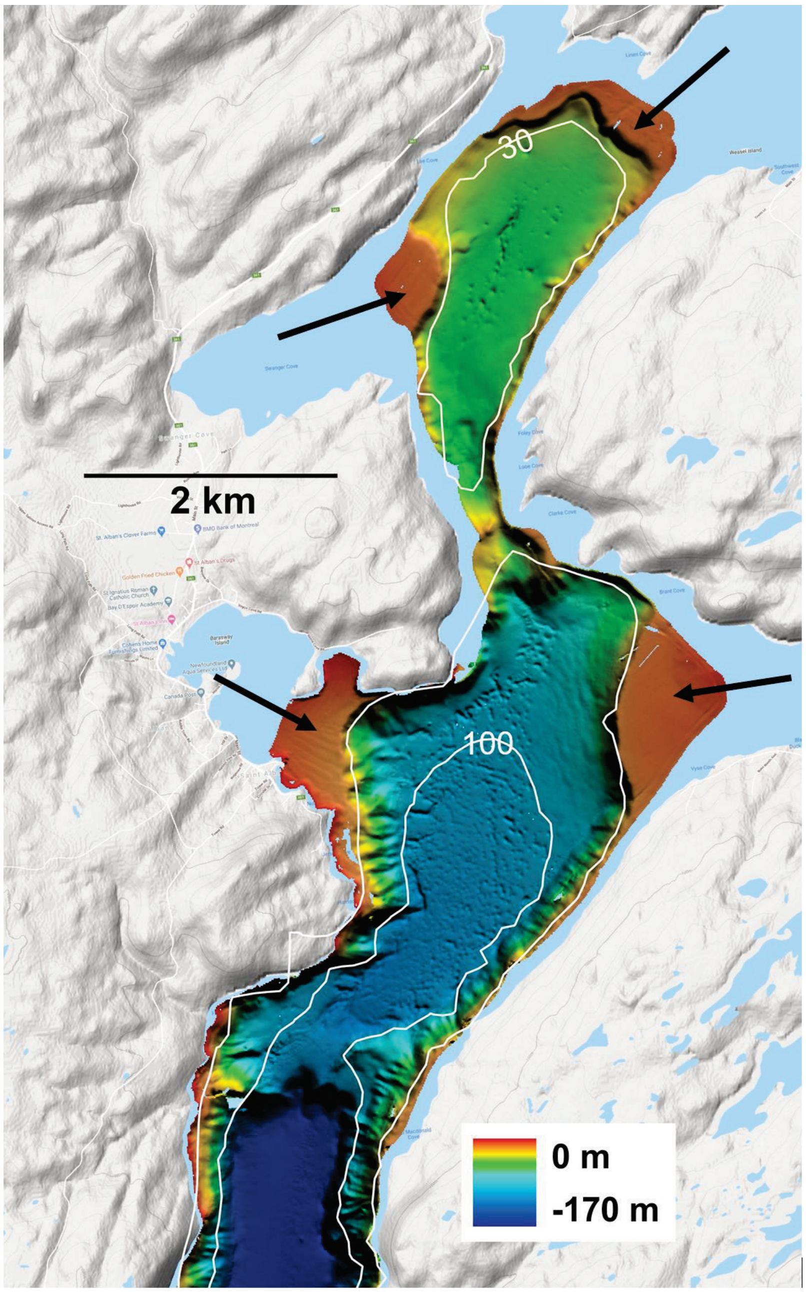


Figure 62. *Mid-Holocene deltas are highlighted by black arrows. Note also the fluid-escape features (pockmarks) indicating instability in the basin, especially between the 30 and 100 m isobaths. Background map data: Google.*

2. **Fiord-mouth moraines**

At the mouth of several of the fiords in this region are moraines, such as at Facheux Bay (Figure 63). A seismic profile across this moraine (see Shaw and Potter, 1995, Fig 35) indicates that the moraine, composed of till, interfingers with acoustically stratified glaciomarine sediments. The moraines in this region and their implications for glacial history are discussed in Shaw (2003).

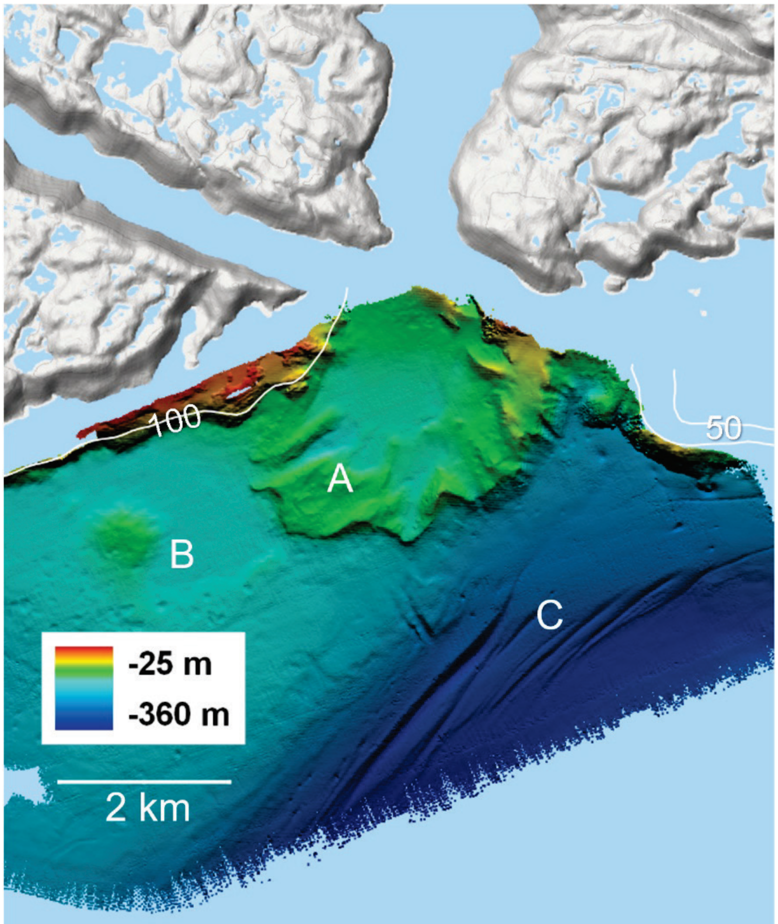


Figure 63. *Fiord-mouth moraine at Facheux Bay (A). Note the pockmarks across the level platform of fine-grained sediments (B) and the troughs on the south east slope indicating sediment mobility (C). Background map data: Google.*

FAVOURABLE FACTORS, POTENTIAL CONSTRAINTS, AND HAZARDS

- Bedrock is steep, irregular, and high relief
- Mid-Holocene deltas are flat-topped, consist of thick sequences of sand and gravel, and exist in shallow waters
- Pockmarks in muds indicate unstable sediments and fluid release
- Very little seafloor between 0 and 100 m depth outside of fjord heads

Region 15: Burin

SUMMARY

Lower relief, sedimentary coastal features typify the coastline in this region, with irregular, high-relief bedrock, large fields of glacial landforms, and mid-Holocene landforms (e.g. deltas) prevalent in shallow waters. A sandy shallow shelf exists south of the Burin Peninsula.

<u>Favourable</u> conditions for foundation emplacement include paraglacial deltas that are flat, shallow, and consist of ideal substrate; a lack of active bedforms; a sandy shallow shelf south of Burin Peninsula

<u>Constraints</u> for foundation emplacement include high relief bedrock; Quaternary sediments are often covered, or characterized, by cobbles and boulders; deep troughs where currents are strong

A series of GSC maps and products for Placentia Bay (e.g. Shaw et al. 2011) provide thorough information for the eastern portion of this region.

GEOLOGY

Geomorphology The Burin Peninsula region includes the eastern shore of Fortune Bay and the western shore of Placentia Bay (Figure 64). The coastline and inner shelf in this region is less steep than observed further west (e.g. region 14), with raised marine terraces and large coastal deposits common along the eastern shore of Fortune Bay (e.g. Forbes 1984). In Placentia Bay, bedrock and glacial/paraglacial regions are common in shallower waters (Shaw et al., 2011). Following deglaciation, relative sea level were higher than present and fell to a lowstand in the early Holocene, however the relative sea level lowstand magnitude differs on the order of 10 m between the mouth of Placentia Bay, where it was lower, and the head (Shaw and Forbes, 1995). In lieu of multibeam coverage, low-resolution bathymetry, seabed slope and large-scale topographic roughness renderings have been compiled at 1: 500 000 scale for at least 20 km offshore (Cameron et al. 2013). The mosaics span Fortune Bay, in the south, the entire Avalon Peninsula, and north to Bonavista Bay, generally covering the entire inner shelf. It provides an overview from which bedrock and till can be generally differentiated from softer sediment areas on a morphological basis, but actual mapping is presently underway.

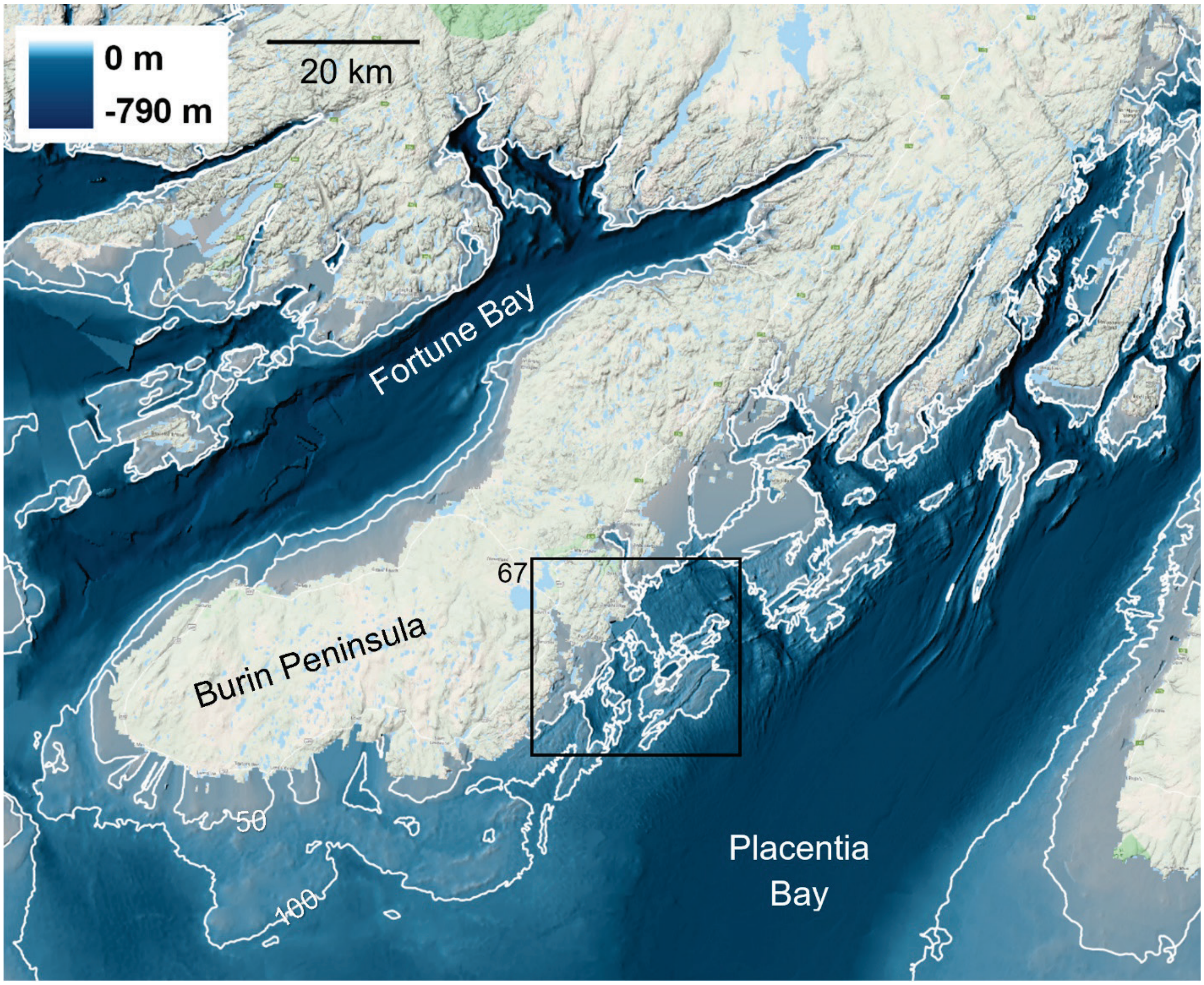


Figure 64*. Bathymetry surrounding Burin Peninsula, with 50 m and 100 m isobaths and figure location shown. Background map data: Google.*

Bedrock Located in the Avalon tectonic zone, bedrock in this area is composed of a complex suite of sedimentary and volcanic rocks. Bedrock deformation and high-relief, irregular exposure is notable where outcropping in Placentia Bay (e.g. Figure 67), and a large proportion of the shallow (< 100 m depth) inner shelf is composed of outcropping bedrock or bedrock covered by a thin veneer of sand and gravel.

Surficial sediments Along the eastern shore of Fortune Bay, data coverage is less extensive than in Placentia Bay. Grab samples collected on the *Hudson* 73006 survey along the inner shelf indicate areas that are predominantly coarser grained gravels and sands. Deeper areas host finer silts and sands. Grab samples from 73006 south of Burin indicate that the area is predominantly sand, with minor gravel, silt, and clay. The shallow shelf in this region generally consists of thin sediment (<10m) where sufficient data exists (King 2014b).

In Placentia Bay, bedrock can be overlain by till, which can be shaped into thick deposits in glacial landforms such as drumlins or megaflutes. Sand and gravel occur as a veneer over glacial sediments, either as boulder gravel (e.g. Figure 65), sandy gravel (often rippled), muddy gravel (on mid-Holocene deltas), or patches of sand and poorly-sorted gravel. Postglacial muds exhibit low relief (Figure 66) and are deposited in shallow basins along the coast, the result of reworking of glacial sediments. Using maps provided by Shaw et al. (2011) and King (2014, Figure 14), in general areas dominated by till are inferred to have a sediment thickness of 3-10m, muds 10-25m, and sand and gravel occur as a thin (0-3m) veneer over bedrock. Note that this doesn't include the shallow mid-Holocene deltas, which likely consist of thicker packages of sediment (e.g. Figure 65, region 14).

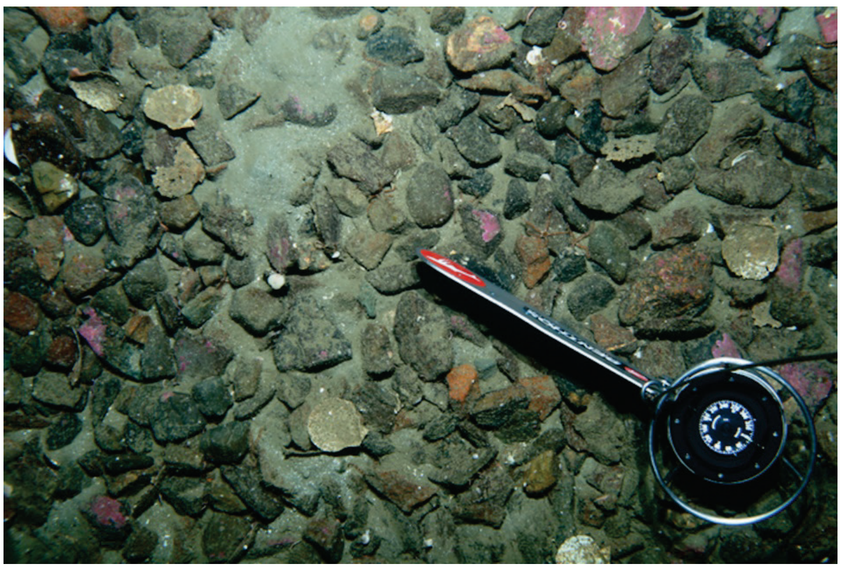


***Figure 65**. Gravel lag observed in GSC picture 2008052-002-1. Location shown in Figure 67. Photograph by A. Robertson. NRCan photo 2020-239.*

PRINCIPAL GEOMORPHIC REGIONS

This region is divided into four geomorphic regions, each with a unique morphology, stratigraphy, and surface texture:

- *Bedrock:* High relief ridges, ledges, and pinnacles. Often there is a thin veneer of sand and gravel covering bedrock where it is not outcropping.
- *Postglacial muds:* Deposited by reworking of glacial deposits into sedimentary basins. Low relief, generally flat, and preserves erosional features e.g. anchor drags in harbours.
- *Glacial/paraglacial:* Can either be i) high relief ridges and mounds of sands, gravels, and till organised into drumlin fields, moraines, or megaflutes, or ii) low relief paraglacial deltas formed at the relative sea level lowstand composed of muds, sands, and gravels.
- *Widespread veneer of sand and gravel:* East and south of Burin Peninsula, a veneer of sand and gravel of an unknown thickness (likely thin – coarse resolution bathymetry appears to show bedrock dominating topography (Figure 64)).

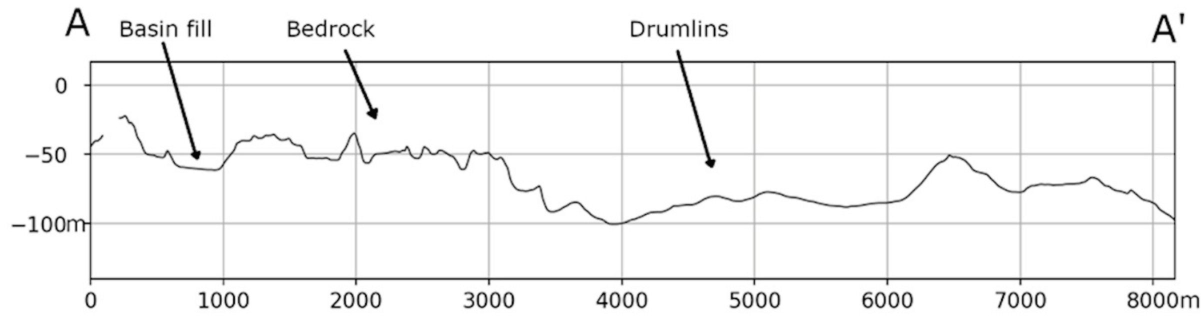


Figure 66. *Cross section across a shallow shelf portion of Placentia Bay (location Figure 67). Note the low relief mud-filled basin, high-relief irregular bedrock region, and drumlin field (note the profile goes along the drumlin axes and not across-axis, which would show higher relief).*

VIGNETTES

1. Seafloor variability in shallow areas:

Placentia Bay has been extensively mapped and described (e.g. a detailed map in Shaw et al. 2011, discussion in Shaw et al. 2009b, list of resources in Shaw and Potter 2015 p.43). Extensive fields of mounds of glacial materials, largely formed into drumlins (Figure 67 B) and megaflutes (C), are found both on the shallow inner shelf (above 100 m depth) and deeper. Bedrock (D) is high relief, ridged, and deformed, with a surface veneer as discussed above. Although much of it lies within the "white zone", where no data can be obtained with multibeam sonar due to shallow depths, it appears as though much of the shallower nearshore and littoral zone is bedrock dominated and morphology suggests it is crystalline (E) rather than sedimentary as found further offshore. Within inlets, mid-Holocene deltas (F) can again be found similar to those found in region 14. These are flat topped, shallow, and consist of a range of grain sizes from mud to sand to gravel. De Geer moraines (G) indicate a readvance of ice imprinted upon bedrock and drumlins (Shaw and Potter, 2015). In Mortier Bay, near Marystown (bottom right), a bedrock or boulder knoll has experienced trough erosion on either side (H), similar to the mud moats described in Lunenburg, NS (King et al., 2017; King and Beaver, 2017). The constricted entrance to the bay has eroded down to bedrock, indicating strong currents.

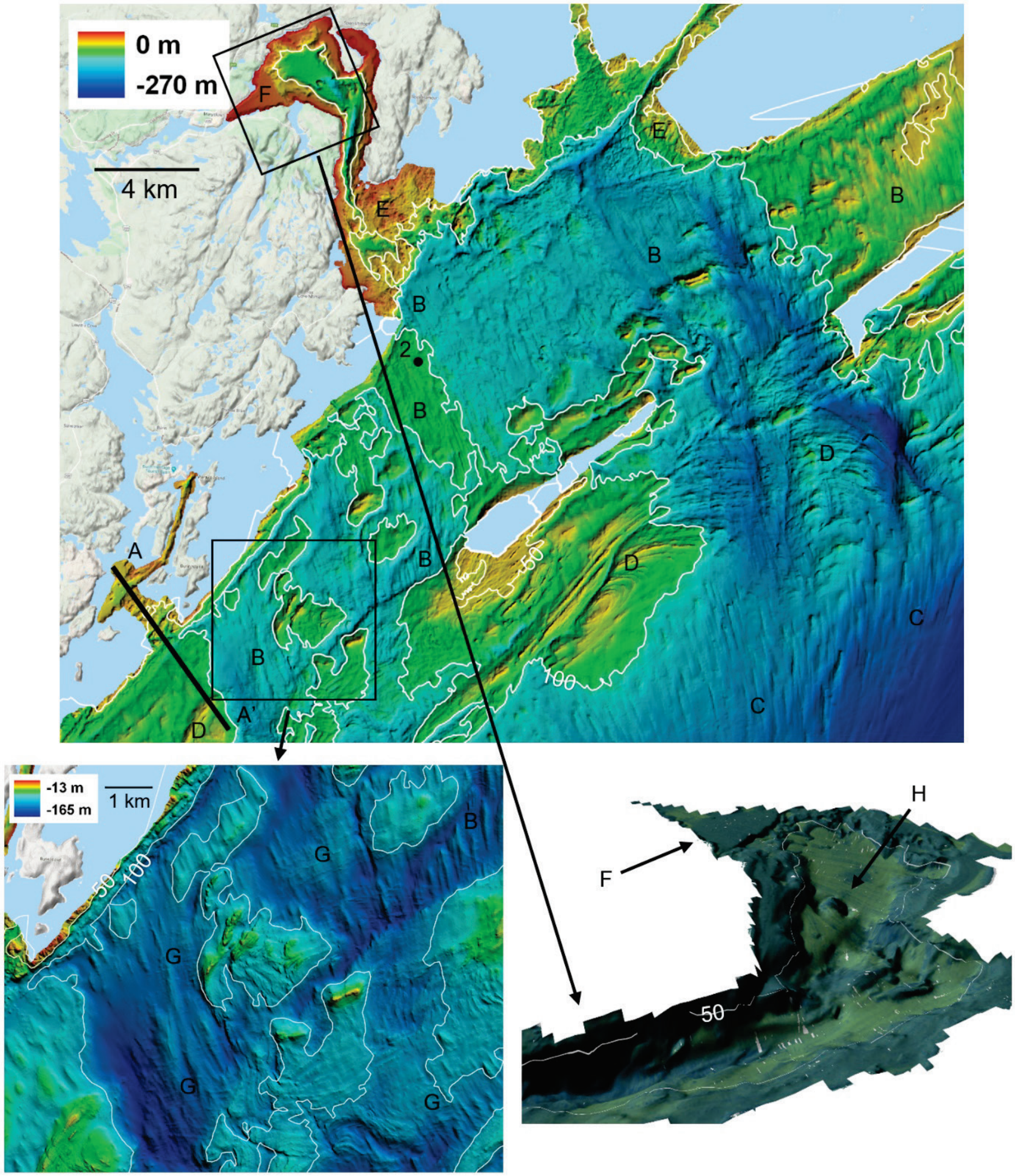


Figure 67. *(Top)The location of Figure 65 and profile from Figure 66 are shown. (Bottom left) De Geer moraines appear when the artificial sun illumination angle in the terrain model is changed. (Bottom right) 3D perspective view of Mortier Bay with backscatter returns overlain (darker colours = high backscatter, gravel, bedrock; lighter colours = low backscatter, sands, muds). Note the seaward coarsening grain size of the delta, trough eroded to bedrock, and bedrock/boulder knoll with mud moats on either side (H). Background map data: Google.*

FAVOURABLE FACTORS, POTENTIAL CONSTRAINTS, AND HAZARDS

- Extensive previous work and data for the area.
- Areas of glacial deposition likely consist of thicker Quaternary deposits, however most likely composed of glacial till. They also show little evidence of extensive reworking post-glacially, outside of channel constrictions and troughs.
- Mid-Holocene deltas are flat, consist of ideal substrate, and exist in shallow waters (notably near Marystown and at the head of Placentia Bay, e.g. Come By Chance, Arnold's Cove).
- There is a sandy shallow shelf south of the Burin Peninsula.
- Bedrock is irregular and high-relief, but lower relief crystalline rocks may occupy a significant portion of the shallower (< -30m) waters.
- Areas with Quaternary sedimentation may be dominated by cobbles and boulders, at least as a veneer in the upper sediments.

Region 16: Avalon

SUMMARY

Coastlines in this region are varied, with embayments often hosting low-relief sand/gravel beach and lagoon systems, including a well-studied strandplain at Placentia. A shallow, low relief sedimentary platform dominates the southwest inner shelf of the Avalon Peninsula and a broad inner shelf area of relatively unknown geology exists to the south. Cobbles and boulders are widespread and northern Placentia Bay is mostly irregular bedrock. Bedforms are common where large areas of sand exist.

<u>Favourable</u> factors for foundation emplacement include a broad area of shallow inner shelf; paraglacial deltas are flat, shallow, and consist of ideal substrate; sand and gravel are widespread in this region.

<u>Constraints</u> for foundation emplacement include iceberg impacts in the southeast of this region; slope instability in places; Quaternary sedimentation is often covered by a cobble or boulder lag; sandy sediments are mobile; little data in south of region

Existing high-quality MBES data exists for the majority of the inner shelf in Placentia Bay, highlighting landforms that were reworked or formed during the postglacial sea level lowstand, among other geomorphic regions. The Placentia Bay seascape map (Shaw et al., 2011) and Shaw and Potter (2015) provide the bulk of information on this region.

GEOLOGY

Geomorphology When compared with the western edge of Placentia Bay, the eastern edge has a broader shallow shelf and a higher proportion of Quaternary sediments at the surface. Glacial/paraglacial, recently mobile sediment, and muddy sediments are common in shallower waters. A broad sedimentary platform exists along the southwest coast of the Avalon Peninsula that is more irregular under ~40 m depth, above which littoral processes had denuded the surface during the previous sea level lowstand (Shaw et al., 2011). Less data exists for the very broad (the 100 m isobath is as much as 55 km offshore) inner shelf off the south coast of the Avalon Peninsula, however what data that does exist indicates the seafloor is either predominantly gravel or outcropping bedrock. Several strandplains and barrier beaches exist along the west coast of Avalon Peninsula, and become rarer along the south coast. This region experiences high wave impact from increased exposure to the Atlantic and is impacted by icebergs drifting south from the Labrador Current along the south and southeast coastlines. Following deglaciation, relative sea level followed a similar pattern to those observed further west, however relative sea level is postulated to have fallen much lower in the southeast of Placentia Bay than observed at the head (Shaw and Forbes, 1995; Shaw and Potter, 2015).

Bedrock A late Proterozoic and early Paleozoic shallow-marine succession unconformably overlies a range of Late Proterozoic lithologies, all within the Avalon tectonic zone. Northern Placentia Bay appears to have more inner shelf exposed bedrock than south, with the divide occurring around Long Harbour (Figure 70). Off the south coast of the Avalon Peninsula, a ridge along the outer edge of the inner shelf (near the 100 m isobath) appears to be composed of a series of bedrock pinnacles (Shaw and Potter, 2015).

Surficial sediments At Come By Chance and Arnold's Cove, shallow flat-topped paraglacial sand and gravel grade into irregular glacial landforms at depth, which stand out among the mostly bedrock dominated inner shelf in northern Placentia Bay. Grab samples collected on the *Hudson* 78012 (within the west circle, Figure 68) and *Hudson* 84014 (within the east circle, Figure 68) surveys along the inner shelf margin south of the Avalon Peninsula indicate surficial sediments are predominantly sands or gravels that are likely thin (0-3m), however a thicker band of sediments (3-10m) may exist closer to the 100m isobath (King 2014b). Figure 69 shows an example of a gravel-cobble-boulder substrate found off the southeast coast.

In Placentia Bay, bedrock can be overlain by till, although surface expressions of till in this region have rarely been observed. Sand and gravel occur as a thin veneer over glacial sediments as boulder gravel (e.g. Figure 69), in thick deposits of muddy gravel (on mid-Holocene deltas), or patchy sand and poorly-sorted gravel amongst boulder gravel – the latter is common along the southwest coast of the Avalon Peninsula. Postglacial muds exhibit low relief, are deposited in shallow basins along the coast, and are often metres thick. As with region 15, using maps provided by Shaw et al. (2011) and King (2014, Figure 14), in general areas dominated by till are inferred to have a sediment thickness of 3-10m, muds 10-25m, and sand and gravel occur as a thin (0-3m) veneer over bedrock. Note that this doesn't include the shallow mid-Holocene deltas, which likely consist of thicker packages of sediment (e.g. Figure 61).

PRINCIPAL GEOMORPHIC REGIONS

This region is divided into four geomorphic regions, each with a unique morphology, stratigraphy, and surface texture (based on Shaw et al. 2011):

- *Bedrock:* High relief ledges and pinnacles, with generally flat tops. The high amount of ridging and deformation is less common than bedrock on the west side of Placentia Bay. Often there is a thin veneer of sands, gravels, and muds covering bedrock where it is not outcropping.
- *Postglacial muds:* Deposited postglacially by reworking of glacial deposits. Low relief, generally flat, and preserves erosional features such as anchor drags in harbours. Found predominantly just offshore Long Harbour, Ship Harbour, and on approach to Argentia (Figure 71; Shaw et al., 2011).
- *Glacial/paraglacial:* Can either be i) high relief ridges and mounds of sands, gravels, and till organised into groups of glacial landforms, ii) low relief paraglacial deltas formed at the relative sea level lowstand composed of muds, sands, and gravels, or iii) a low relief platform off the southwest coast of the Avalon Peninsula.
- *Mobile/altered sediment:* Either sand and muddy sand or poorly-sorted sandy gravel organized into mobile bedforms. Found mostly at the tidal current constriction at Placentia and around Argentia (mobile sediments outside the harbour, anthropogenically altered sediments within).

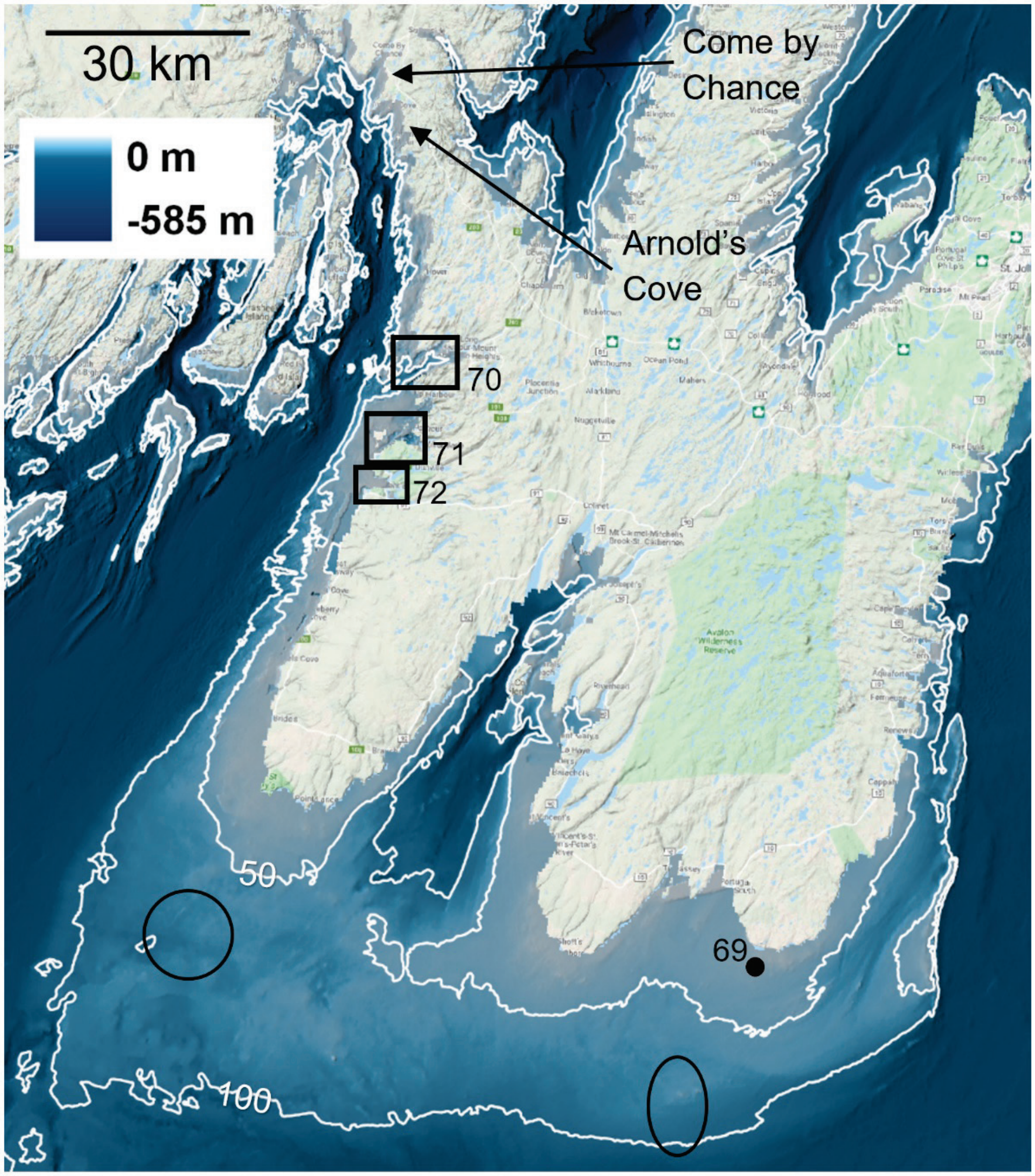


Figure 68. *Bathymetry on the west and south coast of the Avalon Peninsula, with 50 m and 100 m isobaths. Numbers show figure locations and open circles show approximate coverage of grab samples discussed below. Background map data: Google.*

Figure 69. *Pebbles, cobbles, and boulders observed in GSC seabed photo 8180.3, CCGS Hudson cruise 85005. Location shown in Figure 1. Photograph by the staff of the CCGS Hudson. NRCan photo 2020-240.*

VIGNETTES

1. Long Harbour delta

At Long Harbour (Figure 70), a mid-Holocene delta is observed in the east (Figure 70A), which is mostly flat and at a depth of 16 m, used to constrain the sea level lowstand in this area (Shaw and Forbes, 1995). There are dredge spoils covering muddy sediment as well as on top of the submerged delta (B). Much of the harbour is composed of fine grained (muddy) low relief sediment (C). Steeply sloped (as much as 30°) coarse grained sediments occur close to land in the bay, however there is no evidence of slope failure.

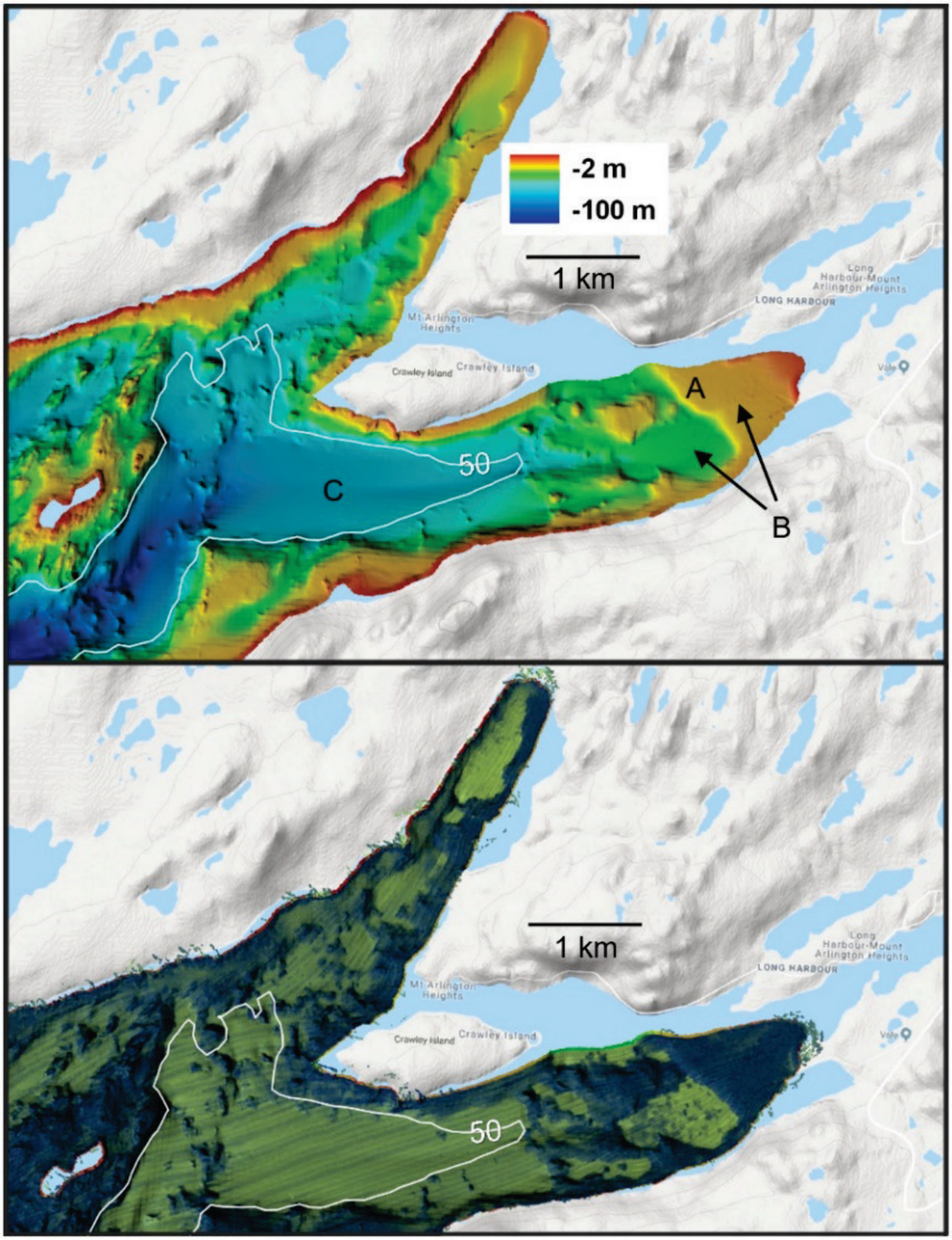


Figure 70. *Geology of Long Harbour, showing bathymetry (upper) and backscatter (lower). High backscatter (blue) indicates a hard substrate (e.g. bedrock or gravels) while low (green) indicates softer sands and muds. Background map data: Google.*

2. Argentia

This location has a complex anthropogenic history covered extensively in Shaw and Potter (2015). Mobile sandy bedforms are traversing across exposed till (Figure 71A), and a sand wedge is prograding into an adjacent basin to the east (B). Note the extensive gullying in the basin as well. Transverse moraines of sand and gravel (C) deposited as ice retreated were denuded to flat, low-relief platforms during the subsequent sea level lowstand. Dredging to remove sills as barriers to sheltered harbours removed appreciable amounts of sediments at (D). At (E), large concrete blocks historically used to anchor anti-submarine nets are clearly visible in the multibeam data.

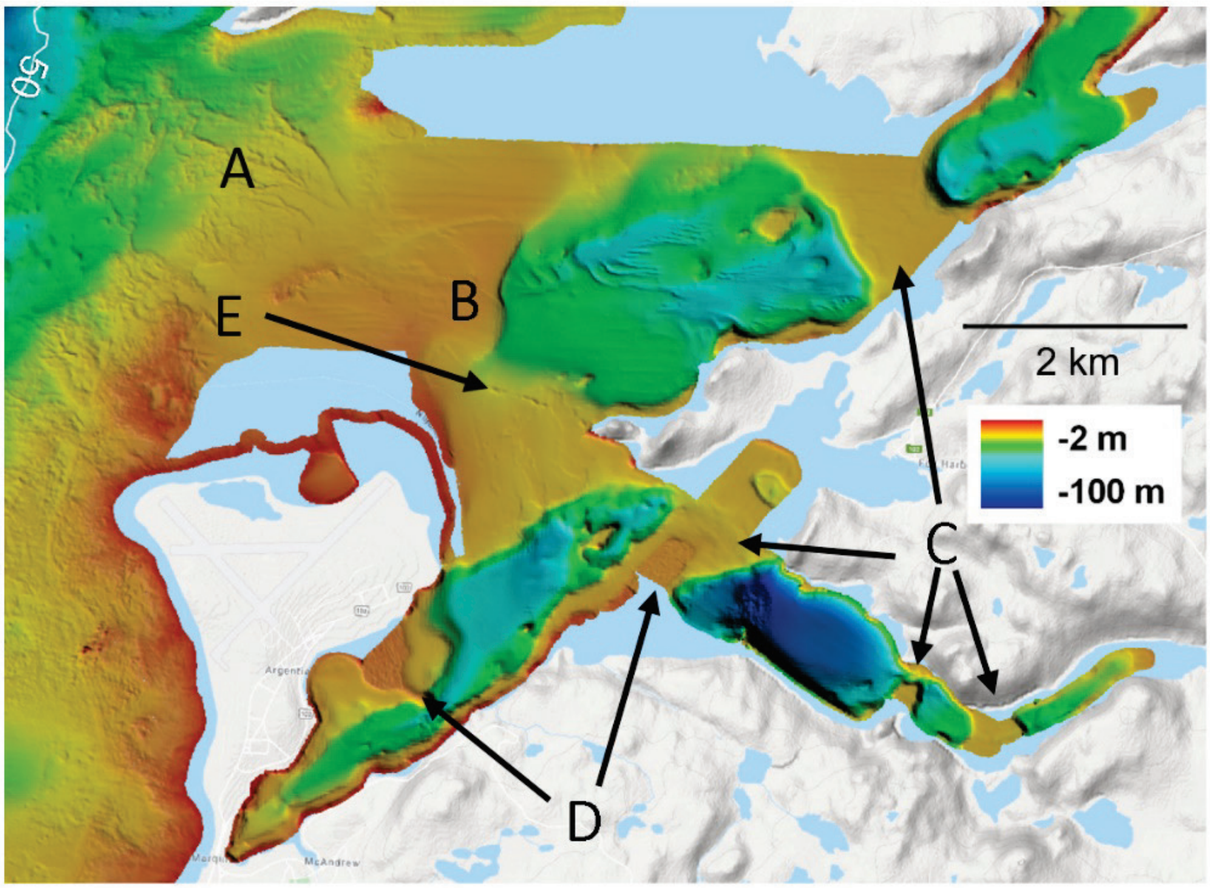


Figure 71. *Bathymetry of the region surrounding Argentia (airfield visible in the lower left), described in the text above. Background map data: Google.*

3. Placentia Gut

A large, low backscatter, shallow sandy mud bank (Figure 72A) that is likely to be ~5m thick over older glacial sediments (Shaw and Potter, 2015) sits offshore of the Placentia Gut (B), a narrow tidal constriction formed by the development of the Placentia strand plain to the immediate south. An ebb tide trough (C) is eroding the seafloor to a depth of 19m just to the west of the Gut. The 7 m thick sands that form the flood tide delta (D) are highly mobile, with the surface covered by dunes (see Shaw and Potter, 2015, Fig. 45).

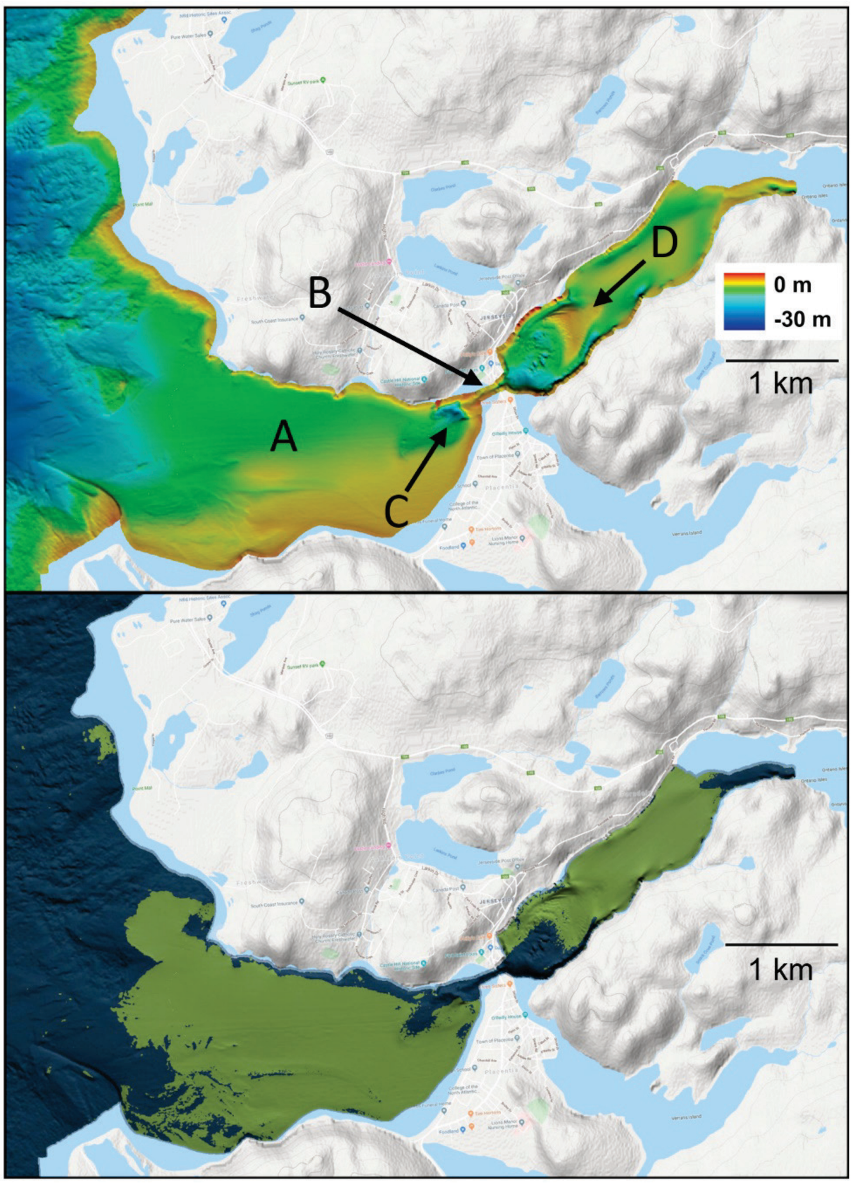


Figure 72. *Geology of Placentia Gut, showing bathymetry (upper) and backscatter (lower). High backscatter (blue) indicates a hard substrate (eg bedrock or gravels) while low (green) indicates softer sands and muds. Background map data: Google.*

FAVOURABLE FACTORS, POTENTIAL CONSTRAINTS, AND HAZARDS

- An extensive, shallow, low-relief, low-slope platform consisting of Quaternary sediments borders the coastline of southeast Placentia Bay.
- Mid-Holocene deltas are flat, may consist of ideal substrate, and exist in shallow waters. A prism of sand near Placentia has similar characteristics (although may be thinner).
- There is a very extensive, relatively flat (based on coarse bathymetry) shallow shelf south of Avalon Peninsula that shows evidence of (at least pockets of) a sandy seafloor.
- Areas of slope instability are limited to deeper waters (Shaw and Potter, 2015, p.47, 49).
- Areas with Quaternary sedimentation are dominated by cobbles and boulders, at least as a veneer in the upper sediments, particularly on the low relief platform in southeast Placentia Bay.
- Areas of sandy sediments often are mobile (e.g. Figures 71, 72).

Region 17: Eastern Newfoundland

SUMMARY

This region is characterized by a rugged, mostly bedrock coastline with a narrow inner shelf heavily impacted by glaciers and sea ice. Sandy sediments may be common in the region, particularly at the head of several large inlets and fjords where paraglacial deltas and shallow basins exist, and bedrock can be either low relief or highly deformed and irregular.

Favourable factors for foundation emplacement include flat-topped paraglacial deltas consisting primarily of sand; protected shallow basins at the mouths of inlets; low relief bedrock exists

Constraints for foundation emplacement include common iceberg impacts on the seabed; little shallow shelf area; bedrock is common and relief can be variable; high exposure to wind and wave activity

Existing high-quality MBES data highlights the complex sedimentation patterns in Bonavista Bay, which was highly influenced by a prolonged period of deglacial sedimentation. King (2013) provides a thorough investigation of a representative section of the eastern shore of Avalon Peninsula, and Shaw and Potter (2015) provide an in-depth regional overview.

GEOLOGY

Geomorphology The inner shelf in this region is 12 km wide at its widest point off Bonavista Peninsula, but is generally narrow (1-3 km) (Fig. 73). The regional geology trend is in a northeast/southwest direction, and as the region is mostly fully exposed to waves and currents from the Atlantic Ocean, the inner shelf is deep and narrow and much of it is likely composed of exposed bedrock and bedrock covered by a thin bed of till (e.g south of St. John, Shaw and Potter, 2015). Several fiords contain thick deposits of glaciomarine and postglacial sediments, and sheltered harbours host interesting glacial and postglacial landforms over bedrock where detailed mapping exists. Sedimentary coastlines are rare in the region, however pocket beaches and barrier beaches can be found mostly in Conception Bay (with isolated occurrences in other bays). Following deglaciation, relative sea level generally dropped to a lowstand and slowly rose to modern levels, with the magnitude of the sea level lowstand decreasing as you head to the centre and north of the island (Shaw and Forbes, 1995; Shaw et al., 2002). The eastern shore of the Avalon Peninsula may be the only region of Newfoundland that never experienced relative sea level above modern (Liverman, 1994).

Bedrock Within the Avalon tectonic zone, bedrock is composed of a range of Late Proterozoic lithologies overlain unconformably by a Late Proterozoic and Early Paleozoic shallow-marine succession. In the northern edge of the region, the Dover Fault divides the Avalon from the Gander Zone at Freshwater Bay (within the larger Bonavista Bay). Gander Zone rocks are primarily sedimentary of Cambrian to Ordovician age with Proterozoic to Cambrian intrusive rocks. Where bedrock has been mapped with high resolution (such as at the mouth of Bonavista Bay), a range of exposures from streamlined (smooth) to irregular and high relief exist.

Surficial sediments Ground truth data on the eastern shore of the Avalon Peninsula suggests that where bedrock isn't outcropping the surficial sediments are dominated by sand (e.g. *Moresby* 94075 grab samples) or a cobble lag/till (e.g. Figure 74). King (2013) interprets a wide variety of bedforms on a stretch of coast in this region, including iceberg scours, pockmarks, buried channels, drumlins, lowstand deltas, and smooth sand or mud sheets. Sediment thicknesses vary between 0-50m (King 2014b), with the thickest sediments occurring again in low-stand deltas at water depths of ~50m, with the majority of other thick sediment sequences occurring in deeper water (King 2013). In Bonavista bay, a seismostratigraphic unit classification, including unit thickness maps, together with limited sediment coring and radiocarbon dating is documented in Cummins et. al. (1992). They also reconstructed three retreat glacial margins. Where deeper sequences exist, bedrock can be overlain by till, e.g. in thicker deposits hypothesised for sills observed near the mouth of several bays. Sand and gravel occur at early/mid Holocene or ponded deltas near the mouths of inlets (e.g. Figures 75, 76), in shallow depressions between bedrock outcrops, may comprise streamlined glacial landforms (e.g. drumlins, megascale glacial lineations), and can underlie postglacial muds in basins found in fjords and inlets. Glaciomarine or postglacial muds exhibit low relief and are deposited in shallow and deep basins along the coast. They are often found in fjord basins where they can be metres to tens of metres thick.

Another vignette-style map series covers the nearshore conditions on the east coast of the Avalon Peninsula (King, 2103 and King and Mostaghimi, 2014). There a surficial geology map demonstrates abundant outcrop, till sheets sculpted into drumlins and moraines and local basins with moderate thickness of late and post-glacial muds. Sediment types, stratigraphy and thicknesses are documented. Typically the harbours and inlets formed where the bedrock was cut during multiple glaciations to form coastline-normal corridors containing continuous glacial and post-glacial sediment fill from inner harbour to the offshore. Post-glacial sediment gravity failures are recognized. These conditions afford a variety of foundation conditions coupled with potential cable-routing corridors which avoid difficult terrains.

PRINCIPAL GEOMORPHIC REGIONS

This region is divided into four geomorphic regions, each with a unique morphology, stratigraphy, and surface texture:

- *Bedrock:* High relief ledges and pinnacles. Ridging and deformation is observed in several locations where high quality data exists (Figure 76), however some areas of relatively low-relief bedrock are observed. Often there is a thin veneer of till or fine sand and mud covering bedrock where it is not outcropping.
- *Glacial/paraglacial:* Low relief paraglacial deltas formed at the mouths of inlets composed of muds, sands, and gravels are also found in this region. Drumlins and eskers can be found on the inner shelf and provide relief, while broader scale deglacial basin fill exhibits a flat seabed. These all are composed of sands, gravels, and/or till.
- *Basin mud:* Fine sand to mud found in protected basins, largely in fjords and inlets. Mostly flat and low relief with few glacial bedforms.

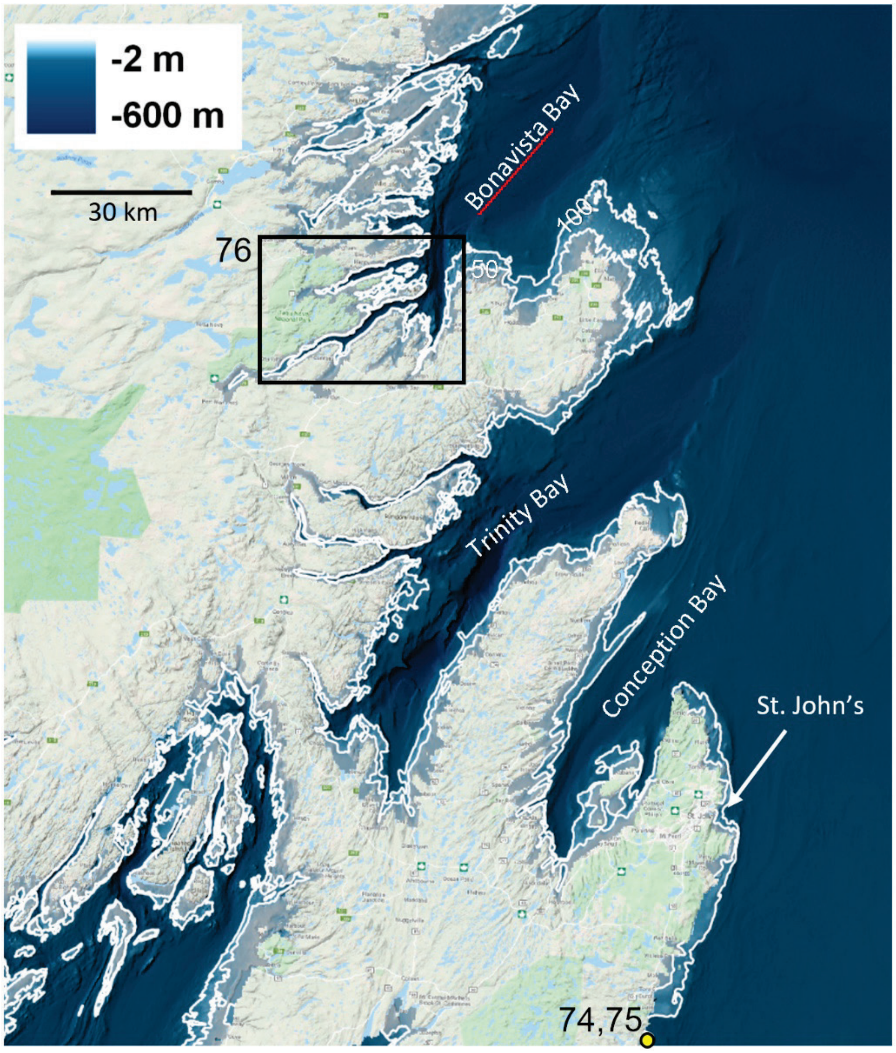
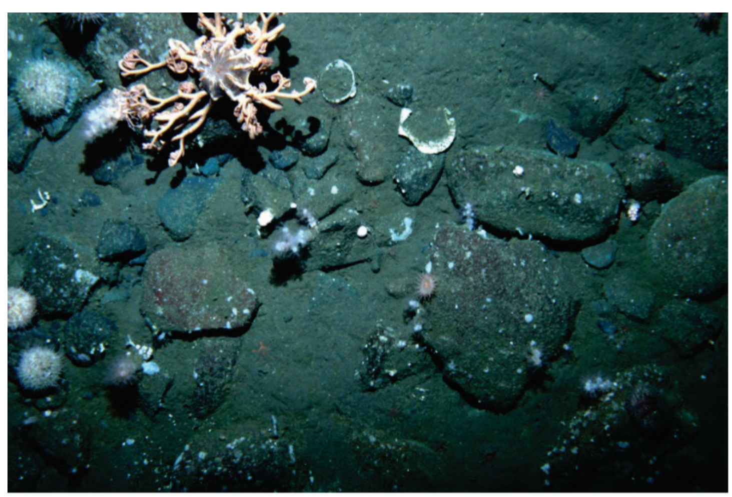


Figure 73. *Bathymetry of eastern Newfoundland, with 50 m and 100 m isobaths. Approximate figure locations shown. Background map data: Google.*

Figure 74. *Cobbles, pebbles, fine sand/mud observed in GSC picture 2009044:0022:58. Location shown in Figure 1. Photograph by G. Cameron. NRCan photo 2020-241.*



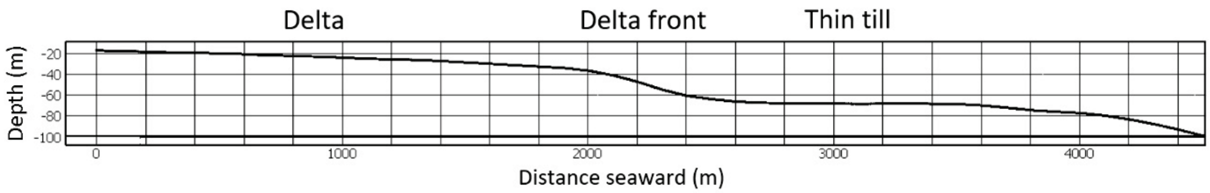


Figure 75. *Seabed profile of an early Holocene delta at the mouth of Cape Broyle Harbour, a relatively common feature on the eastern shore of Avalon Peninsula (e.g. also found at Acquaforte Harbour (King, 2013; King and Mostaghimi, 2014) and St. John's Harbour (Shaw and Potter, 2015). Note the low slope of the shallow water portion of the delta (~ 0.75°). These deltas are commonly composed of sand and gravel 10s of metres thick.*

VIGNETTES

1. Complex seabed in Bonavista Bay

In Figure 76, inset A, a postglacial delta is found at the head of Newman Sound (i). Note that, different from deltas found in other regions (e.g. 14, 15), this delta and one found at the mouth of St. John's harbour formed in a lake elevated above mean sea level due to a sill (ii), and thus gives no indication of previous sea level lowstand. An esker found in kettle terrain indicative of stagnant ice downwasting (Shaw and Potter, 2015), not found anywhere else in Newfoundland, is indicated by (iii) as well as by several arrows in D in Clode Sound. In B, a drumlin with iceberg indents is indicated by (i) and a streamlined bedrock feature, possibly a rock drumlin, is indicated by (ii). Note the deformed and irregular bedrock found to the north of the drumlin as well as on the broad inner shelf indicated in C. Bedrock transitions from slightly lower relief deformed, folded strata with Quaternary sediments infilling basins between beds to higher relief but flat-topped pinnacles near the – 100 m isobath. In E, a backscatter image of the same region as D indicates the lower backscatter (lighter colour) and finer grained sedimentation of the basin fill, the small basins formed by the kettles (around the esker identified in D), and a gravel/sand sediment prism (highlighted by the arrow) at the mouth of Clode Sound. See Patton and Shaw (2011a,b) for detailed mapping of Bonavista Bay.

FAVOURABLE FACTORS, POTENTIAL CONSTRAINTS, AND HAZARDS

- Areas where ground truth data are available suggests a sandy seabed is common where Quaternary sediments are found
- Paraglacial/lake basin deltas are flat, consist of ideal substrate, and exist in shallow waters
- Shallow basins near the head of inlets (e.g. Figure 76A) can be protected from icebergs and significant wave action/currents by sills
- Bedrock on the inner shelf can be relatively low relief or highly deformed
- Much of the region has little shallow-shelf area
- Iceberg furrowing on shelf sediments indicates an active iceberg corridor

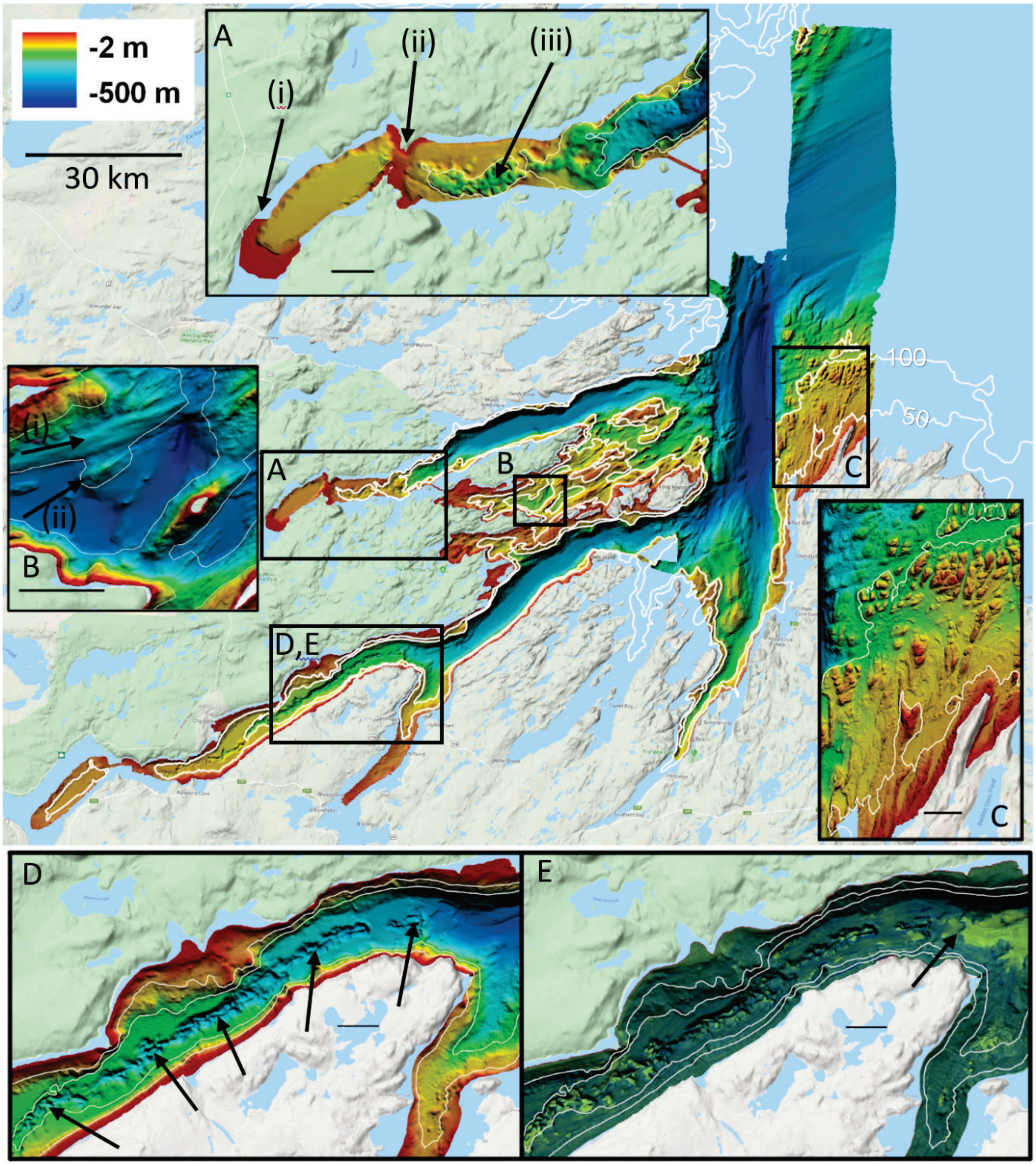


Figure 76. *Geology of Bonavista Bay, showing full multibeam coverage and several insets, described in the text. Note scale bars in insets are all 1 km. Background map data: Google.*

Region 18: Straight Shore

SUMMARY

This region's coastlines are anomalously (for Newfoundland) low relief, hosting predominantly sandy beach-dune systems. A broad inner shelf is characterized by sand and gravel, with exposed bedrock constrained to a relatively flat, shallow platform around Fogo Island and near the -100 m isobath.

***Favourable** factors for foundation emplacement include sand and gravel dominating; a broad area of shallow inner shelf; bedrock is exposed on a flat, shallow platform*

***Constraints** for foundation emplacement include regular impacts from icebergs and sea ice; sand and gravel are highly mobile and generally thin; existing data is sparse*

This region is characterized extensively in Shaw et al. (1999), including a surficial geology and coastal classification map, however the region is absent good multibeam coverage.

GEOLOGY

Geomorphology This region (Figure 77) encompasses the shoreline between Cape Freels to the east and Dog Bay to the west. It includes Gander Bay, the outlet for the Gander River which is the principal river of northeast Newfoundland, and the coastline (dubbed the "Straight Shore") is notable for its low coastal relief and extensive sandy beach-dune systems (Shaw and Forbes 1990). The inner shelf is particularly wide and shallow, and notably has been mapped almost entirely as covered in surficial postglacial sand and gravel (Shaw et al., 1999), and is heavily impacted by icebergs and wave action. Following deglaciation, relative sea level dropped to a lowstand of ~17 m following deglaciation and slowly rose to modern levels (Shaw and Forbes, 1995). Laurentian ice retreat patterns in the area are complex (e.g. Shaw et al. 2017) but generally ice had retreated to the coast by 13ka BP. GSC Bulletin 605 (Shaw and Potter, 2015) provides the majority of the information summarized here (and for the other Newfoundland regions).

Bedrock The bedrock here lies within the Gander tectonic zone, which is composed primarily of sedimentary rocks of Cambrian to Ordivician age with Proterozoic to Cambrian intrusive rocks. The inner shelf in this region is mostly underlain by Devonian granite, of which scattered outcrops exist. Notable bedrock pinnacles (Figure 80) on the inner shelf typically rise from depths of 150m to attain depths of less than 50m, and have posed a navigational hazard in previous survey work (Shaw and Potter, 2015, p69). The terrain offshore Fogo Island is characterized as having a shallow (-50 m) bedrock platform that is 5 – 10 km wide.

Surficial sediments As discussed above, postglacial sand and gravel dominate the surficial materials on the inner shelf in this region. In general, sand and gravel and/or postglacial mud comprise all of the surficial materials in this region, except perhaps where till is preserved in drumlins (Figure 78). Through wave and current action are sand and gravel are typically organized into active bedforms, including large gravel ripples (Figure 79) and sand dunes (Shaw et al., 1999). This region is mapped as having sediment thicknesses generally between 0-3m, however thicker (< 25m) patches of sediment exist (e.g. in bedforms or glacial landforms) (King 2014b). Glaciomarine or postglacial muds exhibit low relief and are deposited either in basins along the coast where sand and gravel are absent or as a veneer on other sediments. A boulder veneer is often found on bedrock in shallower waters or on glacial landforms.

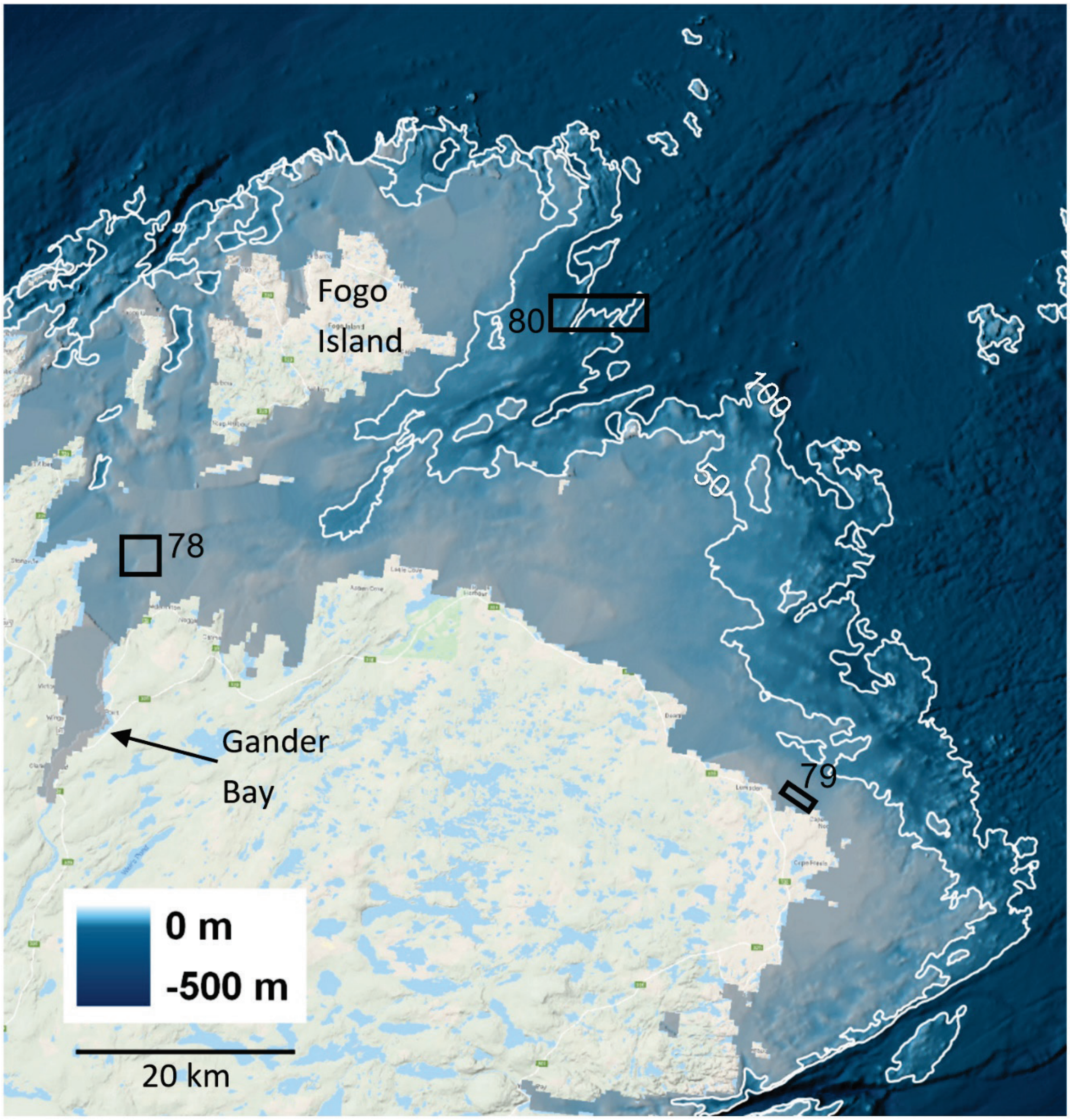


***Figure** 77. Bathymetry of the Straight Shore, with 50 m and 100 m isobaths. Note the relatively smooth shallow (< 50 m depth) inner shelf composed mostly of mobile sand and gravel and irregular deeper waters where outcropping bedrock is more common. Figure locations indicated.*

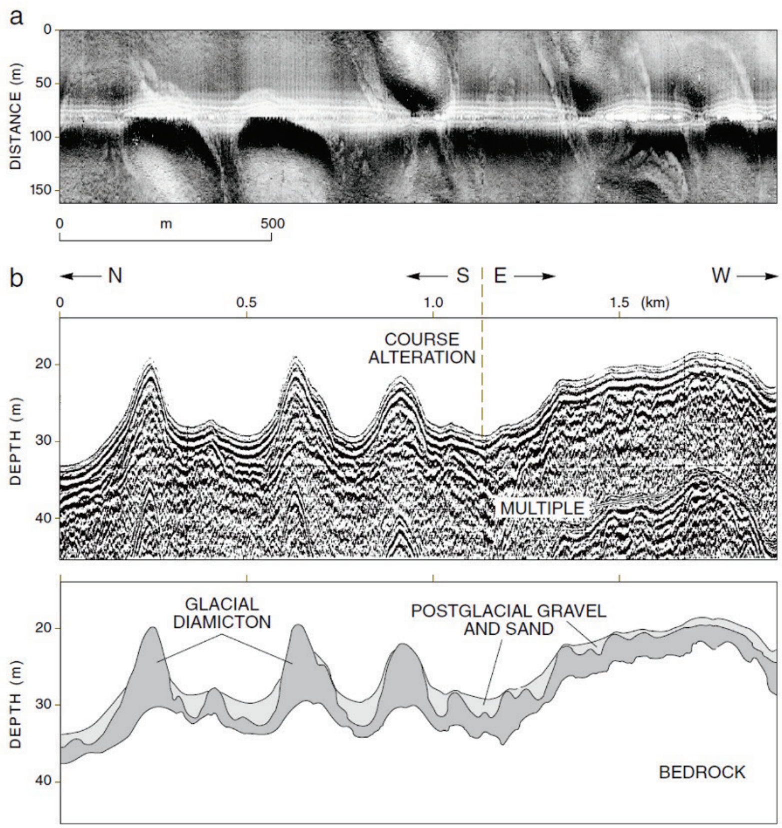


Figure 78. *a) Sidescan sonar image of drumlins in Hamilton Sound, at the mouth of Gander Bay. b) Seismic reflection profile and interpretation across the drumlins, showing thick deposits of till (glacial diamicton), rare for this region. From Shaw et al. (1999).*

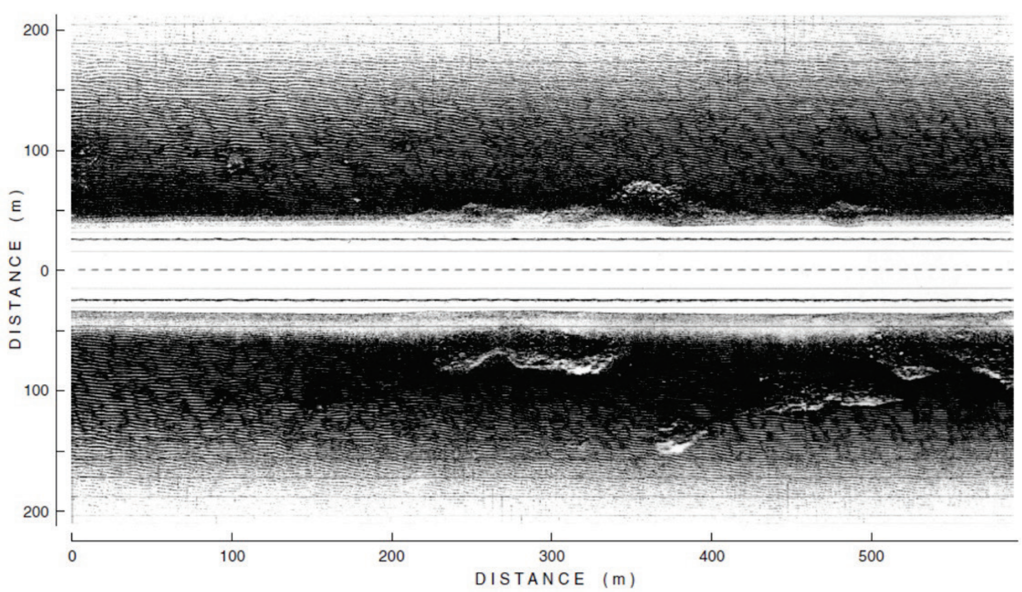


Figure 79. *Sidescan sonar image of extensive gravel ripples and scattered bedrock outcrops, showing a typical seabed configuration along the shallow inner shelf. Location in Figure 1. From Shaw et al. (1999).*

PRINCIPAL GEOMORPHIC REGIONS

This region is divided into two geomorphic regions, each with a unique morphology, stratigraphy, and surface texture:

- *Exposed Bedrock:* Predominantly in the area around Fogo Island (Figure 77), a shallow (-50m) platform exhibits greater relief and irregularity near its outer margins. Isolated pinnacles raise upwards of 100m above the seabed outside of this platform (Figure 80).
- *Mobile sand and gravel:* Postglacial sand and gravel are likely composed of reworked paraglacial sediments deposited as glaciers retreated from the area, and are organized into highly mobile ripples (wavelength average 2.3m) and sand dunes (wavelength average 8m at one location) (Shaw et al., 1999; Figures 79, 81).

FAVOURABLE FACTORS, POTENTIAL CONSTRAINTS, AND HAZARDS

- Sand and gravel dominate the surficial cover.
- There is a large area of shallow, inner shelf.
- Bedrock on the inner shelf is exposed in a relatively flat, shallow platform.
- Existing data is sparse.
- Sand and gravel are highly mobile and in general thin.
- Icebergs and sea ice impact the area frequently (Figures 80, 81).

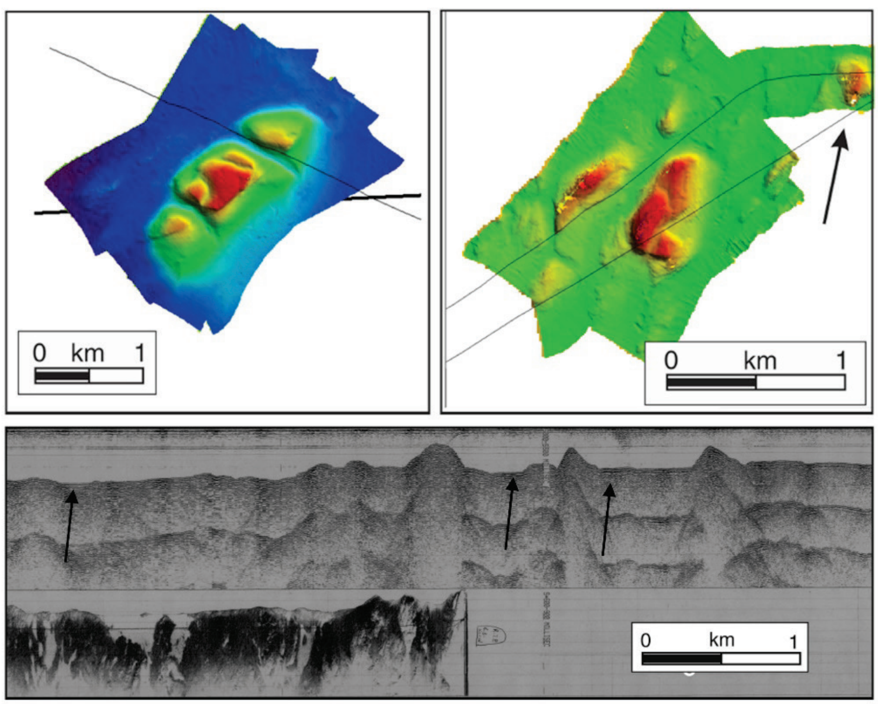


***Figure 80**. (Top) Bedrock pinnacles found in the study area (location in Figure 1) with ship tracks overlain. (Bottom) Seismic and sidescan sonar transect across the upper right pinnacle. Note rare postglacial muds infilling iceberg furrows in seismic image (arrows) and as light coloured patches in sidescan (modified from Shaw and Potter, 2015).*

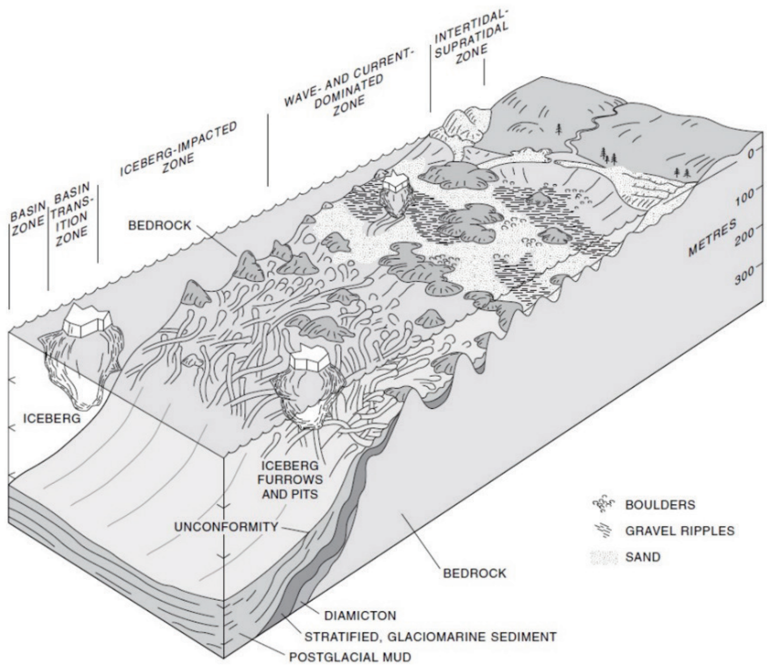


Figure 81. *Conceptual model of the inner shelf geology of the Straight Shore, from Shaw et al. (1999). Note the deeper sedimentation along the shallow inner coast and patchy, thin sand and gravel with isolated bedrock outcrops*

Region 19: Notre Dame

SUMMARY

The shoreline in this region is heavily indentured by inlets and fjords, with steep rocky coasts common. The shelf in this region is characterized by a large offshore trough and several deep fjords, with low-relief bedrock dominating the inner shelf and Quaternary sedimentation that can be extensive. Gravels and cobbles are common as surficial sediments and sediment depths are shallow. Iceberg and strong wave action is common on shallow inner shelf.

<u>Favourable</u> factors for foundation emplacement include common sand and gravel and flat platforms of bedrock.

<u>Constraints</u> for foundation emplacement include regular impacts from icebergs and sea ice; deeply fractured bedrock (between platforms); gravel/cobble surficial lags common; sand and gravel are mobile.

Existing high-quality MBES data highlights anthropogenic influences in the area as well as broad areas of sand and gravel interspersed with bedrock pinnacles and shelves, summarized in Shaw et al. (1999), Shaw and Potter (2015), and Shaw and Longva (2017).

GEOLOGY

Geomorphology The large offshore Notre Dame Trough and several small, deep fjords with sill depths of at least ~200 m dominate the south coast of this region (Fig. 82). The inner shelf is narrow and rocky, and most is exposed bedrock or bedrock with a thin mantle of Quaternary sediments (muds or gravels) above 100 m depth. Coastlines are bedrock dominated, with rare depositional landforms indicating the lack of Quaternary sediment in the region. Shallow areas of the shelf are heavily impacted by icebergs and sea ice, evidenced by furrows and pits in inter-bedrock sedimentation. Following deglaciation, relative sea level were 75 m above modern at the mouth of Green and Halls Bays (Liverman, 1994) and experienced a lowstand just above (in the west of the region) or just below modern (in the east) (Shaw et al., 2002).

Bedrock This area lies within the Gander and Dunnage tectonic zones, and the bedrock covers a wide range of lithologies aged from Late Proterozoic to Silurian. The wide range of multibeam coverage in this region suggests that the majority of shallow bedrock exposure is intrusive, showing characteristic fracture patterns and lacking the deformed bedding observed elsewhere. Bedrock exposure is common at shallow depths (Shaw et al., 1999).

Surficial sediments Sand and gravel can be found in isolated pockets around bedrock exposures or possibly in larger areas around New World Island or in very shallow regions as rippled gravels. The mouth of Green Bay hosts a shelving bench dominated by gravel and patchy sand, and the area north of Baie Verte Peninsula hosts appreciable amounts of gravel in the shallow inner shelf (e.g. Figure 86). In these areas, where the shallow inner shelf broadens slightly, the sand and gravel are not inferred to be appreciably thick (King 2014b). The majority of seabed imagery suggests, however, that at least a veneer of gravel covers much of the surficial sediments in sheltered bays and inlets (e.g. Figure 83), which may also be an erosional lag expression of till surficial materials (see below). Glaciomarine or postglacial muds exhibit low relief and are deposited mostly in depressions and basins around bedrock exposures (Figures 84, 85). Inlet heads may contain thin veneers of muds overlying bedrock, and iceberg furrows typically contain postglacial muds. Pockmarks indicating gas escape are rare but observed in Halls Bay. Till is rarely exposed at the surface, but has been found at the head of Baie Verte or New Bay at shallow depths or in moraines in the Bay of Exploits and Green Bay.

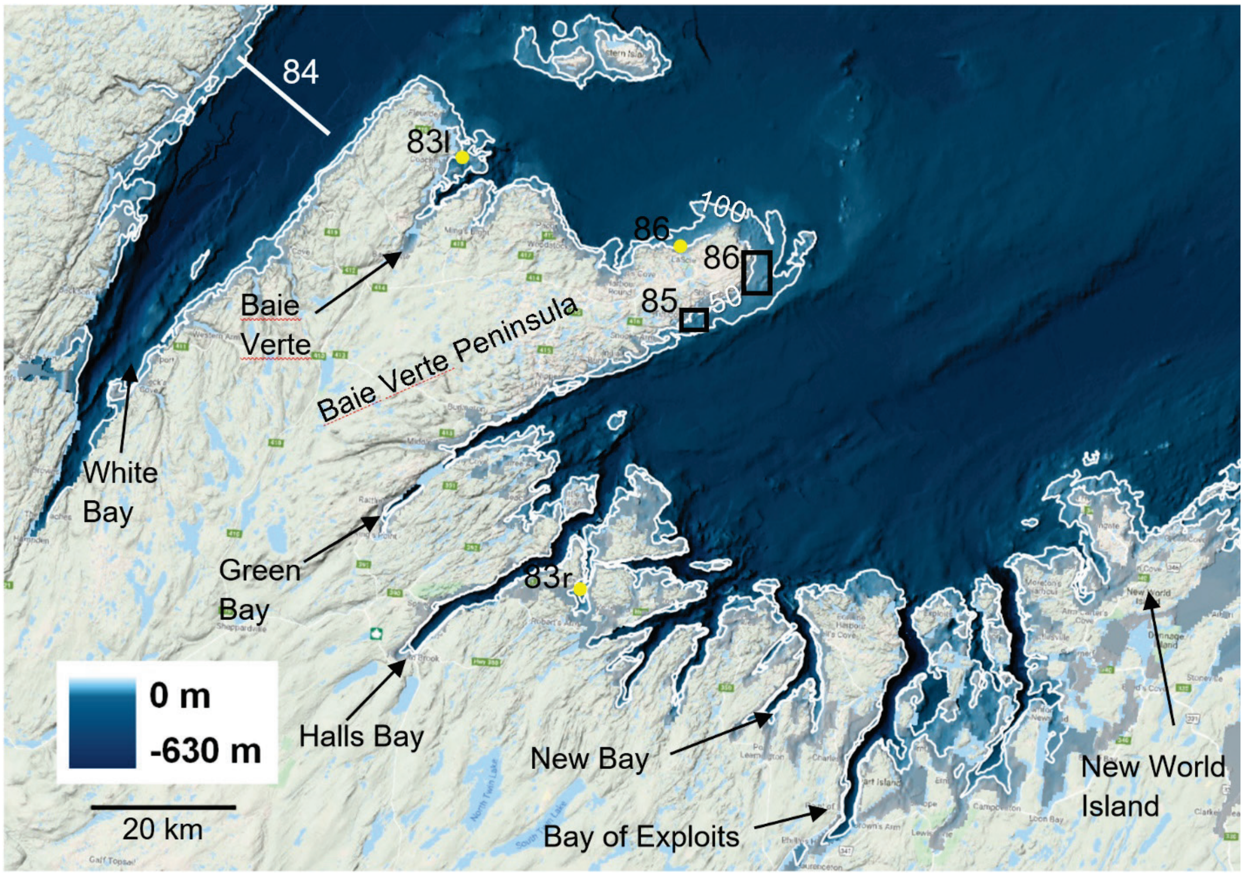


Figure 82. *Bathymetry of the Notre Dame region. Approximate figure locations (photos are yellow dots, seismic profile white line) are shown.*

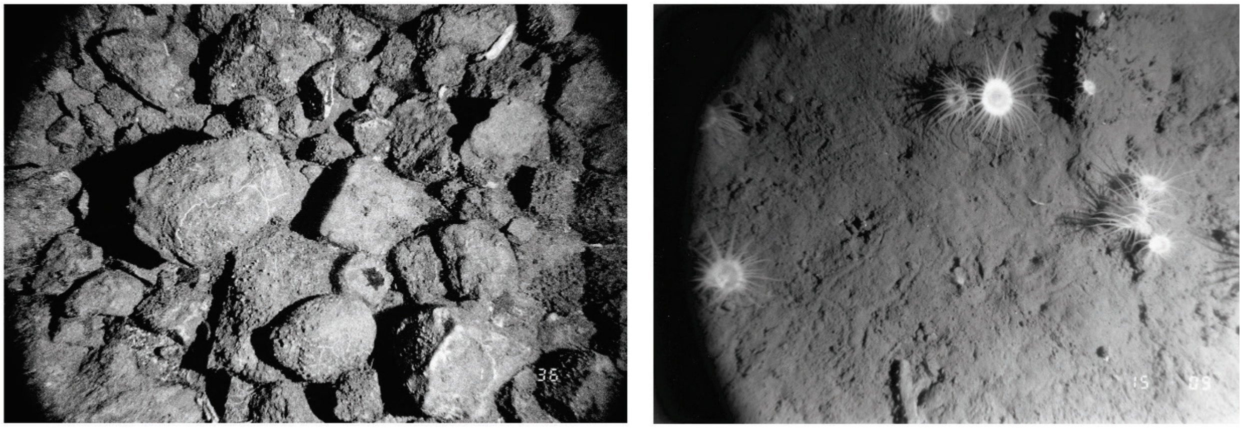


Figure 83. *Left: GSC image 4236 from cruise 90035 at the mouth of Baie Verte showing gravel/cobble surficial materials with little other surficial cover. Right: GSC image 90035:4289 in Halls Bay showing soft muddy postglacial surface with active bioturbation. Locations shown in Figure 82. Both photographs by J. Shaw. NRCan photos 2020-242 and 2020-243.*

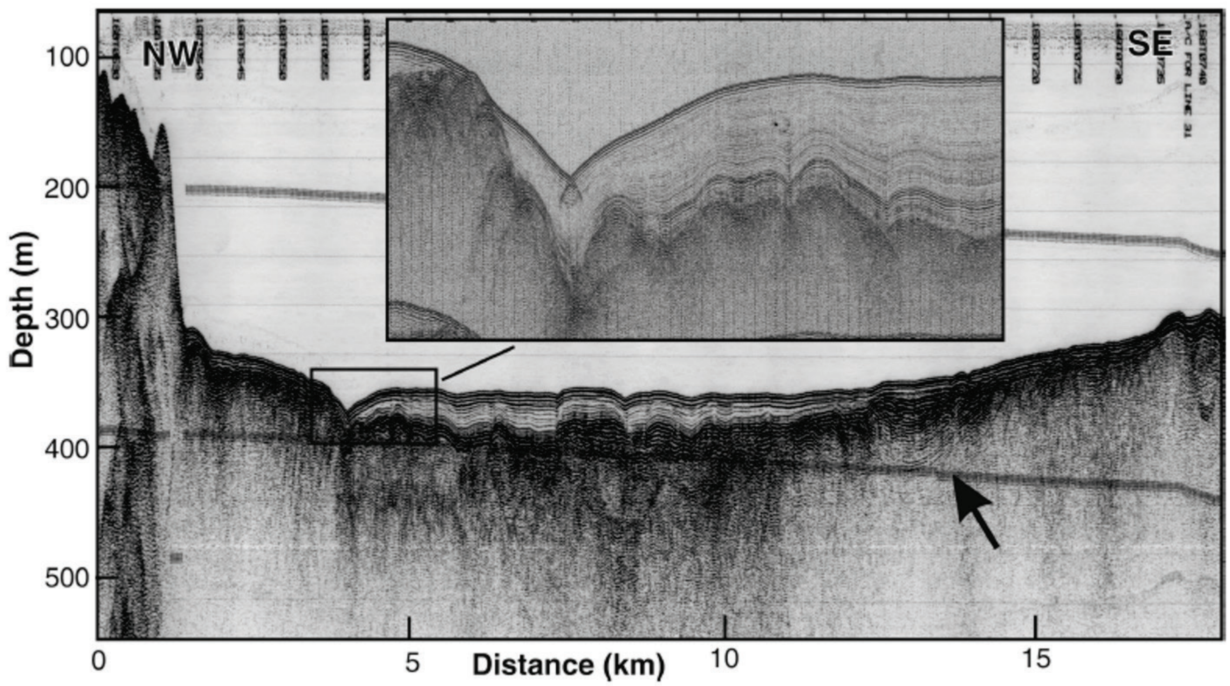


Figure 84. *Sleeve-gun seismic-reflection record (location Figure 82) and Huntec Deep-tow system subsection across White Bay, showing typical seabed configuration in the region with exposed bedrock dominated shallow inner shelf and sediment drape/infill in deeper basins (From Shaw and Potter, 2015).*

PRINCIPAL GEOMORPHIC REGIONS

Shallow waters in this region are divided into two geomorphic regions, each with a unique morphology, stratigraphy, and surface texture:

- *Exposed Bedrock:* The dominant shallow water seabed type, reflecting the high energy waves and currents of this region. Available multibeam (e.g. Figures 85, 86) suggests that most bedrock is typified by intrusive rocks (also see Figures 73-87, Shaw and Potter, 2015), which can show lower relief upper depths (platforms) and deep fissures infilled by Quaternary sediments.
- *Quaternary infill:* Undifferentiated sedimentation that fills depressions and fractures in bedrock surfaces (e.g. Figure 85). Can be any of the surficial materials described above and may rarely contain mobile bedforms in very shallow nearshore waters. Unlikely to be appreciably deep (e.g. > 50m) at shallow depths.

VIGNETTES

1. Tilt Cove

At Tilt Cove (Figure 85), copper mineralization was discovered in 1857 and mining operations between 1957 and 1967 (a second phase of mine operation) resulted in 5-6 million tonnes of tailings slurried into the ocean (Shaw et al., 1999). This is visible in the multibeam data as a fan emanating from the west point of Tilt Cove bight (A) that shows several examples of pits showing recent evidence of iceberg impacts (B – only two are highlighted but there are many). Note the number of bedrock pinnacles rising to within tens of metres of the surface, and the Quaternary infill also shows clearly defined iceberg furrows (C). A sunken barge is also visible in the multibeam data (D).

2. Shallow seafloor off Cape St. John

The multibeam data for this nearshore area (Figure 86) shows what is typically described (Shaw et al., 1999; Shaw and Potter, 2015) for the shallow seafloor around the end (north, northeast and northwest) of the Baie Verte Pensinsula. Quaternary sedimentation is more extensive here, exceeding the amount of exposed bedrock in Figure 86, and seismic data for this area suggest there are areas where sedimentation extends deeply. Iceberg furrows are once again common, however the increased density of furrows in deeper troughs suggests reworking of sediments at shallower depths.

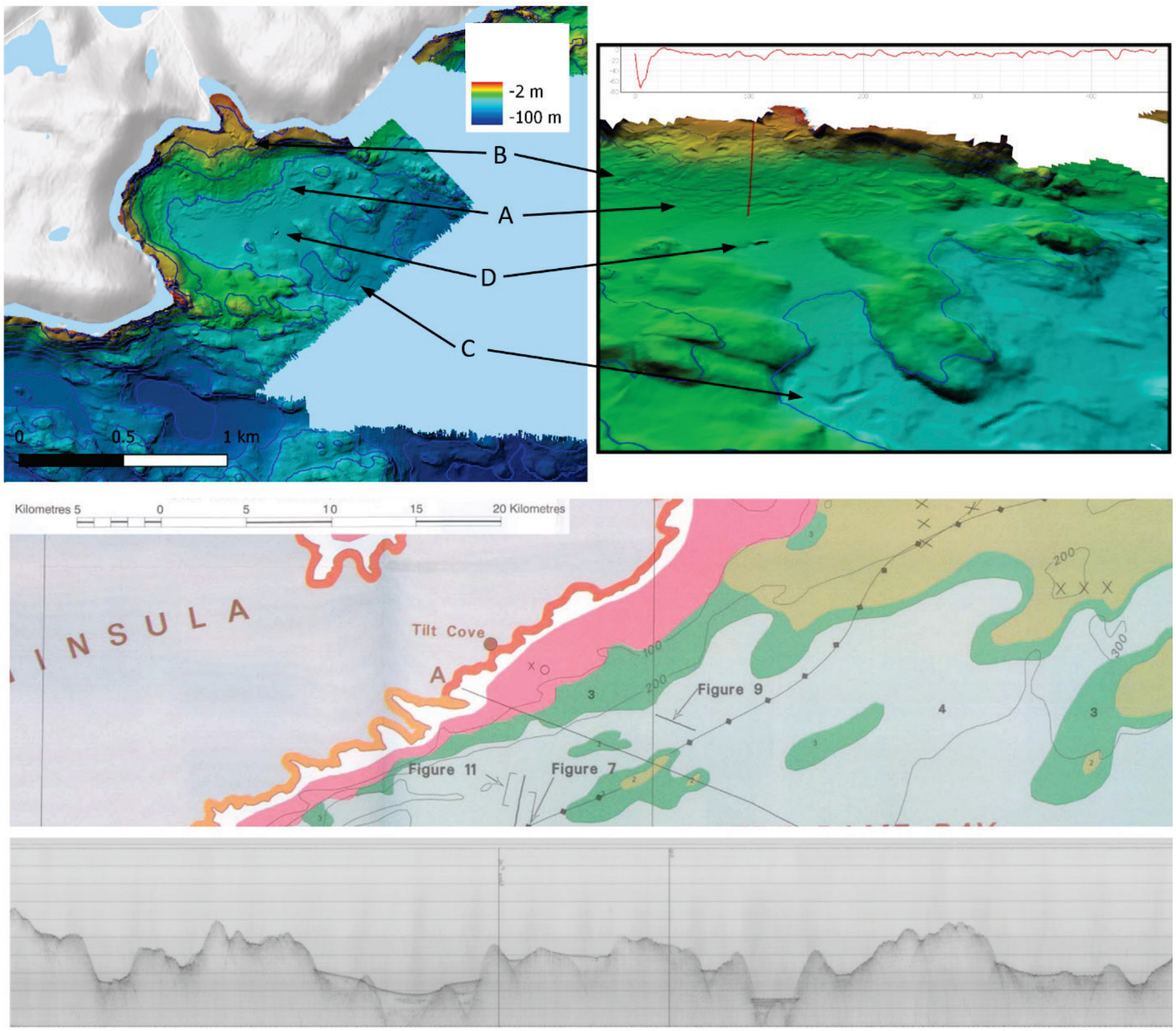


***Figure 85**. (Top left) Seafloor geology of Tilt Cove with 10m contours superimposed. Letters discussed in text. Note the typical inner shelf geology, with bedrock surrounded by Quaternary infill. (Top right) 3d perspective view of Tilt Cove fan showing the botryoidal pattern suggesting creep is occurring. Inset profile at the top is a slope profile (not topographic), showing the multiple "steps" in the fan and the wave-smoothed upper portion above 20 m depth. (Middle) Subset of surficial geology map in Shaw et al. (1999), showing increased detail that can be obtained with multibeam (top) but also the general geology of this region, in that exposed bedrock is mapped almost ubiquitously above 100m depth. (Bottom) representative seismic profile (Matthew 2001030, Seistec) from the Tilt Cove area showing Quaternary infill between bedrock exposures.*

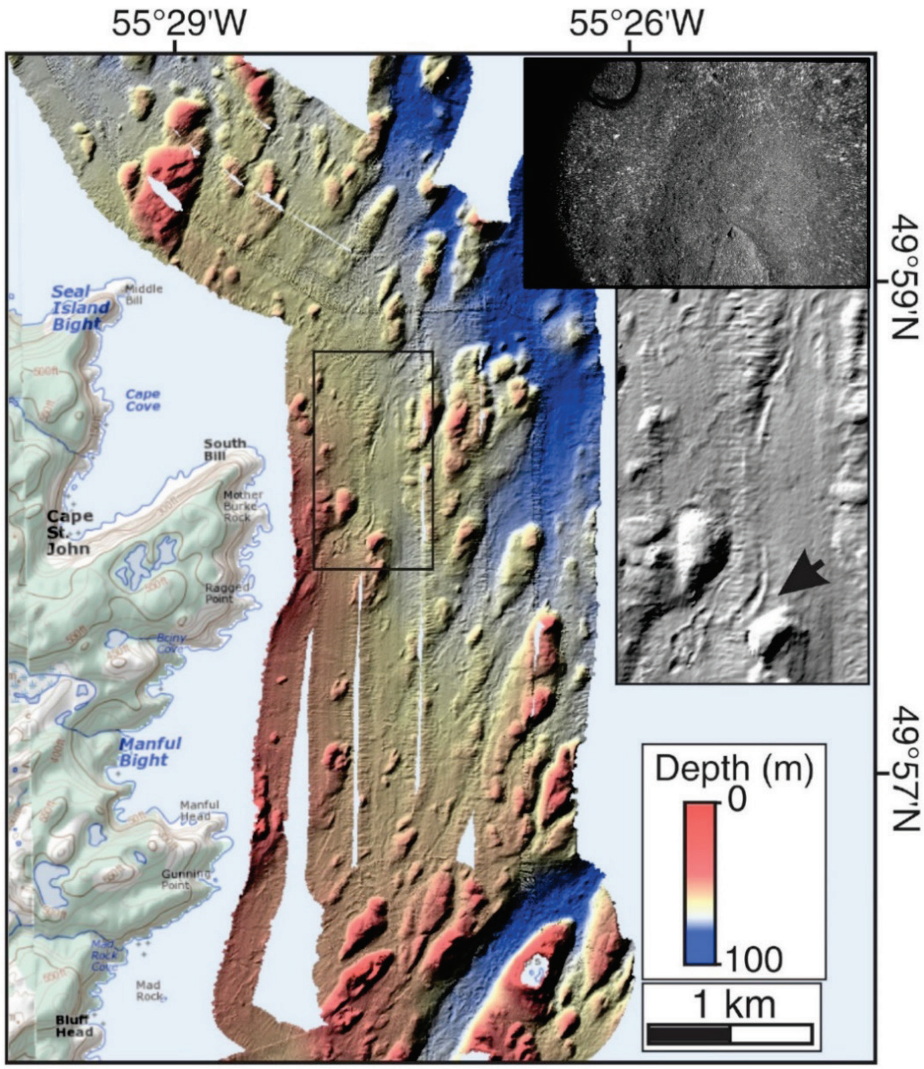


Figure 86. *Shallow seafloor (all >100 m depth) off Cape St. John (modified from Shaw and Potter, 2015), showing bedrock outcrops and gravelly Quaternary infill (evidence provided by backscatter – not shown) with recent iceberg furrows highlighted by an arrow in the inset relief map. Inset picture (GSC photo 90035-4271), taken off LaScie (Figure 82) shows coarse sand/gravel Quaternary sedimentation in the area.*

FAVOURABLE FACTORS, POTENTIAL CONSTRAINTS, AND HAZARDS

- Where Quaternary sedimentation is common, sand and gravel dominate.
- Exposed bedrock on the inner shelf forms flat platforms (with deep fractures).
- Gravel/cobble lag or surficial sediment common, and sediment depths typically shallow.
- Sand and gravel are likely mobile, evidenced in smoothed exposures and ripples.
- Icebergs and sea ice impact the shallow shelf regularly.

Region 20: Great Northern Peninsula

SUMMARY

This region's coastlines are mostly steep and rocky. The inner shelf is characterized by a shallow, fairly narrow bedrock platform that widens towards the north. Exposed bedrock, which is common, can be relatively flat and low relief where crystalline. Sand and gravel exist in isolated basins but may be mobile and sediment depths are shallow. Icebergs regularly impact the shallow shelf.

<u>Favourable</u> factors for foundation emplacement include flat, low relief (in some locations) bedrock

<u>Constraints</u> for foundation emplacement include regular impacts from icebergs and sea ice; mobile sand and gravel that are patchy and thin; bedrock is commonly irregular and high-relief

Shaw and Potter (2015) provide the best summary of available data for this region, including the limited high-quality MBES data.

GEOLOGY

Geomorphology The linear NE-SW trending coastline is broken up by several small fjord-like inlets and the larger Canada and Hare Bays in the north of the region (Fig. 87), both of which contain deposits of glaciomarine and postglacial mud. The inner shelf in this area is narrow, with appreciable areas of shallow seafloor found only west of Groals Island and within Hare Bay, extending north to the inner shelf just south of the Strait of Belle Isle. Shaw and Potter (2015) divided the region into two parts, the southern part within White Bay characterized by the deep central basin and a narrow zone of bedrock close to the coast, while north of Canada Bay the bedrock inner shelf widens to 3-7 km off the coast, mostly above 100m depth. Pockets of mud are found in bedrock depressions in shallow waters and evidence of sand and gravel is documented around Coney head (Shaw et al. 1999). The most extreme relative sea level history on the island of Newfoundland is found on the Peninsula, where following deglaciation relative sea level were 130m above present and have been falling since (Shaw and Potter, 2015). Note, however, that there is a strong east-west component to the magnitude of the highstand, and this region (when compared to region 21 on the west coast) had a somewhat muted signal, perhaps only as high as 94 m below present (Shaw et al., 2002).

Bedrock Within the Humber tectonic zone, an extension fault separating the basement rocks (intrusive and meta-igneous) onshore with Carboniferous rocks offshore results in the linear coastline. A notable feature of the bedrock on the inner shelf is the bench that extends 3-7 km out from the coast along the northern part of the peninsula. Bedrock exposure is common on the inner shelf and can be expressed in the flat-topped, fractured morphology of the intrusive basement rocks or ridged, deformed, high relief Carboniferous rocks (Figure 91).

Surficial sediments Generally in this region, where data exists, bedrock is exposed and minor amounts of glaciomarine/postglacial mud or sand and gravel may be found in isolated locations. Sand and gravel can be found in isolated pockets around bedrock exposures, in numerous small perched basins, or possibly in larger areas around Coney Head. They are likely to be furrowed extensively by icebergs. Gravel is rippled in areas (Figure 88). Deposits are not appreciably thick (King 2014b; Shaw and Potter, 2015). Glaciomarine or postglacial muds exhibit low relief and are deposited mostly in depressions and basins around bedrock exposures (Figures 88, 89, 91). Deep basins in insets contain deep sequences of muds and iceberg furrows typically contain postglacial muds (Figure 90).

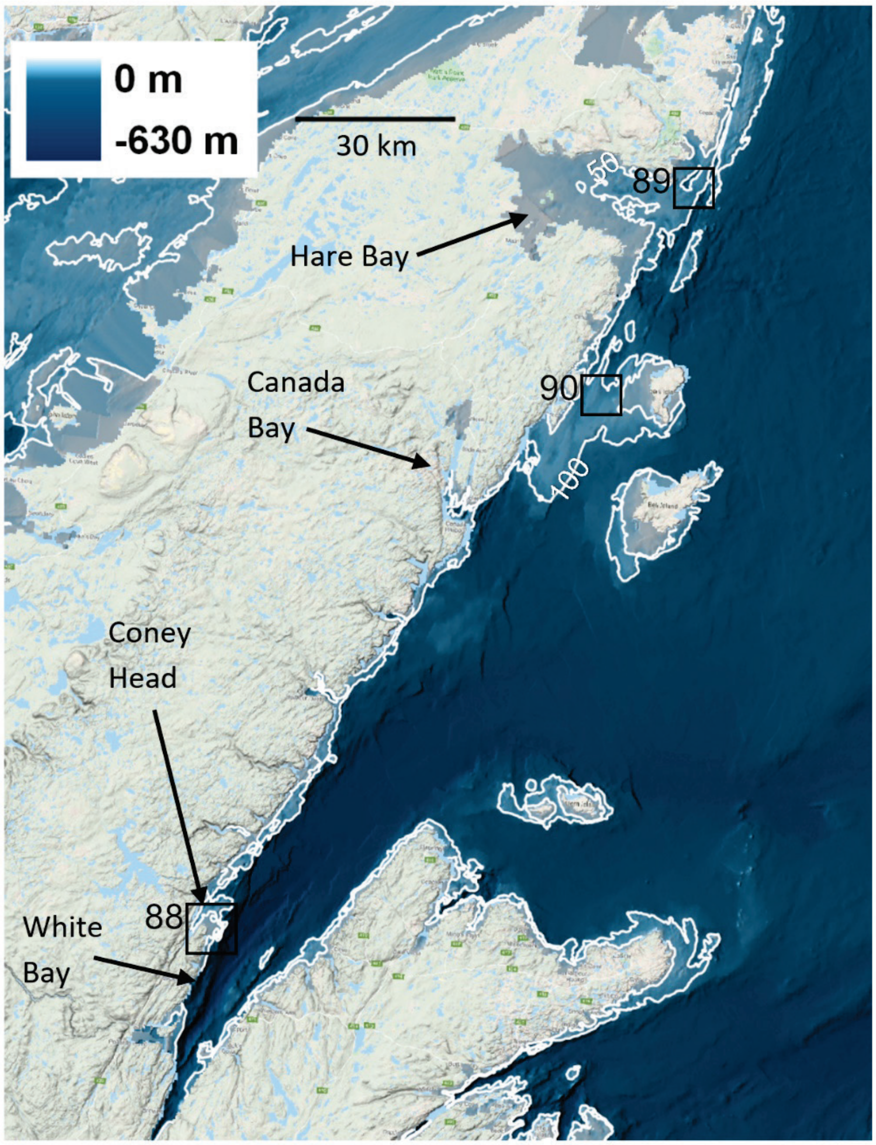


Figure 87. *Bathymetry of the Great Northern Peninsula region. Approximate figure locations are shown.*

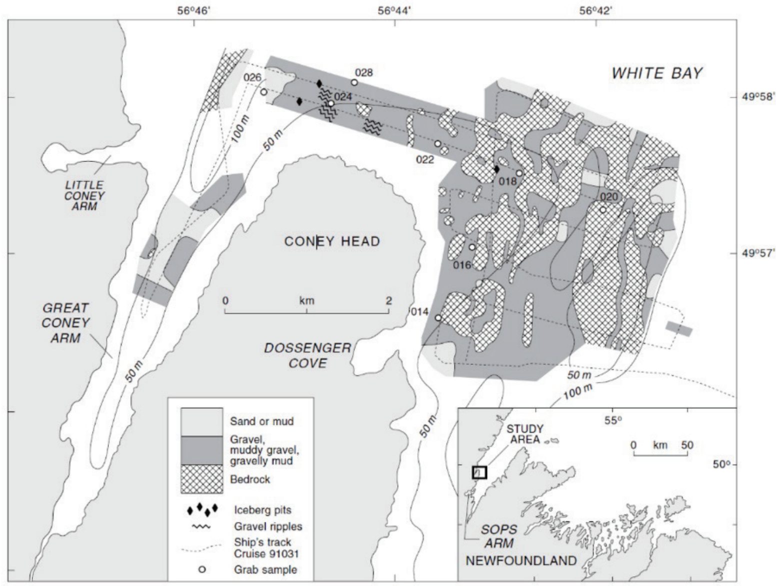


Figure 88. *Geology of the seafloor surrounding Coney Head (from Shaw et al., 1999). Note the sand and gravel.*

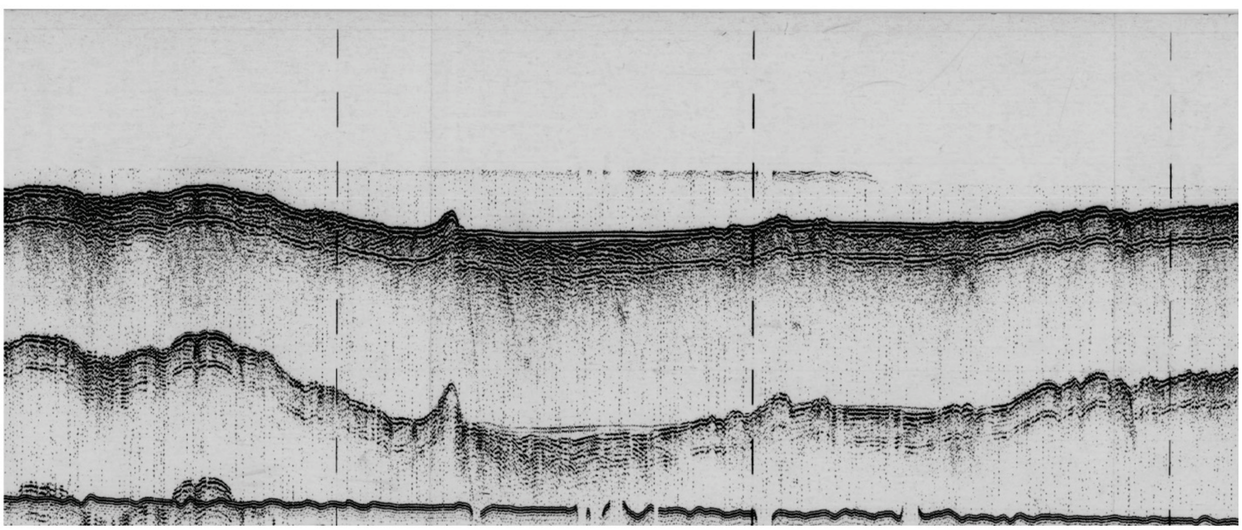


Figure 89. *Unprocessed Huntec Seismic data from the inner shelf west of Groais Island, GSC cruise Hudson 75009PHASE3. Note bedrock outcrops and low-relief Quaternary sediments (glaciomarine or postglacial mud). Location Figure 87.*

PRINCIPAL GEOMORPHIC REGIONS

Shallow waters in this region are divided into two geomorphic regions, each with a unique morphology and surface texture:

- *Inner bedrock bench:* At shallower depths (< 100 m), close to the coast, there is a bedrock bench composed of either predominantly intrusive rocks, with large fractures and Quaternary infill, or Carboniferous rocks, with ridges, high relief, and possibly areas with a greater degree of Quaternary sedimentation (Figure 91b,c).

- *Coney Head sand and gravel:* Muddy gravel, sand, or mud predominates. Gravel is rippled and iceberg pits/furrows are present in the muddy gravel. Sediment sequences may be as deep as 50m, with postglacial sandy mud overlying glaciomarine sediment (Shaw et al., 1999). This region may be found elsewhere in this area (e.g., Figure 90).

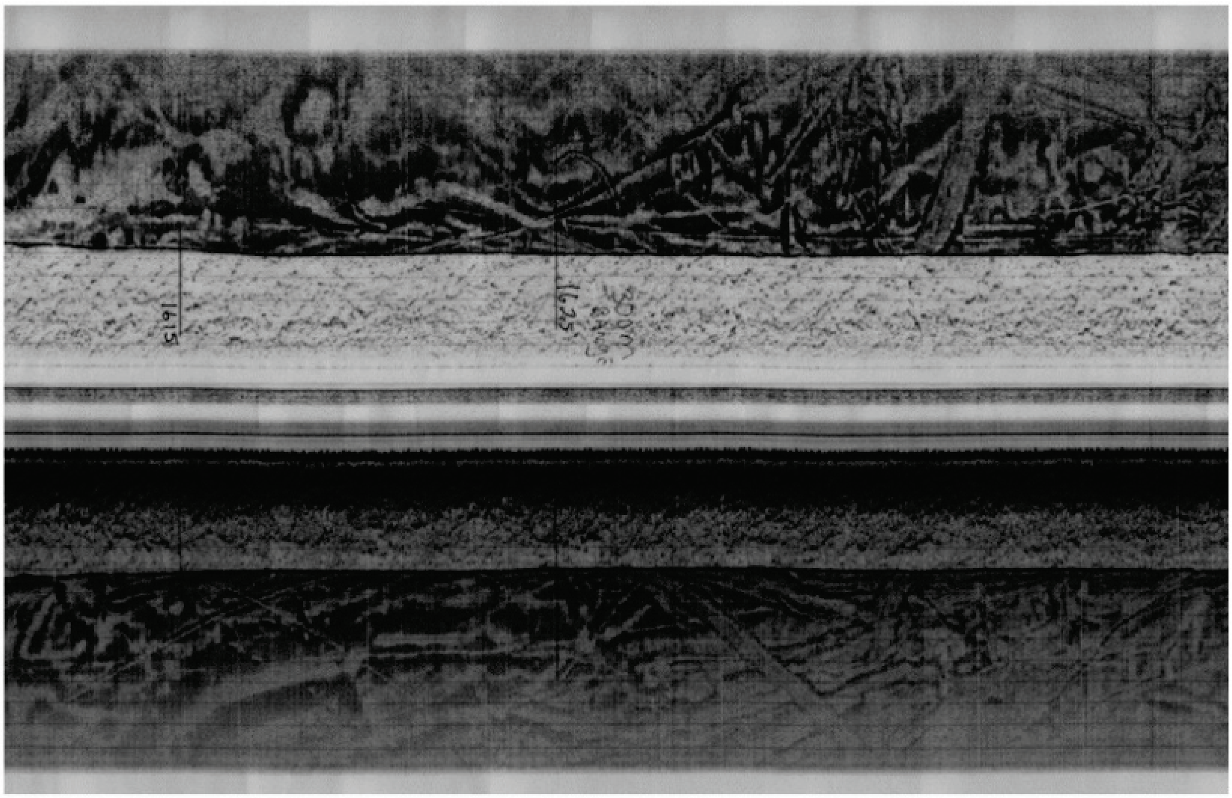


Figure 90*. Sidescan sonar image from the mouth of Hare Bay, GSC cruise Pandora II 81054. Note intensive and cross-cutting iceberg furrows with sands or muds deposited in the furrows, indicating that the substrate is impacted frequently by icebergs.*

VIGNETTES

1. Bedrock along the inner shelf

Figure 91a shows the extent of multibeam coverage along the inner shelf of the Great Northern Peninsula. A bedrock knoll is shown in the inset, rising into shallow water from a seafloor deeper than the bedrock shelf. In b), the contact between basement rocks in the shallower water and ridged Carboniferous rocks in the deeper water is quite visible, and the inset backscatter map shows the Quaternary infill (light color, likely mud) in depressions around the basement rocks. The dashed black line shows the extent of the map shown in Figure 88. In c) bedrock outcrops are primarily Carboniferous, and Quaternary cover is more widespread. The contact between bedrock types (A and B) is again quite clear, and the white dashed line shows the axis of a fold in the Carboniferous rocks.

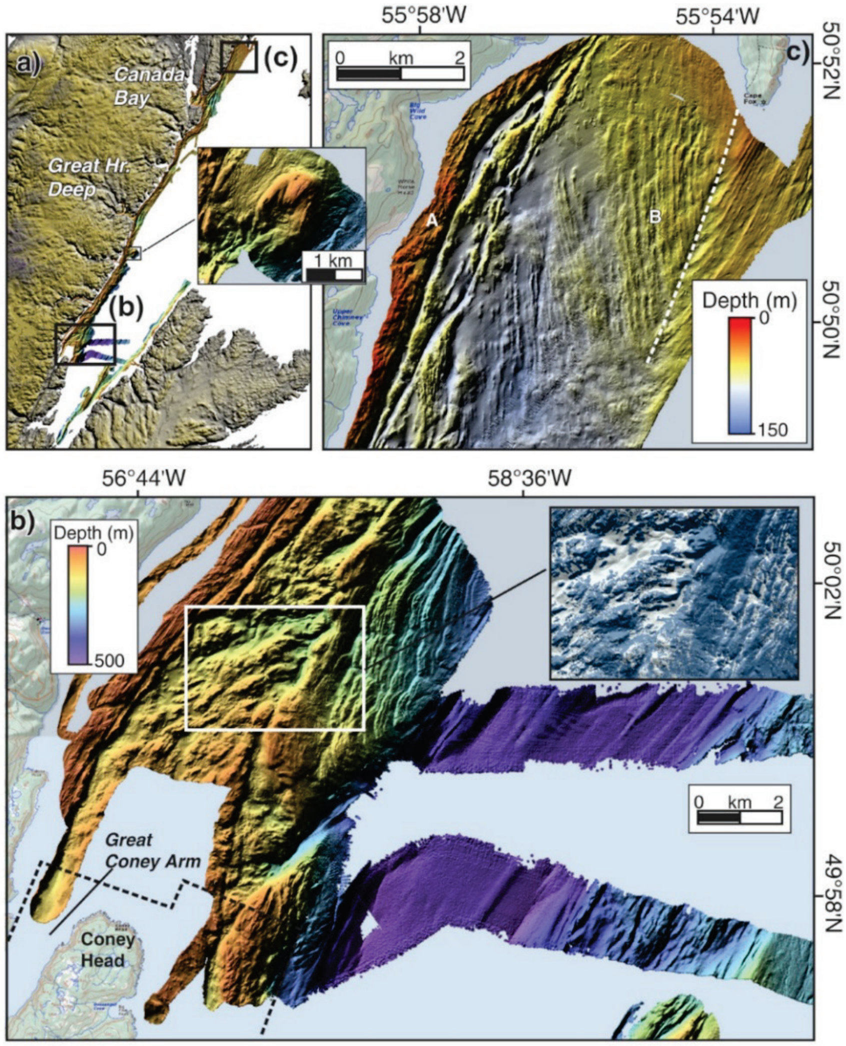


Figure 91. *Multibeam coverage in this region, letters described in the text. Modified from Shaw and Potter (2015).*

FAVOURABLE FACTORS, POTENTIAL CONSTRAINTS, AND HAZARDS

- Exposed bedrock on the inner shelf forms flat platforms in some locations.
- Pockets of sand and gravel exist but are rare and sediment depths are shallow.
- Sand and gravel are mobile in some regions.
- Icebergs and sea ice impact the shallow shelf regularly.

Region 21: West Newfoundland

SUMMARY

This region has a coastline that transitions from low-relief sandy coastal systems in the north to steeper rocky coastlines further south. The inner shelf is similarly characterized by a shallow sedimentary platform that widens toward the south to as much as 50 km to the -100 m isobath. Some areas of the shelf are characterized by low relief and postglacial sediments (muds, sands, gravels) are common and formations can be thick.

<u>Favourable</u> factors for foundation emplacement include a broad inner shelf and thick Quaternary sedimentation in places.

<u>Constraints</u> for foundation emplacement include variable relief; mobile sand and gravel; mass wasting common.

Existing high-quality MBES data (Shaw et al., 2001; Shaw and Potter 2015) highlights channel-fan systems off the shallow platform around Bonne Bay and the complex seafloor associated with the Bay of Islands moraine.

GEOLOGY

Geomorphology The coastline here is varied, with a broad, flat carbonate terrain with well developed sandy coastal systems in the north (Fig. 92). This is contrasted with steep rocky coastlines at Bonne Bay and further south, where the coast meets the Long Range Mountains and is intersected by several large fjords. The inner shelf along the south half of this region is much broader than many other areas on the island; the broad carbonate bench that is terrestrial in the north transitions to a shallow shelf region in the south. A sill at the north end of the Strait of Belle Isle is at a depth of 62m, preventing larger icebergs from entering the Gulf of St. Lawrence (and this region) from the southward Labrador Current. Perhaps due to the wide geographic range of this region, there is also a wide range of surficial sediments and bedforms, however in general sediments are characterized by thin sand and gravel over thin till in the north, with thicker deposits of sand and gravel (e.g. >50m in Port au Port Bay, Figure 93) or till (e.g. in moraines – Figure 94) found further south (Shaw and Potter, 2015). Bedrock exposure is relatively common. The most extreme relative sea level history on the island is found on the northern end of the Peninsula, where following deglaciation relative sea level were 130 m above present and have been falling since (Shaw and Potter, 2015). Because of the higher sea level, icebergs were able to traverse the strait and impact the seabed on the Gulf side of the peninsula, as evidenced by common relict iceberg furrows along the inner shelf. There is a strong north-south gradient in relative sea level response, however, with a lower-magnitude highstand (~20m above present) followed by a lowstand (25m below present) by 9ka BP at Port au Port (Shaw et al., 2002).

Bedrock This area lies within the Humber tectonic zone. Cambrian and Ordovician shelf-facies carbonate rocks are both on and off-shore in the northern part of this region (Shaw and Potter, 2015). A fault separates basement rocks in shallow waters and Carboniferous sedimentary rocks in deeper waters of the southern shelf (Sanford, 1998). Where exposed, bedrock is generally ridged and high-relief in sedimentary basin rocks and lower relief in basement rocks.

Surficial materials Sand and gravel are found in a wide range of morphologies, bedforms, and depths. Up north, they generally form a thin sheet of stratified sediments with sand waves, megaripples, dunes, and ribbons that overlays till. Further south, large sediment prisms, fans, and bedforms of sand and gravel form on shallow portions of the inner shelf. Glaciomarine or postglacial muds are found as acoustically stratified (glaciomarine) or transparent (postglacial) units in deep basins within fjords or as a relatively thick (20-45 m) drape over bedrock or till in shallow portions of the shelf. Till forms either an acoustically incoherent thin bed of sediments underlying sand and gravel in the north (but also including some ribbed moraines and De Geer moraines indicating retreat of Labrador and Island of Newfoundland ice, respectively), or deposits up to 100 m thick in trough-mouth moraines (e.g. seaward of Bonne Bay (~30 m thick) and the Bay of Islands (100 m)).

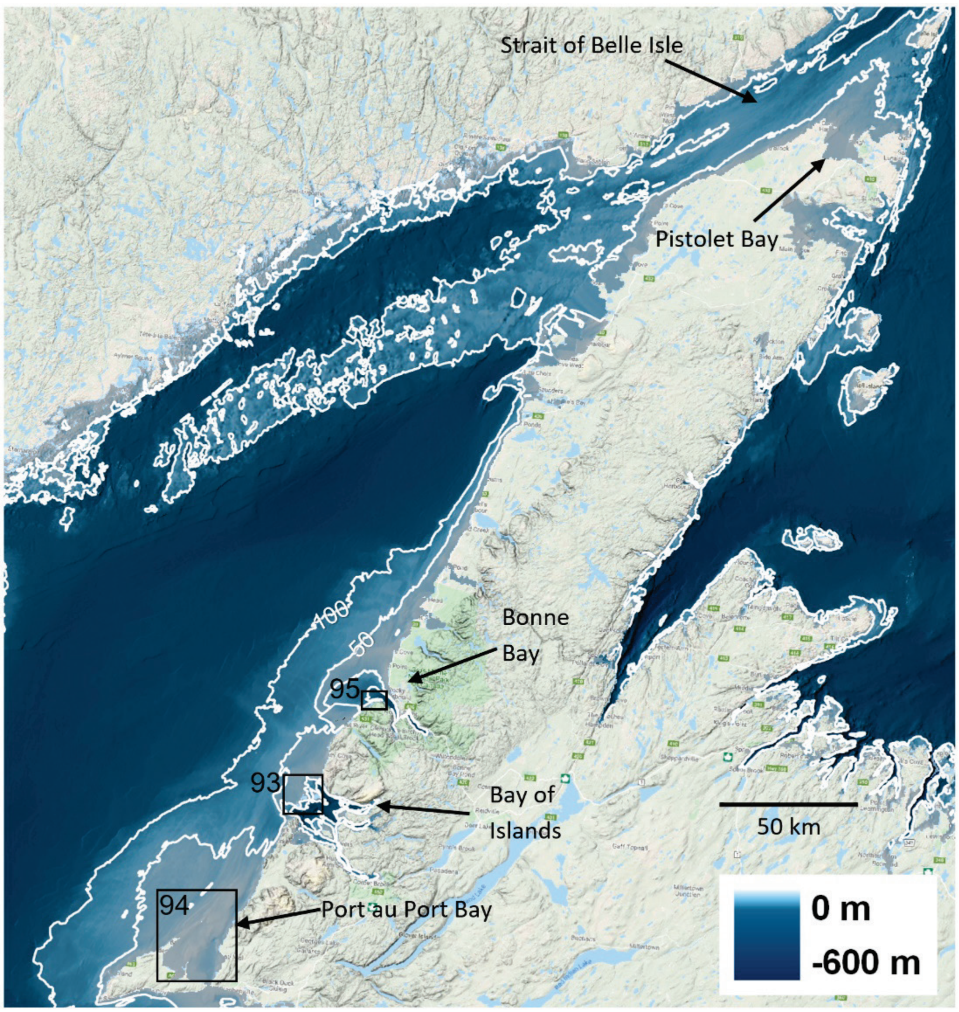


Figure 92. *Bathymetry of the Great Northern Peninsula region. Approximate figure locations are indicated.*

PRINCIPAL GEOMORPHIC REGIONS

Shallow waters in this region are divided into four geomorphic regions, each with a unique morphology and surface texture:

- *Strait of Belle Isle and North Coast:* Thin sand and gravel overlying thin till, with outcropping bedrock common. Currents through the strait are strong and bedforms in the sand and gravel reflect this. Ridges of till (ribbed and De Geer moraines) are also found in this region. A shallow, smooth seafloor (based on coarse bathymetry) in Pistolet Bay (Figure 92) may be an extension of unconsolidated sediments mapped around and south of the bay (Liverman and Taylor, 1994).
- *Fjords:* Deep basin fill of glaciofluvial and postglacial muds, with steep walls where v-shaped gullies formed by late-glacial slumping is common. Anthropogenic influences are found in this region (e.g. outside Corner Brook, Shaw and Potter (2015) Figs 103, 104), and grounding-line wedges of sediment can be found near the mouth of the Bay of Islands.
- *Glacially modified south coast:* Dominant features include the two large fjord-mouth moraines seaward of Bonne Bay and Bay of Islands, but also includes several smaller northwest-southeast ridges of till and smaller moraines superimposed on the broader Bay of Islands moraine (Figure 94). There may be areas of streamlined glacial bedforms that have yet to be mapped in detail.
- *Mobile sediment:* Found throughout the region but in thicker deposits further south (e.g. Figs 93, 94, 95), these areas include sediment prisms, migrating dunes, fans, rippled gravel, and progradational/spillover wedges. Also includes broad areas of erosion of muds via currents (e.g. Shaw and Potter, 2015, Figure 95).

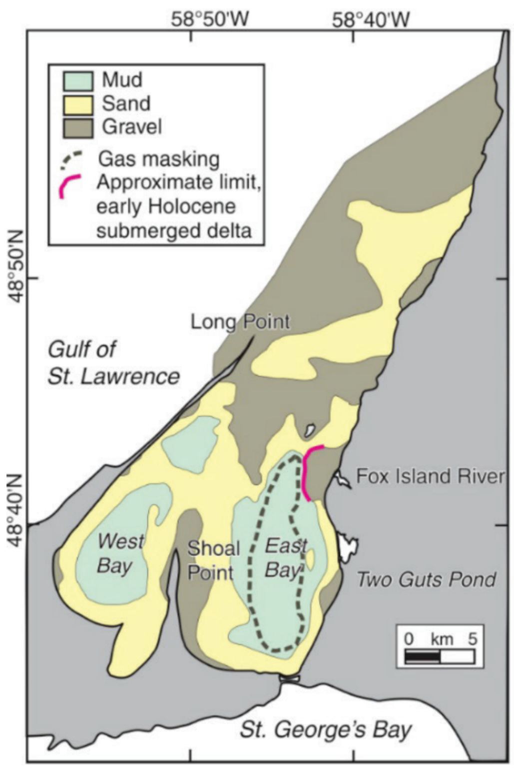


***Figure 93**. Simplified map of Port au Port Bay surficial geology, from Shaw and Potter (2015) and based on Eddy (1989).*

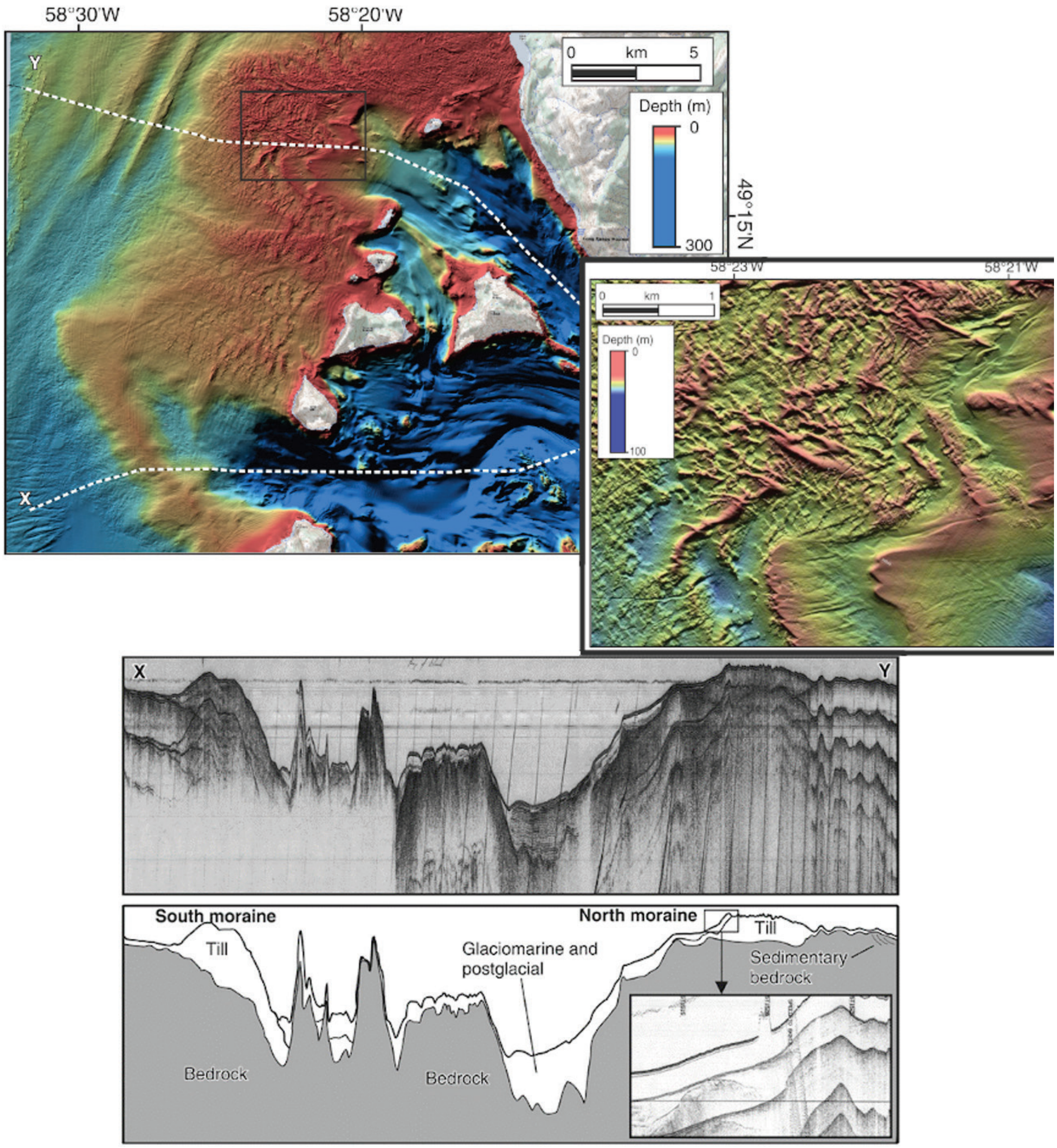


Figure 94. *(Top) Multibeam coverage at the mouth of the Bay of Islands. The lobate moraine reaches as high as -45m depth in the south and -25m in the north. Black box is for middle inset, and bottom profile location shows as white dashed line. (Middle) close up image of the irregular moraine surface, with bedforms, smaller moraines, and iceberg furrows. (Bottom) Seismic-reflection profile that traverses the Bay of Islands moraine twice, entering the bay in the south and exiting in the north. Inset is a higher resolution Huntec DTS record. Note the rough surface on the shallower north (right) moraine. Modified from Shaw and Potter (2015).*

VIGNETTES

1. Submarine fans and sandy inner shelf – entrance to Bonne Bay

Figure 95 shows a subset of the multibeam coverage along the southern entrance to Bonne Bay. Large lobes of sand, possibly reflecting the north-flowing current, are indicated on top of the shallow platform and along the break in slope. Rippled gravel (sidescan, Figure 95; also see backscatter map in Shaw et al. (2002c)) also speaks to sediment mobility on the platform. Several submarine fans emanate from the shallow platform, extending as much as 1km offshore at slopes of 3 – 4°. Several are associated with erosional embayments on the platform that may indicate continued landward erosion of the platform. Shaw and Potter (2015) hypothesise that the fans result from sediment gravity flows mobilized by sand suspension on the inner shelf platform during storms.

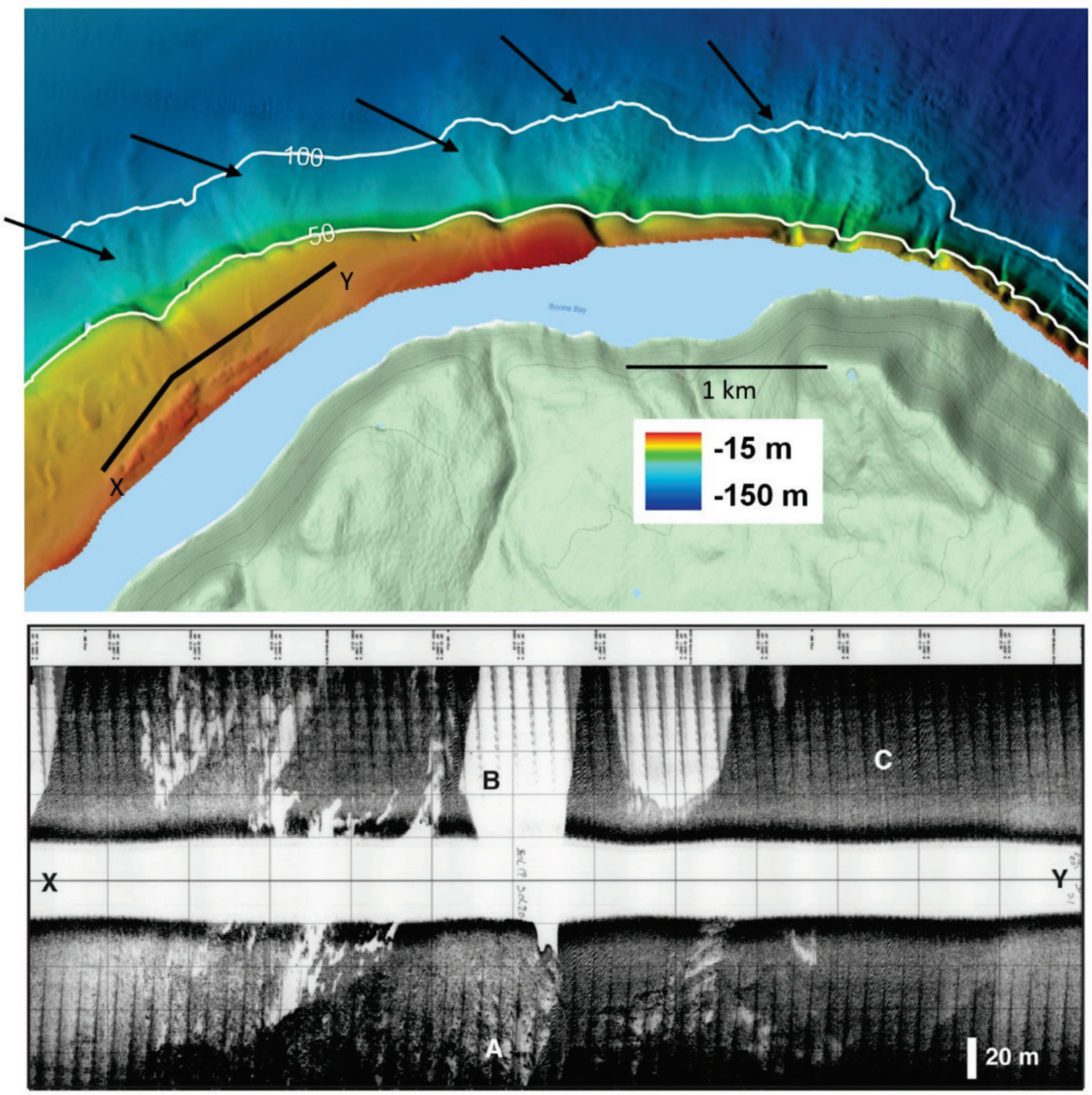


Figure 95. *(Previous). (Top) Multibeam data for Bonne Bay. Sidescan image location show, and multiple fans emanating from the inner shelf highlighted by arrows. The steep slope is incised by channels with several metres of relief, some of which are levéed. (Bottom) Sidescan sonar record along X-Y, showing bedrock (A), sand (B), and rippled gravel (C), from Shaw and Potter (2015).*

FAVOURABLE FACTORS, POTENTIAL CONSTRAINTS, AND HAZARDS

- Shallow sedimentary platform on the inner shelf that widens toward the south.
- Sediments can be very thick (100m).
- Relief is variable – bedrock and glacial surfaces can be high relief (with exceptions – see Shaw and Potter (2015) Figure 96) and postglacial sedimentation is low relief.
- Sand and gravel are mobile indicating strong currents on the inner shelf.
- High occurrence of mass wasting in and around fjords.
- Seabed iceberg furrows appear to be relict – the region experiences minimal iceberg incursion.

Region 22: St. George's Bay

SUMMARY

This small, discrete region includes a wide range of coastal features including spits and lagoons. The inner bay hosts a large, shallow, sedimentary sill, with a range of relatively thick surficial sediments (glacial and postglacial) overlying a range of mostly sedimentary rocks. The sill, large wave- and current-driven spillover deposits, and mass wasting on steep slopes provide important geologic context in the bay.

<u>Favourable</u> factors for foundation emplacement include thick, shallow packages of Quaternary sediments; low relief sedimentary coastlines

<u>Constraints</u> for foundation emplacement include a high proportion of till; gas escape and mass wasting indicate sediment instability; salt diapirs at depth; mobile sand and gravel

A series of GSC maps (Shaw et al., 2006b,d,e) and report (Shaw and Potter, 2015) provide a comprehensive source of information.

GEOLOGY

Geomorphology The main feature of the bay is a large sedimentary sill that stretches across the inner bay. The majority of the bay is shallower than 100 m and the sill and inner coasts are shallower than 50 m (Fig. 96). Relative sea level was slightly higher (~20m) following deglaciation, then fell to a lowstand of -25 m in the early Holocene, slowly rising to present since (Shaw et al., 2002).

Bedrock The bay is bounded by Ordovician carbonate rocks to the north (Port au Port Peninsula), complex post-Ordovician overlap sequences to the south, and a floor of Carboniferous rocks. They were heavily incised into valleys by glaciation to 195 m below sea level and subsequently filled by a package of glaciomarine muds. In the outer bay (west of the sill), bedrock exposure is more common and dominates the morphology of the seabed. The Carboniferous rocks belong to the Magdalen Basin salt-diaper zone and show similar features as those found in region 4 (Dafoe et al. 2016).

Surficial materials Bedrock is overlain in some places by thick packages of Quaternary sediments. Shaw et al. (2006b) indicate that shallow water depths are dominated by post-glacial sand and gravel and ice-contact sediments (till). Thicknesses range from upwards of 30m sand and gravel, 100m of till (found mostly on the sill, which is a postglacially modified moraine, e.g. Fig. 97), and 60m of glaciomarine and postglacial muds (found in the basins).

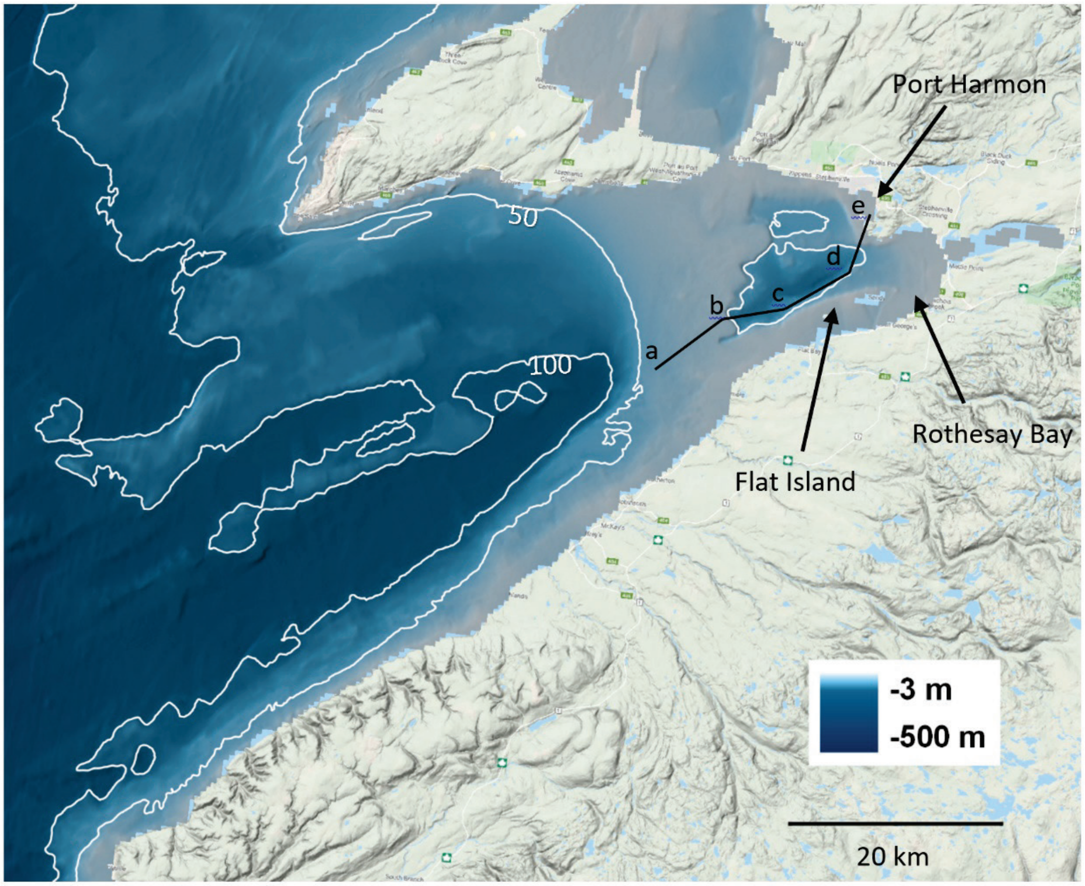


Figure 96. *Bathymetry of St. George's Bay, with 50 m and 100 m isobaths. Location of cross section a-e in Figure 98 is shown. Note that Flat Island is covered by the bathymetry data.*

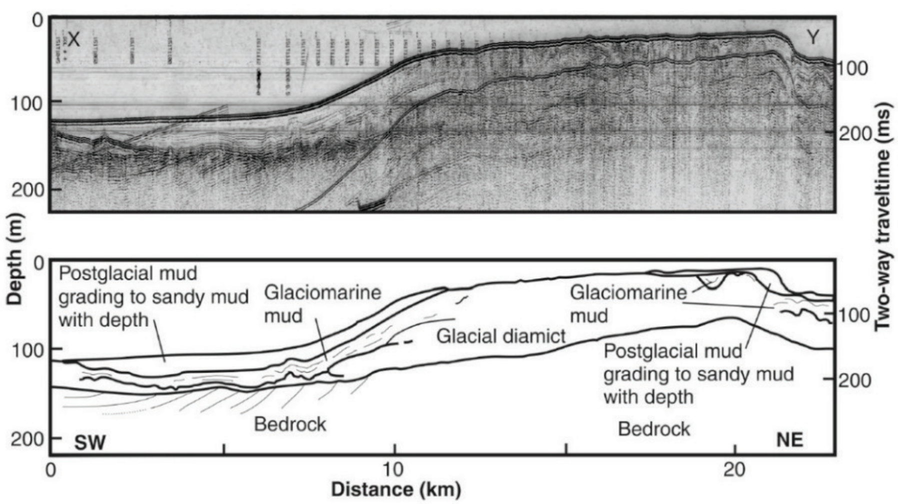


Figure 97. *Representative airgun seismic reflection profile (top) and interpretation (bottom) of the moraine across St. George's Bay. Location (X-Y) in Figure 99. From Shaw and Potter (2015).*

PRINCIPAL GEOMORPHIC REGIONS

Shallow waters in this region are divided into three geomorphic regions, each with a unique morphology, stratigraphy, and surface texture:

- *The sill:* A distinct east-to-west pattern exists in the surficial sediments on the sill. Further west near the mouth, a relatively shallow veneer (15m at its deepest) of postglacial sand and gravel overlie a thick package of ice-contact sediments (mostly till) that are exposed further east. At the eastern edge of the sill spillover sand and gravel form thick (up to 50m) wedges that prograde over the basin muds.
- *Postglacial sand and gravel:* Found to the east of the sill as well as in the littoral zone and spit platforms around Port Harmon, Rothesay Bay, and Flat Island. Mostly consists of well sorted medium sand, can be thick (e.g. Figure 98 – 30m), and often covered with active bedforms (e.g. Figure 99E).
- *Basin fill:* In water depths greater than 40m, thick units of glaciomarine mud can be overlain by postglacial muds that may show pockmarks. Where spillover deposits have prograded over this region, mud units can be deformed.

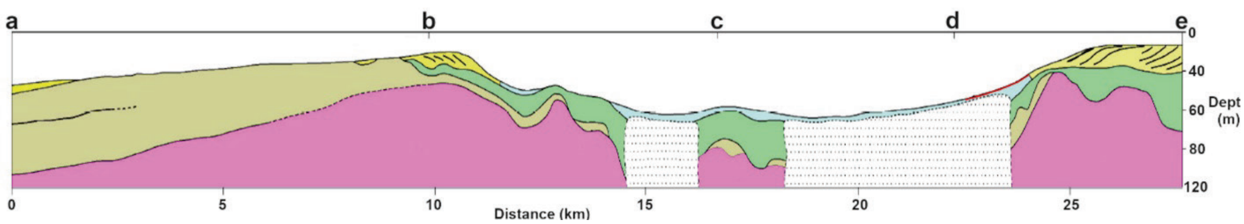


Figure 98. *Geological cross section from the mouth of St. George's Bay to Port Harmon, near Stephenville. Purple: bedrock; brown: till; green: glaciomarine mud; yellow: sand and gravel; blue: postglacial mud; red: dredge spoil; white dotted: gas masking. Location in Figure 96. Modified from Shaw et al. (2006b), where the full legend can be found.*

VIGNETTES

1. The sill – a postglacially modified moraine

Figure 99 shows the multibeam coverage in St. George's Bay. (A) is centred on the broad sill across the mouth of the inner bay. Spillover deposits on the sill show up as several lobes (e.g. (B)), some of which have since collapsed (C). Sand and gravel (smooth, (D)) bury the glacial till (rough, further east) to increasing depths toward the west. An example of sandy bedforms in the postglacial sand and gravel is shown at (E) and the associated inset, however they are common elsewhere (e.g. on (B)). (F) and (G) show the basin fill regions, with the latter showing several pockmarks. The sand and gravel platform outside of the Flat Island barrier complex (J) shows several fans and channels (see inset, K, L) indicating mass wasting on the steep slopes flanking the platform.

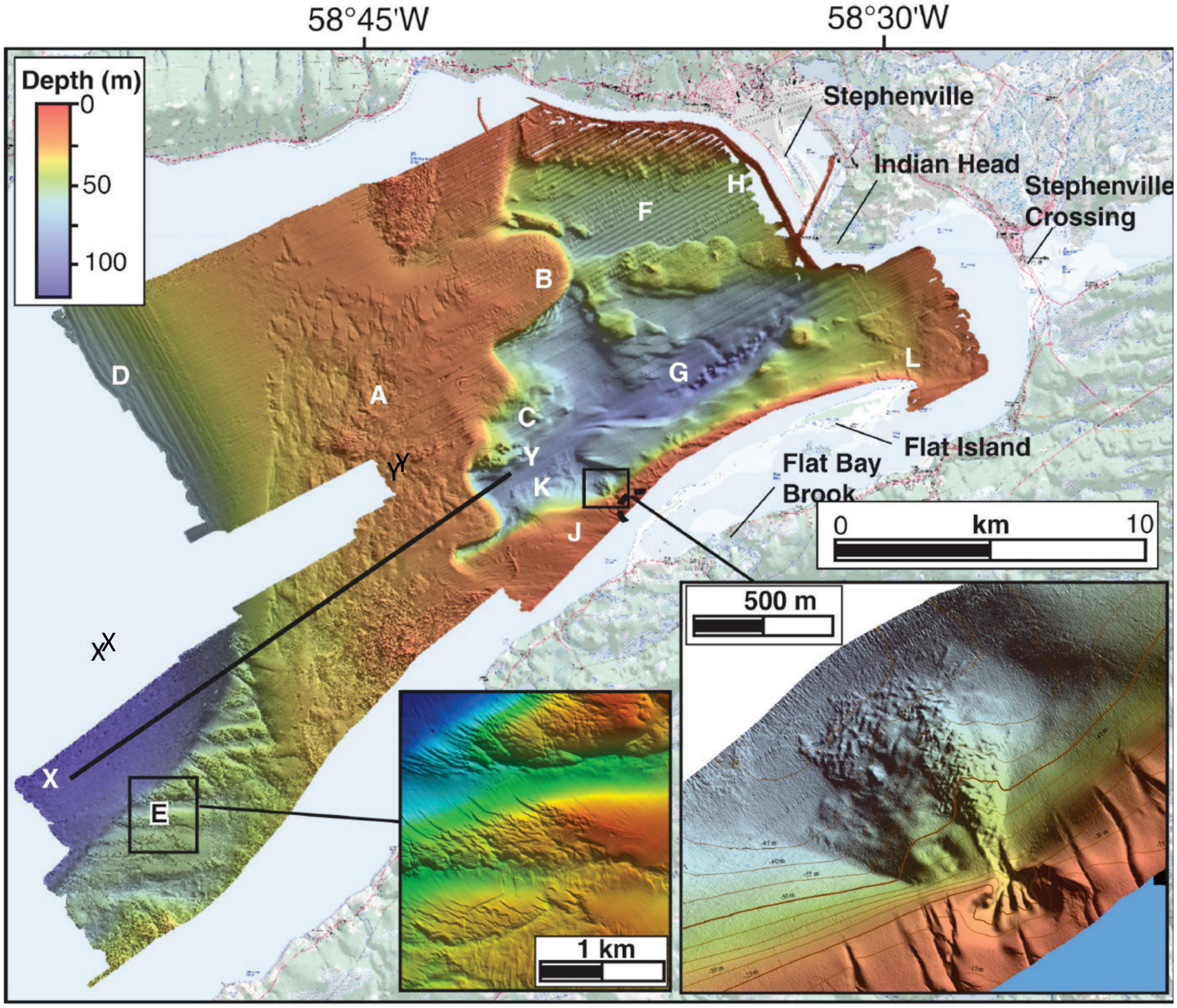


Figure 99. *Multibeam coverage in this region. Location for seismic profile X – Y in Figure 97 shown. Letters discussed in the text. From Shaw and Potter (2015).*

FAVOURABLE FACTORS, POTENTIAL CONSTRAINTS, AND HAZARDS

- Large areas of Quaternary sediments that can be thick and relatively low relief.
- Much of the sedimentation is till, however large packages of sand and gravel exist.
- Pro- and post-glacial muds show evidence of instability via gas escape.
- Salt diapirs and associated bedrock deformation exists, although salt is deeper than in region 4.
- Sand and gravel are mobile in shallower waters indicated by bedforms.
- High occurrence of mass wasting from steep slopes formed in sand and gravel.
- There is a high proportion of low-relief, sedimentary coastlines in the region.

Region 23: Cape Ray Shelf

SUMMARY

The inner Cape Ray Shelf is relatively narrow, with a coastline characterized by a wide suite of sedimentary features including broad tidal deltas, eroding bluff headlands, and some of the most extensive coastal dunes in Newfoundland. It is characterized by an active inner shelf canyon, several extensive, thin sand sheets and prisms (some shore-attached and some not, some with bedforms and some without), ice contact sediments, and a geologic contact between high relief deformed and folded sedimentary rocks and low-relief crystalline basement rocks, widely exposed.

Favourable factors for foundation emplacement include: large, low relief sand sheets exist; bedrock can be flat, low relief; bountiful data exists

Constraints for foundation emplacement include sediment starvation of sand sheets, with potential losses to deeper water; sands may be thin; high relief bedrock is common

Key readings include Shaw and Potter (2015), who provide a thorough overview of this region, and Shaw et al. (2019) with a recent analysis of the area covered by a high resolution multibeam-LiDAR mosaic dataset.

GEOLOGY

Geomorphology The coastline and inner shelf of this region is quite linear in a north-south orientation (Fig. 100), contrary to the regional geology which is characterized by northeast trending faults. Coastlines are characterized by sandy barrier beaches off the Codroy River valley, which also supply well developed tidal deltas. In the south, bluffs of glacial sediments erode to form sandy beaches, back-barrier lagoons, and extensive coastal dunes. The inner shelf is narrow, with the 100 m isobath extending no more than 7 km out from the coast, narrowing in the south. The shelf is characterized by widespread bedrock exposures, thin sheets of mobile sand, and a submarine canyon similar to those found elsewhere on the edge of the continental slope. Sea level in this region remained below present from deglaciation to present, with a lowstand of ~-30m occurring in the early Holocene (Shaw and Forbes, 1995).

Bedrock This region crosses the Humber (north) and Dunnage (south) tectonic zones, and bedrock is characterised by primarily Carboniferous sedimentary rocks in the north that is expressed in high-relief, deformed and folded ridges of sedimentary beds exposed at the seafloor. Further south, Proterozoic/Paleozoic basement rocks are commonly exposed, and are primarily crystalline which tends to be lower relief, with flat tops and deep fracture surfaces at high angles to each other (Figures 103, 104). Bedrock geology becomes more complex in the Cape Ray fault zone (Figure 104).

Surficial sediments Bedrock exposure is common in this region. Where Quaternary sediments occur on the seabed on the shallow inner shelf, they often form a thin drape over bedrock – a stark difference from the deep nearshore formations of sand and gravel associated with nearby sedimentary coastlines discussed in nearby Region 22, St. Georges Bay. Sand thicknesses are estimated to be as much as 2m thick north of Cape Ray and 10m thick (maybe more) immediately south (Figure 104). Further seaward, where they exist, a veneer of high-backscatter glacial sediments (presumably till, e.g. Fig. 101)) grade into glaciomarine and postglacial mud that thicken with depth (Figures 102, 103).

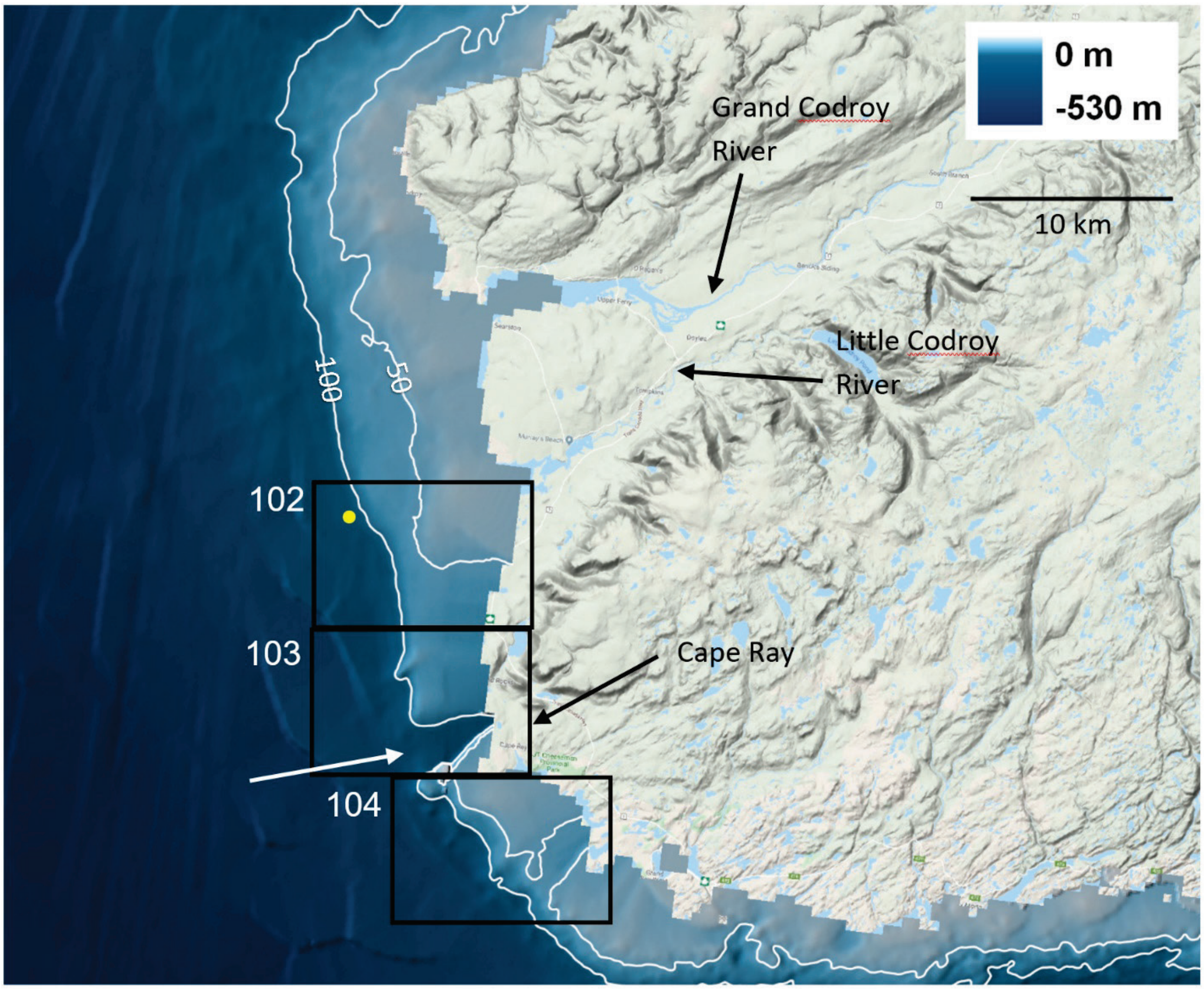


Figure 100. *Bathymetry of the Cape Ray Shelf, with 50 m and 100 m isobaths. Yellow dot is approximate location of figure 101, and boxes show location of figures 102, 103, 104. Note the deep trough highlighted by the white arrow is an exaggeration of the Cape Ray canyon, an artefact of the poor resolution Atlantic Canada-scale bathymetry data used, as evidenced by the higher resolution data used for Figure 103.*

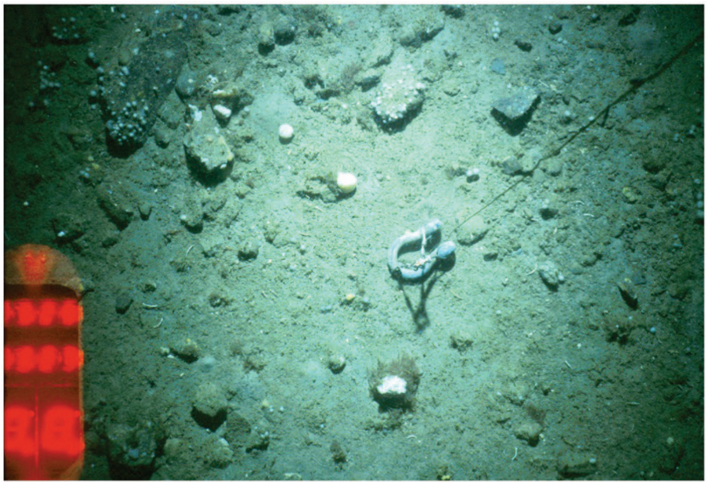


Figure 101*. Representative photo (GSC photo 7377_287_15 taken on Hudson 95006 of angular gravels on sandy sediments. Photo location Figure 1. Photograph by the staff of the CCGS Hudson. NRCan photo 2020-244.*

PRINCIPAL GEOMORPHIC REGIONS

Shallow waters in this region are divided into four geomorphic regions, each with a unique morphology, stratigraphy, and surface texture:

- *Exposed bedrock (north):* Bedded sedimentary bedrock in the northern section of this region is expressed in shallow (50 m depth and above) waters as ridges that have relief of 1-2m and sand and gravel between the ridges (A in Figure 102). The bedrock is highly deformed (a fold is clearly visible in Shaw and Potter (2015) Figure 18), but absent of large changes in topography (beyond a few metres).
- *Exposed bedrock (south):* South of what is assumed to be the seaward extension of the Long Range Fault (Figure 102), crystalline rocks dominate the bedrock exposed seafloor. These are reflected in generally flat topped, highly fractured surfaces with either no surficial cover or a veneer of sands and gravel, also found in the deep fractures.
- *Sand sheets:* Areas of low backscatter and a smooth, low relief seabed are interpreted as sand sheets and prisms. Some are attached to their sediment source, e.g. through nearshore bar systems (Figure 102 E,G; Figure 104), and some are detached (e.g. Figure 102 F and Figure 103). Bedforms (e.g. submarine dunes) are uncommon or absent. Sediment thickness ranges from a few metres to possibly 20 m.
- *Deeper glacial and postglacial sedimentation:* In a seaward gradient, generally below depths of 50 m, till then glaciomarine/postglacial sandy muds form a thickening sequence of sedimentation. Small De Geer moraines are possibly observed in Figure 102C, and relict iceberg scours are found at greater depths (Figure 102M).

VIGNETTES

1. North end of multibeam-lidar coverage – deformed bedrock and sediment gradient

South of the outlet for Little Codroy River, bedded sedimentary bedrock dominates the seafloor at depths shallower than 50 m (Figure 102 A). The Long Range Fault is probably represented at the southern boundary of this bedrock exposure and several smaller faults are visible (note that (B) is an artefact). Probably De Geer moraines with relief of 1.5 m about 40 m apart (C) are formed in till and were preserved as they were below the postglacial lowstand. Sand bodies are thin and low relief and are shoreface-connected (D, E) through nearshore bars (G, H) or separated by a zone of bedrock (F). Bedrock anchors one of the bar/beach systems (J). With depth, till is imprinted with relict iceberg scours (M) and postglacial sandy mud overlies glacial deposits (N).

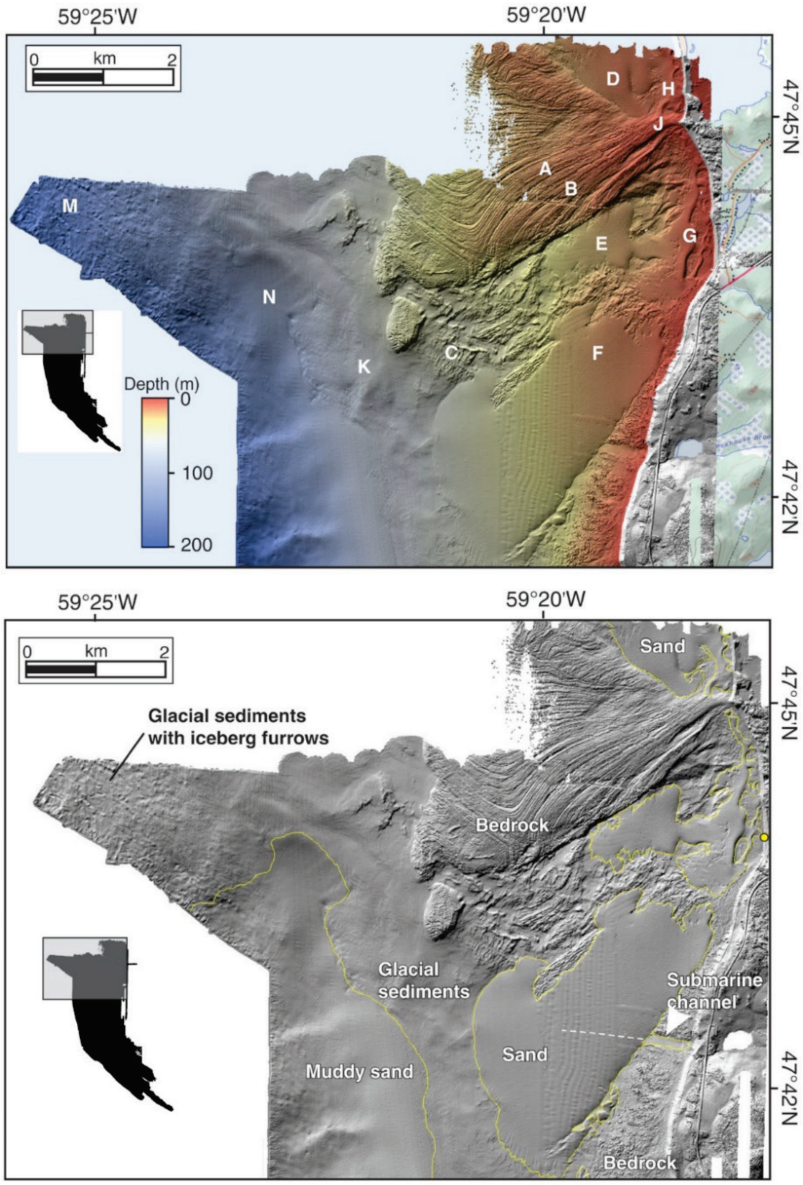


Figure 102. Northern end of the data coverage, location in Figure 100 (From Shaw and Potter, 2015). (Top) letters described in text. (Bottom) Geological interpretation of seabed. Note the white dashed line is inferred to be the continuation of a submarine channel buried by a migrating sand sheet (F – top).

2. Centre of multibeam-lidar coverage – Cape Ray canyon

Further south, crystalline bedrock dominates the nearshore and inner shelf seaward for about 2-3 km except for a large offshore sand body separated from the coast by 100 m (Figure 103A). Estimated to be 2 m thick, it thins seaward to interfingered sand (high points) and gravel (depressions) that suggest sediment starvation – sand being eroded into the canyon system (seaward of (B)) through sediment movement down the canyon and (presumably) landward canyon headwall erosion. For further discussion of this canyon, termed the Cape Ray submarine canyon, see Shaw and Potter (2015) and Shaw et al. (2019). (C) shows a separate, small nearshore bar/barrier system at Bear Cove.

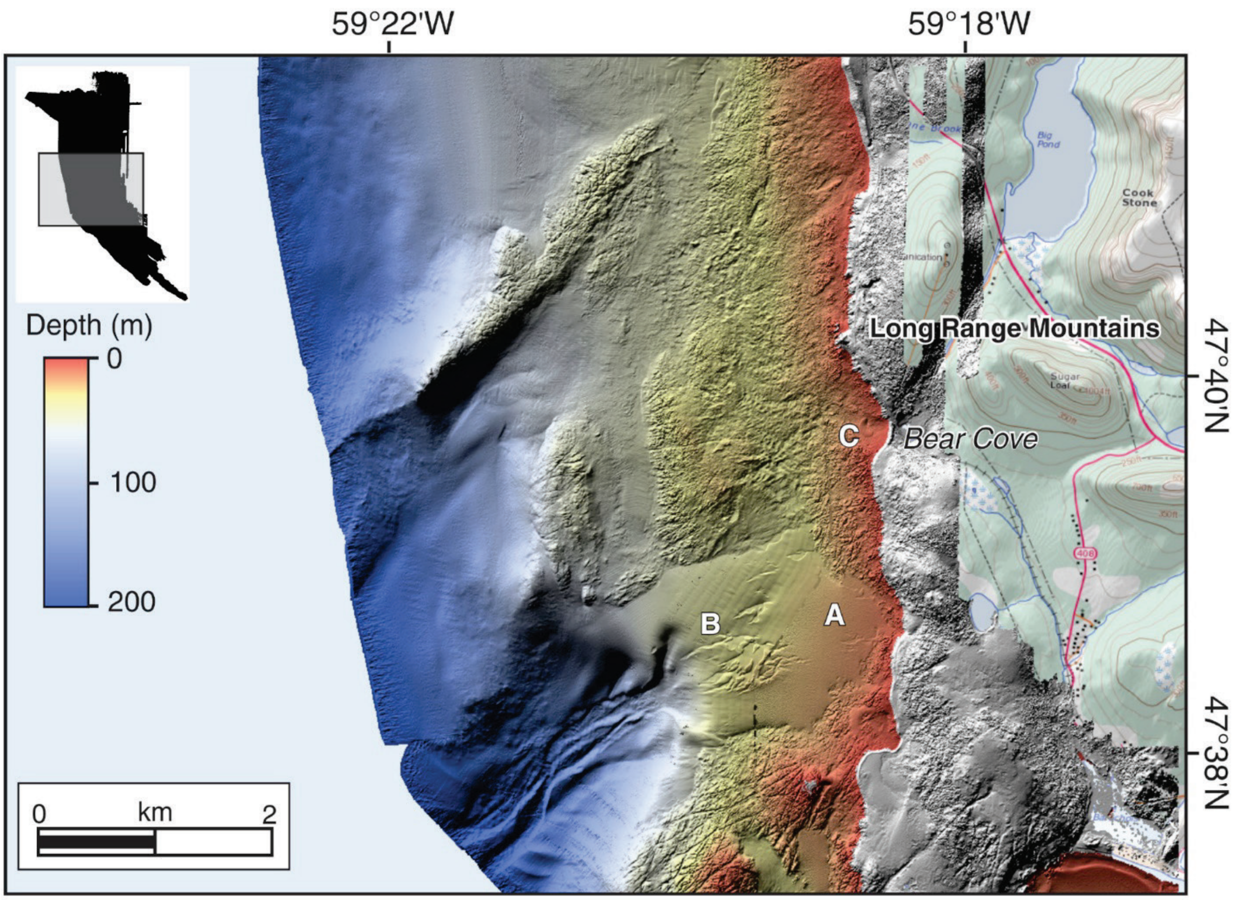


Figure 103. Centre region of data coverage, location in Figure 100 (From Shaw and Potter, 2015). Letters described in text.

South end of multibeam-lidar coverage – Offshore sand deposits

The Cape Ray fault zone (two black dashed lines, Figure 104) separates crystalline rocks in the north from gneiss in the south, with a variety of lithologies found in the fault zone (between the two black dashed lines). Large onshore stores of sediments (dunes, beaches, and inlets) are connected in places to large stores of nearshore sediments, including a 1.5 m high bar (near the X end of the profile in Figure 104) and a large prism of sand that may be 20 m thick and gradually sloping seaward (~ 1°) to 3km offshore, where the slope increases (~ 4°).

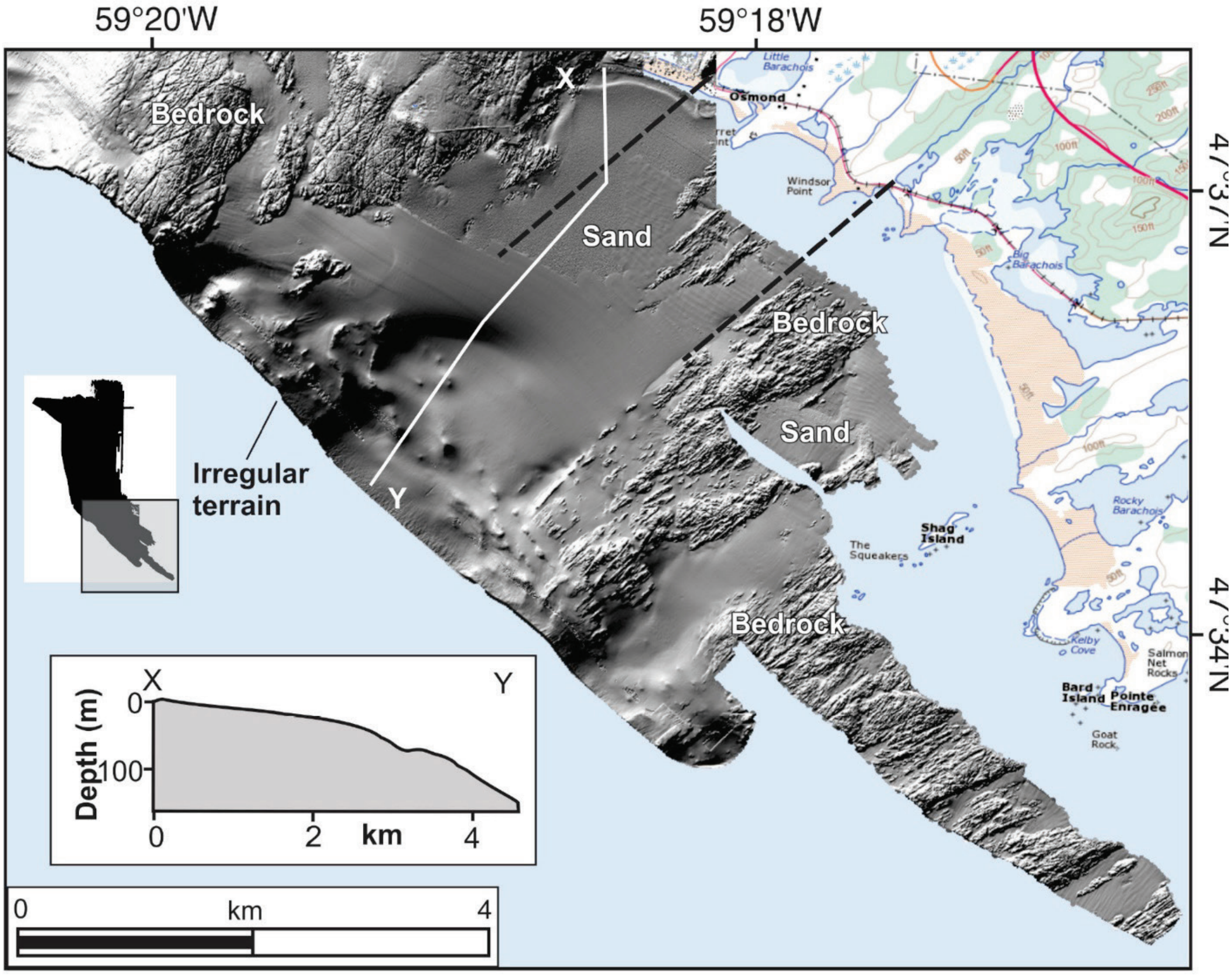


Figure 104. *Geological interpretation of the southern region of data coverage, location in Figure 100 (From Shaw and Potter, 2015).*

FAVOURABLE FACTORS, POTENTIAL CONSTRAINTS, AND HAZARDS

- Large sheets of sand are low relief, don't show evidence of high mobility (except for erosion at Cape Ray canyon) and exhibit (generally) gentle slopes.
- Bedrock can be low relief, flat, and hard in the south where crystalline rock prevails.
- Sand and gravel can be sediment-starved with loss through canyons and lack of input.
- Sand sheets are mostly thin (on the order of metres) however a thicker unit in the south exists.

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