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MINERAL RESOURCE ASSESSMENT OF THE SHALLOWEST BEDROCK AND OVERBURDEN, LAURENTIAN CHANNEL, NEWFOUNDLAND: POTENTIAL MARINE PROTECTED AREA

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ABSTRACT

A proposed Marine Protected Area (MPA) has been identified for a large portion of the eastern flank of the Laurentian Channel by the Department of Fisheries and Oceans (DFO) and has been designated as what is referred to as an Area of Interest (AOI) leading to a minerals assessment by Natural Resources Canada (NRCan). This report will examine the shallowest bedrock and overburden within the AOI. It complements a full assessment of deeper resources, mainly hydrocarbons, which is presented under a separate report. New and previously published maps, cross sections, and sample analyses showing the distribution of the bedrock subcrop pattern, the locally thick Quaternary overburden, and the surficial geology are presented with the aim to document the geological conditions more completely than previous compilations. However, conclusions regarding potential resources are derived much more from inferences than from direct sampling.

Carboniferous bedrock in the Sydney Basin has been shown to be coal-bearing across a very expansive area. However, given ephemeral economic viability of onshore and offshore coal mining in the Sydney Basin, these potential resources, despite very poor understanding of amounts, could only be important in a different energy/economic environment than presently foreseen. The Sydney Basin may be a significant producer of gas, given widespread occurrence of gas-formed pockmarks at the seabed and the very expansive basin (12 000 km^2 in the DFO AOI and 60 000 km^2 otherwise). Tills are voluminous, 75 m thick on average and locally hundreds of metres thick, with a volume estimate of 1250 km^3 of (mainly) till within the Department of Fisheries and Oceans area of interest boundaries. The numerous stacked tills result from the latest and retreat deposition phases of an ice stream and are broadly distributed in combination with relatively old tills that subcrop beneath surficial mud. Tills have mostly not been sampled and mineral assessment is by inference. Given the dispersive nature of the subglacial process and the successive erosion of older tills, together with the dominantly mud- rich character, probability of a resource is considered low. Muds overlying the till comprise up to 200 km^3 in the AOI, are better sampled but the analyzed suite of minerals suggest there is little that is unique or of economic value. Aggregate is practically nonexistent in the area as the AOI is consistently below the latest low-stand of sea level where, on the adjacent bank, sea-level rise resulted in large sand-dominated bodies. Geohazards are largely restricted to seismicity, and its side-effects, and potential natural gas escape at the seabed, but both processes have been more active in early post-glacial times than at present.

INTRODUCTION

Natural Resources Canada (NRCan) has been asked to provide a mineral resource assessment of the northwestern flank of the Laurentian Channel on the continental shelf of Eastern Canada. This is in anticipation of an Area of Interest (AOI) designation by the Department of Fisheries and Oceans (DFO), which can lead to declaration of a Marine Protected Area, with all the benefits but the mineral exploitation restrictions of such a designation. The deeper bedrock and hydrocarbon potential is considered in a seperate NRCan report (Hannigan and Eietrich, 2011) while the shallow geological conditions are considered here. The Geological Survey of Canada is currently updating the seabed and shallow subsurface geology through surficial mapping and shallow bedrock mapping. This new mapping is based on reinterpretation of existing (legacy) sonar data of various types, much of it dating back to the early 1970s but well supplemented with similar but more modern data collected under several expeditions on CSS Hudson, beginning in 2003 and up to 2010.

The proposed MPA is almost entirely restricted to the flank and deeper waters of the outer, eastern flank of the Laurentian Channel (simply "the Channel" occasionally in this report). The eastern boundary falls in water depths below the elevation of inter-glacial low-stands of sea level. This has a strong bearing on this minerals assessment because the paleo-coastal process of washing, sorting, and redistribution, which typically generated marine-based minerals of potential value, occurred only on the adjacent banks and not within the proposed MPA boundaries. Typically a marine minerals assessment considers a broad range of materials, including heavy minerals, precious metals, and aggregate. Most of the sampling and their analysis necessary to make a proper assessment is lacking. This is not an uncommon situation in marine areas with thick sediments. Instead, this report documents the state of knowledge of both the shallow bedrock and overburden, drawing conclusions regarding potential mineral potential mainly from general inferences about the deposits and their depositional or diagenetic processes.

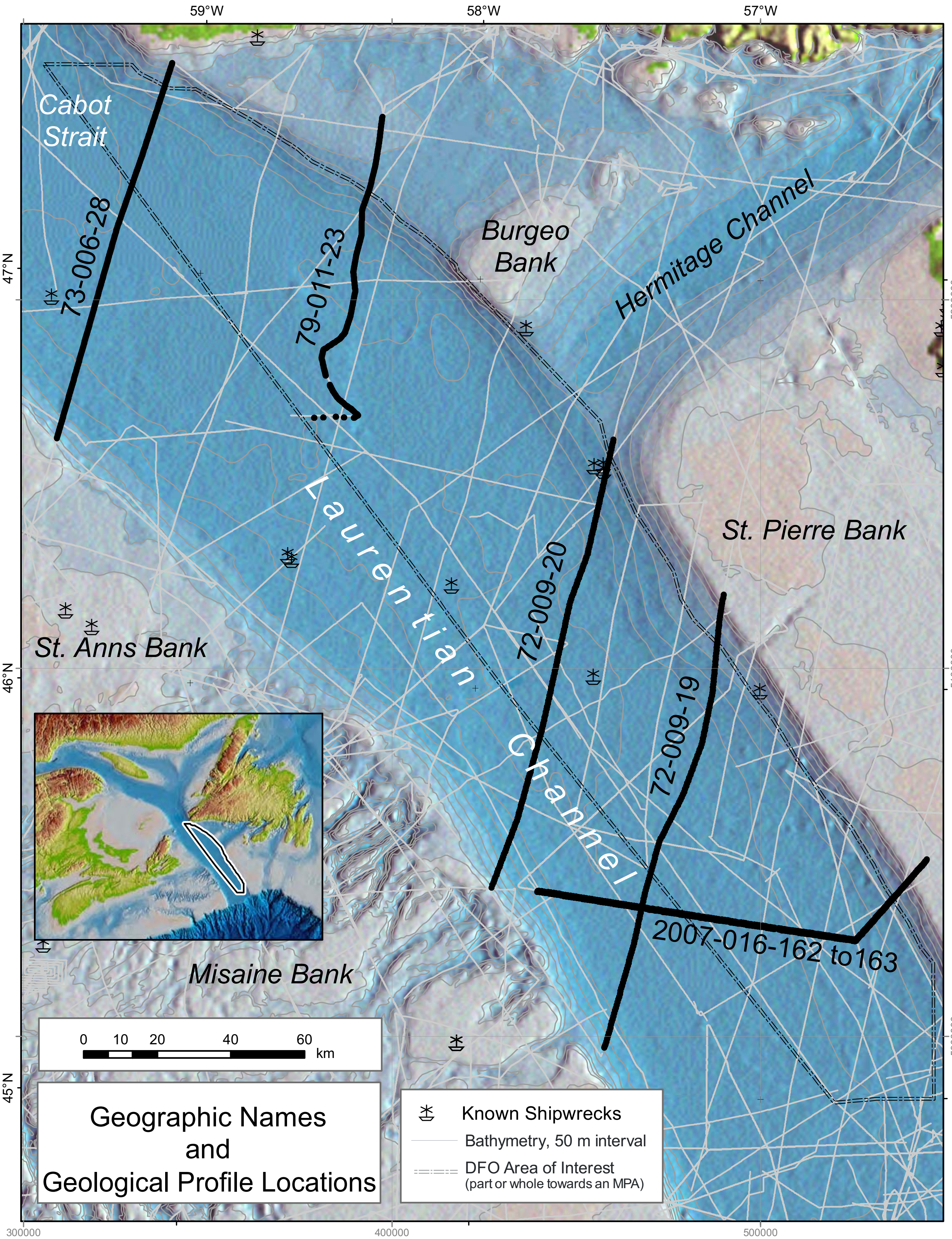


Figure 1. The Department of Fisheries and Oceans Area of Interest, local geographic names, geophysical traverse line control (white), ship-wrecks, and location of geological profiles (thick black lines with expedition/profile numbers) presented in the following figures.

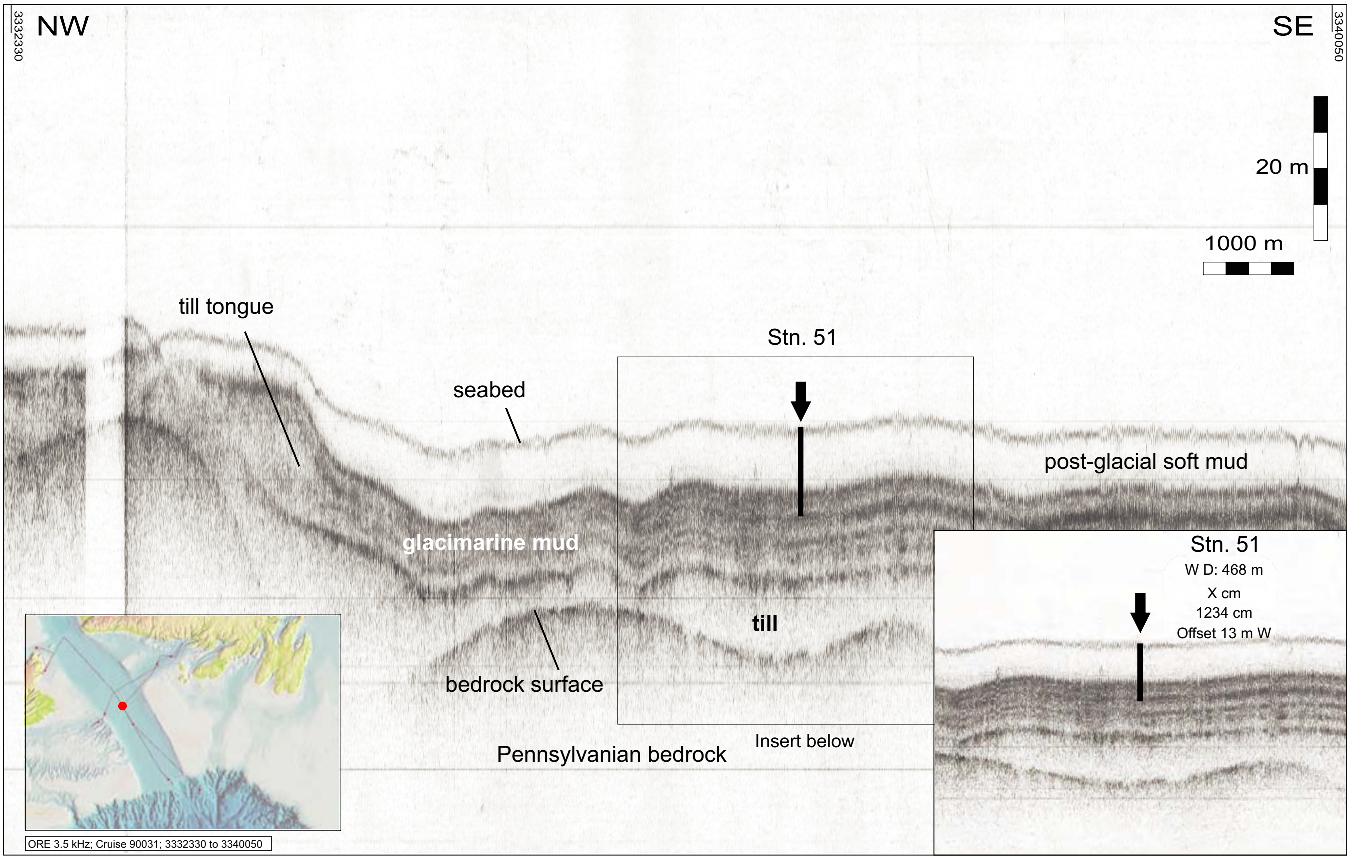


Figure 2. Expedition 90031, 3.5 kHz profile from western Laurentian Channel, immediately south of a moraine, showing typical acoustic character of the till (below the base of the core), glaciomarine mud (stratified), and postglacial mud (transparent). Location of the core is shown in the insert.

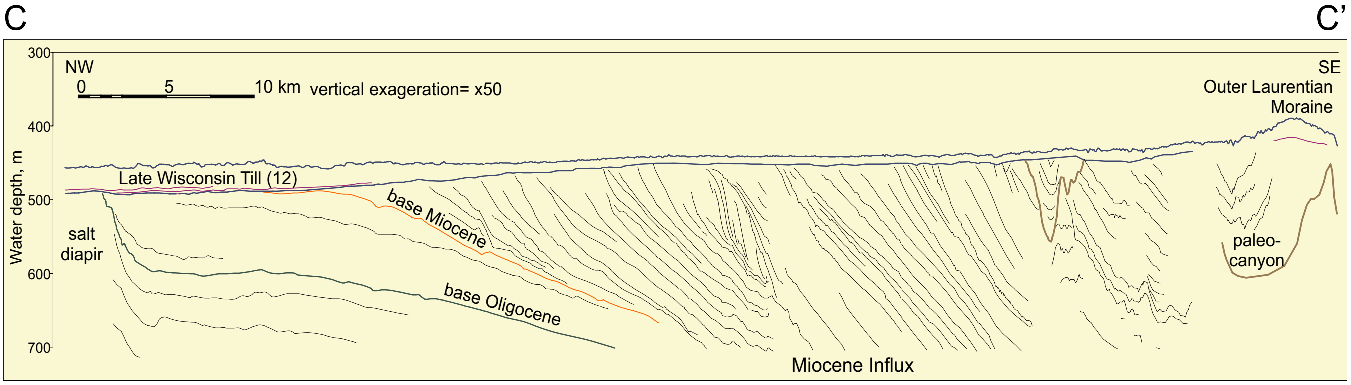
Map Illustrations

The map illustrations in this report are provided with switchable layers so that the reader can customize, simplify, and print through removing or adding attributes such as text labels, grids, contacts, symbols, legends, masks, etc. It is recommended that for these pages the reader activate the Adobe option “View layers and show/hide their contents”, located on the left panel and expand the relevant layers.

Data Set

The data set drawn upon for this report is varied, including legacy and relatively recent geophysical (sonar) and limited sample data, existing publications, unpublished databases of core analysis, surface and buried features derived from the geophysics, a recent but ongoing compilation of Quaternary stratigraphy of the Laurentian Channel from seismic data, an ongoing compilation of bedrock mapping and features, a recently completed compilation of the surficial geology and unpublished technical reports for industry and other government departments covering smaller parts of the region (King, 2010b). The author has had major responsibility for most of the latest compilations that appear in this document; many are custom map compilations and unpublished interpretations.

Geological profiles derived from interpretation of high- and lower resolution seismic profiles form the basis for the maps. Figure 1 shows the Laurentian Channel DFO AOI with some of the geographical names and location of a series of profiles derived from the lower resolution (air gun or sleeve gun) profiles crossing the Laurentian Channel. Most of the geophysical dataset is old technology, collected in the mid 1970s but nonetheless adequate. The profiles provide a sense of the type, coverage, and detail that can be extracted from such information. In addition, Figures 2 to 6 depict interpretations of a typical mix of old and new high-resolution profiles. These are critical for investigation of the seabed and shallowest geology, used for mapping, and the local setting of short cores and other samples. One set of seabed photographs at three locations along with limited video was collected in a joint DFO GSC-A cruise (2008015). Investigations were conducted within the present DFO AOI and reported (King, 2010a). These videos and photographs characterize the mud and epifauna for presumably large areas of the muddy seabed. Multibeam bathymetric data, which generally provide depth, topography,



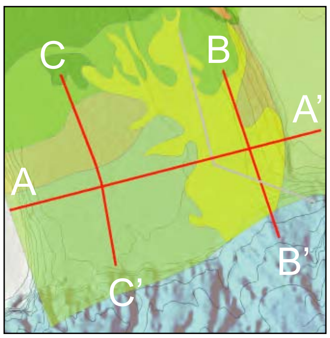


Figure 3. Geological profile from seismic data along line C- C' shown to the left. During the Miocene, a massive influx of sediment to the margin often manifest in prograding sheets, both here and beneath St. Pierre Bank. Although cross-cutting relationships with the canyon are not clear, it is assumed that the canyon initiated with this influx. Note the high vertical exaggeration in this presentation.

and sediment grain-size proxies, are the present standard for such marine mapping but this was entirely lacking in the region. Sample or ground-truth data (cores and grabs) are very limited but considered sufficient to generally characterize the area, given a relative homogeneity of sediment types at the seabed.

GEOLOGICAL SETTING

Bedrock Subcrop Setting

The term bedrock in this part of the report is defined as the rocks and strata below Quaternary age overburden. The older units comprise bedrock in its conventional sense, while much of the younger (especially the Cenozoic) is commonly poorly lithified, never having undergone great burial or extensive exhumation. The basic basin and platform setting of the outer Laurentian Channel is outlined in a separate report focusing on the hydrocarbon assessment of the region (Hannigan and Dietrich, 2011). The map in Figure 7 provides details of the overburden subcrop pattern of the basic bedrock subdivisions, based primarily on age. The original maps of King and MacLean (1976), Fader et al. (1989), and Sanford (1998) have been modified significantly in terms of subcrop distribution but little in overall concept. Exploration wells provide some crude age control (MacLean and Wade, 1992) for high-resolution seismic picks and Tertiary age differentiation in the outer Channel area. The new map also portrays the shallow structure of the strata in terms of strike and dip and regional faults and folds.

The oldest rocks are generally late Proterozoic acoustic basement (no internal structure visible), depicted in purple and pink tones on Figure 7. In the Laurentian Channel, the presumably crystalline rocks of the Burin Platform protrude up through the surrounding Pennsylvanian strata in a series of topographic highs. This is the eastern extension of Precambrian rocks on the south coast of Cape Breton and they are tentatively assigned a similar age affinity, but cross-cutting relationships only confirm a pre-Carboniferous age. The topographic highs mark approximately the southern boundary of the Carboniferous Basin even though, in central Laurentian Channel, they protrude through Pennsylvanian strata. Old, mainly crystalline rocks also mark the boundary of the Carboniferous Basin along the south coast of Newfoundland (Port aux Basques and eastward) but the Carboniferous strata generally extend to within a few kilometres of the Newfoundland coast.

The Carboniferous basin is very extensive, extending from land on Cape Breton to very near shore along much of the southern coast of Newfoundland and very limited exposures on the southern part of Newfoundland. A further eastward extension as far as the Eastern Shoals (51ºW, 46ºN) is suggested from seismic relations and an old exploration well (HERMINE E-94). Characteristic of the strata is a broad folding and upper angular unconformity. Dips are very shallow, typically under 5 degrees. However, acoustic profiling can only resolve shallow-dipping strata; instances steeper than about 10 degrees have reduced shot-to-shot coherency and are generally not resolved. Generally the angular unconformity has been modified (cut) to a very smooth surface, with a clear glacial sheet erosion character. Commonly the Carboniferous basin

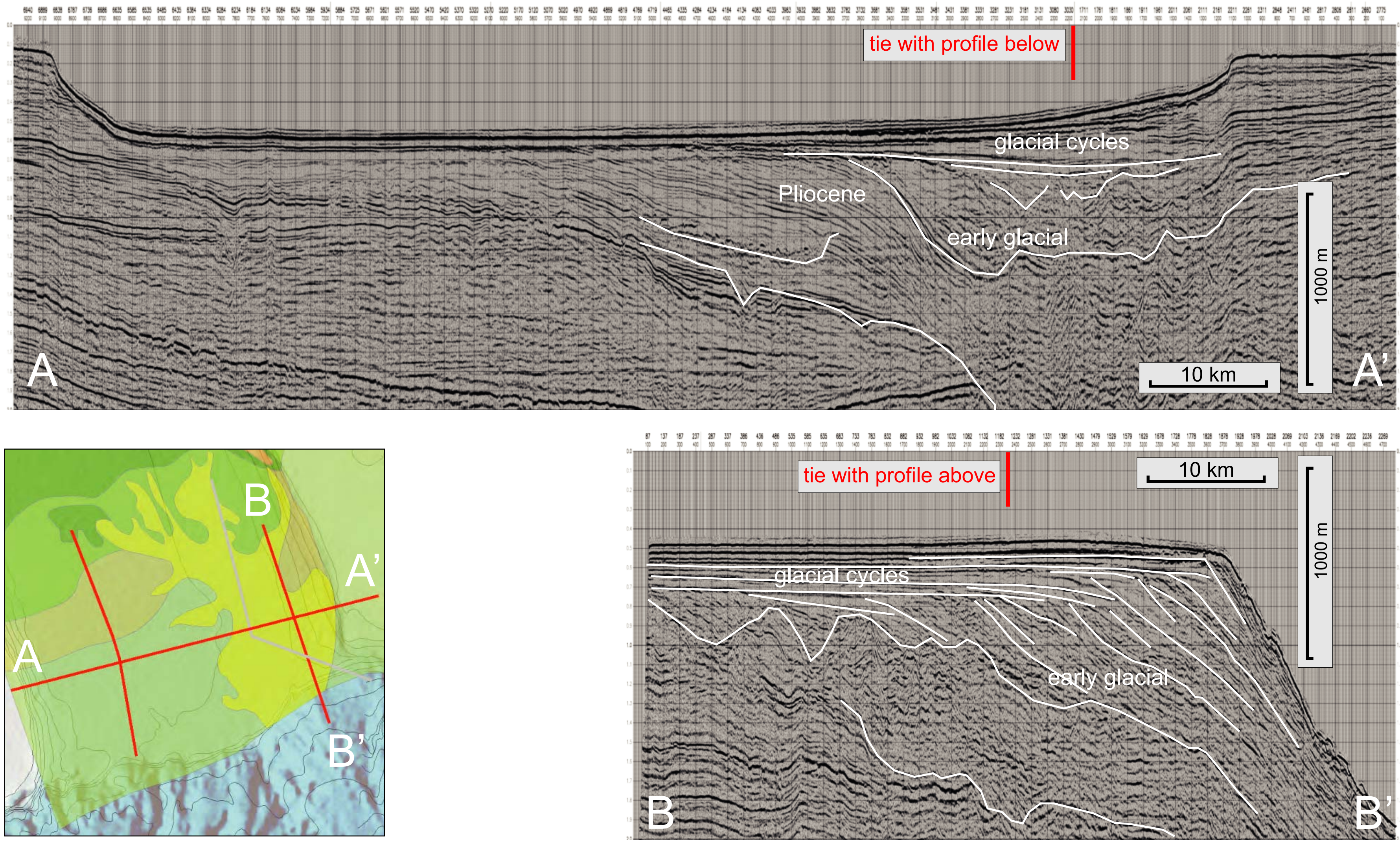
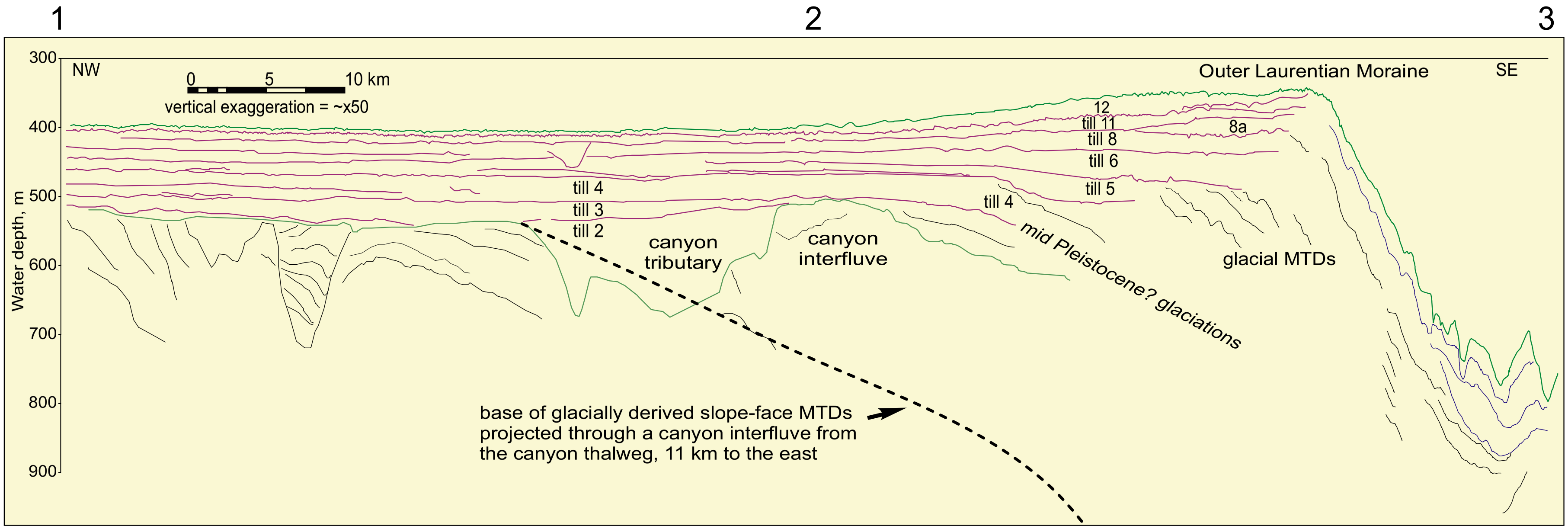
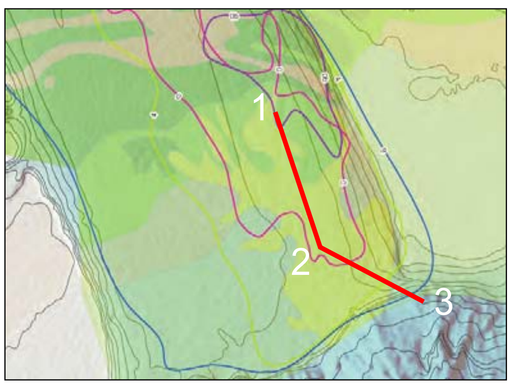


Figure 4. Multichannel seismic profiles help delineate various generations of cut in a large, previously unrecognized, canyon. It represents the response to large volumes of fluvial- and shallow shelf-sourced late Oligocene and Miocene supply from large prograding sheets (see Fig. 3). Near syndepositional incision reached 80 km into the shelf with a tributary system 50 km across and mouth and about1 km deep at the present shelf break. This is followed by abundant Pliocene infill. Multiple tills bound by flat-lying, bevelling erosion surfaces cut by successive ice streams help differentiate tills from sediments pre-dating glaciers reaching the paleo-shelf-break. The map at left traces the canyon at the stratigraphic level interpreted as base of glacial fill. The numerous glacial tills are better recognized on high-resolution sleeve gun (see Fig. 5) and mapped in detail, presented in figures that follow.





Mesozoic Ceonozoic bedrock subcrop and profile location.

Figure 5. This axial profile crosses near the deepest part of a Miocene-Pliocene canyon (light olive green at left) where the earliest glacial fill is buried over 800 m. The dashed line, marking the assumed base of Quaternary deposits, is derived from a tie with processed multichannel seismic traverse with deeper penetration than possible with single channel sleeve-gun (Fig. 4). An intervening canyon interfluve precludes stratigraphic continuity of the early Quaternary deposits along this path. Attempts to correlate with much better established chronology in the slope stratigraphy (many papers by D. Piper and coworkers), which was established through a hydrocarbon well on the shelf to the east, was less than satisfactory. Despite this, ties with till tongue chronology immediately to the east, off southern St. Pierre Bank (Piper et al., 2005) clearly show that MIS 12 glaciation (considered onset of frequent glaciations) is stratigraphically shallower than the deep canyon fill and more likely correlates with Tills 4 or 5, above. Here, the general style of the Quaternary deposit evolved from chaotic progradational mass transport deposits (MTDs) to dominantly aggradational unconformity-bounded stacked blankets with associated slope-situated MTDs. These thick, flat-lying sequences within an ice-stream setting are attributed to largely vertical aggregation of a subglacial slurry, analogous to a deforming till, envisioned conceptually by R. Alley and coworkers in Antarctic examples.

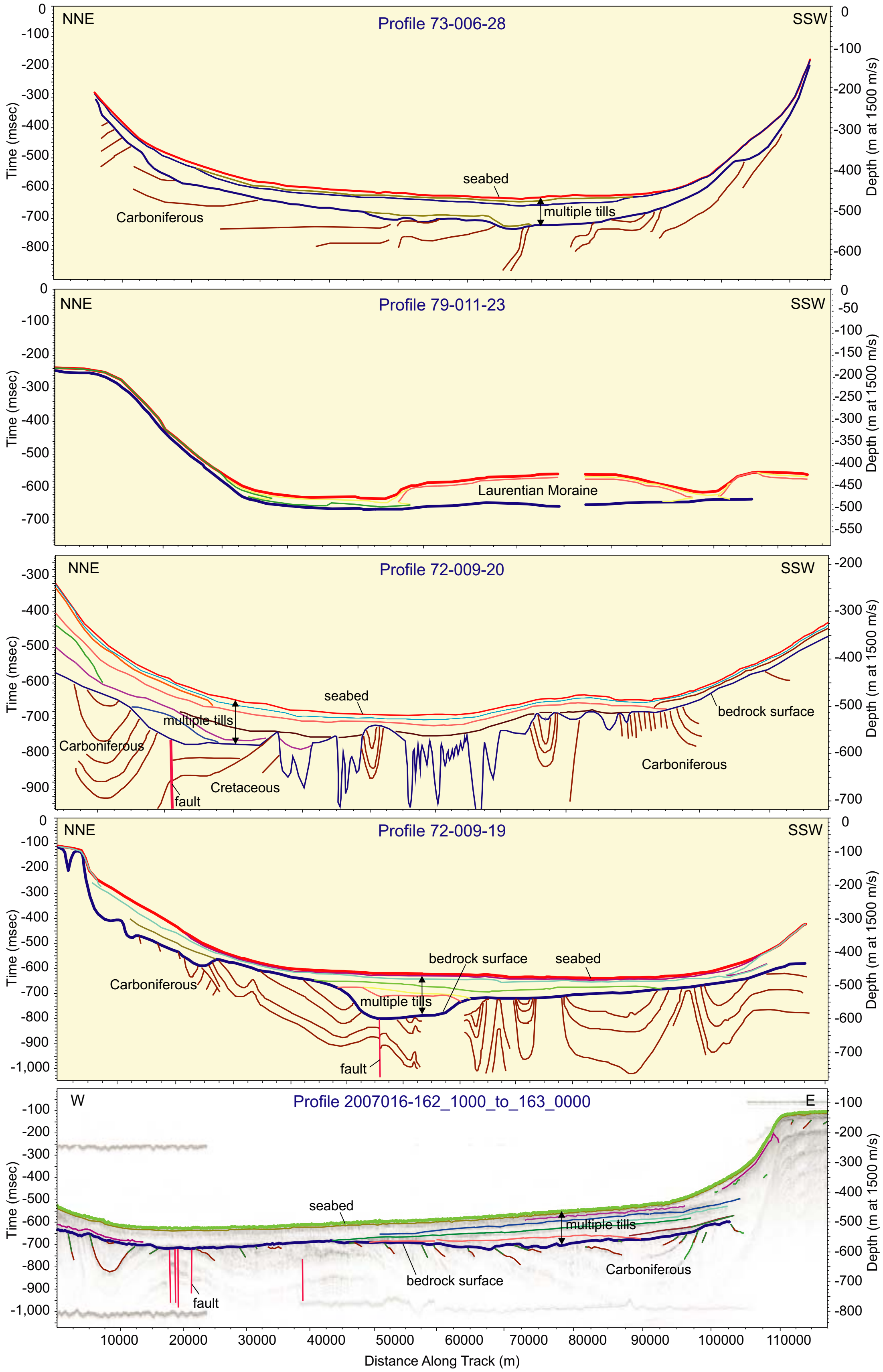


Figure 6. Geological profiles across the Laurentian Channel from north (top) to the south (base). The following maps are based mainly on cross-sections such as these where broad bedrock units and multiple Quaternary stratigraphic units are differentiated. Profile locations are shown in Figure 1.

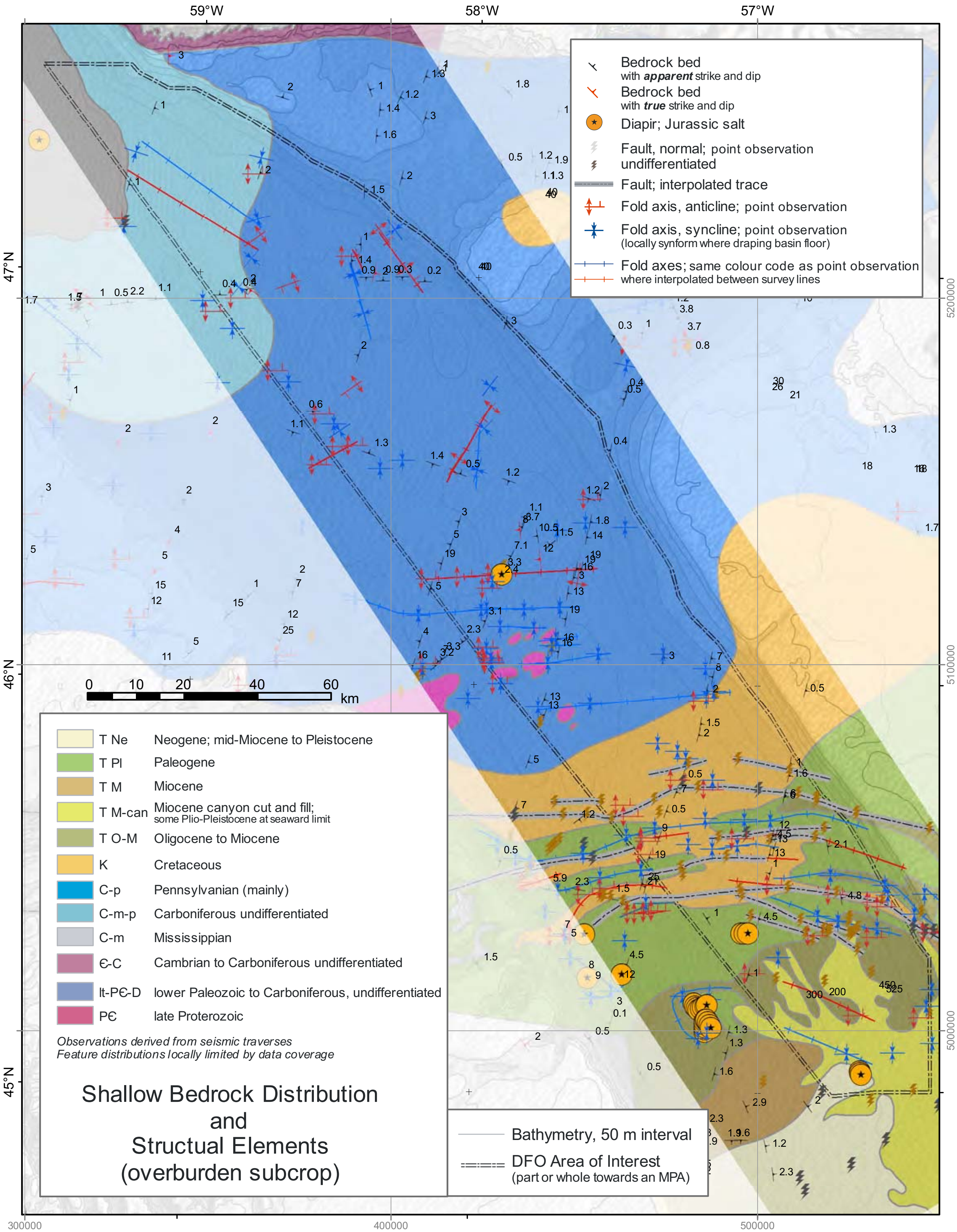


Figure 7. Bedrock subcrop pattern and structural elements.

flanks onlap older metasediments and crystalline rocks, where seismic character of the Carboniferous strata diminishes to the point that the contact is difficult to distinguish. This is assumed to be due to tighter and unresolved folding (strata are too steep) and possibly more prevalent faulting. Attempts to extrapolate and correlate fold axes between widely spaced seismic tracks are met with some success, but in many locations this is not possible. The southern basin flank on the Burin Platform has axial trends paralleling the high (east-west) but compression orientation may swing more than 90 degrees towards the north (Fig. 7). The Carboniferous strata are coal-bearing and this has long been exploited in the Sydney Cape Breton area, including a few kilometres sub-sea. Differentiation of Mississippian and Pennsylvanian strata is based on extremely little hard data; Pennsylvanian grey and green sandstone and siltstone with carbonaceous stringers were sampled in Placentia Bay (King et al., 1983), and Mississippian far to the east in an old exploration well (Grand Banks Corehole #10). Without clear structural trends the mapped Mississippian-Pennsylvanian contact is poorly defined. The generally circular subcrop pattern of Mississippian strata in Cabot Strait (based mainly on the map of Sanford and Grant, 1990) suggests greater glacial erosion, but the contact trace is not well constrained. Carboniferous strata subcrop in over half of the DFO AOI, covering nearly 12 000 km^2.

Mesozoic coastal plain sediments overlie the Carboniferous strata almost everywhere in a seaward (south and southeast) direction but it is suggested in the updated map that rare outliers are also present to the north on top of the shallow banks on both sides of the Laurentian Channel (Burgeo and St. Ann’s Banks; Fig. 7). These have not been sampled and distribution is only based on unconformable relationships with the underlying Carboniferous strata and internal seismic character. Mesozoic sediments are thin compared to the massive influx of Cenozoic sediments. A stratigraphically higher pick on the Cretaceous-Tertiary seismic boundary, based on better quality and data coverage, and an attempt at differentiation of the Paleogene deposits, represents a significant improvement on the original map. The faults following the southern flank of the Burin Platform are now much better delineated. The largest is a complex associated with the Chedabucto Fault system extending across Nova Scotia, following a path south of Chedabucto Bay and extending across the Channel where it swings east-southeastward below St. Pierre Bank, not paralleling the Laurentian Channel flank as depicted on the original map. It has a throw of nearly 100 m locally. Many of the northern flank faults of the Laurentian subbasin parallel this major fault system and are recognized on the high-resolution air-gun profiles that image the upper few hundred metres sub-seabed. They control the subcrop pattern of the T-K boundary, throwing up the older strata and creating mini-basins for the Paleogene sediments to fill. Otherwise, faulting around salt diapirs and upturning has modified subcrop patterns locally.

A large, filled canyon system near the mouth of the Laurentian Channel has recently been recognized (Figs. 4, 7). It represents the response to large volumes of fluvial- and shallow shelf-sourced, late Oligocene and Miocene supply from large prograding sheets located both within the channel and to the northeast, below St. Pierre Bank (Fig. 3). Incision in the upper reaches of the canyon stretched 80 km into the shelf with a tributary system 50 km across cutting as deep as Cretaceous strata. The canyon mouth is cut to about 1 km deep at the present shelf break location (Fig. 4). Cross-cutting relationships suggest a Miocene age for initial cutting, perhaps at the mid Miocene unconformity event (MacLean and Wade, 1992), but an evolution of cutting extending into the Pliocene is recognized and lower canyon deposition is nearly synchronous with tributary cutting in a thick Pliocene infill (Fig. 4). The canyon eventually became a major Quaternary depocentre, a subject discussed in more detail in a following section of this report. Other smaller and poorly mapped canyon heads are present at the Channel mouth but not within the DFO area of concern.

Mineralization in Bedrock

An economic assessment of the bedrock, mainly its Hydrocarbon resources, is covered in a separate MERA report (Hannigan and Dietrich, 2011); the shallowest extents are considered here.

A complete and locally very thick overburden (over 50 m, commonly over 100 m) acts to restrict accessibility to the bedrock from an engineering viewpoint. This inaccessibility also greatly limits ability to assess economic mining potential of the bedrock. Any conventional precious or base metal mineralization is assumed to be restricted to the crystalline and metasediments. Nothing is known about specific lithologies or diagenesis and the nearest onshore affinities are much too distant to speculate about mineralization similarities. Subcrop area within the DFO zone is about 100 km^2 but overburden is at least 20 m and locally over 100 m of (mainly) till (Fig. 7).

Extensive Coal-Bearing Carboniferous Strata and Shallow Gas

The presence of shallow gas-related features, in the upper 100 metres or so below seabed, demonstrates that coal and related gas is present within the AOI boundary but its distribution and magnitude are very poorly understood. This could only be regarded as a stranded energy source under the present world energy setting; even the land-based and coastal sub-seabed exploitation of this resource has suffered repeated closures in the Sydney, Cape Breton area.

Coal-bearing strata are confirmed farther basinward than the Sydney area coal mines in wells just east of Sydney (Hacquebard, 1986). Coal is possibly very extensive and is at least present locally at the basin's northeast flank as indicated by its presence in both short rock cores in Placentia Bay (King et al., 1983) and Quaternary glacial sediments sampled with short cores in Placentia Bay and north of St Pierre Bank. The large extent of the basin (12 000 km^2 in the AOI alone) and indications of coal suggest there may be world-class coal resources here.

Extensive pockmarks, which indicate post-glacial seabed seeping of natural gas, attest to hydrocarbons, from either or both coal gas and other sources. However, the source of this seepage is not clear; methane from the coal measures is likely yet pockmarks are also known in areas over non-hydrocarbon rocks (generally within fjords) with only glacial sediment decomposition as a source. There are few other direct indicators of gas presence in the shallow subsurface but both ultra high- and high-resolution seismic sources show some areas with minor gas accumulation. The extent of such gas is not well documented; pockmarks can only record seepage where post-glacial soft muds at the seabed record the events through erosion and dispersion by currents. There is a complicating factor in that recognition of pockmarks with profiler data alone is tenuous; most of the Laurentian Channel has no side-scan coverage due to deep water, so the round or oblong cones visible in plan view can be confused with purely current-generated erosional notches or "V"s in profile view. A transition has been established between true pockmarks over the Carboniferous Basin and nearly exclusively erosional or non-depositional depressions over the Cenozoic strata, farther southeast toward the mouth of the Laurentian Channel. Here, the depressions in the surficial mud reach down to an ice-scoured and fluted till surface and their pockmark affinity is questioned. No studies have demonstrated the history or present seepage rate of gas. The presence of pockmarks only indicates post-glacial gas seepage (post ca. 11 000 yrs) but the flux with time is unknown. Conceivably gas or hydrates could have assembled and been temporarily inhibited from leaking under full continental shelf glaciations only to be released at an accelerated rate immediately following deglaciation.

Displaced Jurassic salt nearly reaches the subcrop bedrock surface at three known sites in the AOI (Fig. 7). Here, overburden is as little as 20 m at the northernmost diapir but over 80 m at the other two sites. Economic value is assumed to be negligible (hydrocarbon potential excluded).

Cretaceous strata are covered with only 20 m overburden over a small area along the eastern flank of the Channel but elsewhere coverage exceeds 100 m. No known wells intersect these strata in the area but elsewhere they comprise poorly lithified siltstone, sandstone, and mudstone. About 50 below the top is a seismic marker bed, the Wyandot Chalk, at least 30 m thick locally. As stated earlier, these beds are up- and downthrown along an east-west trend. Salt and gypsum might be present. A land-based outlier of Cretaceous sands in Nova Scotia contains clean quartz presently being exploited but there is no information if they are extant in the AOI.

Quaternary (Overburden) Deposits

The Laurentian Channel form evolved into a shelf-crossing trough generated primarily from multiple glaciations. Recent investigations show that the present channel was likely initiated by inheriting a preglacial low-stand drainage system along the southeast flank of the present form. This drainage system terminated in the large Miocene-Pliocene shelf-edge canyon. Much of its present form developed through cutting into bedrock strata on the floor and depositing and partially cutting of older glacial deposits on the flanks and outermost Channel. This gradually evolved through time to a more straight and narrow channel. While the adjacent banks see only short-lived preservation of relatively thin Quaternary deposits, the Channel has experienced local long-term preservation, building a stratigraphy locally hundreds of metres thick. This is especially so along the outermost eastern channel flank and channel floor. On the floor, accommodation space provided by the Miocene-Pliocene canyon allowed many glacial cycles to deposit direct glacial-fed, chaotic progradational mass transport deposits (MTDs) followed by multiple aggradational (till) layers (Figs. 4, 5). On the flank, a combination of glacial feeding from Halibut Channel and St. Pierre Bank has deposited a series of tills and related material that are only partially preserved; successive ice stream-dominated glacial cycles bevel the flanking deposits (Fig. 6), leaving only remnants but in the long term, create a narrower and straighter channel flank.

Multiple Buried Tills

Figure 8 shows the distribution of a series of unconformity-bounded till units, 18 differentiated here. These are so numerous that their succession and distribution is also provided in an expanded, stacked display of the succession in Figure 9. Still more late tills lie above the uppermost mapped here, but just north and west of the DFO AOI boundary. Though a long succession of gla-

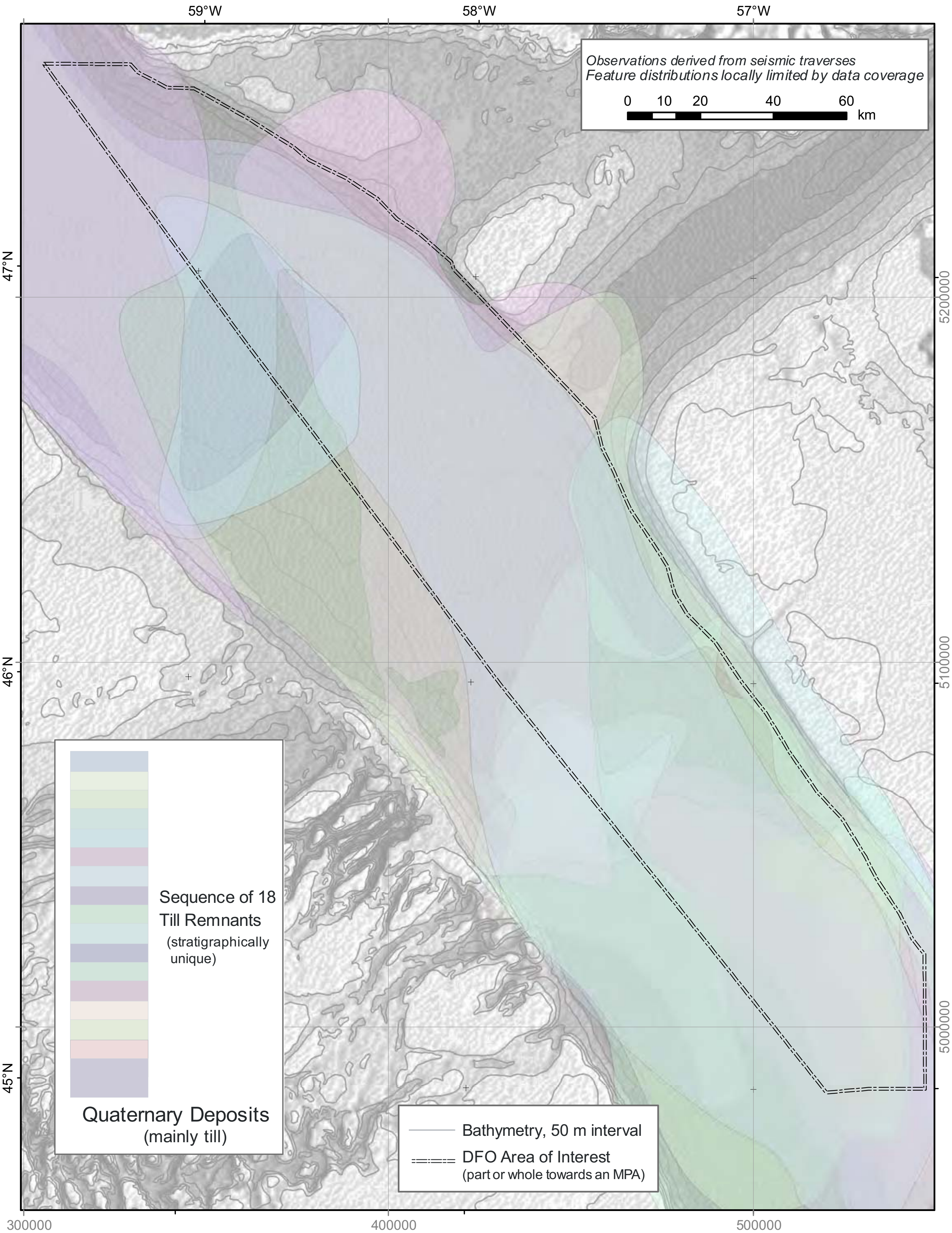


Figure 8. Distribution of a sequence of 18 till units.

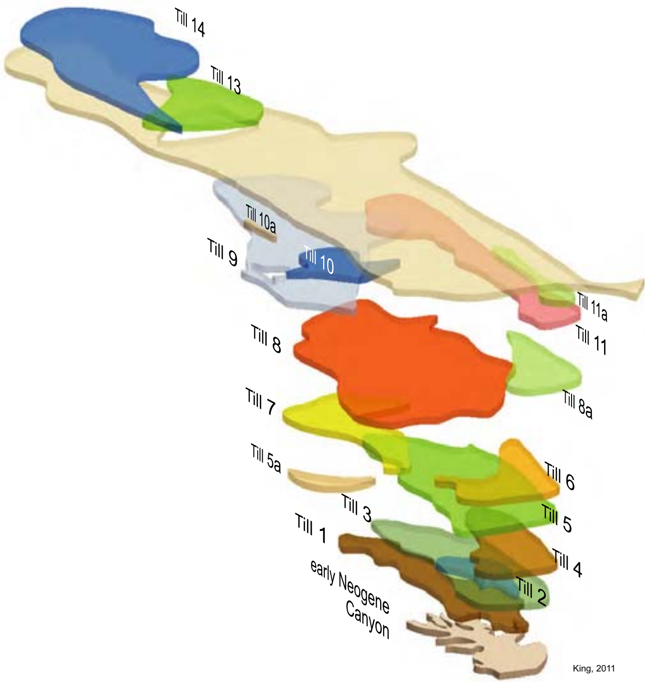


Figure 9. Expanded display of the main stratigraphic units in the outer Laurentian Channel. A Miocene-Pliocene canyon provided a path and accommodation space for the earliest preserved glaciation record, Till 1, possibly of late Early Pleistocene age. Successive tills represent glacial cycles, stadial-interstadial events and at least, for the uppermost two tills, still-stands and re-advances of a Laurentian Channel ice stream during deglaciation. Based on stratigraphic mapping by M. Pitts and E. King.

cial deposits is represented, likely spanning the entire mid and late Pleistocene, this does not necessarily represent fully18 glacial cycles. Some of the till blankets represent full glacial-interglacial cycles, some stadial-interstadial cycles, and some through auto-cyclic glacial regime-induced still-stands and retreats related to ice-stream behaviour.

Figure 10 shows a retreat pattern with approximate ages as deciphered by Josenhans and Lehman (1999). Though this follows generally the present understanding, the new mapping and dating of recently collected cores will provide the basis for some adjustment, especially in the outer mouth of the Channel. Figure 11 shows the distribution of the tills as they subcrop the late and post-glacial muds; most of the area is covered by the latest tills.

Pre-glacial and post-glacial stratified mud, which dominate the latest inter-glacial cycle and are present across much of the present seabed, are locally 10s of metres thick but their analogues from earlier cycles are almost never preserved, eroded with successive glacial cycles. One notable exception is thick (many 10s of metres), stratified, and presumably glaciomarine deposits deeply buried beneath later tills located just west of St. Pierre Bank. A similar sequence is preserved in inner Halibut Channel, part of an entirely different glacial system. This suggests that there may have been a long-lasting period of (early or mid Pleistocene) glaciations reaching coastal areas but not the shelf break.

Seabed Geology

Figure 12 is a legend showing the classification and stratigraphy of the surficial geology, incorporating both maps with a descriptive explanation of the abbreviations on the map legend. The present seabed distribution of sediments is shown in Figure 13. This map is derived mainly from penetration echo-sounder profiles, which enable a stratigraphic classification based on acoustic character and sediment sequence. This is supplemented with limited seabed grab samples and cores and very limited video transects. The map presented is an overlay of two maps; the original by Fader et al. (1982) and a newer version that only covers the southern half of the Department of Fisheries and Oceans (DFO) AOI (Cameron and King, 2010).

The general sequence of sediment types overlying bedrock are, from the bottom up 1) till (GTt and GTu), with numerous sequences as described earlier and with occasional interbedded glaciomarine sediment; 2) glaciomarine mud (GMt and GMu); 3) post-glacial clay-rich mud (PGm), restricted to the lower energy areas, with approximate time equivalents of Adolphous Sand; and 4) sand and gravel (PGsg) on the banks. Thickness of the muds (GMt, GMu, and PGm) is shown in Figure 14.

Till

Multiple tills underlie the entire Channel within the DFO AOI as established above. Figure 11 shows the distribution of the tills that subcrop beneath the deglacial and post-glacial mud cover. The latest till, from the Late Wisconsinan (MIS stage 2 glaciation) covers almost the entire floor of the channel with the exception of thin bands on both channel flanks where it thins to nothing to expose older tills, either beneath the surficial muds or at the seabed. Otherwise, younger, late glacial retreat-phase tills are only present in the northern part of the DFO area, one comprising the Laurentian Moraine and another and even later till.

Physical Properties: The till is not well sampled so geotechnical and lithological/mineralogical analyses are largely lacking. In general the till is a cohesive poorly sorted mud or diamict, variously compacted, deposited primarily beneath the glacier and competent enough to preserve some of the ice sole characteristics providing it with typically 10 metres relief. Upon ice stream retreat, the calving icebergs impacted the seabed with enough current-driven force to plough furrows up to several metres deep, primarily but not always along the general axial direction of the Channel.

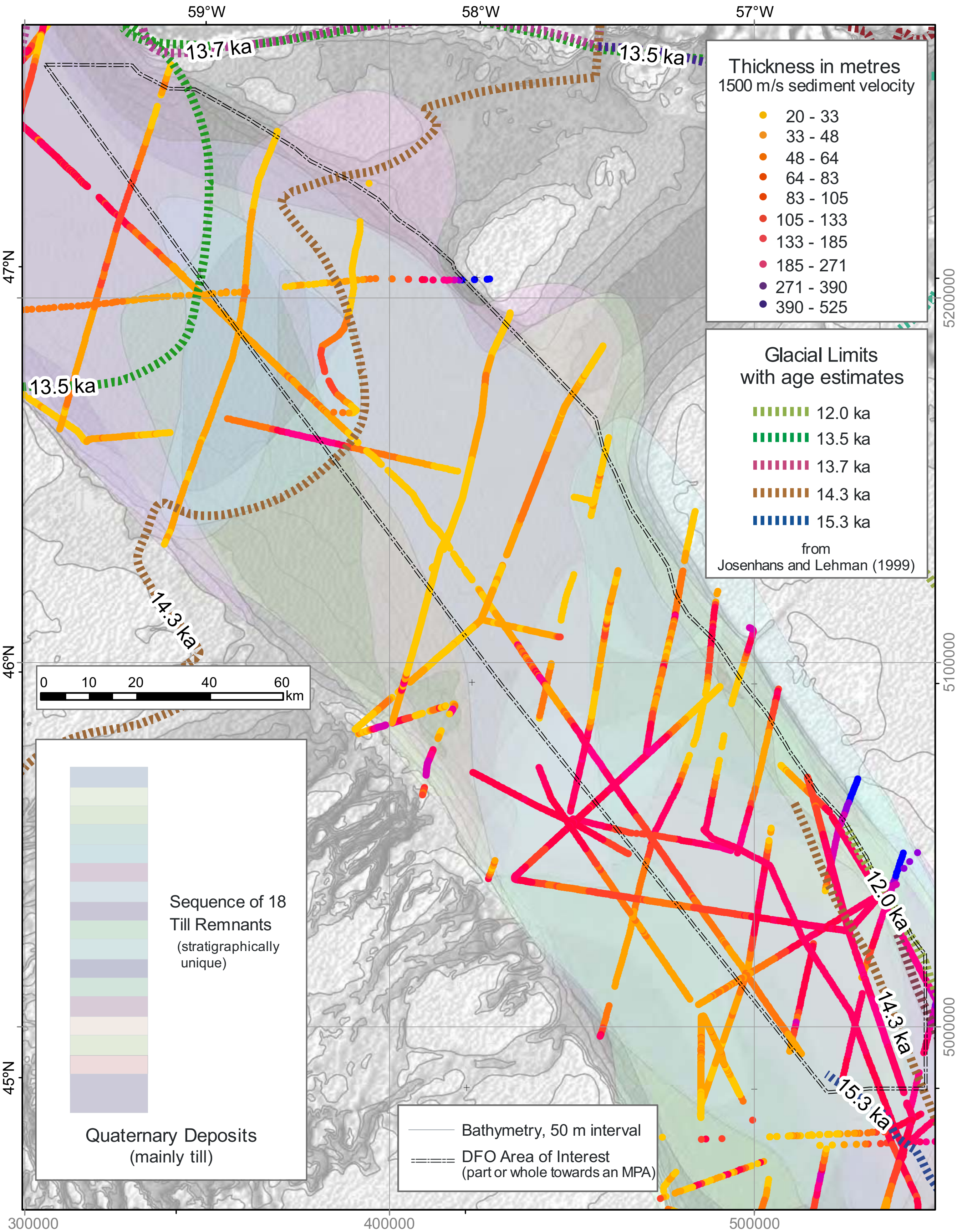


Figure 10. Thickness of all till units (seabed to base of Quaternary) with till distribution, suggested ice margins, and ages from Josenhans and Lehman (1999).

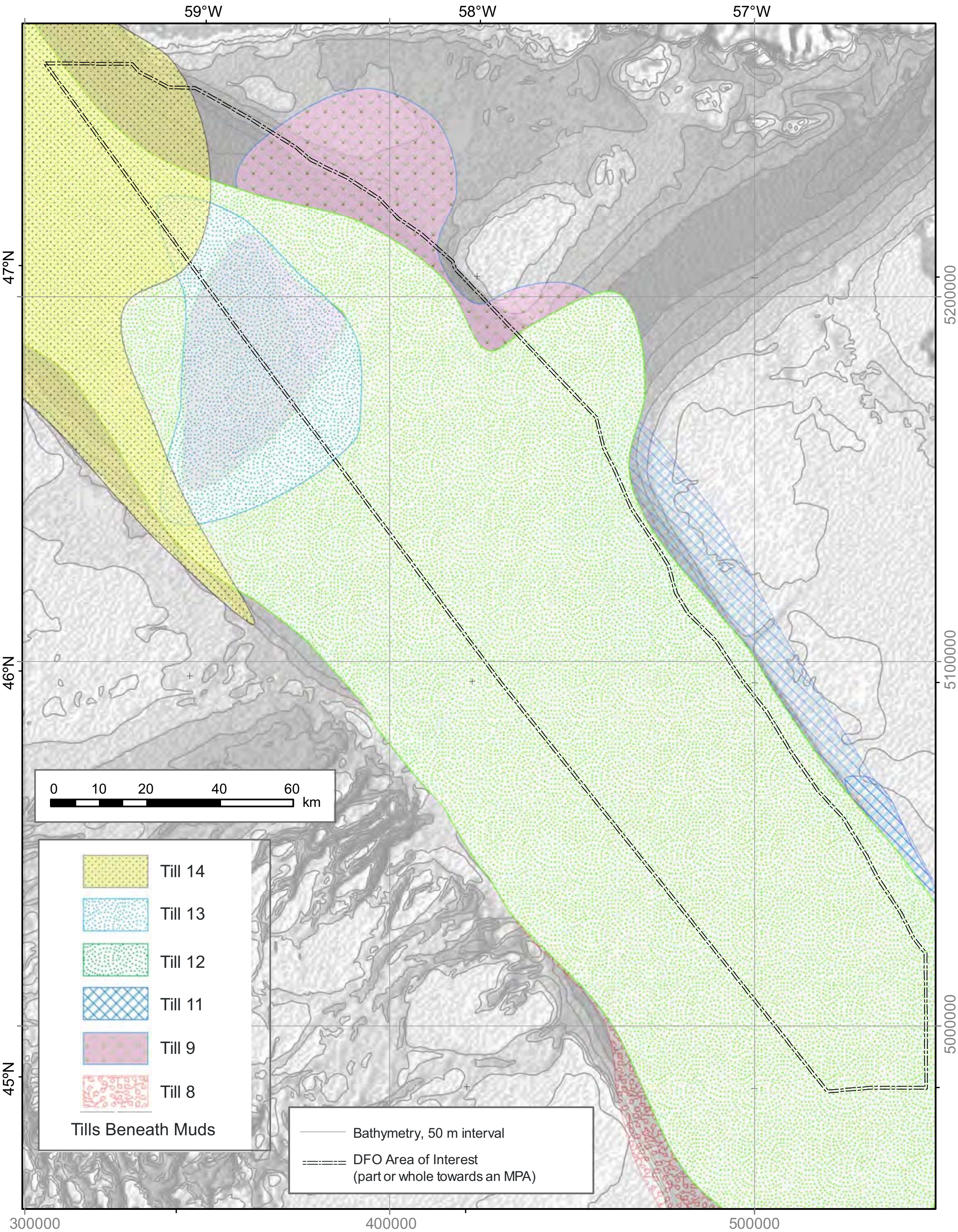


Figure 11. Distribution of tills at the seabed or covered with a thin blanket of post-glacial muds.

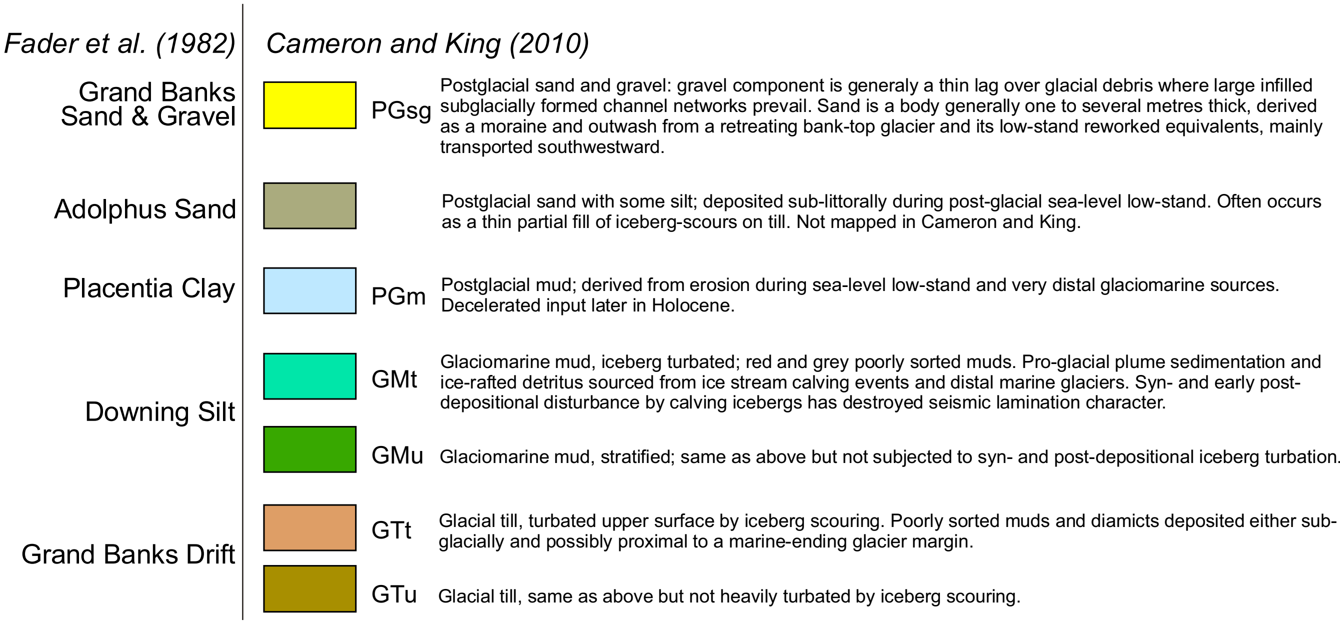


Figure 12. Legend and description of the surficial stratigraphic units on the Surficial Geology map (see Fig. 13).

These have only been slightly modified by currents since their formation, generally enhancing a cobble, gravel-boulder remnant on the berms and locally filling the troughs with the finer, sandy component. The iceberg scours provide an additional roughness element to the till surface but in the range of 1 to 3 m relief. Till is only exposed at the seabed on the flanks of the Channel, having been lapped by glaciomarine and post-glacial muds in the deeper areas.

Figures 15 and 16 show the setting and analysis of core 2003-033-0030, which penetrated overlying glaciomarine mud and upper till. It is considerably more competent (higher strength) than the overlying sediment and at about 150 kpa, compares with other strength values obtained outside the region. Strengths ranging from 30 to 300 kPa are typical for marine tills. Bulk density is about 2.2 gm/cc. Though this core has a coarse sand and fine gravel component, it lacks the gravel and cobble component that many tills contain. A cobble and boulder component can only be inferred for other tills in the area, given that a lag of gravel, cobble, and occasional boulders is typical of seabed photographs over till. Nevertheless such seabed lags are generally current and iceberg scour modified and likely overemphasizes the internal content of the coarse clasts.

Table 1 (from MacRae, 2004) shows further physical properties. This should be viewed in conjunction with Figure 16. The lowermost sample value likely is in the till, the uppermost in the post-glacial mud, and the remainder from glaciomarine mud.

Glaciomarine Muds: The till is covered in most of the area with a thin blanket of glaciomarine mud, generally stratified or iceberg turbated, containing some ice-rafted coarser material up to pebble size. It is several metres thick and up to just over 30 m thick locally. Glacial margin plume sedimentation initiated at the mouth of the Laurentian Channel about nineteen thousand years ago (Calibrated calendar years, C-14), possibly later along the eastern outer margin, under the influence of a glacier covering St Pierre Bank. Calving would have occurred in rapid events but glacial still-stands and re-advances continued for another four thousand years in the Cabot Strait areas (Josenhans and Lehman, 1999), maintaining a glaciomarine sediment input until about 15 000 years (Calendar). Figure 14 shows an approximation of the mud thickness covering the till. This includes both the glaciomarine and overlying post-glacial muds.

Two red mud events found in core attest to events of calving, possibly with associated catastrophic flooding as they span the timing of a glacial outburst for which there is ample evidence at the upper slope (Piper et al., 2007).

A band of glaciomarine sediment diagonally crossing the mid-map area of the Channel (Fig. 12) is a thin, generally iceberg-turbated blanket overlying a till ridge

Table 1. Atterberg limit summary for Expedition 2003033 Station 30 (from MacRae (2003).

Depth (cm)	Water Content (%)	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)	Liquidity Index (%)
50	152.7208	105.935	45.1845	60.7507	1.770124
374	64.944538	45.1358	25.0333	20.1025	1.985389
423	63.07775	47.0028	26.0929	20.9099	1.768441
500	34.74445	27.781	17.7658	10.0152	1.695288
612	23.10103	20.6729	13.6281	7.04478	1.344467

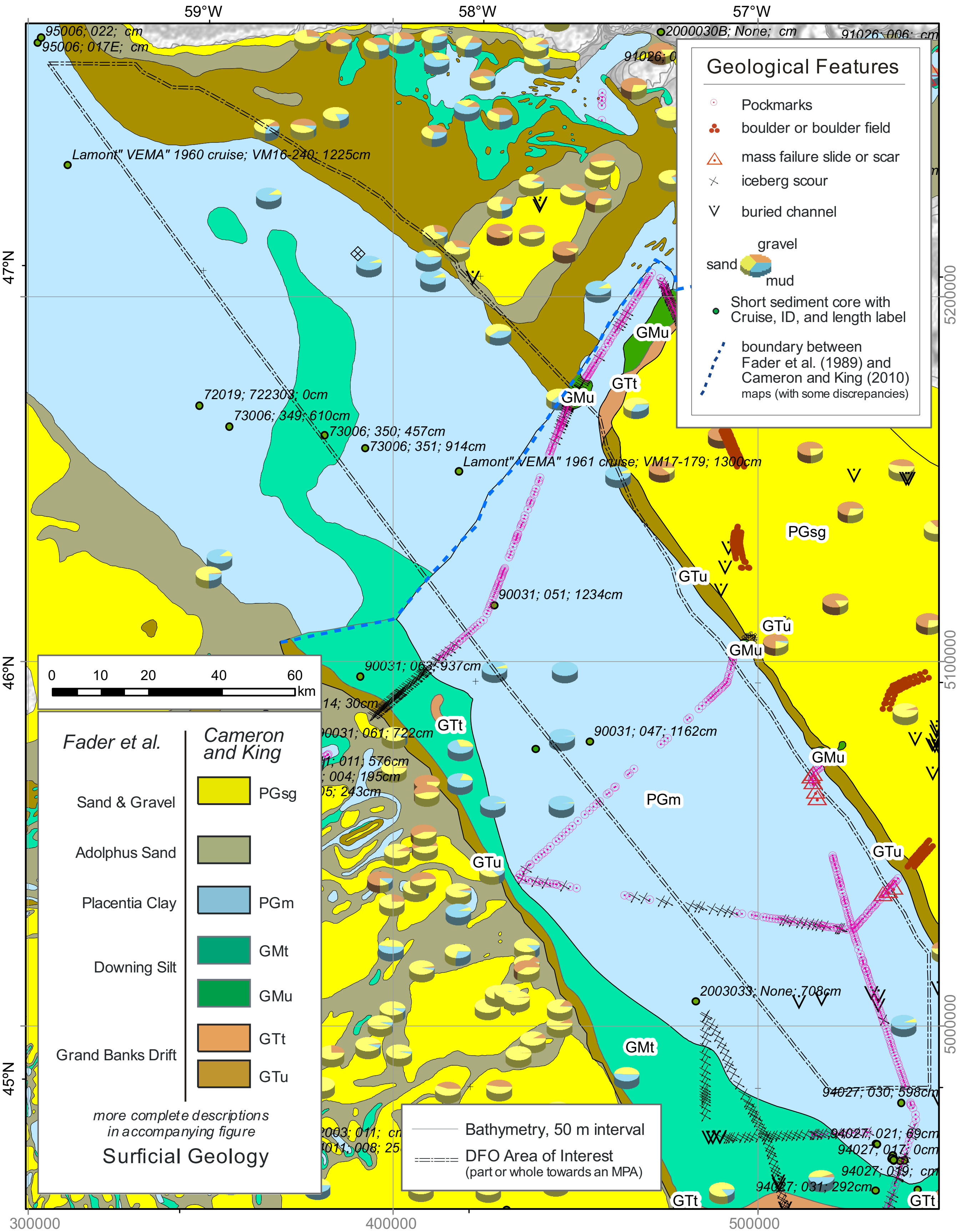


Figure 13. Surficial geology, grain size from grab sample analyses, and features symbolized along geophysical tracks.

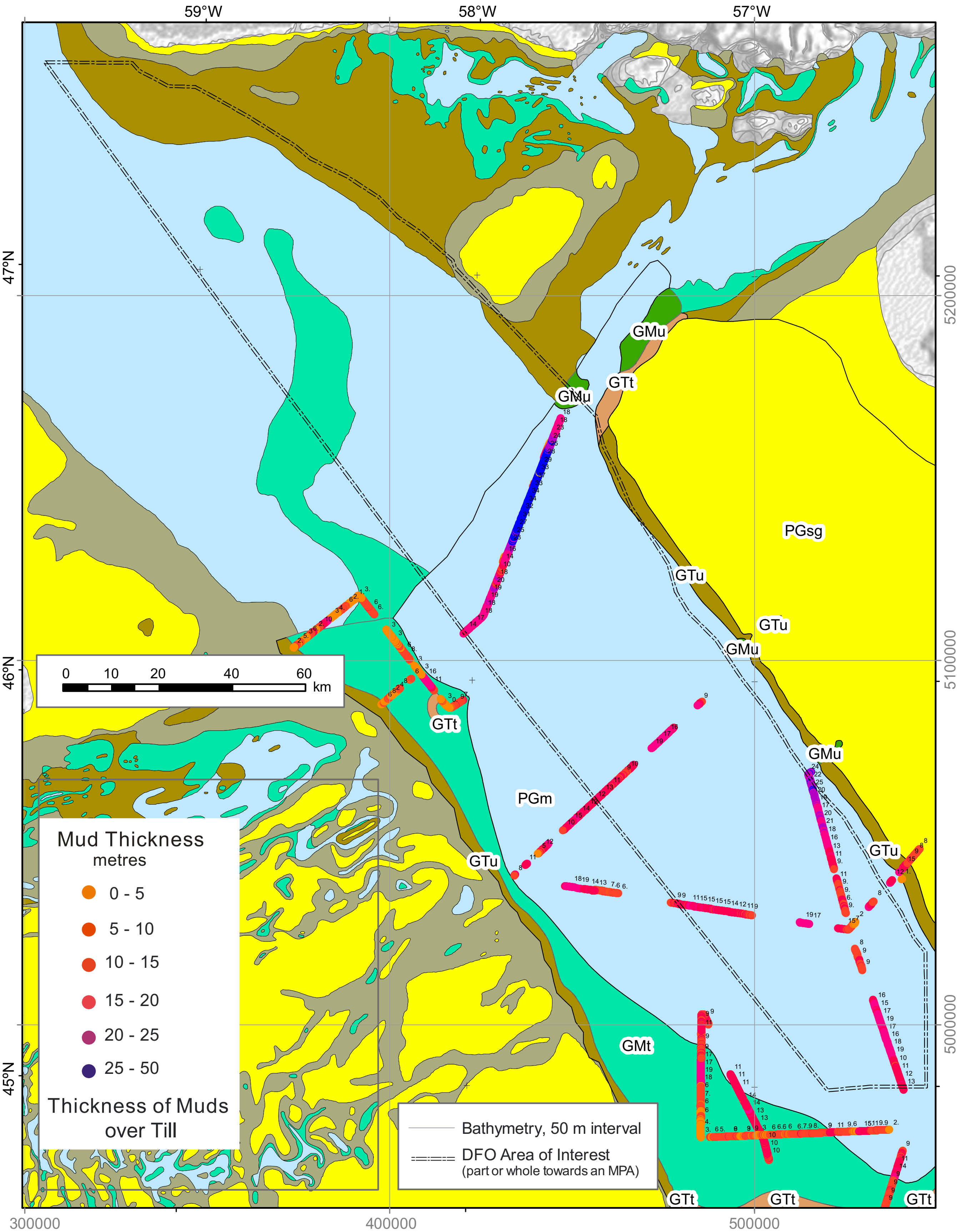


Figure 14. Thickness of muds over tills.

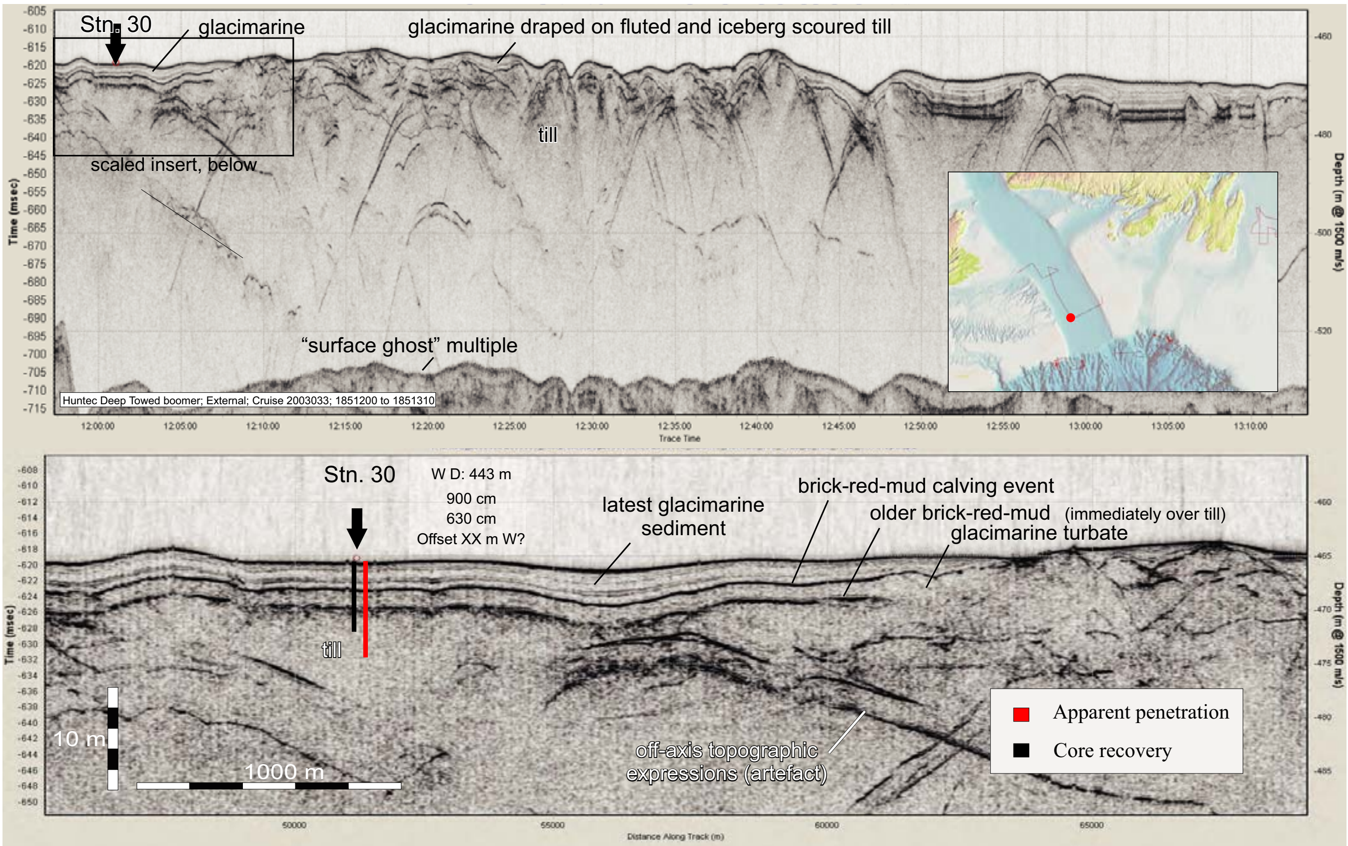


Figure 15. Expedition 2003033 Huntec boomer profile across Station 30. This core penetrated the glaciomarine section, including two brick-red muds (BRM), interpreted as calving events, and into the till. The upper BRM reflector is depicted in the core physical properties plot. The lower BRM also creates a strong reflector that cannot be differentiated from the top of the till, as these are separated by only 50 cm in the core. The stratified glaciomarine sediment is heavily turbated to the right (south) as it is over much of the floor of the outer Laurentian Channel. See the environmental interpretation in the Figure 16.

representing a still-stand and minor advance of the ice stream during overall deglaciation and retreat. This is depicted in the cross section, second from the top, in Figure 6. The shallower elevation of this site has prevented appreciable post-glacial clay deposition.

Physical Properties: Figure 16 and Table 1 show some physical properties of the glaciomarine sediment found in core 2003-033-0030. Shear strength is typically under 10 kPa and bulk density is generally less than 1.8 gm/cc, diminishing to 1.3 at the core top. A study of core sediments located just to the east of the northern boundary of the DFO AOI (Core VM16-240, locations in Fig. 13) was conducted in the 1960s when grain petrology was standard procedure. This gives the only known characterization of such properties in the area of interest. Conolly et al. (1967) recognized the glaciomarine sequence with about 2 to 3 m of overlying thin (grey) post-glacial clay. Both brick-red mud horizons of core 2003-033-0030 are also present, indicating a widespread depositional event. Figure 17 shows the core analysis. Another core (V17-079 PC, Fig. 18) shows a similar stratigraphic sequence and age control. The glaciomarine sediment (reddish and brown) is about 20% sand but otherwise silt-rich with between 35 and 45% clay and occasional clasts of presumably ice-rafted dropstones. Quartz and feldspar make up between 70 and 85% of the sand fraction. Diverse rock fragments comprise the bulk of the remainder, and none of the other 19 classes of minerals are particularly dominant. One exception is a relatively high pyrite concentration in the late glaciomarine and post-glacial sediments but iron precipitates are a common product associated with infauna as climate conditions warmed.

Post Glacial Mud: Mapping of the post-glacial mud is based mainly on seismostratigraphic character. The seismostratigraphic contact is clear in the mid and northern part of the map, marked by a change in seismic character from well stratified with strong density variations among beds to a much weaker contrast and thus more homogeneous muds. Typically a bloom in microfauna and shells, compared to the nearly barren underlying glaciomarine sediment, marks the change to post-glacial sediments and corresponds to this seismic transition seen in Figure 2. The base of the mud unit is locally marked by a change in sedimentation style including some ponding of the latest glaciomarine sediment in local depressions. This has a subtle uncon-

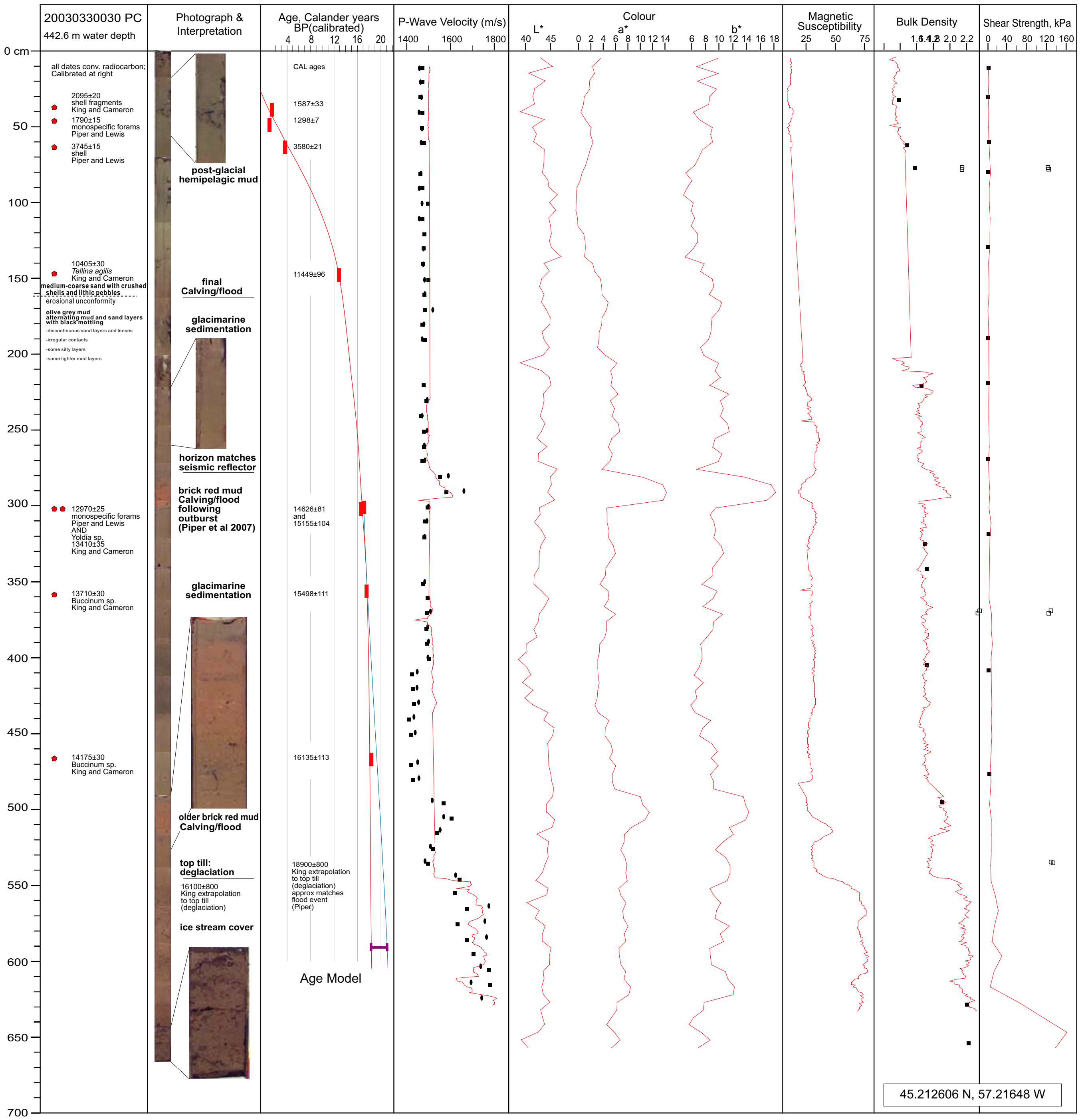
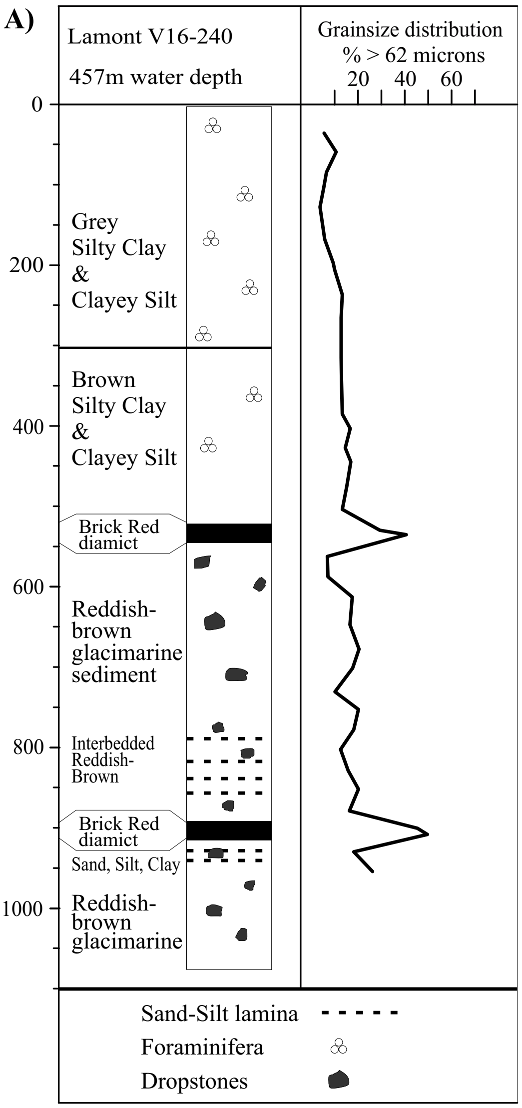
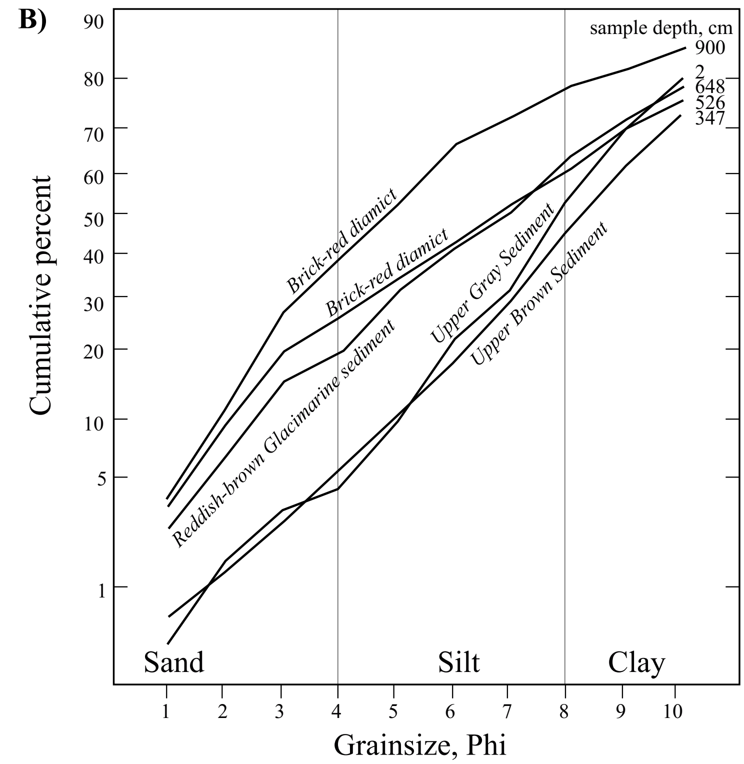


Figure 16. Properties of the core from Expedition 2003033 Station 30, recovered from a site in the mid Laurentian Channel, just outside of the DFO Area of Interest (Mosher and Piper Hudson expedition). For the location, see Figure 15. The core penetrated a condensed section of the glacial and post-glacial deposition. The black point represents spot analysis for control of the MST (multisensor track continuous curves). Analysis by staff and students of the Geological Survey of Canada – Atlantic core lab; King and Cameron radiocarbon dates analysed at USC lab. Dates reported as "Piper and Lewis" (D.J.W.Piper and M. Lewis, GSC-A, sample submitters) are from the NRCan, GSC-Atlantic radiocarbon dating database.

formable nature, especially in the southern half of the map area, and suggests either a flooding event associated with calving in the Cabot Strait or a short-lived enhancement of oceanographic currents during the time between deglaciation and while the sea-level was much lower. This boundary is difficult to recognize near the mouth of the channel but seismic mapping and limited dated core samples show agreement given that this change in environment took place between 11 and 12 thousand years ago (calendar years).

Physical Properties: The grab samples show almost always 100% mud at the seabed (Fig. 12). The post-





C)

Sample Depth (cm)	Sand and Granules >62 microns	Coarse and Medium Silt 62-16 microns	Fine and Very Fine Silt 16-4 microns	Coarse Clay 4-1 microns	Fine Clay <l micron
	Upper Gray and Brown Sediment				
2	4.6	17.5	32	26 7	19.2
347	5.7	12.4	28.2	27.9	25.8
	Glacial Marine Sediment				
526	26.4	17.2	18.8	14.8	22.8
648	20.1	22.3	22.1	15.1	20.4
900	40.1	27.4	11.9	6.5	14.1

Figure 17. Characteristics of the uppermost glacial and post-glacial muds in the Laurentian Channel from core V16-240 (Lamont). **A)** Sketch and grain size. **B)** Full grain-size analysis. **C)** Grain-size breakdown. Reconfigured and redrawn from portions of Connoly et. al. (1967).

glacial mud in other regions is often softer than the underlying glaciomarine sediment but two cores in the area show a typical down-core preconsolidation pattern. Cores 2003-033-0030 and V16-240 (Figs. 16, 17) show little change in grain size or geotechnical properties upwards besides a density decrease.

Sand and Gravel:

Areas above the post-glacial low-stand of sea level experienced much higher energy conditions than the deep waters of the Laurentian Channel. New understanding of the post-glacial sea-level low-stand elevation has been established in the region. It ranges from 80 to 60 metres across St. Pierre Bank (deeper on the southwest end, shallower on the northern margin). The low-stand delivered coastal and high-energy processes to the banks immediately after glaciations and so had a strong influence on redistribution and reworking of the glacial sediments. Originally thick sands (perhaps 10 m) on the bank top, thought to be mainly glacial outwash-derived, were largely redistributed and transported towards the southwest part of the bank. The northern half of the bank was swept clean to leave only a thin lag, while a fairly uniform sandy blanket was maintained on the northern and eastern part of St Pierre Bank and thick progradational sand sheets built with sea-level rise in the southwest. Since these deposits lie within shallower water depths than in the DFO AOI area, they are not considered further. These would have been the only candidates for marine aggregate. There is one minor exception. A glacial hanging valley located on the east flank of the Channel, emanating from St. Pierre Bank (approximately 47ºN, 57ºW) had been the conduit for glaciomarine sediment to the floor of the

D)

Sample Depth (cm)	Monocrystalline Quartz	Polycry-stalline Quartz	Plagio-clase	Orthoclase	Sedimentary Rock frags	Clay Pellets	Volcanic Rocks	Calcite Grains	Lime -stone	Opaques	Diabase	Granitic Rocks	Amphibole Garnet Pyroxene	Foram-inifera	Mollusca
Upper Gray Sediment															
260	71	1	4	10	3	3	3	Trace	1	1	–	2	1	–	–
Upper Brown Sediment															
336	63	5	5	1	10	4	1	3	–	5.5	–	1	0.5	–	–
Lower Red Brick Mud															
900	58	5	2	5.5	16	4	2.5	4	–	3	–	–	–	–	–

Sample Depth, cm	Hornblende	Garnet	Magnetite and Ilmenite	Leucoxene and Limonite	Actinolite	Clinopy-roxene	Chlorite and Serpentine	Biotite	Zircon	Hyper-sthene	Pyrite	Apatite	Epidote	Staurolite	Tourmaline	Hematite	Others
	Upper Gray Sediment																
55	28	15	17	11	1	–	1	3.5	1	7	5.5	3.5				6.5	
278	18.5	7.5	11.5	11.5	0.5	0.5	0.5	2	2	5.5	33	2				5	
	Upper Brown Sediment																
310	11	7	6.5	9	1	0.5	0.5	0.5	2	6	42.5	5			1	8.5	
400	15	5	8	13	1	–	–	1	2	10	3	5	–	–	1	9	
	Upper Brick-Red Till																
530	2	3	46	10	–	0.5	1	–	3	4	0.5	10	1	1	1	24	
	Lower Brick-Red Till																
900	15	5	20	11	0.5	0.5	1	0.5	2	8	4	4.5	3.5	3	0.5	16	
	Reddish Brown Glacmarine Mud																
625	17	6	16	12	1	0.5	2	2	2	4	–	1.5	1	5	–	26	2

E)

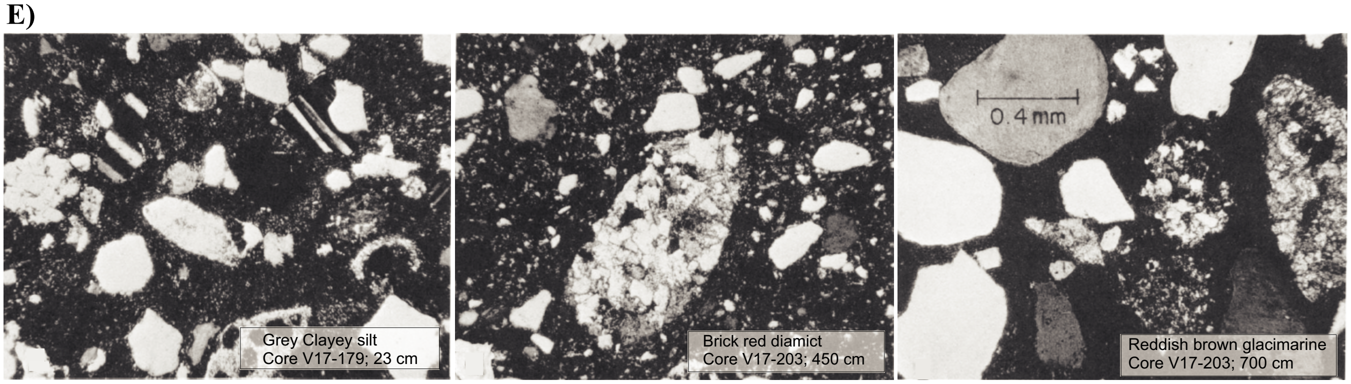


Figure 17 continued. D) Mineral and rock fragment content in the sand fraction. **E)** Thin sections. Redrawn from Conolly et al. (1967).

Channel. The same valley now has sand waves, which attest to occasional transport of sandy material also under today's conditions. This was also the site of early post-glacial gravity mass failure.

There are some discrepancies in the geological contacts at the boundary between the older and the newer maps (blue dashed line, Fig. 12). The more recent map (to the south) recognizes a greater extent of thin post-glacial mud and deemphasizes a very thin sublittoral sand unit (Adolphous Sand) depicted in the former. The original map built on the understanding that the low-stand boundary was at about 110 m across the entire region. Accordingly, the low-stand sublittoral map units comprising thin silty sand over till were mapped at the low-stand transition (comprising Adolphous Sand and its Scotian Shelf equivalent, Sambro Sand, grey-brown colour on the map). On the new map, despite an even higher low-stand than previously thought, there is no recognition of these map units. Apparently wave and current processes maintained high enough energy to wash and redistribute the sands and gravels into bed forms, even at the edge of the banks and so there is little differentiation between the coastal post-glacial sand and gravel unit (PGsg) and their sublittoral equivalents.

Overburden Volume

Figures 10 and 14 show the total overburden thickness along track lines of the multiple till and the overlying mud, respectively. Till thicknesses range between just under 20 m to over 450 m (assumed velocity of 1500 m/s). The bedrock surface is as deep as 680 m below sea level where the first glaciers eroded and over-deepened to their greatest depth in the area seaward (down-ice) of the Burin Platform. Otherwise, the bedrock elevation is as shallow as 170 m below sea level (on the

Channel flanks) but most of the Channel area within the proposed DFO MPA has an average bedrock elevation of 500 m below sea level. An average of 75 m overburden thickness corresponds to a rough volume estimate of 1250 km^3 of mainly till within the DFO MPA boundaries.

Mud thickness (overlying the till) is less well compiled at present. A rough estimate of the total mud volume is 200 km^2 assuming an average thickness of about 15 m. Of this only about 60 km^2 comprises the uppermost post-glacial soft mud.

Mineral Potential of the Overburden

The thick overburden represents a long depositional record spanning numerous glacial cycles locally preserved in the proposed MPA area. Volumetrically, most of the sequence comprises thick tills, and represents large volumes of material. It has largely not been sampled and will remain so until a costly (multi-million dollar) boring program is mounted, for which there are no present drivers. This limits conclusions about mineral potential severely; only inferences based on glacial till deposits in general can be raised.

Sand and gravel is so limited in extent within the present DFO AOI boundaries that it is not considered. This would change if the eastern boundary were migrated onto southwest St. Pierre Bank where thick, prograding (and presumably washed) sand-gravel sheets are present.

Tills can be mineral-bearing to the extent they support economic mining but generally only for precious metals. No assays of such have been reported in the Laurentian Channel area though offshore tills over gold-bearing metasediments in coastal Nova Scotia show local gold (e.g. Stea and Fowler, 1979). The question becomes how much the glacial action of till transport and deposition would potentially concentrate such minerals and what might be their provenance. On both counts, probabilities of valuable assets are inferred to be low. Tills have little or no intrinsic value (e.g. aggregate) and offshore, mud-rich, and inaccessible deposits are likely even less so. Were there a future discovery of some valuable attribute of the tills, the volume of deposits alone (over 1200 km^3 in the AOI) might present some interest. However, tills generally represent dispersal media rather than concentration by nature. Adding to this, the characteristic stacking of tills indicates that successive tills would have some part (perhaps significant) of their source material in older tills and overlying glaciomarine sediments, acting to further disseminate anything of value. Secondly, apart from the approximately 100 km^2 subcropping of presumably Precambrian (unknown) lithologies located mid channel (magenta in Fig. 7), the ice streams (both main and tributary) are quite distant from conceivable sources of minerals, the main path having followed large Carboniferous and Triassic drainage zones.

The muds overlying the tills also represent large volumes (200 km^3) but the only existing analysis of minerals suggests little of potential value. Similar deposits are common in nearly all basinal areas of the eastern Canadian continental shelves but no instances of potential economic content are known and, apart from volume, Laurentian Channel muds do not have known unique character. The post-glacial (uppermost) muds are one of the few recognized geological recording medium for past (and present?) natural gas escape and this property has sometimes been used as an aid for hydrocarbon prospecting, but attempts to differentiate petrogenic from biogenic source are generally problematic.

GEOHAZARDS

While the Laurentian Channel has been the site of phenomena considered geohazards in the past, the present probability is largely unknown given the restricted understanding of both the setting and the long-term (pre-historical) phenomena. Seismic activity and its related phenomena (tsunamis, gravity mass failures) is clearly the greatest geohazard, as demonstrated by the damaging 1929 earthquake with its epicentre on the slope just seaward of the DFO AOI. Within about 100 km of the AOI about 100 events exceeding MN 2 have been recorded (data from the NRCan, GSC website, 2009; Earthquakes Canada, http://seismo.nrcan.gc.ca/stnsdata/nedb/bull_e.php). A cluster of measured earthquakes is located along the midline of the western DFO AOI boundary, possibly related to salt diapirism or faulting on the Precambrian contact. None has exceeded 5.7 MN since recording initiated, excluding the 1929 events. Recognized gravity mass failures, likely earthquake triggered given this setting, are limited in number and their timing, though imprecise, suggests early post-glacial activity in all of about 6 or 8 sites surrounding the channel area (King and Huppertz, 2009 and unpublished data). Pockmarks, if still seeping natural gas, must be considered a potential risk, given that no studies have managed to identify their present activity, or lack of gas escape, nor if the gas release is catastrophic or simply slow seep.

Anthropogenic hazards are not considered here but unexploded ordinance is likely but the distribution is largely unknown. Known shipwrecks are shown in Figure 1.

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