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Canyon-head evolution and the influence of glacial regime along the southeast Canadian margin

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INTRODUCTION

Shelf-break and slope morphology along the of southern Atlantic Canada margin varies considerably, largely in terms of the degree of canyon development. Their evolution and response to shelf processes is key to understanding sediment transport from the shelf to the deep ocean as these canyons are commonly a source to sink conduit second only to large translational slides.

Comparison of canyon systems on the shelf-edge demonstrates that the process of canyon head sediment supply from the shelf generally evolves through the Pleistocene transition to glacial conditions, serving to either diminish or enhance canyon head growth. There is a similar evolution within single glacial cycles but with diminished contrast. End-member examples are presented where the contrasting canyon head evolution appears to be sensitive to mode of glacial meltwater conditions.

Complete or nearly complete infilling of canyon heads is associated with glaciers with little sub-glacial connectivity of meltwater conduits, where sediment supply is dominantly a till slurry. These contrast with settings where the canyon headwall communicated directly with shelf-situated sub-glacial tunnel valleys.

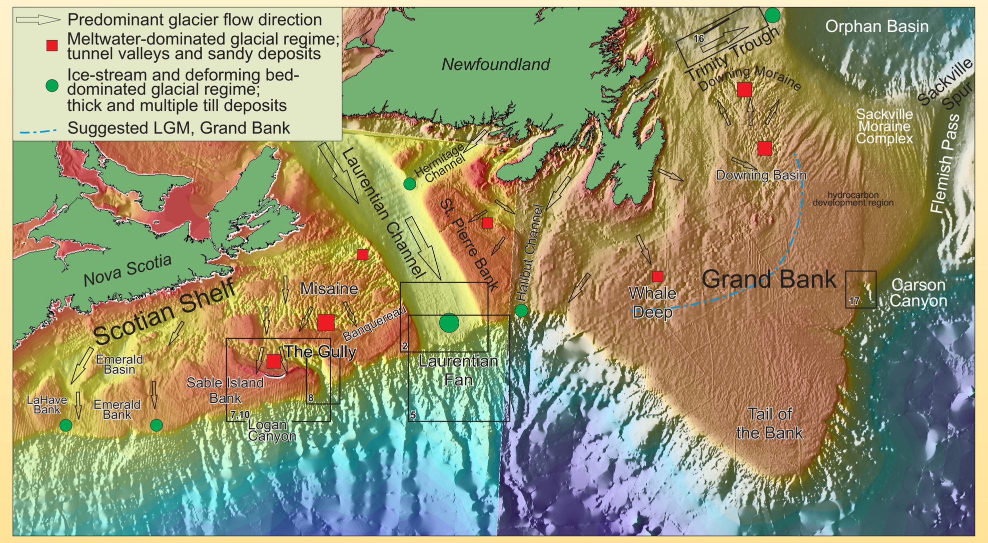

Figure 1: Morphology of the SE Canadian margin. The shelf break is generally at the yellow to blue colour transition. Some parts of the margin have smaller scale canyons than others. Geographic areas of focus in this poster are identified with black open rectangles. Arrows denote dominant glacier flow direction while circles and squares denote dominantly confined and unconfined meltwater flow regimes respectively. Figure numbers in location squares.

PURPOSE

This poster aims to first demonstrate contrasting glacier processes from features and deposits in the Scotian Shelf and Grand Banks region and suggest they are largely governed by the state of connectivity (flow process) of sub-glacial meltwater. Examples show that this state evolves both geographically, with successive glaciations, and within a glacial cycle. Secondly, the association between meltwater state and canyon head growth or infilling is demonstrated. Nevertheless, recent improvement in establishing an LGM margin position on Grand Bank and Holocene sea-level reconstruction on Sable Island Bank help establish that some canyons are dominated by more "classic" low-stand sand and contourite feeding. This improved understanding of sediment supply process to canyon heads and their morphological response can be applied to much of the SE Canadian shelf margin.

The temporal and geographic variety in sediment supply to the shelf break in a glaciation-dominant setting may lead to better insights into paleo deep-water hydrocarbon reservoirs.

SETTING: Contrasting Glacial Regimes and Canyon Head Response

Through the penultimate and earlier glaciations reached the shelf break along the whole margin, the Last Glacial Maximum (LGM) reached the shelf break in most areas with the exception of eastern and southern Grand Bank and Georges Bank (see far-right panel). The shelf-crossing troughs, identified with circles in Figure 1, have supported ice streams and are dominated by thick and multiple clay-rich tills lacking any expression of meltwater channels. The anastomizing channel areas, marked by squares, are mostly seabed expressions of glacial tunnel valleys, much deeper and more extensive in the seaward direction. These formed sub-glacially, under meltwater-rich channelized flow. These contrasting glacial regimes have governed canyon head development.

Two of the poster panels, through several examples, outline the features and deposits leading to the interpretation of these two contrasting regimes and then demonstrates the canyon head response. Some are healed or partially filled by glacial debris while others are maintained or expand. Others do not develop canyons until the glacier retreats. A third (far-right) panel contrasts the glacially-influenced canyons with more "classic" low-stand-fed canyon (Carson Canyon) and other examples perhaps more strongly mass-failure-governed.

EVOLUTION IN A CANYON HEAD SUPPLY THROUGH INCEPTION, SUCCESSIVE GLACIALS AND WITHIN A GLACIAL CYCLE

A large canyon is shown to have developed with massive Miocene influx to the margin. It proceeded to cut landward, partially cannibalizing Miocene deposits and progressively cutting into older sediments, even down into Mesozoic rocks. At the same time it infilled locally, including near the paleo-mouth, with major influx in Pliocene time. However, with the onset of glaciations to the shelf-break, cutting largely ceased. The accommodation space provided a sink for a thick glacial sequence. The canyon probably influenced the path of the Laurentian Channel through glacial drawdown and with abundant deformable sediment at its base, enhanced ice stream development. A catastrophic flood was the last major event of deglaciation (Fig. 5). Perhaps coincidentally, it followed a path across the canyon.

A Large pre-Glacial Canyon at the head of Laurentian Fan

A large, buried canyon system of Late Miocene age is now recognized at the mouth of the largest shelf-crossing trough, Laurentian Channel. Figure 2 shows its Quaternary sub-crop as a light green body. It represents the response to large volumes of fluvial and shallow shelf sourced late Oligocene and Miocene supply from large prograding sheets (Figs. 3 & 4). Near syn-depositional incision reached 80 km into the shelf with a tributary system 50 km across and mouth and about 1 km deep at the present shelf break (Fig. 2, A-A'). It is filled with successive ice stream fed tills with flat-lying bounding erosional contacts, aggrading stepwise over thick upper slope prograding chaotic deposits, remnants of mass failures. These are mainly glacially-derived as demonstrated from their association with the capping tills; they form the foundation for glacier advance (Figs. 3, B-B' and Fig. 13).

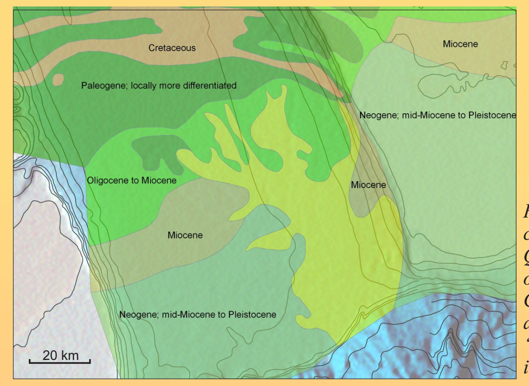

Figure 2. Bedrock sub-crop (below thick Quaternary sediments) of outer Laurentian Channel. This is as large as the adjacent canyon "The Gully" but fully infilled.

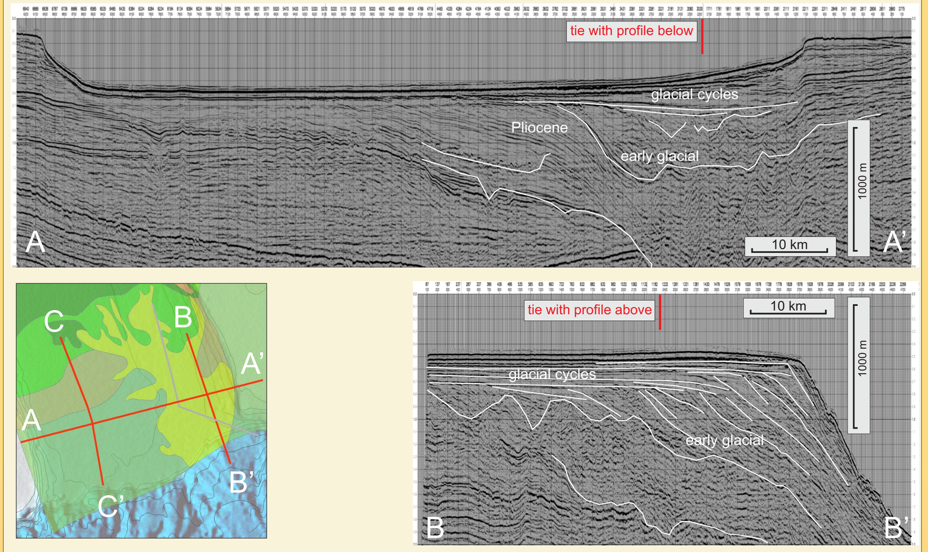

Figure 3. Multichannel seismic profiles help delineate various generations of cut in a large, previously unrecognized, canyon. Detailed Cenozoic mapping indicates a large Pliocene infill. Multiple tills bound by flat ice-stream cut beveling erosion surfaces help differentiate tills from sediments prograding glaciers reaching the paleo-shelf-break. The map (Fig. 2) traces the canyon at the level interpreted as base of glacial fill. The numerous glacial tills are mapped in detail (Fig. 12)

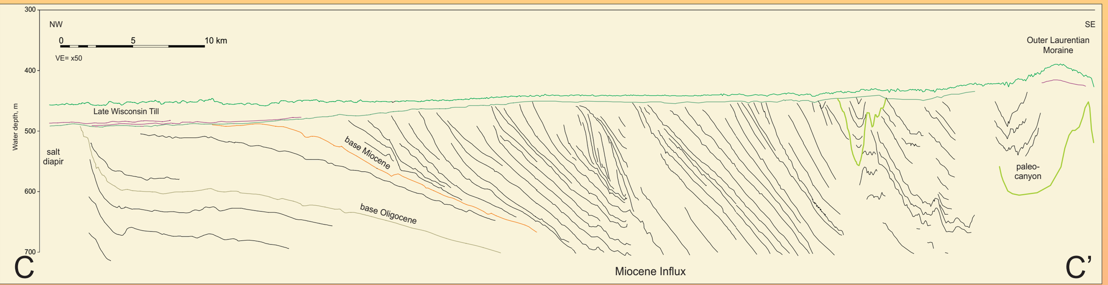

Figure 4. Geologic profile from seismic, location in Fig. 3. The Miocene saw a massive influx of sediment to the margin. Although cross-cutting relationships with the canyon are not clear, it is assumed that the canyon initiated with this influx. Clearly it evolved and broadened; later tributaries cut the distal parts of this prograding sheet. The "paleo-canyon" noted here at the mouth of the Laurentian Channel is not well mapped but a connection with the large canyon is unlikely. Only till from the latest glaciation is preserved here as accommodation space was limited.

Catastrophic outburst from ice streams: A signature "swan song"?

Heinrich events are the well-documented ice-rafted and freshwater events stemming from collapse events of the Hudson Strait glacier. Smaller scale equivalents, though still large catastrophic events, were recognized by D. Piper on the Laurentian Fan (Piper et al 2007) and follow-up work has suggested that such events on other trough mouth fans can produce a characteristic flat-bottomed chute on the slope rather than typical canyons (Piper pers comm. and presentations).

Now catastrophic flood events have been recognized in two other Grand Banks shelf-crossing troughs; see Cameron and King 2011 poster, this conference. They seem to be about proportional in magnitude to the ice stream size. All three events are very late-stage events, signaling the major collapse of the ice stream from the trough.

Implications in a source to sink context for catastrophic events have to be considered, especially if such final-stage flooding, a so-called "swan song", is a inherent characteristic of Laurentide (and earlier?) ice stream deglaciation.

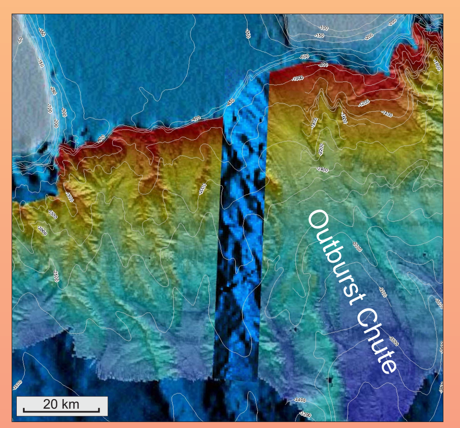

Figure 5. A flat-bottomed chute was recognized as a catastrophic canyon modification with a 16.5 ka (19.3 CAL) outburst at the ice stream mouth (Piper et al. 2007). Smaller outbursts have since been recognized at two other ice stream mouths surrounding Grand Bank.

CANYON SETTINGS WITH CONDUIT-GOVERNED MELTWATER (free-flowing)

Sable Island Bank: A Canyon Disconnect

Sable Island Bank, situated on the outer Scotian Shelf (Fig. 1), is adjacent "The Gully", the largest open canyon system on the margin and a marine protected area. Glacial ice reached the outer bank in perhaps five episodes leaving a stacked till sequence 150 m thick (King, 2001). Borehole sampling reveals a very sandy till, reflecting a largely Cenozoic shelf environment siliciclastic "bedrock" source and abundant meltwater action during at least some stages of glaciation, evidenced by an extensive cut and fill tunnel valley system across the northern half of the bank (Figs 7 and 9). Under LGM conditions ice flowed mainly out the mouth of The Gully and covered Sable Island Bank, including Logan Canyon. This canyon was successively filled with each glacial phase/cycle (Fig 6 and adjacent panel, Fig. 11) but The Gully remained open.

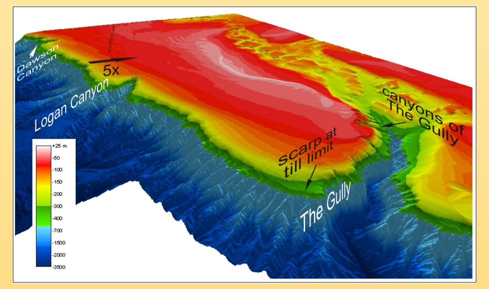

Fig. 6. This 3-D view is similar to Fig. 7 but with lesser vertical exaggeration to better depict the dissected slope canyon topography. Black arrow and open arrow denote north direction and "sun" illumination angle respectively. (applies also to Figs. 7, 9 & 10)

The contrasting fate of The Gully and Logan Canyon with onset and multiple glaciations, despite their proximity, is compared in this and the adjacent (right) panels (Figs. 11 & 12). Basically, Logan Canyon experienced till deposition and The Gully made connection with the tunnel valley-dominated regime where till deposition was very limited in favor of free meltwater-flow and resultant highly active canyon mass-wasting processes.

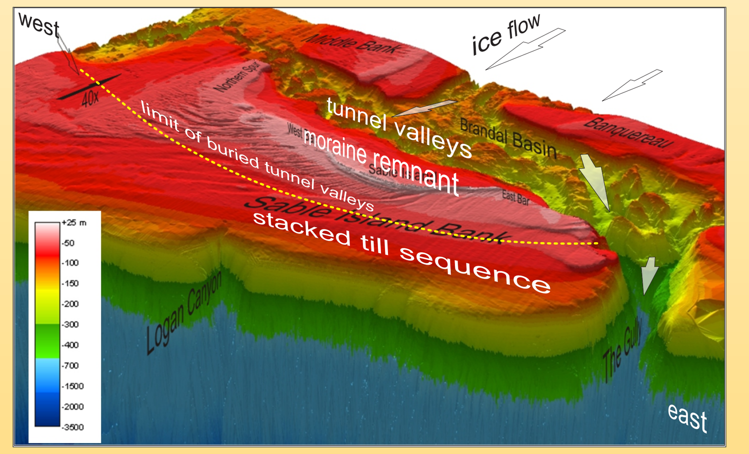

Fig. 7. Sable Island Bank and adjacent canyon, The Gully. Glacial deposits vary greatly across the bank; the highly tunnel valley-dissected Brandal Basin contains thick deglaciation sediment fill, while across Sable Island, a re-advance tidewater moraine remnant covers multiple phase buried tunnel valleys which terminate seaward and 150 m of up-dip stacked tills and outwash are preferentially preserved at the eastern shelf break, here surviving erosion in the ice shadow of the large ice tongue which filled The Gully.

The "Sable" Gully: A Large Glacial Meltwater-Fed Canyon

"The Gully" is large but fully open canyon system. It has been erosion-dominated over the long term with products bypassing the slope to the ocean basin. Its origins are unclear but it appears little different than other deeply buried Tertiary-age canyon systems along much of the margin. It was fed from the hinterland with the general Tertiary thermal uplift and accelerated building of the coastal plain.

In The Gully, the glacier reached 1000 m water depth but deposits consist only of a thin, sandy till with subtle retreat moraines and deglacial plumites (Cameron et al 2008a & b). To what degree glacial-fed sediment has grown the canyon is unclear; the answer lies in the unexplored abyssal plane deposits. However, it could have been significant given that the Holocene imprint alone is significant. Active cutting following deglaciation removed portions of the flanking tills and exhumed Tertiary bedrock.

Free meltwater was in large supply as the tunnel valleys attest, even with retreat to the mid-shelf where a later meltwater-dominated ice margin stood. The situation at The Gully is a notable exception; similar tunnel valley systems ring entire bank areas marking LGM and deglaciation still-stands at several locations on the SE Atlantic margin, notably north of Banquereau and Misaine on the Scotian Shelf and north of St Pierre Bank, in Whale Deep, and north of Downing Basin on the Grand Banks. However, the tunnel valleys abate before reaching the shelf break in all these cases. Sub-glacial meltwater flux could not generally communicate directly with canyon heads except for occasional glacial plumite deposits. See the Cameron and King poster at this conference for discussion of the floods.

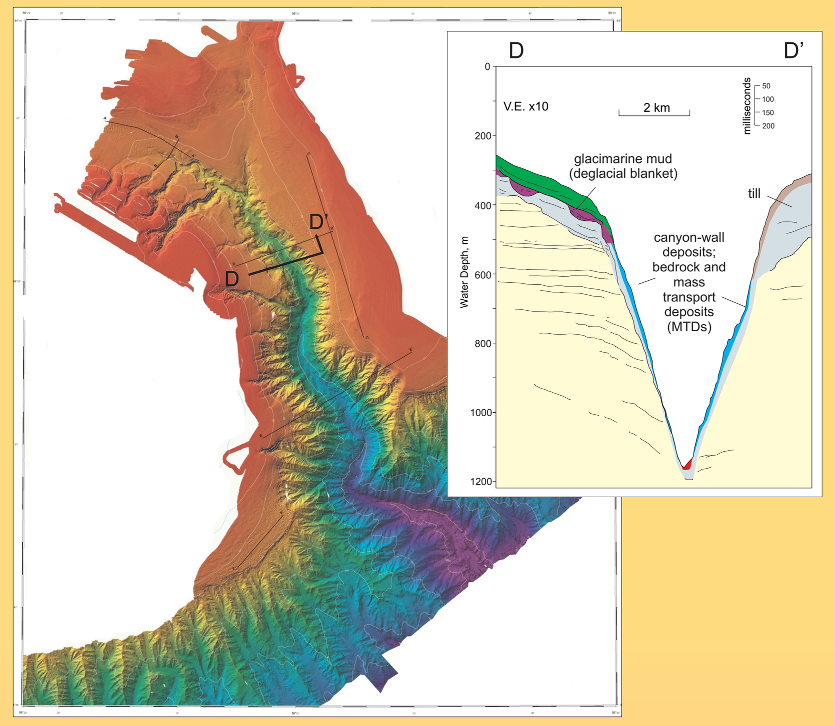

Figure 8. Morphology of The Gully (Cameron et al 2008), the largest open canyon system of the Atlantic Canadian margin. Geo-section D-D', crossing the canyon (upper right, from Cameron et al., 2008b) shows very thin glacial cover accumulations on the upper flanks. It is eroded deeply into sediments spanning most of the Tertiary and surficial deposits are largely mass-transport-related. Event the age of the flanking canyons are largely a post-glacial development (Fig. 9), assuming they were completely destroyed under glacial cover.

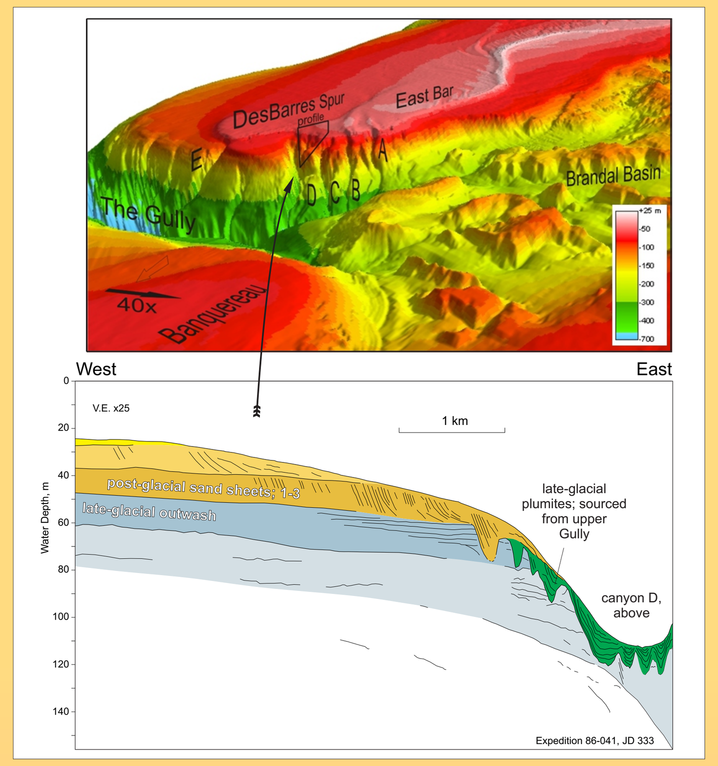

Figure 9. Canyon evolution does not end with glacial feeding in The Gully. With progressive post-glacial sea-level rise, successive prograding sand sheets developed through redistribution of the Sable Island Moraine sands (top panel), migrating toward the east flank of The Gully. Here small canyons developed quickly on the flank of The Gully but as successive, stacked sand sheets developed, they each formed a sediment transport barrier to earlier side canyons such that a progressive series of sand-fed canyons arose and became moribund, starting at A and ending at E. Lower panel modified from Cameron et al., 2008b.

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CANYON SETTINGS WITH LITTLE FREE MELTWATER (Porespace-confined)

Logan Canyon: Glacially -"healed"

In contrast with The Gully, Logan Canyon filled with successive glaciations, despite sandy tills. Interglacial and low-stand sand flux apparently keeps the canyon open but it is a minor process.

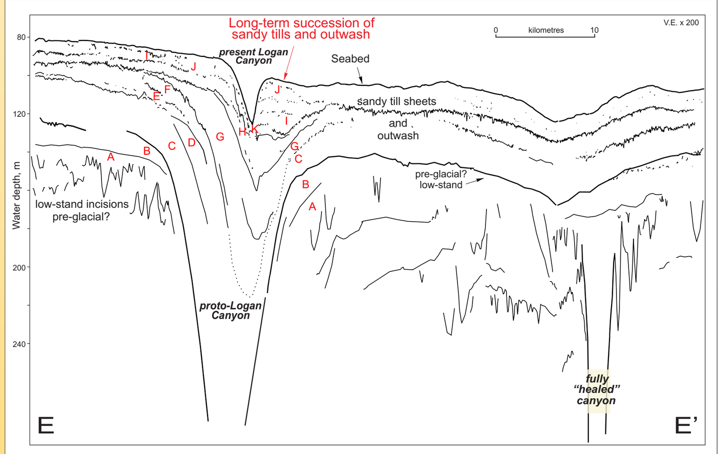


Fig 10. A cross-section through Logan Canyon, derived from high and ultra-high resolution reflections seismic, depicts some of the multiple till sheets preserved on SE Sable Island Bank. This line of section crosses the uppermost canyon head as shown at right. Despite pre-existence of a canyon here, and despite relatively sandy tills, successive glacial cycles infilled, rather than provided "cutting" material to the canyon. An unnamed canyon to the east was overwhelmed and filled completely. Clearly the nature of the glacial material made it less susceptible to mass failure and non-cohesive turbidity flows.

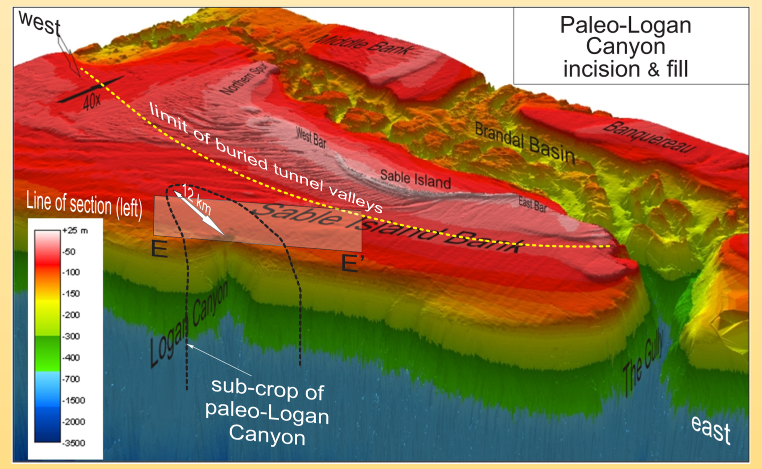


Fig 11. An approximate sub-crop pattern of the ancient Logan Canyon, possibly from pre-glaical time. It was over 12 km further incised into the shelf than today and nearly as broad as The Gully yet was nearly completely infilled with glacial sediments. Logan Canyon did not communicate with the glacial buried tunnel valleys. However, to the northeast, the tunnel valley system north of Sable Island Bank breached Tertiary strata to join with the head of The Gully. It is suggested that development of this connection and subsequent meltwater-rich feeding to The Gully is responsible for its survival and growth in contrast to the nearby Logan Canyon.

Laurentian Channel Fan: Glacial -"healing" of a large canyon

Deposition of the very thick, flat-lying till sequences in Figure 13 within an ice stream setting is attributed to largely vertical aggregation of a sub-glacial slurry, a concept largely envisioned by R. Alley and coworkers in Antarctic examples. This was adopted to explain their continuity with glacigenic debris flows (GDFs) on the adjacent slope emanating from the Norwegian Channel (King et al. 1998). Many aspects are identical here. A water-rich deformable bed is inferred, yet devoid of meltwater in conduits; no channels are ever observed

It is suggested that this property precludes sorting of the till slurry and thus sandy, canyon-eroding turbidity flows and associated tributary do not develop; the resultant slope process reflects this. While many trough-mouth fans build GDF's (see Fig. 14), the Laurentian Fan is uncharacteristically steep. Likely, the glacial debris fail immediately and, if non-cohesive turbidites develop, it is not before dissociation much farther downslope. Establishing a rough chronology of the glacial deposits is important to furthering the thesis that glacial deposits made a fundamental change in ceasing canyon growth. Some inferences are made in the Figure 13 caption.

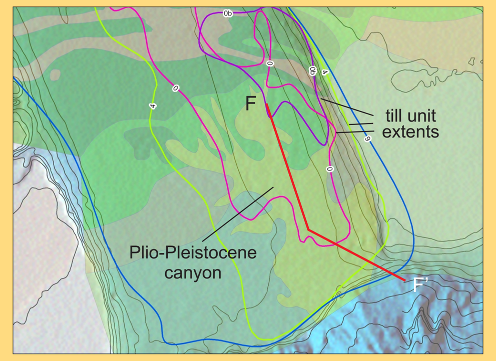


Fig. 12. The large canyon at the mouth of Laurentian Channel was overridden by an ice stream in multiple phases. Each phase generally cannibalized earlier tills (and removed more bedrock) to deposit a thick sequence of presumably muddy mass transport deposits in a chaotic progradational pattern (Fig 13, location of section D-D'; note this line of section also shown in Fig. 3). This built a foundation to further advance the ice stream seaward followed by a till "top set". The canyon afforded accommodation space adequate for preservation of many tills. An outline of the till deposits extent is shown for the eldest and youngest glaciations and some stratigraphically intermediate tills.

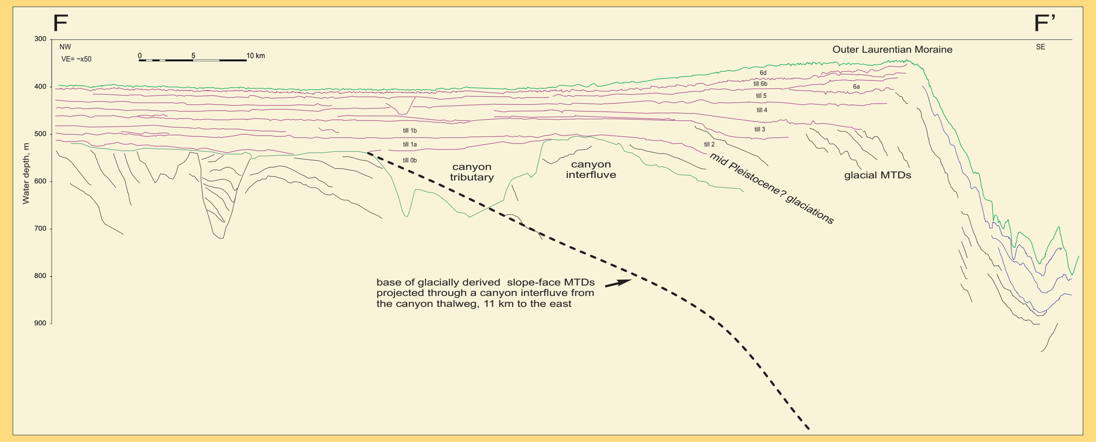
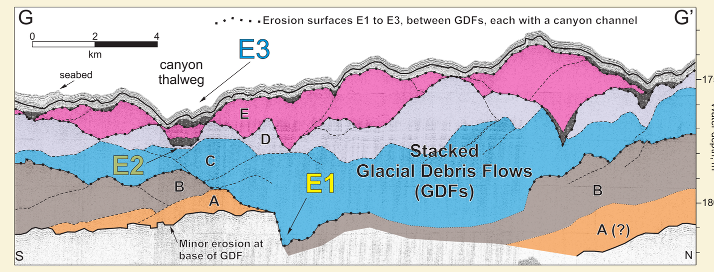


Fig. 13. This profile crosses near the deepest part of the canyon where the earliest of the glacial fill is over 800 m buried. The dashed line is derived from a tie with processed multichannel seismic with deeper penetration than possible with single channel, from which this was derived (Fig 3, B-B' on far left panel). An intervening canyon interfluve precludes stratigraphic continuity along this track. However, the multichannel data do not resolve the stacked tills as well. The assignment of a glacial affinity to such deep deposits is partly because of the similar style of prograding MTDs capped with a till throughout the sequence, marked by a change from more regular aggradation in the Pliocene (and early Pleistocene?) deposits below (Fig. 3, A-A' on far left panel). Note the upward (up-ice) tilt on the bounding surfaces of the tills (magenta horizons) near the mouth of the Channel. Some of this is due to the partial deviation from dip direction of the seismic track. However, this phenomenon is common in Antarctic ice stream mouths also. However, a downward tilt at depth is attributed to subsidence (from sediment loading). This interpretation attributes a significant time span on the glacial deposits. This and the depositional style shift noted above point to a long-lived and relatively complete glacial depositional record, perhaps back to when glaciers first reached the slope break in the early Pleistocene. Attempts to correlate with much better established chronology in the slope stratigraphy (many papers by D. Piper and coworkers), established through a hydrocarbon well on the shelf to the east, are 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 2 or 3, above.

Trinity Trough Fan: Canyons overwhelmed by Glacial Debris Flows (GDFs)

Fig 14, right. The mouth of Trinity Trough, which supported an ice stream under the LGM, has a stratigraphy dominated by a constructional geometry comprising muddy glacigenic debris flows, differentiated here in presumed separate glacial phases. Tripsanas and Piper (2008) recognized three regional erosion horizons extending well into Orphan Basin, each with a thalweg but no distinct canyon head was discerned. These attest to at least some canyon development, apparently between GDF phases marking glacial maxima. Location, Fig. 15.



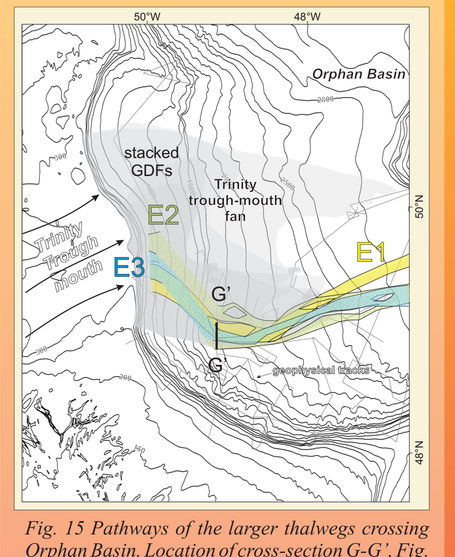


Fig. 15 Pathways of the larger thalwegs crossing Orphan Basin. Location of cross-section G-G', Fig. 14. This and Fig. 14 modified from Tripsanas and Piper 2008.

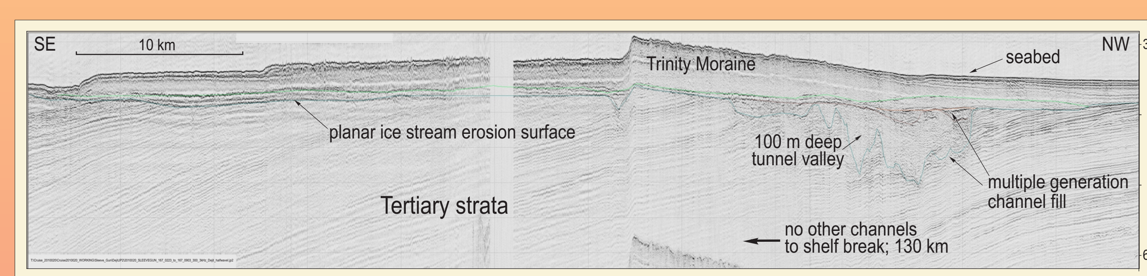


Fig 16. Mid-way across the northern Grand Bank shelf, in Trinity Trough is a Late Wisconsinan retreat-phase moraine built over a planar glacial erosion surface developed through repetitive glaciations. The 100 m deep infilled channel shown here lies over 130 km from the shelf edge and has no connection with canyons. Such an overdeepened channel is attributed to sub-glacial tunnel valley. This recently recognized channel in is the northernmost recognized example of a series of hundreds of tunnel valleys which arc a path across the entire Grand Banks of Newfoundland (King et al. 2001). Its position conforms to the seaward limit of such features. Clearly, meltwater in free-flowing conduits was not a dominant aspect of Trinity Trough. Location, Fig. 1.

CANYONS WITH LITTLE GLACIAL INFLUENCE: Outside the glacial reach

Not all SE Atlantic Canadian canyons appear to have a strong glacial imprint. Difficulties establishing the easternmost Grand Banks position of the last glacial maximum (LGM) have precluded canyon head process understanding in a context of sediment source, path and supply, given that glacier proximity is such a dominant factor. Recent advances in glacial chronology and setting suggest that most outer Grand Banks canyons did *not* experience glaciation under the LGM and that processes more common to non-glaciated settings prevailed.

First, arguments for the non-glacial setting (during LGM) are briefly presented. Flemish Pass examples are summarized followed by the setting at Carson Canyon; the objective is to lend credence to the glacial-influence thesis by demonstrating nearby but less glacially-influenced examples.

The eastern Grand Banks LGM position

Long-standing questions of the LGM position and deglaciation pattern across the Grand Banks of Newfoundland are being addressed. Evidence is mounting for an LGM position mid-way across Grand Bank (see approximation, Fig. 1). Expansive tills and morainal complexes reaching the shelf-break to 400 m water depth, are now thought to represent MIS 6 glaciation despite clear evidence that LGM position reached the shelf-break in the shelf-crossing troughs (Sonnichsen and King 2005; Huppertz and Piper 2009). Though beyond the scope of this presentation, this evidence lies in factors such as extremely thin Stage 2 shelf-break glacial plumites, poorly constrained till-edge stratigraphic correlations with older slope situated plumites, a flat low-stand cut platform across the outer bank, unwarped by glacial isostasy, but clearly warped on the inner shelf, combined with outer bank crustal subsidence estimates consistent with long-term rates and patterns, independent of glacial isostasy (King and Sonnichsen 2000; King et al. 2001), abundant shells on the mid to outer shelf, some with ages spanning the LGM (below the low-stand) and shells with radiocarbon dates pre-dating the LGM which glaciation presumably would have destroyed/transported (Sonnichsen et al. 2003), a mid-bank-situated tidewater moraine complex (King et al. 2001), and recently dated LGM-age ice margin deposits situated mid-shelf.

Canyons at Flemish Pass: Few and Starved

The margin of north of the northeastern Grand Bank flank, along Flemish Pass, north of Carson Canyon (see below) marks a drastic change to few and less well-developed canyons compared to south of here (Fig. 1). The canyons commonly head at the seaward limit of till. This transitions, in deeper water, to iceberg-scoured glacial plumites and (rare?) contourites. Sediment source/supply was clearly not from sand mobilization across the adjacent shelf, which here comprises a large expanse of immobile till with little or no sand cover. In at least northern Flemish Pass even sand from the LGM low-stand did not transport as far as the shelf-break. This is manifest in small, sandy turbidites only and even small MDTs ceased (Huppertz and Piper 2009). The notable canyons, in terms of size, have associated debris flow lobes and this style of mass transport is prevalent at quite regular intervals throughout the well-preserved Quaternary section in the Pass. They are likely glaciation, earthquake and possibly gas hydrate dissociation-related but no clear association pattern is recognized (Campbell 2005; Piper and Campbell 2008).

Carson Canyon: Low-stand and Contourite Fed

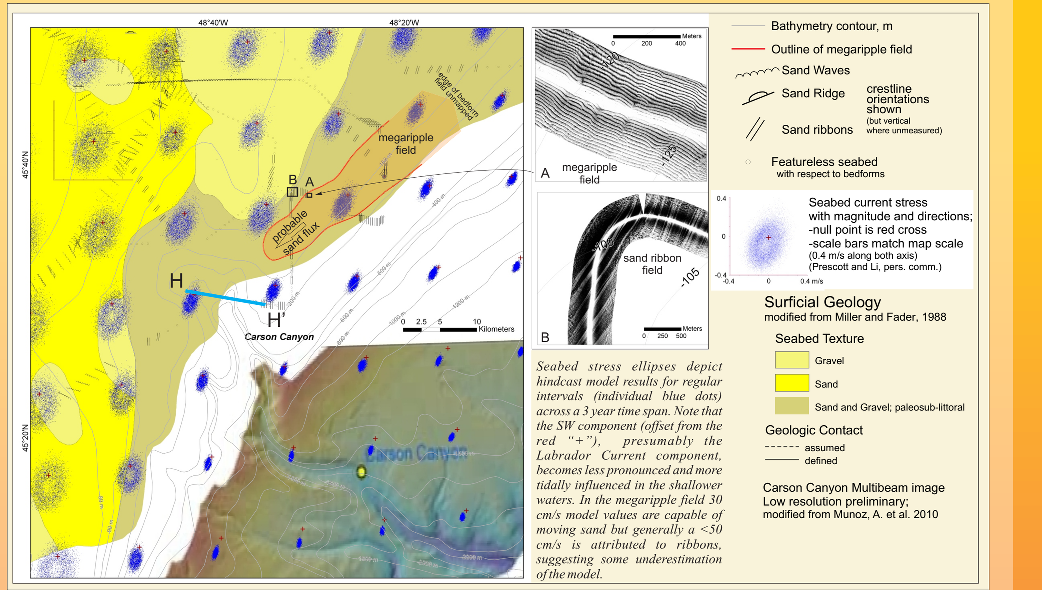
Carson Canyon, on easternmost central Grand Bank is a relatively simple canyon system compared to other examples on this presentation. There is no direct link to a glacial source, at least under the LGM. A mid-shelf-situated glacier likely deposited abundant meltwater-dominated morainal and sub-aqueous and subaerial outwash which was destroyed during the following transgression and redistributed into large shallow water situated bank-top sand ridges. Ridge remnants remain in close proximity to the present canyon head (Fig. 17).

Contour current feeding of the upper canyon with sand is apparent even under present high-stand conditions. Sidescan surveys in 2010 help delineate a large field of presumably active bedforms (large 2-D megaripples) . Crestline orientations are slope-normal and assymetry suggest southerly migration, consistent with the Labrador Current. Associated sand ribbons (flow parallel) attest to an even greater flow regime. Hydrographic modeling of seabed stress (from tide, wind-driven and general circulation) provided courtesy of M. Li and R. Prescott (pers. comm. 2010) confirm but possibly underestimate a dominantly southerly flow (Fig. 17).

Seismic profiling from 2010 demonstrates no recognizable till or till-like deposits but rather a cleanly incised upper Tertiary age bedrock (Fig. 17).

A heavily instrumented seabed lander deployment was recently recovered from this bedform field (M. Li and A. Robertson, GSCA) but analysis has not yet commenced. It was deployed in the Labrador Current upstream position relative to the canyon. These new data will demonstrate the degree of bedform activity. From this, a sand flux estimate can be derived; in this setting the assumption is that most of this current-driven sand will be captured by the large bank-top reentrant of Carson Canyon.

In summary, this canyon experiences processes little influenced under glacial conditions apart from the low-stand feeding affect, and may be more typical of those on non-glaciated shelves. Sand bypass is the dominant process.



Seabed stress ellipses depict hindcast model results for regular intervals (individual blue dots) across a 3 year time span. Note that the SW component (offset from the red "+"), presumably the Labrador Current component, becomes less pronounced and more tidally influenced in the shallower waters. In the megaripple field 30 cm/s model values are capable of moving sand but generally a <50 cm/s is attributed to ribbons, suggesting some underestimation of the model.

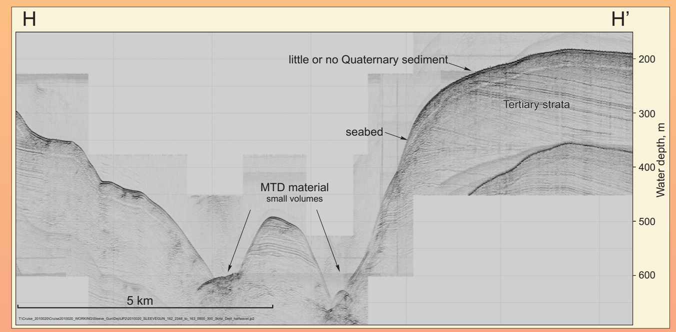


Figure 17. Morphology, surficial sediments, bedforms and modeled seabed current stress in Carson Canyon region. Blue line of section refers to sleevegun panel to left. The surficial geology map depicts a paleo sub-littoral shelf-edge deposit but recent surveys show that these sands are at least partially active, responding when the combination of tidal, storm and Labrador Current stresses align. Only a veneer of Quaternary sediment (sands and gravels) has collected within the canyon as the profile shows, suggesting nearly complete bypass from the shelf.

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