Late Cenozoic evolution of the continental margin of eastern Canada

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Piper, D.J.W.: Late Cenozoic evolution of the continental margin of eastern Canada. *Norwegian Journal of Geology,* Vol. 85, pp. 305-318. Trondheim 2005, ISSN 029-196X.

Almost the entire continental shelf off eastern Canada has been glaciated and its morphology consists of transverse troughs, which are deeper in the north, and intervening banks. Following Miocene prodeltaic muddy sedimentation, with deep bottom current reworking on the continental rise, in many areas submarine canyons, leveed channels and turbidite deposition became prominent in the Early to mid Pliocene. An abrupt change in sedimentation style is marked by the diachronous onset of shelf-crossing glaciation, ranging from Late Pliocene age at Hudson Strait to mid Pleistocene on the Scotian margin.

Pliocene and Early Quaternary progradation was marked by prodeltaic or shelf-edge clinoforms; later Quaternary progradation by stacked till tongues. In the Late Quaternary, plume fallout sediments dominate on the middle and lower continental slope, with mud turbidites on the rise. Major deep-water constructional features include submarine fans, notably off Hudson Strait and the Laurentian Fan, modified by episodic catastrophic release of meltwater that cut submarine valleys. Sediment drifts formed along the Labrador and Grand Banks margins, notably in the Late Miocene and Pliocene. On southern margins, shelf-indenting canyons remained active through interglacials. Turbidites are most common around glacial maxima: some result from direct hyperpycnal flow of meltwater and others from fallout of plume sediments. Sediment failures, such as the 1929 "Grand Banks" failure, also result in turbidity currents. Storm waves can trigger sandy flows in shelf-indenting canyons.

Modern iceberg draft at the Grand Banks is ca. 200 m but was nearly 500 m at times in the Late Pleistocene and as much as 650 m during major ice-rafting (Heinrich) events. Iceberg scour, together with storm-driven currents, strongly influenc the geology of the upper continental slope. Multiple input points of ice-rafted detritus (IRD) are distinguished at the Last Glacial Maximum. Both IRD and plume sediments of carbonate-dominated rock flour were deposited along the entire eastern Canadian margin from Hudson Strait to off Georges Bank during Heinrich events.

Styles of sediment failure include: simple slump failures; shallow retrogressive slump failures that evolve into debris flows; "stripped off" bedding planes that might result from glides but more likely from evacuation of retrogressive failures; slides with toe compression; and creep deformation that may lead to major valley wall collapses creating enormous debris avalanche deposits on the continental rise. Magnitude-frequency relationships and correlative failures in multiple valley systems suggest that most failures are earthquake triggered, with some seismicity induced by glacio-isostasy.

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Introduction and purpose

This paper provides a conceptual link between numerous local studies in order to summarize the Late Cenozoic evolution of the eastern Canadian continental margin. These local studies have been undertaken recently in response to renewed hydrocarbon exploration since 1998. The paper first provides a brief summary of the morphology and oceanography of the margin and the Neogene geologic history. The paper then focusses on Quaternary glacially dominated sedimentation, dealing first with constructional features and processes and then with erosional features and processes. It should provide a useful comparison with other North Atlantic margins considered in this volume.

In this overview, only that part of the Canadian margin south of 62°N, i.e. from Georges Bank to Hudson Strait (Fig. 1), is treated in a comprehensive manner. Farther north, on the continental margin off Baffin Island, there has been little new work since the 1987 synthesis of Keen & Williams (1990), and reference is made to this area only as necessary to understand the overall evolution of the continental margin.

Tectonic setting

Rifting and sea-floor spreading on the eastern Canadian margin occurred in three phases. Off Nova Scotia, there was Triassic rifting and Early Jurassic sea-floor spreading; off the eastern Grand Banks sea-floor spreading began in the Early Cretaceous, and in the Labrador Sea and Baffin Bay it began in the Late Cretaceous (Louden et al. 2004). Late Cenozoic subsidence is influenced by this tectonic framework. In

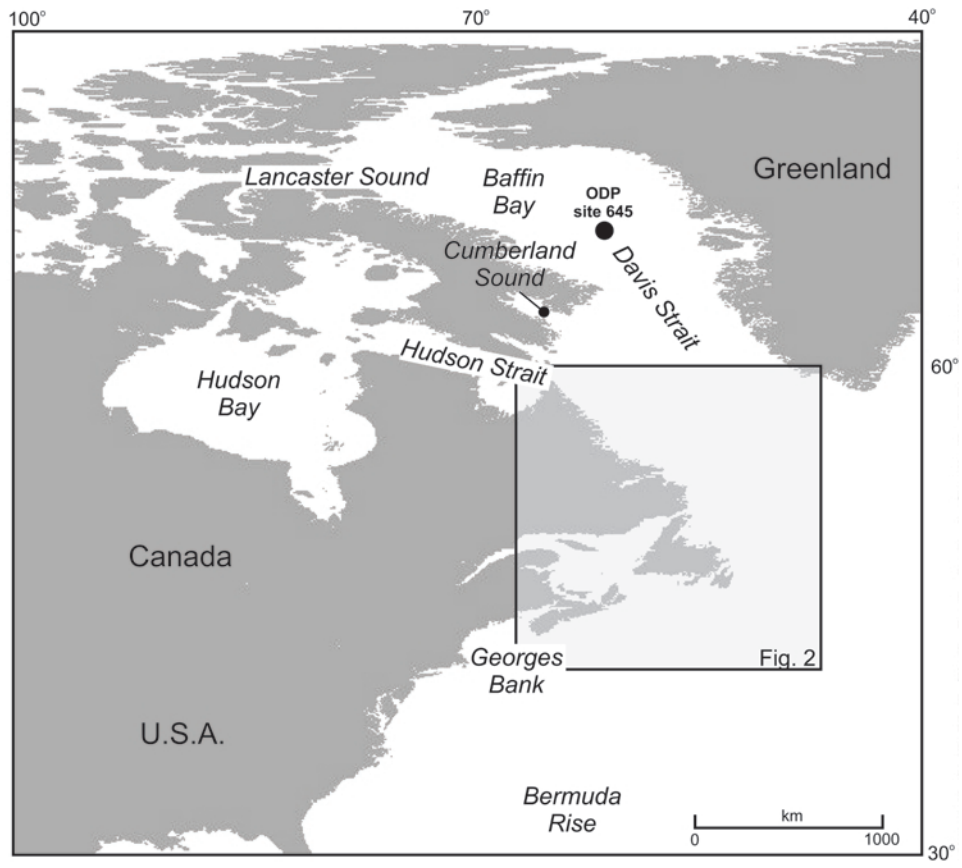

Figure 1. Location map for eastern Canada.

the region affected by Triassic rifting of the central North Atlantic Ocean (Jansa et al. 1980), from the eastern Grand Banks to the Scotian Shelf, margin evolution is strongly influenced by salt tectonics (Shimeld 2004). Whether Pliocene plate reactivation (Cloetingh et al. 1990) has played a role in influencing subsidence is uncertain, but there is evidence of considerable later Cenozoic uplift of Baffin Island and high rates of Late Neogene subsidence on the Labrador Shelf (Keen et al. 1990).

Morphology and oceanography

Almost the entire continental shelf off eastern Canada has been glaciated numerous times in the mid to Late Pleistocene. The resulting morphology consists of transverse troughs and intervening banks (Piper 1988). There is a zone of deep basins (marginal trough) at the landward edge of the Mesozoic-Cenozoic wedge, which is most prominent on the Labrador Shelf, forming the Labrador marginal trough, but basins are also developed in this position in the Gulf of Maine, the Scotian Shelf and Grand Banks (Fig. 2). The mean depth of continental shelves increases from south to north, but the relative importance of various contributing factors is uncertain. These factors include subsidence related to the age of the adjacent ocean, other tectonic subsidence, glacio-isostatic loading, glacial erosion, and low rates of glacial sedimentation between ice streams on shelves with deep shelf breaks. The increase in mean depth of the shelf is paralleled by an increase in the depth of the shelf break (Fig. 2), both off transverse troughs and off the intervening banks. North of the Grand Banks, virtually none of the continental shelf in the Labrador Sea is shallow enough to have been emergent at glacial lowstands, in contrast to quite large areas of the Grand Banks and Scotian Shelf that are less than 100 m (and even less than 50 m) deep (Fig. 2) and were emergent at lowstands.

From north to south, the depth of the adjacent ocean basin increases, from 2200 m in Baffin Bay, to 3000-4000 m in the Labrador Sea, to over 5500 m in the central North Atlantic Ocean. These depths influence the evolution of gravity flows entering the deep marine realm. Deep-water morphology is complicated by continental fragments and seamount chains on the margin, including the 800 m deep Davis Strait sill between Baffin Bay and the Labrador Sea; Orphan Knoll, Flemish Cap and the enigmatic Southeast Newfoundland Ridge off the Grand Banks; and the Newfoundland, Fogo, and New England seamount chains (Fig. 2).

A powerful southern or western sea-surface current is present close to the continental shelf break all along the

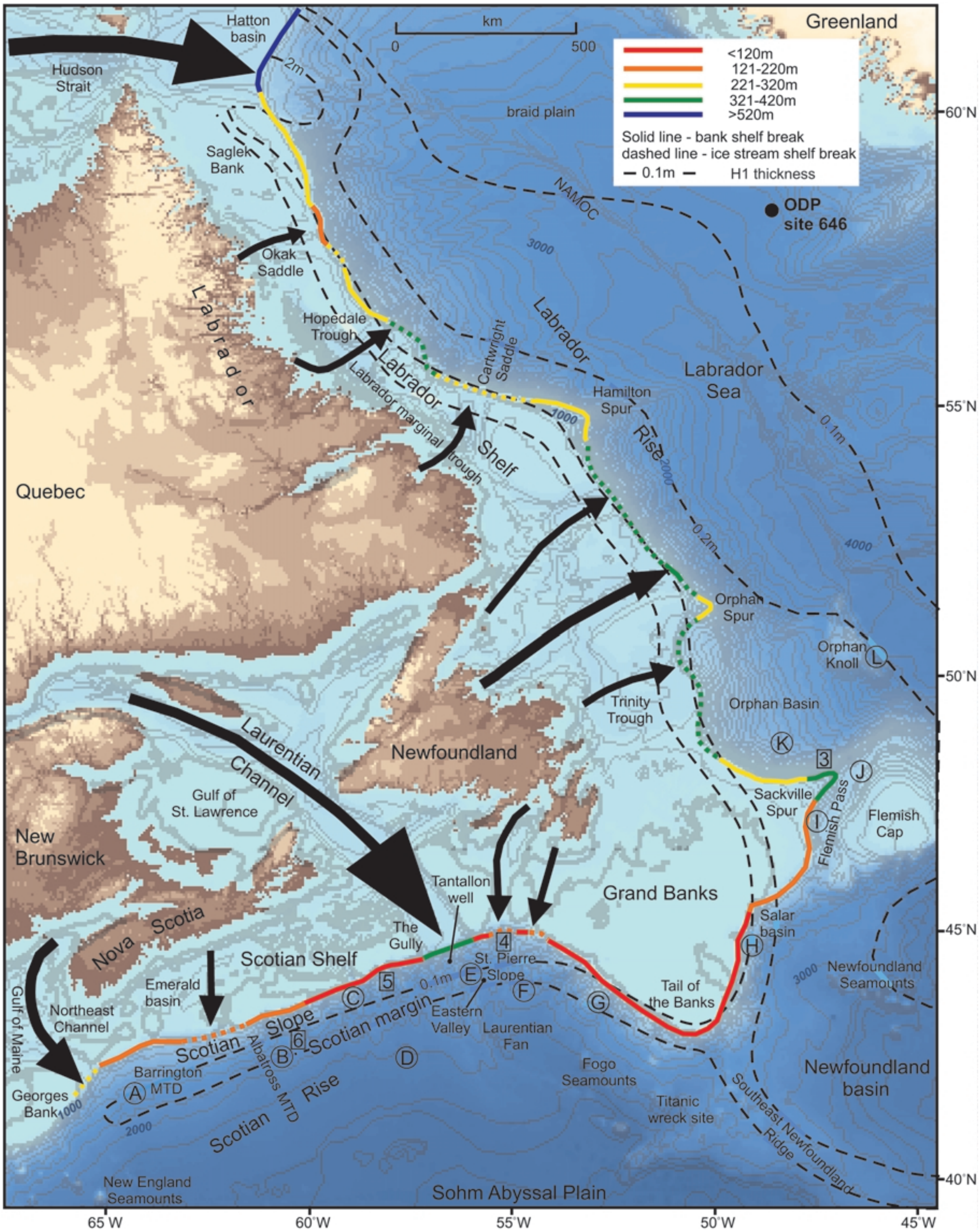

Figure 2. Morphology of the eastern Canadian continental margin south of 62EN. Bathymetry from GEBCO. Ice streams shown by bold arrows. Depth of shelf break colour coded. Thickness of the H1 Heinrich layer shown by dashed lines. Letters (A) to (L) refer to areas in Fig. 4; numbers in boxes show location of Figures 3-6.

southeastern Canadian margin, known as the Labrador Current and its continuation around the Grand Banks and along the upper Scotian Slope (Smith & Schwing 1990). The Labrador Current scours the seabed to water depths of 1300 m (Mackie 2005). Deep-water circulation forms the Western Boundary Undercurrent, which is more vigorous at times of greater deep-water production, for example during interglacials. It flows at

2500 m water depth on the Labrador Rise, 3800 m southwest of the Grand Banks and near 5000 m on the Scotian Rise. In addition, on the Scotian and Grand Banks rises, seabed current activity is largely the result of interaction with Gulf Stream eddies (Weatherly & Kelley 1985; Fofonoff & Hendry 1985; McCave et al. 2002).

Preglacial sedimentation

Early Neogene history

Miocene and Pliocene evolution of the continental margin is not well known. Thick, predominantly muddy Miocene successions are developed on the Scotian Slope following widespread Oligocene canyon cutting (e.g. Wade et al. 1995) and similar strata are present in places on the Grand Banks and Labrador margins (e.g., Wielens et al. 2004; Hinz et al. 1979). On the continental rise, there is considerable winnowing and reworking of sediment by bottom currents, starting in the Oligocene in the Labrador Sea and southwards (Gradstein et al. 1990).

In the Early to mid Pliocene on the Scotian margin, there is a pronounced change in sediment style that includes accumulation of turbidites on the upper Scotian Rise (Piper & Ingram, 2003) and on the Laurentian Fan (Uchupi & Austin, 1979; Piper & Normark, 1989) and the development of leveed turbidity current channels on St Pierre Slope (Piper et al. 2005). On the Grand Banks margin, significant progradation took place towards Flemish Pass and Orphan Basin (Deptuck 2004; Sonnichsen & King 2005). On the Labrador margin, there was significant slope progradation in turbidite facies only north of 56°N (Myers & Piper 1988).

The onset of glaciation

Evidence for the onset of glaciation is best controlled around Baffin Bay, as a result of ODP Site 645 (Arthur et al. 1986). Isolated ice-rafted granules are found in the Upper Miocene deposits, but the onset of major ice-rafting dates from 3.4 Ma. In the mid-Pliocene, the R-1 unconformity of Srivastava et al. (1987) marks the base of a thick wedge of sediment prograded westwards from Greenland, probably corresponding to the onset of shelf-crossing glaciation from Greenland, and marked by an increase in abundance of ice-rafted detritus at ODP Site 645 at about 2.5 Ma (Hiscott et al. 1989). In the Early Pleistocene, there was an increase in detrital carbonate, suggesting a greater role for ice supply from the Canadian Arctic Island channels.

The supply of glacial detritus through Hudson Strait is indicated by the presence of silt turbidites of carbonate rock flour in ODP Site 646, dating back to about 2.5 Ma in the mid- Pliocene (Piper & deWolfe 2003). On the Scotian margin, the onset of shelf-crossing glaciation has been dated by the record of detrital palynomorphs and coal eroded from transverse troughs as mid Pleistocene, probably in MIS 12 (Piper et al. 1994, 2002). The sediment record on the Bermuda Rise at ODP Site 1063 shows peaks in supply in glacial stages back to MIS 14 and also in MIS 20 (Giosan et al. 2002). Prior to that, there was likely significant upland glaciation as indicated by palynomorphs indicating cool conditions on the Grand Banks

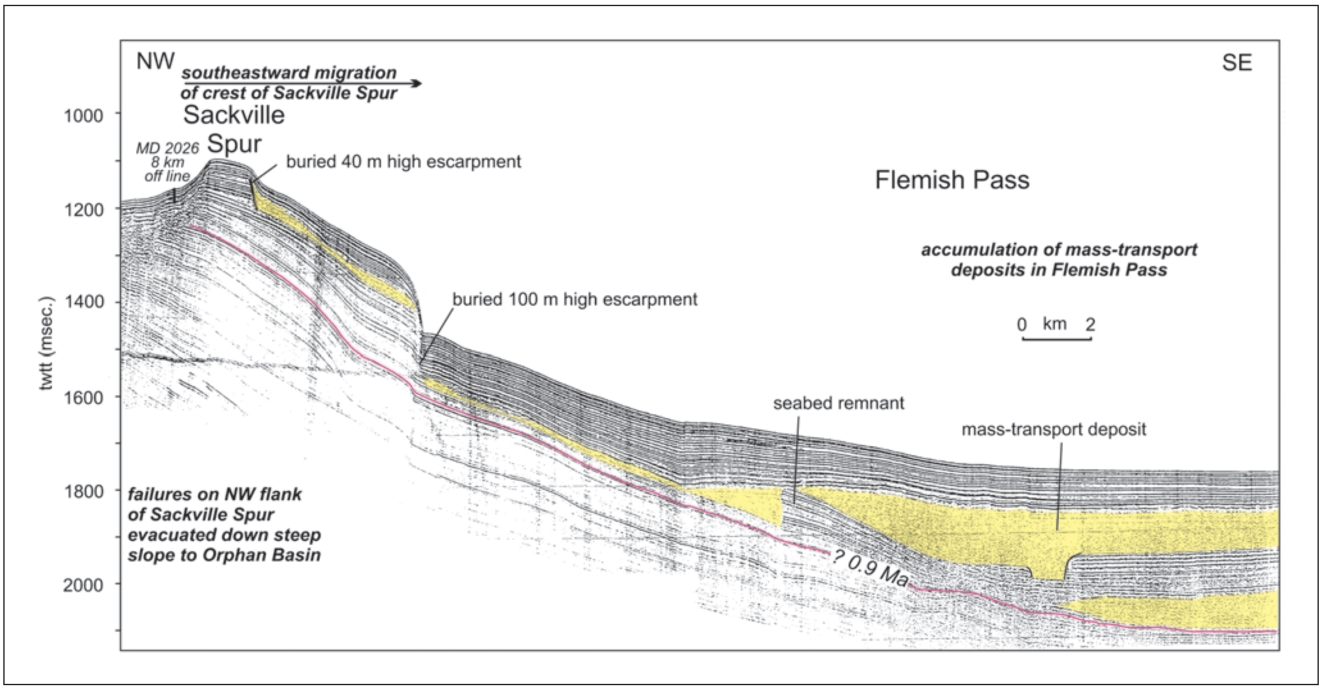

Figure 3. Seismic-reflection profile across Sackville Spur, an upper slope sediment drift. Details of chronology in Piper and Campbell (2005).

back to 1 Ma and the supply of Upper Pliocene gravel to the Laurentian Fan (Hughes Clarke et al. 1990). In Flemish Pass (Piper & Campbell 2005), estimates suggest the onset of shelf-crossing glaciation at about 1 Ma in the mid Pleistocene, but these ages are not well controlled.

Bottom-water circulation

The history of bottom-water circulation is preserved in the dated sediment record on the Labrador Rise and on the US continental margin. The earliest evidence of strong deep thermohaline bottom-water circulation is in the Oligocene, with a prominent intensification at 8.4 to 9.2 Ma in the Late Miocene (Mountain & Tucholke 1985; Mountain et al. 1994), corresponding to horizon U of Hinz et al. (1979) in the Labrador Sea. It was followed by a phase of drift growth in the Labrador Sea culminating in the Late Pliocene in a period of intensified bottom current activity, followed by less evidence of bottom current activity in the Quaternary (Myers & Piper 1988), when both bottom circulation and the Labrador Current were more vigorous in interglacials than in glacial periods (Hillaire Marcel et al. 1994).

The 1000 m deep floor of Flemish Pass preserves a record of the strength of the Labrador current. A significant unconformity dates from the mid-Oligocene (Kennard et al. 1990), probably corresponding to the well developed sediment waves in a paleo-water depth exceeding 2000 m of apparent Oligocene to Early Miocene age identified by Deptuck (2003, his figures 4.12, 4.14). A more regional unconformity dates from the Late Miocene (Deptuck 2003), probably corresponding to the intensification noted by Mountain et al. (1994). The shallow Sackville Spur sediment drift (Fig. 3) has been built since that time, as proglacial sediment plumes became available.

Quaternary tectonics

Locally, there is evidence of neotectonic activity in the Quaternary. On the eastern Scotian and southwestern Grand Banks margin, vigorous salt tectonic deformation (Shimeld 2004) resulted in substantial offsets in Quaternary strata on the continental shelf (Piper & Gould 2004) and in the deep basin (Ledger-Piercey & Piper 2005). On the Grand Banks, the Murre fault has been active to near the surface (Sonnichsen & King 2005) and there is evidence for active faulting in Salar basin (Toews 2003) and Orphan Basin (Piper 2004).

Quaternary constructional features

Sediment fans

Well-defined submarine fans are rare on the eastern Canadian continental margin. The best known is the Laurentian Fan (Uchupi & Austin 1979; Skene & Piper 2003), which had the morphology of a typical passive-margin submarine fan from the mid Pliocene to the mid Pleistocene, but experienced a fundamental change in sediment architecture following the onset of shelf-crossing glaciation. Subglacial outwash floods eroded the continental slope and the main fan valley (Piper et al. in press); proglacial fine-grained plume sediment and resulting fine-grained turbidites accumulated in interchannel areas (Curran et al. 2004). The submarine fan off Northeast Channel appears to have an architecture similar to that of Laurentian Fan, but is on a smaller scale (Hundert 2003).

Along much of the intervening area of the Scotian margin, there appears to have been a line source of glacial sediment at the glacial ice margin, supplying sediment to a series of channels that cross the continental slope and rise and transport sediment to the Sohm Abyssal Plain (Hughes Clarke et al. 1992). The largest channels, such as that seaward of The Gully (Fig. 2), have developed prominent levees on the continental rise (Piper & Ingram 2003). Linear sediment supply from glacial margins also characterises much of the Grand Banks and Labrador margin, with numerous submarine canyons and channels transporting sediment across the continental slope and rise. The submarine channel patterns are best known in the northern Labrador Sea from the work of Hesse and his students (Hesse 1995; Hesse & Klaucke 1995; Wang & Hesse 1996). On the margin of the Grand Banks at Flemish Pass, canyons or even gullies are rare (Piper & Pereira 1992), perhaps because the basin floor was insufficiently deep for continuous vigorous turbidity currents to evolve. On the southern Grand Banks, sediment supply was likely principally from glacial outwash, but the shallow depth of the shelf break meant that beaches would have nourished a series of closely spaced submarine canyons (Savoye et al. 1990).

Features resembling trough-mouth fans are developed seaward of Trinity Trough in Orphan Basin (Hiscott & Aksu 1996), Okak Saddle (Benetti et al. 2004), Hudson Strait (Piper & Hesse 1997), and Lancaster Sound (Aksu & Piper 1987). The Orphan Basin fan is constructed of stacked mass-transport deposits (Campbell 2005), which, where cored, are seen to consist of homogenous diamict interpreted as deposited by direct flow of mudflows of till from the ice margin on the upper slope off Trinity Trough (Tripsanas et al. 2005).

Seaward of Hudson Strait, seaward-dipping Tertiary strata on the central shelf are overlain by prograded diamict wedges on the outer shelf (Andrews et al. 2001). The outer shelf diamict wedges continue down the continental slope and their acoustic character resembles trough-mouth fans well described from the

Norwegian and Antarctic margins. Two distinct fans are recognised: the main (southern) fan lies seaward of Hatton basin, whereas the northern fan was probably sourced by a Cumberland Sound ice stream (Andrews et al. 2001) (Fig. 1). High-resolution seismic-reflection profiles also show stacked mass-transport deposits. The upper slope is strongly dissected by canyons and gullies, which suggest that at times subglacial meltwater was discharged seaward of the shelf break. Hyperpycnal flows constructed the submarine braid plain in the northwestern Labrador Sea (Hesse et al. 2001), whereas fallout of fine-grained sediment from meltwater plumes created muddy turbidity currents (Hesse et al. 1997, 2004) that nourished the NAMOC submarine channel system (Fig. 2) (Klaucke et al. 1997, 1998 a, b).

Sediment drifts

Prominent sediment drifts are of two types. Deep-water drifts, sculptured by the Western Boundary Undercurrent, are reviewed by Faugères et al. (1999). On the continental margin, such Quaternary features are small, occurring on the south side of Flemish Pass and around the Southeast Newfoundland Ridge (Parson et al. 1985). Large-scale drift features of Pliocene or Early Pleistocene age are found in Orphan Basin (Piper et al. 2004; Mackie 2005) and bottom current sculpturing is also described from the Labrador Sea (Myers & Piper 1988) and Newfoundland Basin (Parson et al. 1985). Many parts of the deep continental margin south of Newfoundland, including the Titanic wreck site, are areas of very condensed deposition as a result of topographic intensification of bottom currents (e.g. Cochonat et al. 1989).

Shallow-water drifts have been constructed by the Labrador Current on the continental slope since the onset of widespread shelf-crossing glaciation supplied large amounts of suspended sediment. The best known drift is Sackville Spur (Kennard et al. 1990) (Fig. 3), but similar features are found south of Cartwright Saddle ("Hamilton Spur"; Myers & Piper 1988), at the northern end of Orphan Basin ("Orphan Spur"), and complex drifts are developed at the southern end of Flemish Pass (Deptuck 2003, his figure 4.13; Piper & Campbell 2005). Most drifts show a balance between drift deposition and episodic failure (Fig. 3).

Shelf-edge progradation

Significant shelf-edge progradation took place along much of the eastern Canadian margin in the Quaternary, although this process has not been systematically documented. Many transverse troughs terminate at bulges in the continental shelf, suggesting that these are preferred sites of progradation (Fig. 2). Pliocene or Early Quaternary progradation was essentially prodeltaic and has been documented but not well dated in Hudson Strait (Andrews et al. 2001), Hopedale Trough (Josenhans et al. 1986; Myers & Piper 1988), around the eastern and northern Grand Banks (Deptuck 2004) and on the Scotian margin (Flynn 2000).

On rapidly subsiding continental margins, such as the southwestern Grand Banks margin where salt tectonism is active, mid to Upper Quaternary till deposits (which form till tongues terminating at paleowater depths of around 500 m) tend to aggrade (e.g. Piper et al. 2005; Piper & Gould 2004). Where subsidence is less, such as on the central Scotian Slope (Piper et al. 2002) and Hudson Strait (Andrews et al. 2001), successive till tongues have prograded seaward.

Deposition on the continental slope

Deposition on the continental slope takes place principally from sediment fallout from proglacial plumes and sediments consist of muds with dispersed ice-rafted detritus (Hill 1984; Piper & Skene 1998; Hesse et al. 1999). Some thin sand beds, probably of turbidite origin, are found at horizons corresponding to maximum ice advance (Campbell 2000). Sediment thickness is greatest close to major transverse troughs, as demonstrated for Heinrich layers south of Hudson Strait by Rashid et al. (2003) and for sediments on the east Scotian Slope by Piper (2001). Petrographic studies (Piper & deWolfe 2003) and sediment thickness variations show that smaller transverse troughs also play an important role in supplying sediment, particularly close to glacial maxima. The predominant southwestward advection of the Labrador Current all along the eastern Canadian continental margin results in such plume sediments moving southward in the Labrador Sea and westward along the Grand Banks and Scotian margins. Thus, for example, plume transport of carbonate rock flour in Heinrich events from Hudson Strait (Andrews & MacLean 2003) can be tracked all along the eastern Canadian margin (e.g. H1 thicknesses shown in Fig. 2). Such carbonate rock flour is recognised at least as far to the southwest as the submarine fan off Northeast Channel (Hundert 2003). Red plume sediments derived from the Gulf of St Lawrence, which dominate Laurentian Fan and the Scotian Slope, are absent immediately east of the Laurentian Channel outlet on St Pierre Slope (McCall et al. 2004).

The origin of turbidites on the deep-water margin

On the deeper parts of the continental slope and on the continental rise, there is a progressive increase in the importance of turbidity current deposits at the expense of plume deposits. Much of this deposition is muddy (Piper 2001; Benetti et al. 2004) and may include

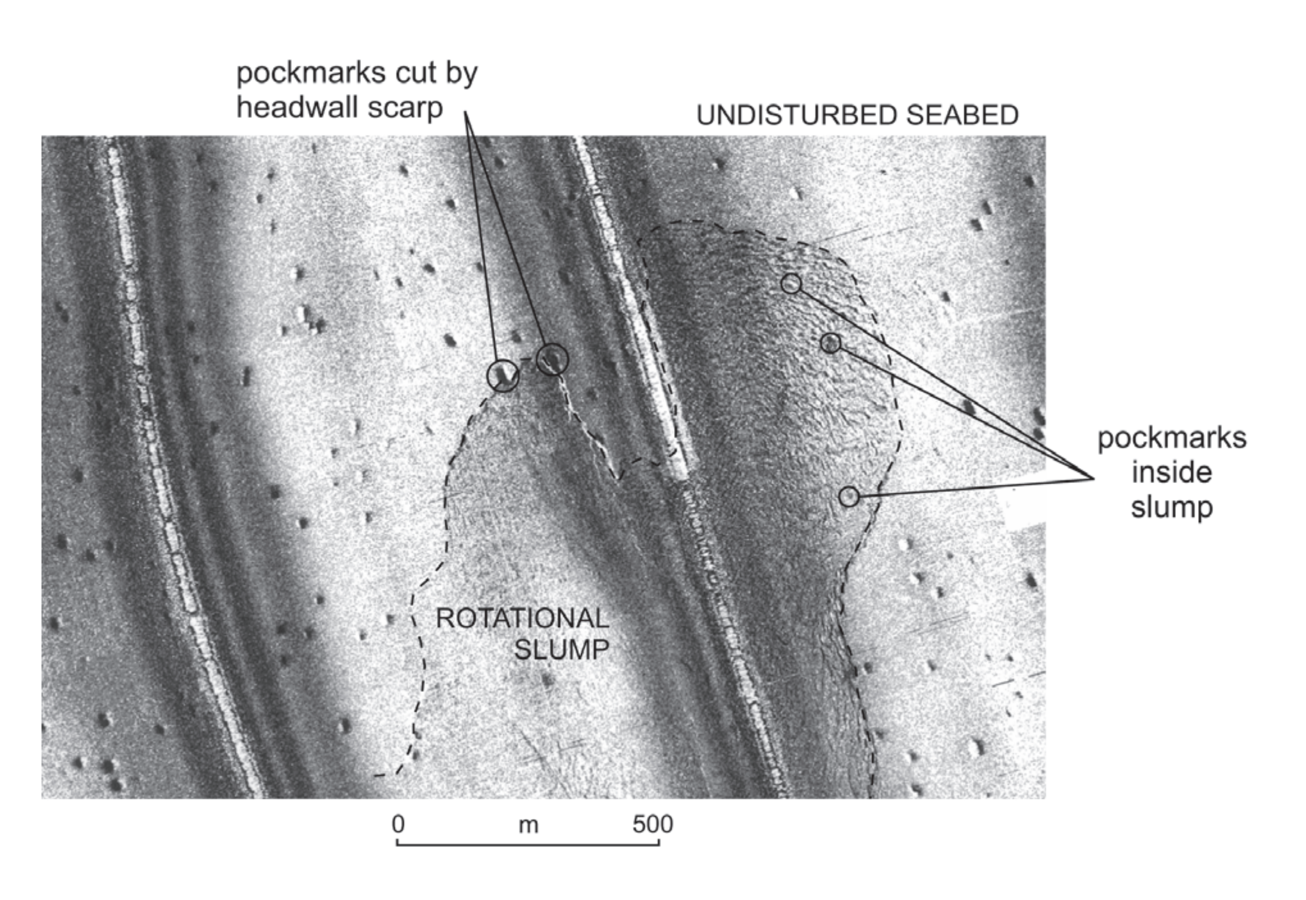

Figure 4. Sidescan image showing pockmarks and retrogressive slump failure resulting from the 1929 Grand Banks earthquake, at 700 m water depth on St Pierre Slope. Details in Piper et al. (1999).

deposits of lofted turbidity currents (Hesse et al. 2004). In general, turbidites are most common at and following glacial maxima, when at least some resulted from direct hyperpycnal flow of meltwater (S. Migeon, pers. comm. 2003) and others from fallout of plume sediments. Sediment failures, such as the 1929 "Grand Banks" failure, also result in turbidity currents by transformation of slumps to debris flows to ignitive turbidity currents (Piper et al. 1999). Storm waves also trigger sandy flows in shelf-indenting canyons and such turbidites have a ~10^3 yr recurrence interval at highstands of sea level. Smaller flows may be initiated on the upper slope (Baltzer et al. 1994).

The seafloor distribution of sediment

The distribution of sediment types at the seafloor is a consequence of the modern current regime, which along most of the continental margin is greatly intensified compared with that during glacial periods. Storm waves also rework the upper slope, which would have been protected by a much longer sea-ice season in glacial times (de Vernal et al. 2000).

Almost all of the upper continental slope is underlain by glacial till, with its surface scoured and pitted by icebergs. This is an area of sediment reworking by internal waves, storm waves, and the Labrador current and its continuation in the shelf-edge current. The seafloor consists of sorted sand, generally thickest in depressions, and locally coarse sand and gravel, with till outcropping on scour berms (Piper & Campbell 2002). Downslope, muds generally predominate on the seafloor in water depths of > 600 m on the Scotian Slope (Hill & Bowen 1983) and > 1300 m on the Labrador Slope (Carter et al. 1979; Carter & Schafer 1983; Schafer et al. 1985). However, over topographic highs, winnowed sands may be present to water depths of 1500 m on the Scotian Slope (Piper 2001).

Deep-water corals are known from Northeast Channel (Mortensen & Buhl-Mortensen in press), in lesser abundance elsewhere on the Scotian margin (Kostylev 2002), and at Orphan Knoll (Smith et al. 1999). Cold-seep chemosynthetic communities are known from the Laurentian fan (Mayer et al. 1987). Pockmarks are widespread on those areas of the Scotian margin (Baltzer et al. 1994) and St Pierre Slope (Piper et al. 1999) that have been surveyed with high-resolution, deep-towed sidescan (Fig. 4).

Erosional features

Erosion by subglacial meltwater discharge

Seaward of major ice streams, there is evidence of occasional catastrophic erosion by sub-glacial meltwater discharge, that is best documented off the Laurentian Channel and off Hudson Strait. On Laurentian Fan, a major subglacial meltwater discharge at 16.5 ka (radiocarbon years) transported large amounts of sand and gravel down Eastern Valley (Piper et al. in press). Such large flows have a recurrence interval of 10^5 years during glacial periods and not all major discharges of muddy plumes appear to have a corresponding erosive hyperpycnal component. A similar process is inferred for the origin of the northern Labrador Sea braid plain off Hudson Strait (Hesse et al. 2001). Erosional features off Northeast Channel (Hundert 2003) and the enormous indentation of The Gully into the Scotian Shelf (Fader & King 2003) suggest that similar processes may have acted there.

It is less clear whether some submarine canyons might be the result of subglacial meltwater discharge. Tunnel valleys are widespread on parts of the Grand Banks (Sonnichsen & King 2005) and Scotian Shelf (Boyd et al. 1988; Loncarevic et al. 1992; King 2001) and the valley planform on the eastern Scotian Shelf converges towards the head of major canyons (Flynn 2000; Piper et al. in press). There appears to be no consensus in the literature as to whether tunnel valleys are the result of "normal" subglacial meltwater flow or catastrophic processes: in either case, they have the potential to deliver sandy erosive hyperpycnal flows to the upper slope. Upper slope erosion on the southwestern Grand Banks margin was ascribed to subglacial hyperpycnal flows by Piper & Gould (2004).

Iceberg scour

Iceberg scour, together with storm-driven currents, strongly influences the geology of the upper continental slope. Modern icebergs that impact the eastern Canadian margin are principally derived from northwestern Greenland and an inventory of about 40 000 icebergs is maintained in Baffin Bay (Lewis & Woodworth-Lynas 1990). Modern drafts of 427 m are known from Baffin Bay. Maximum draft at the latitude of the Grand Banks is ca. 200 m but iceberg scour depths suggest drafts were nearly 500 m at times in the late Pleistocene, with extreme values of 750 m on the Labrador margin, 650 m at Flemish Pass, and 500 m on the Scotian Slope. There is circumstantial evidence that the extreme drafts are associated with Heinrich events (Piper & Gould 2004) and that iceberg scour may be an important process in triggering slope failure and turbidites during during Heinrich events (Piper & Campbell 2005).

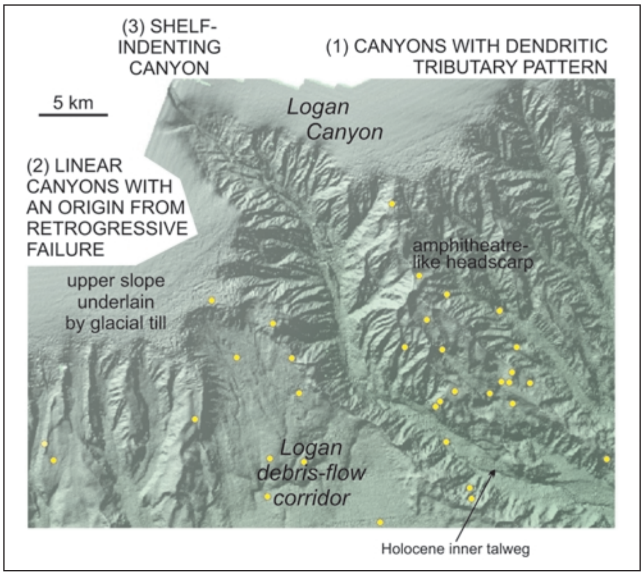

Figure 5. Multibeam bathymetry on the central Scotian Slope showing different types of canyons. 1 = dendritic canyons, just down-flow from The Gully outlet (Fig. 2); 2 = more linear retrogressive canyons; 3 = Logan Canyon, a large canyon cutting the shelf break with a Holocene inner talweg. Image modified from Mosher et al. (2004).

Sediment failure

Styles of sediment failure

Sediment failure is widespread on the eastern Canadian margin, both in preglacial sediment (Campbell et al. 2004) and prominently in the glacially dominated section. Sediment failure on the Scotian Slope is synthesised by Mosher et al. (2004), around the 1929 Grand Banks earthquake epicentre on St Pierre Slope by Piper et al. (1999; 2005) and McCall et al. (2004) and elsewhere on the margin by Piper & McCall (2003). Piper et al. (2003) and Mosher et al. (2004) have argued that most failures are likely triggered by earthquakes. These studies have shown at least six styles of failure:

a) simple slump failures, leaving an amphitheatre-like headscarp, are common on the incised walls of canyons and slope valleys (e.g. on the east wall of Logan Canyon, Fig. 5).

(b) retrogressive rotational failure, commonly initiated on steep slopes related to slope channels or salt tectonism on the lower slope and upper rise. Retrogression can move headwards until the upper slope till limit is reached. Slumps transform on steep slopes into debris flows, which then transform into turbidity currents through hydraulic jumps on steep gradients (Piper et al. 1999).

(c) in many places, stratified proglacial sediments appear to have been evacuated along bedding planes (e.g. Baltzer et al. 1994; Mosher et al. 2004). Whether this takes place through a process of glides or by retrogressive slumps that completely transform to turbidity currents (as demonstrated by Piper et al. 1985 and inferred from the stepped character of erosion beneath mass-transport deposits) is generally not known.

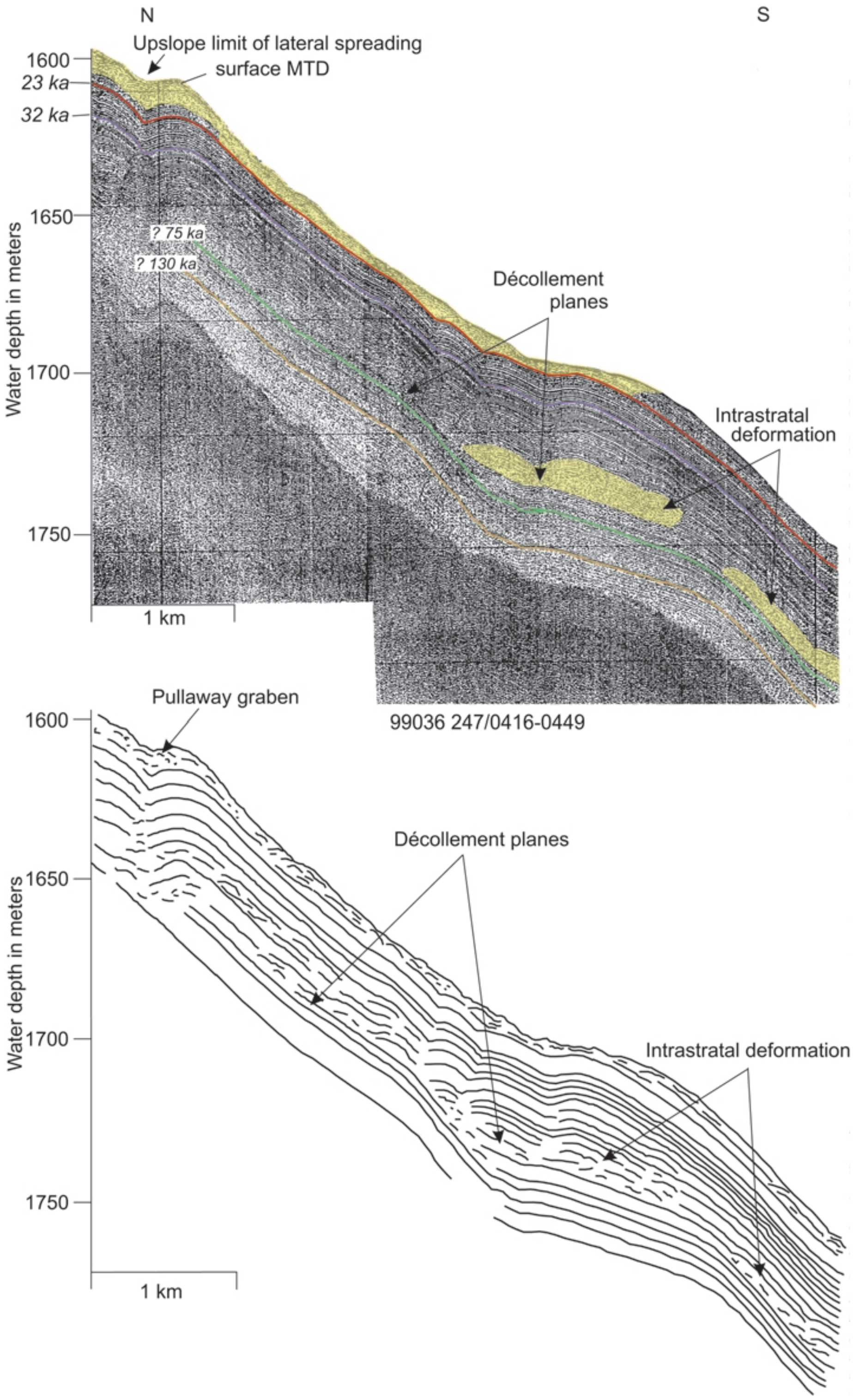

Figure 6. High-resolution sparker profile showing creep deformation, central Scotian Slope (from Gauley 2001).

(d) A few classic slides appear to have been initiated on the lower slope or upper rise: they have a prominent headscarp, tens of kilometres of run-out, and compression at the toe (e.g. Savoye et al. 1990; Hughes Clarke et al. 1992).

(e) Creep deformation has been inferred in a few places on the Scotian Slope (Gauley 2001) from undulating folds in a stratified sediment slab 50-100 m thick, that is unsupported downslope due to erosion, appears to overlie a decollement surface, and has an upslope graben formed by extension (Fig. 6). However, such features are very difficult to distinguish in seismic-reflection profiles from the case of a thin rough surface formed by an old mass transport deposit, draped by younger plume fall-out muds. Intact slabs 2-5 m thick are known in a few cases overlying deformed sediment at the margin of larger failures (Piper 1999; core 46) and suggest that some buried horizons may be more susceptible to failure during earthquake shaking.

f) Some major inter-valley ridge collapses involve sediment columns more than 100 m thick (Logan debris-flow corridor of Piper 2001; Mosher et al. 2004; Henderson 2004; see Fig. 5) and have geometries that do not support an entirely retrogressive origin (Piper & Ingram 2003). Such large failures may result from eventual collapse of deforming bodies above buried decollement horizons.

Styles of failure deposits

The styles of failure deposits are inferred from geometry and acoustic character in seismic-reflection profiles and, where available, 3-D seismic and from studies of cores that generally penetrate only the upper parts of mass-transport deposits.

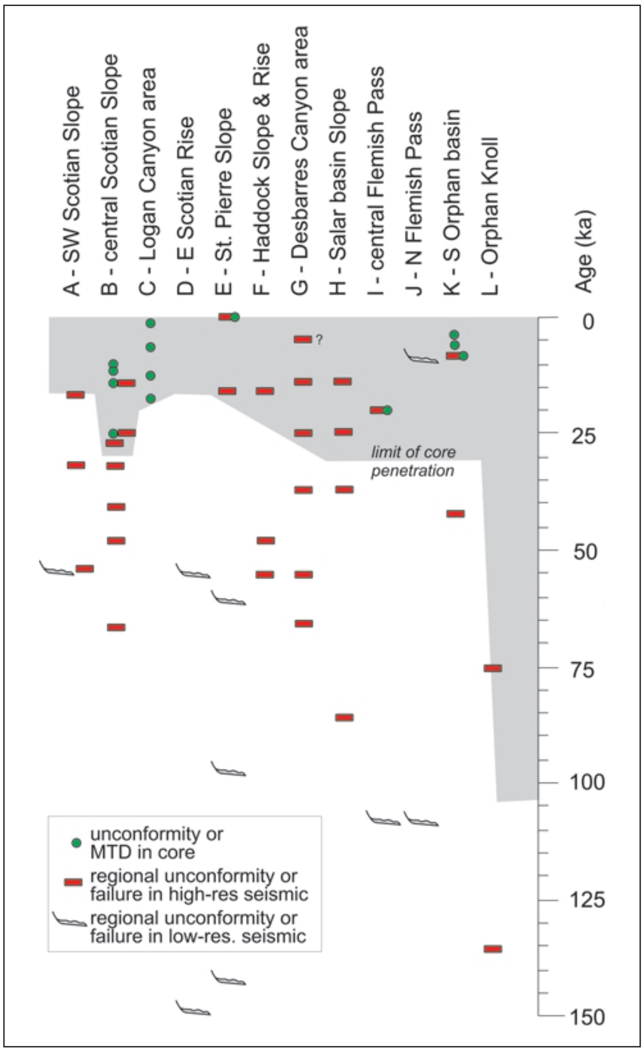

Figure 7. Occurrence of regional failures on different parts of the southeastern Canadian margin in the past 150 ka. Modified from Piper et al. (2003) with additional data from K. Jenner (pers. comm. 2005); Ledger-Piercey & Piper (2005); and Tripsanas et al. (2005).

Flow tills are very rare on the southeastern Canadian margin: till-tongues, commonly of overconsolidated diamict, all terminate at much the same water depth on the upper slope and in most areas there is no evidence of diamict downslope from their terminations. Diamict has been seen on upper Laurentian Fan (Hughes Clarke et al. 1989). In general, where acoustically incoherent mass-transport deposits are interpreted downslope from till tongues, by their acoustic character and from cores, they consist of rotated blocks of proglacial sediment or mud-clast conglomerate (Piper et al. 1985; Brunt & Piper 2005). The exception is the presence of diamict on trough-mouth fans, described above.

Retrogressive slumps interpreted from sidescan and multibeam echo-sounding produces a ridged sea floor (Fig. 4) and dipping blocks are recovered in cores. Such deposits pass downslope into material that produces a smoother sea floor and fills depressions, interpreted as muddy mass flow. Cores show mud clast conglomerate, some matrix supported, some clast supported (Tripsanas et al. 2005). Very large mass-transport deposits, such as the Albatross "debris flow" (Shor & Piper 1989; Mulder et al. 1997), the Barrington mass-transport deposit (Campbell et al. 2004), and mass transport deposits on the east Scotian Rise (Piper & Ingram 2003) are seen to contain blocks on a horizontal scale of 10^2-10^3 metres (based on sidescan or 3D seismic). These blocks are either inferred to previously have been buried to many tens of metres, or have been sampled and show strength properties that confirm such overconsolidation. Such deposits resemble large mass-transport deposits recently imaged elsewhere by 3D-seismic (e.g. Gee et al. 2005; Dahlgren & Vorren 2004) and cored on the Amazon fan by ODP Leg 155 (Piper et al. 1997).

Distribution and frequency of sediment failure

Information on the distribution, apparent magnitude, and frequency of failure on the eastern Canadian margin was synthesised by Piper et al. (2003) and an updated summary is presented in Figure 7. Only large failures are recognised from industry seismic-reflection profiles (Piper & Ingram 2003; Campbell et al. 2004) . Thin-bedded failures are recognised in high-resolution seismic-reflection profiles and very local failures may be recognised in cores from unconformities or thin mass-transport deposits. Most of our mapping of failure distribution is based on Huntec ultra-high-resolution sparker profiles that commonly image about the last 10^5 yr of sedimentation (e.g. Fig. 6) and can be directly dated from radiocarbon-dated piston cores back to 36 ka. Deeper horizons can be tentatively correlated through till tongues on the upper slope to major glacial advances. A crude magnitude-frequency relationship is interpreted for slope failures, with small failures on the continental slope having a recurrence interval of perhaps $5x10^3$ yr (Piper et al. 2003) whereas large failures have a recurrence interval of $>2x10^5$ yr (Piper & Ingram 2003; Piper & Campbell 2005).

There does not appear to be a systematic relationship between failure frequency and regional gradient, although locally steeper slopes are clearly more prone to failure, as shown by the greater abundance of small failures on active fault scarps created by salt tectonics (Ledger-Piercey & Piper 2005). Failures are more common on continental slopes adjacent to glaciated continental shelves, compared with slopes of similar gradient that also receive muddy plume sedimentation far offshore at Orphan Knoll (Toews & Piper 2002). Regional failures do not appear to be more abundant in areas of active salt tectonics (Piper & Gould 2004) than elsewhere.

Regional failures appear to be synchronous in multiple drainage systems and many cannot be accounted for by retrogression from a single point failure. Such synchronous failure over a large area probably results from earthquake triggering, although glacial meltwater discharge and consequent canyon widening is a possible mechanism in certain situations. Such regional failures are dated from their position within a high-resolution seismic stratigraphy, dated by cores with radiocarbon dates and Heinrich layers (e.g. Gauley 2001; Piper et al. 2003; Piper and Gould 2004); the chronology is reliable back to 36 ka. The decrease in frequency of failures offshore and the greatest abundance of failures during deglaciation suggests that some of the seismicity was induced by glacio-isostasy. Several factors may precondition sediments to fail more readily, including underconsolidation due to high sedimentation rates from proglacial plumes (> 3 m/kyr on St Pierre Slope - Piper et al. 2005; and 4.5 m/ky at the Tantallon well site on the east Scotian Slope: Piper 2001).

Evolution of submarine canyons

Submarine canyons along the eastern Canadian continental margin show a variety of morphologies and are inferred to have a corresponding variety of origins. At least five types are distinguished:

1. Dendritic canyons that have developed downslope from the limit of till (type 1 in Fig. 5) have been imaged by multibeam bathymetry on the central Scotian Slope (Mosher et al. 2004) and in sidescan west of Mohican Channel on the Scotian margin (Baltzer et al. 1994) and off Saglek Bank in northern Labrador (Hesse et al. 1996). They are inferred elsewhere on the Labrador Slope from conventional bathymetric data (Piper 1988). The dendritic pattern is best developed in areas just down-flow from transverse troughs and the pattern is interpreted to result from fall-out of plume sediments creating small muddy turbidity currents that erode the seabed, in much the same manner as rills develop from rainfall in badlands.
2. More linear canyons that also head at the till limit have been imaged by multibeam bathymetry on the western part of the central Scotian Slope and retrogressive failure appears to have been important in their development (Pickrill et al. 2001) (type 2 in Fig. 5). Some canyons on the Scotian Slope show features intermediate between types 1 and 2.
3. A few large canyons on the Scotian Slope and Grand Banks cut back across the shelf break (type 3 in Fig. 5). Most of these lead headward to a converging pattern of tunnel valleys on the continental shelf, suggesting that subglacial meltwater hyperpycnal discharge has played a role in their formation. Because these canyons intersect modern sand transport on the continental shelf, at least some have an inner talweg formed by small Holocene turbidity currents (Pickrill et al. 2001) (Fig. 5).
4. At some transverse trough outlets, numerous subparallel small gullies have formed. such as at the outlet of Emerald Basin on the central Scotian margin (Piper & Sparkes 1987; Piper 2000) and at Hudson Strait (Piper & Hesse 1997). Similar buried gullies are present on the upper slope seaward of Laurentian Channel (Piper & MacDonald 2002), where they were inferred to result from hyperpycnal flow.
5. On the Tail of the Banks, where the shelf break is as shallow as 80 m and glacial till appears to be lacking, numerous submarine canyons head at the shelf break. These canyons are inferred to be similar to those of southern California (Shepard & Dill 1966), maintained by frequent storm-driven flows of suspended sand that evolve into ignitive turbidity currents (Fukushima et al. 1985).

Conclusions

The four most important factors influencing the Quaternary architecture of the eastern Canadian deepwater continental margin are:

(a) Tectonics and accommodation, in particularly through their influence on the depth of the shelf break and thus the transfer of sediment across the shelf and the evolution of submarine canyons.
(b) The distribution of ice streams. Sediment plumes, which dominate slope sedimentation in glacial periods, originate from ice streams. Major ice streams discharge subglacial meltwater to deep water, creating significant erosion and sediment deposition.
(c) The Labrador Current and its southwestward continuation, which advected sediment plumes along the continental margin and built major sediment drifts on the upper slope.
(d) Earthquakes, which are the principal control on triggering slope failures.

Acknowledgements: This synthesis would not have been possible without the ongoing work of my colleagues David Mosher, Kimberley Jenner, Calvin Campbell and Efthymios Tripsanas; the contributions of many students, particularly Jon Mackie, Ken Skene, Sara Benetti, Rebecca Brunt, Kathleen Gould, Thian Hundert, Adam Macdonald, Curtis McCall, Kent Simpson, and Michael Toews; management of core processing by Kate Jarrett; and the ship's personnel, marine technicians and scientific staff who have sailed with me on CCGS Hudson over the past ten years. I thank David Mosher, Calvin Campbell, Russell Wynn and Anders Solheim for manuscript review and the Geological Society of Norway for the invited talk that led to this synthesis. Work funded by the Geological Survey of Canada, the Natural Sciences and Engineering Research Council of Canada through the Can-COSTA project, the Canada Program of Energy R & D; and an industry consortium comprising EnCana, Marathon, Norsk Hydro, Murphy Oil, ChevronTexaco, and C&C Technologies. This paper is Geological Survey of Canada contribution 2004435.

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