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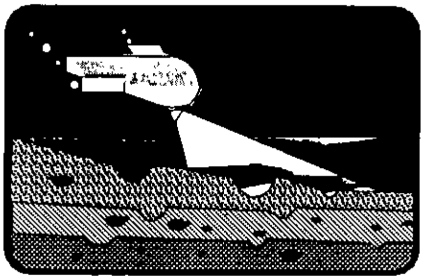

DNAG #3. Glaciomarine Sedimentation on the Continental Slope off Eastern Canada

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Introduction

Continental ice sheets in eastern Canada crossed the continental shelf (Figure 1) several times during the Quaternary, but the preserved stratigraphic record on the continental shelf is largely restricted to the latest (Wisconsinan) glaciation. The adjacent continental slopes preserve a much more continuous glacial stratigraphic record, the outlines of which have been uncovered in the last few years. The continental slopes off eastern Canada, from Nova Scotia to Baffin Island, extend across a wide latitudinal range and a wide range of glacial conditions. They provide the basis for a general model of glaciomarine continental slope deposition. This paper summarizes a number of detailed studies of small areas published in the last few years, and attempts a general synthesis of the style of ice margin sedimentation on continental slopes. The interpretation is limited by the reconnaissance nature of most work on the continental slope, and the difficulty of obtaining high-resolution seismic profiles and precisely located samples in deep water.

The glacial setting

The information in this section is based on a synthesis of the glacial history of the East Coast offshore prepared for the Geology of Canada/DNAG series (Piper *et al.*, in press), where an extensive bibliography is provided.

The slower tectonic subsidence of the eastern Canadian shelf south of about 50°N (Scotian Shelf, Grand Banks) compared with shelves to the north had a significant effect on the physiographic setting of Late Quaternary glaciation (Figure 1). During low stands of sea level in the Late Miocene to Early Pleistocene (largely associated with Antarctic glaciation: Kennett, 1982), the Scotian Shelf and Grand Banks were in part emergent: subaerial and fluvial processes sculpted a cuesta landscape, and there was significant shelf edge progradation. On the more northerly shelves, such as the Labrador and Baffin shelves, there was more sediment aggradation, less upper slope progradation, and Tertiary strata were a lesser influence on shelf physiography.

Glacial ice appears to have crossed the continental shelves off eastern Canada several times in the last 0.7 Ma. Although much of the physiography of the continental shelf may be relict from fluvial denudation in the Late Tertiary and Early Pleistocene, ice was responsible for the overdeepening and straightening of the major transverse channels that cross the shelves (Figures 1 and 2). The gradual increase in hinterland relief from southeastern Canada to Baffin Island and the latitudinal temperature gradient also played an important role in controlling the style of glacial sedimentation on the continental shelf (Figure 3). On the Northeast Baffin Shelf, vigorous ice flow was largely restricted to fjords and their continuation in transverse channels (Praeg and MacLean, in press). On the Labrador Shelf, the more extensive glaciations extended across the entire shelf, whereas less extensive glacial advances were restricted to the transverse channels (Josenhans *et al.*, 1986). Variations in ice extent were probably similar on the Grand Banks and Scotian Shelf (King and Fader, 1986), with the more extensive glaciations crossing the entire shelf, and less extensive glaciations restricted to transverse channels. At least from the Labrador Shelf southward, the most extensive Wisconsinan glaciation was in isotopic stage 4 (Early Wisconsinan), and there was gradual recession since that time. King and Fader (1986) have proposed that recession of Wisconsinan ice on the Scotian Shelf and Grand Banks took place largely through the "lift-off" of ice shelves during isotopic stage 3, the residual parts of which were pinned and stabilized by the complex morphology of shelf basins during the falling sea level phase of the later part of stage 3 and early stage 2. The extent and significance of ice shelves on the Scotian Shelf and Grand Banks is disputed (Oldale, in press); ice shelves were not present on the Labrador Shelf (Josenhans *et al.*, 1986). Whatever the style of isotopic stage 3 glaciation, there is no evidence that ice extended to the upper slope at that time, and ice had receded to near the present coastline by the later part of the Late Wisconsinan. There is circumstantial evidence for glacial surges and rapid calving of icebergs associated with lift-off and break up of ice in Hudson Strait, Lancaster Sound and Jones Sound during the late Wisconsinan rise in sea level (Josenhans *et al.*, 1986; Aksu and Piper, 1987), and Late Wisconsinan ice surges may have crossed the Scotian Shelf and Grand Banks in some deeper channels (Bonifay and Piper, in press).

Anastomosing channels with irregular thalwegs, largely filled with sediment (Boyd, 1986), are a common feature of the shelf areas between the transverse troughs on the Scotian Shelf and Grand Banks. They appear to be sub-ice drainage channels or tunnel valleys (Barnes and Piper, 1978). They are rare or absent on the Labrador and Baffin Shelves. Their presence on the southern shelves reflects the occurrence of a warm, wet-base ice margin along the southern edge of the Laurentide ice sheet (Boulton *et al.*, 1985).

The morphology of the continental slope

A general bathymetric map (Figure 1) reveals considerable variation in physiography along the length of the continental slope off eastern Canada. Little is known in detail about the Baffin Slope; the summary below refers largely to the Labrador Slope and areas to the south.

The depth of the shelf break is quite variable along the continental margin, and may have an important influence on slope sedimentation. The shelf break on the Scotian Shelf and Grand Banks generally lies between 70 and 180 m, with greater depths (up to 400 m) only off the Laurentian Channel (Figure 2). The average depth of the continental shelf increases north of the Grand Banks and the shelf break lies between 120 and 200 m on the Labrador Shelf (Figure 2) increasing to as much as 500 m deep off the transverse channels. The shelf break off Hudson Strait is at about 650 m, shoaling to around 500 m on the Southeast Baffin Shelf. The Northeast Baffin Shelf has a shelf break at about 300 m increasing to 300-500 m off transverse troughs. The break of slope off Lancaster Sound occurs at about 1000 m.

The continental slopes off the Grand Banks and the eastern part of the Scotian Slope are dissected by submarine canyons, many of which extend upslope to the shelf break (2 in Figure 2). Such dissected slopes are restricted to areas where the shelf break is in water depths of about 100 m or less, suggesting that stable shelf-breaching canyons owe their origin to shoreline processes active at times of glacially lowered sea level (Farre *et al.*, 1983). Many of the canyons lie at the seaward end of tunnel valleys on the continental shelf (Boyd, 1986), suggesting that sub-glacial drainage processes may have played a role in their development.

Other areas of the continental slope, which appear relatively smooth on small scale bathymetric maps, are in fact intensely dissected by slope gullies (1 in Figure 2). Most of these gullies originate in water depths of a few hundred metres; upslope, the seabed is relatively smooth and underlain by glacial till (Piper and Sparkes, 1987;

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Josenhans *et al.*, 1987). The gullies have a typical spacing of several kilometres. Other areas of the slope are almost completely smooth, apparently as a result of Late Quaternary sedimentation blanketing older morphology, including slope gullies (Piper *et al.*, 1985a). The morphology of the continental slope off the major transverse troughs is generally very irregular (4 in Figure 2), as a result of both gullying and sediment failure (Hill, 1983; Piper *et al.*, 1985b, Swift, 1985).

Late Quaternary sediments on the Scotian Slope

A general model for glaciomarine sedimentation can be proposed for the Scotian Slope, based on several local investigations of slope facies using both high-resolution seismic reflection profiles and piston coring. This model is limited by the fact that these techniques cannot adequately distinguish between different types of till and coarse ice-margin deposits. Furthermore, in most areas, deposits of the Wisconsinan glaciation appear to be several tens of metres thick, so that it is only this last glacial cycle that can be investigated in detail with these techniques. The greatest Wisconsinan ice extent on the Scotian Shelf was during isotopic stage 4 (Early Wisconsinan) (King and Fader, 1986). The continental slope preserves the record of this ice advance and subsequent recession.

Seismic reflection profiles show that the upper slope, to water depths of about 500 m, is in many places underlain by a reflective, acoustically incoherent unit with similar acoustic characteristics to till that is exposed on the continental shelf. It differs in its acoustic signature from iceberg-turbated strata seen on northern continental shelves (Praeg *et al.*, 1986). Samples show that this material is an non-fossiliferous, apparently overconsolidated diamict (Bonifay and Piper, in press). Where it crops out on the seabed, the upper surface is in many places modified by iceberg scours (Hutchins *et al.*, 1986). The diamict is interpreted as a till deposited from grounded ice, probably close to the buoyancy line. Coarse ice proximal deposits may well be associated with the till: generally they are difficult to distinguish acoustically, and have not been sampled on the continental slope, although they are well known in shallower water (Kontopoulos and Piper, 1982). Downslope, the till wedges out and interfingers with stratified marine sediments (Figures 3 and 4). The extreme downslope limit of the till appears more transparent in acoustic profiles, probably reflecting less consolidation and a higher water content. Locally, thin beds of acoustically similar material extend downslope far beyond the regional limit of the till (Bonifay and Piper, in press): these probably represent bodies of slumped or "bulldozed" till, with mass movement triggered by glacial advance onto unstable till deposits at an ice grounding line on the steep continental slope.

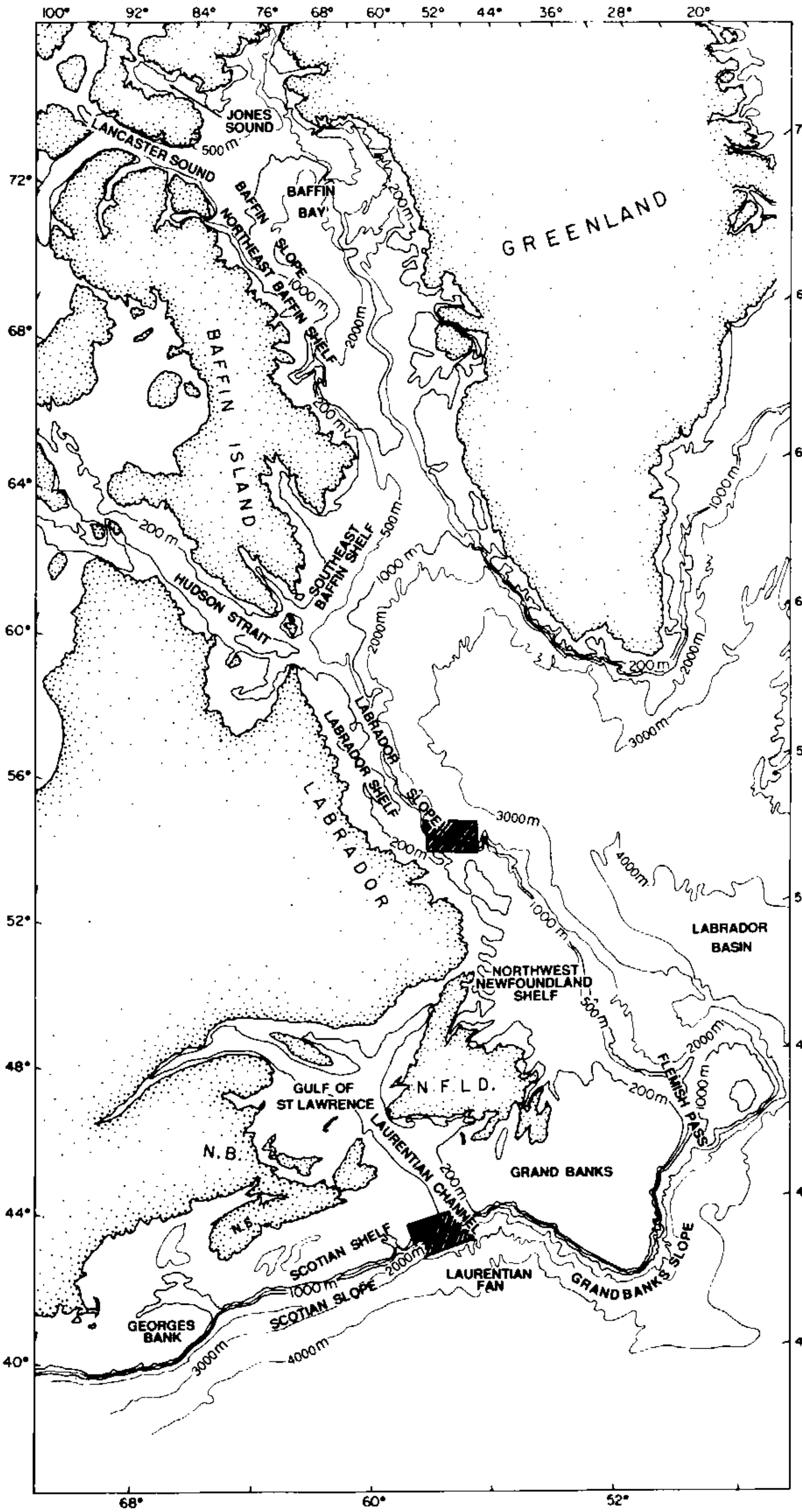

Figure 1 *Location map of Eastern Canada showing the general morphology of the continental shelf and slope. Shaded boxes show location of detailed bathymetric maps in Figure 2.*

Sequences of up to five till tongues on the continental slope can be recognized back to approximately the Middle Pleistocene (Piper *et al.*, 1987). The age of most till tongues is not well known, because of the lack of suitable datable material. Extrapolation of sedimentation rates suggest that the shallowest tongue in most areas is probably of Early Wisconsinan age; but seismic correlation suggests that in some places this shallowest tongue is absent. In one area off the Laurentian Channel, where overlying sediments contain many datable shells, the shallowest till tongue appears to be of Late Wisconsinan age (Bonifay and Piper, in press). Young till may also occur on the central Scotian Slope (Mosher, 1987).

Buried gullies on the continental slope appear from seismic reflection profiles to be best developed at a stratigraphic horizon equivalent to the till tongues. Such gullies are buried too deeply to sample, but they have an acoustically amorphous fill that might be either sand and gravel or debris flow deposits (Piper and Sparkes, 1987). They are thus probably the submarine equivalents of outwash channels, maintained by turbidity currents derived from the ice margin (Figure 5). Some may have formed originally by recessional slumping.

The sediments that lie downslope of, interfinger with, and immediately overlie till comprise stratified silts and muds, which thin rapidly downslope away from the till tongues. They contain a restricted benthic foraminiferal fauna dominated by *Elphidium excavatum* f. *clavata* and *Cassidulina reniforme*. There are occasional dropstones. Bioturbation is of variable intensity, in places masking all primary sedimentary structures in cores. Many of the sediments have a black colour, reflecting the development of iron monosulphides. Thomsen and Vorren (1984) ascribed similar sediments on the Norwegian continental shelf to the presence of low salinity glacial meltwater. Turbidite sands are present in some areas. Where radiocarbon dates are available, they show rates of sedimentation of several metres per thousand years (Mosher, 1987; Bonifay and Piper, in press). On gullied slopes, proximal turbidites occur in slope gullies (Hill, 1984), and sedimentation rates are several times higher in inter-valley areas than in zones of gullying. The acoustic reflectors in the stratified sediments appear to be draped conformably over pre-existing morphology, and in places between valleys form mound-like sediment build-ups (Piper and Sparkes, 1987, fig. 12). These observations suggest that much of the sedimentation took place through suspension fallout, either from surface plumes of proglacial sediment or from proximal turbidity currents. The gullies were sites of sediment bypassing while there was continuous sedimentation in inter-gully areas.

In areas with a relatively shallow shelf break, a near-surface downslope thinning wedge of acoustically reflective sediments occurs beneath the upper slope. These sediments have not been sampled but are probably sands or possibly diamicts (Figure 4). These acoustically reflective sediments pass downslope into stratified sediments with a large number of sandy proximal turbidites that have been dated about 17 ka, and therefore are correlated with the late Wisconsinan (stage 2) low stand of sea level (Mosher, 1987).

Holocene sediments on the continental slope comprise hemipelagic muds, a few centimetres to a few metres thick, which tend to fill depressions in a ponded depositional style. They grade upslope into silts and eventually to shelf edge sands, and appear to be in equilibrium with the modern shelf-edge current regime (Hill and Bowen, 1983).

Evidence for sediment failure, both of Pleistocene and Holocene age, is widespread on the continental slope. Failure is most common in water depths of 500-1000 m, immediately downslope from the till tongues. The sediments here are silty, susceptible to liquefaction (J.M. Konrad, pers. comm., 1985), and have the highest sedimentation rate. Seaward of transverse troughs on the shelf, there may have been a large amount of slumping related to high sedimentation rates on steep slopes (Swift, 1985; Piper and Sparkes, 1987). Elsewhere, failure may have been largely seismically triggered (Piper *et al.*, 1985a, 1985b). There are several styles of sediment failure, depending on the local physiography and sediment type. Where canyons are deeply incised into the upper slope, oversteepening of older consolidated sediments has resulted in extensive blocky debris flows, as for example near the Albatross well on the Scotian Slope. Smaller debris flows occur in many slope gullies

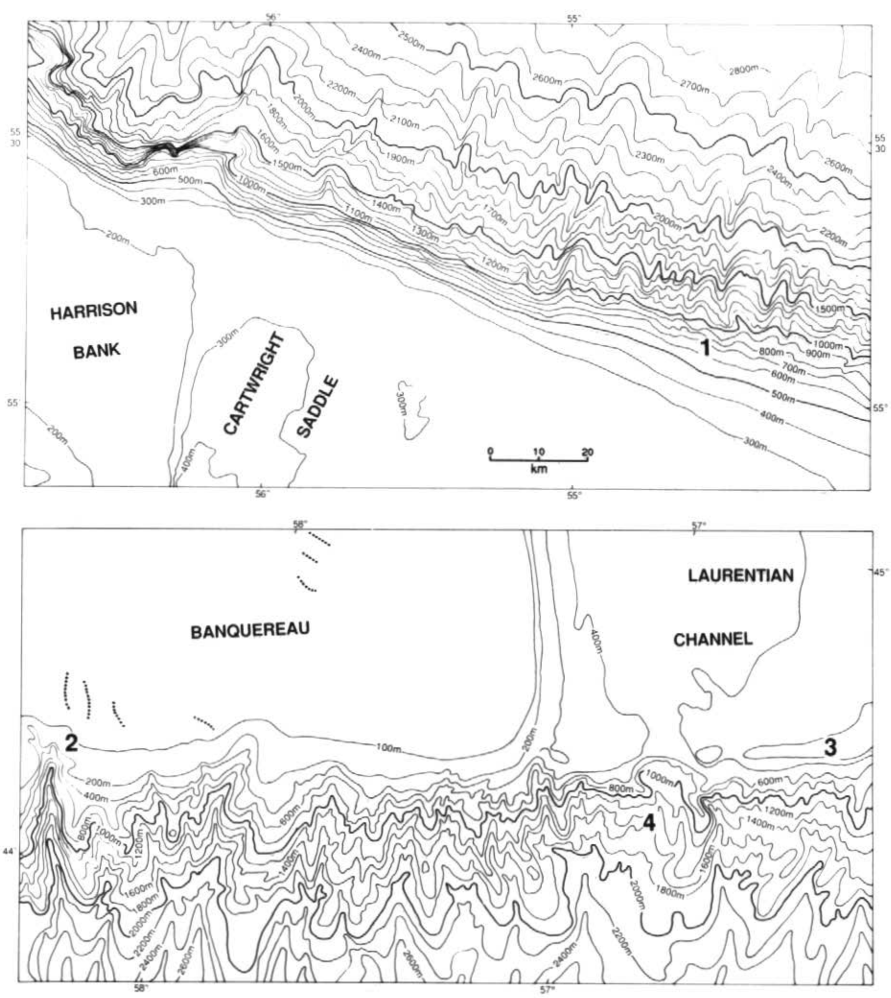

Figure 2 *Detailed bathymetric maps of shelf break off central Labrador Shelf (above) and shelf break off Banquereau (Scotian Shelf) and Laurentian Channel (below). The part of the Labrador Shelf illustrated (map compiled by H.W. Josenhans) has a shelf break between 250 and 300 m, and slope gullies (indicated as* **1***) terminate at about the limit of till, in 400-600 m water depth. Banquereau (from Canadian Hydrographic Service charts 801, 802) has a shallow shelf break and canyons breach the shelf break (***2***); dotted lines show mapped sub-glacial drainage channels from Amos and Knoll (1987). Laurentian Channel is a transverse trough with shelf break at about 400 m marked by a morainal ridge (***3***); downslope, there is an irregular seabed (***4***) developed by slumping and erosion in the 1929 earthquake (Piper, Shor and Hughes Clarke, in press).*

(Josenhans *et al.*, 1987). In areas of stratified pro-glacial silts and muds, bedding plane slides and rotational regressive slumps have led to the development of muddy debris flows and probably turbidity currents (Piper *et al.*, 1985a, 1985b). Liquefaction failure of valley filling sands and gravels has been interpreted as the cause of the 1929 Grand Banks turbidity current (Piper and Aksu, 1987).

A glacio-sedimentation model for the Scotian Slope

The observed morphology and sediment sequence on the Scotian Slope can be used to synthesize a general relationship between glacial conditions and sediment facies (Figure 5). The till tongues represent deposition from a grounded ice sheet that terminated in (present) water depths of 500-600 m, which is also the maximum depth of iceberg scouring on the Scotian margin. Locally, diamict from the ice margin slumped into deep water. Sub-glacial meltwater streams that scoured out the tunnel valleys on the continental shelf would have delivered somewhat sorted sediment to the ice margin. Sand and gravel would have been deposited in ice-contact submarine deltas, which on the steep continental slope would have oversteepened and failed periodically, as do modern high-bedload deltas (Syvitski *et al.*, 1986). The resulting small sandy turbidity currents would have eroded and maintained the slope gullies and larger canyons. Suspended fine sediment would have been distributed more widely as a suspended sediment plume, producing the rapidly deposited stratified muds that interfinger upslope with the tills.

The thick stratified muds that overlie the tills probably reflect conditions where ice had retreated back onto the continental shelf. Coarse-grained sediment discharged from sub-ice drainage was trapped on the shelf, but high rates of sedimentation of fine-grained sediment from meltwater plumes were maintained, and were augmented by rafting of sediment by icebergs. Sedimentation was as rapid as a metre per hundred years off the transverse troughs (Bonifay and Piper, in press), which were the pathways for much of the glacial drainage of the shelf (Swift, 1985).

The Late Wisconsinan low stand of sea level made outer shelf sands (of ultimate glacial origin) available for resedimentation on the upper slope through rip-current and related coastal processes during storms (Inman *et al.*, 1976). Shelf-breaching canyons, probably developed along the pathways of tunnel valleys, were the main loci of sediment transfer from the shelf at this time.

Holocene sedimentation reflects the end of turbid meltwater supply to the upper slope as glacial ice retreated from the shelf and finally disappeared from the land. This change is reflected in microfossil assemblages on the Scotian Shelf (Mudie, 1980) and has been dated in Emerald Basin on the central Scotian Shelf at about 10.5 ka.

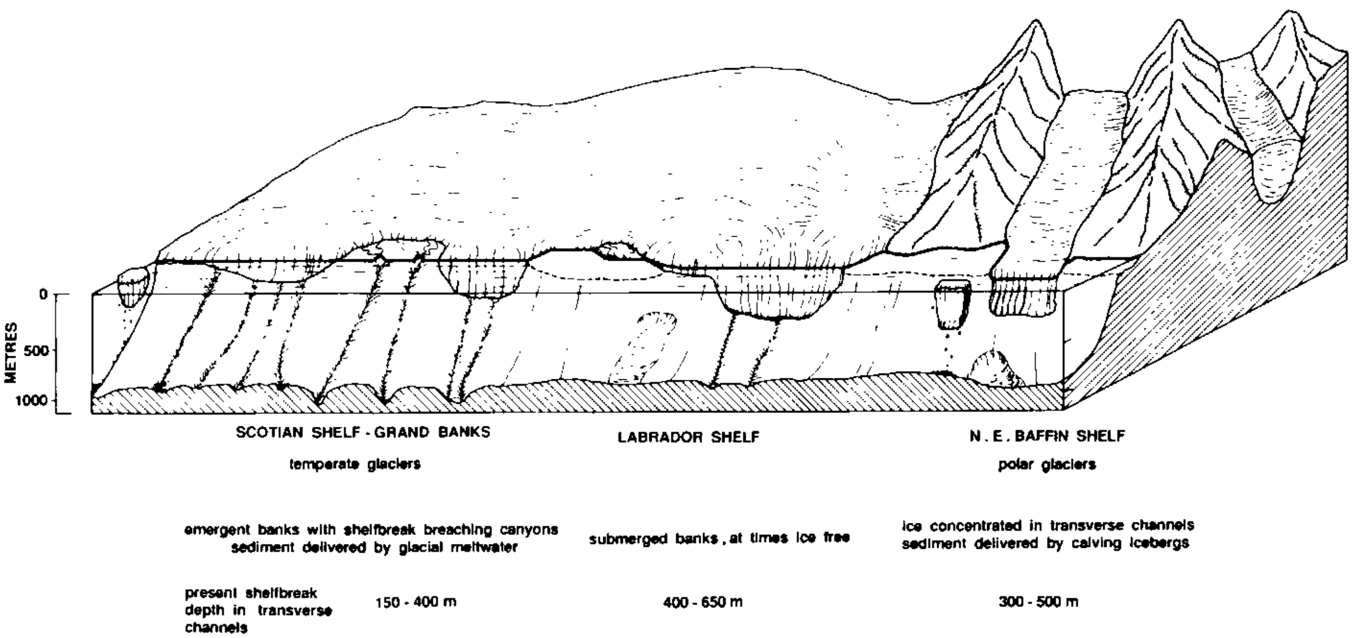

Figure 3 (above) *Cartoon illustrating latitudinal changes off eastern Canada in the physiography of the outer shelf and continental slope and the style of glaciation at ice margins during glacial maxima. Relief features are highly simplified and stylized.*

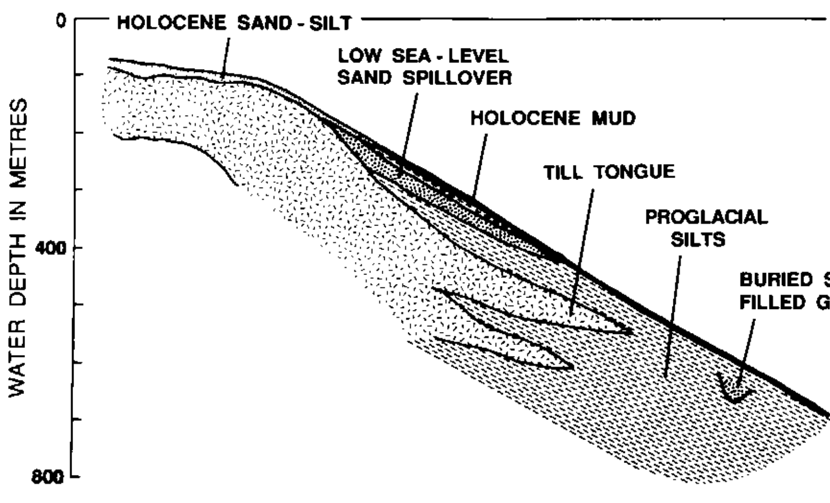

Figure 4 (right) *Schematic stratigraphic section showing glacial and glaciomarine facies developed on the Scotian Slope.*

Holocene sediments are derived largely from wave reworking of bank-top Pleistocene sediments during the Holocene transgression (King and Fader, 1986).

Ice margin sedimentation on northern slopes

Only scattered data are available from other continental slope areas off Eastern Canada. The Grand Banks slopes, including Flemish Pass, appear similar to the Scotian Slope. The Labrador Slope has till extending to depths of 500-700 m (Josenhans *et al.*, 1986). A well-developed gully system on the slope below the till limit and the presence of sediment build-ups on inter-gully highs similar to those on the Scotian Slope both suggest that meltwater discharge at the ice margin played an important role in sedimentation, even though the Labrador Shelf lacks the prominent tunnel valleys found on the southern shelves. The greater depth of relict iceberg scouring on the Labrador and Eastern Grand Banks Slopes probably reflects derivation of large bergs from Hudson Strait, where ice appears to have been grounded to 700 m. The largest bergs calved from Lancaster Sound, where ice was grounded to 1000 m, would have been trapped within Baffin Bay at the shallow Davis Strait sill.

The limited data from the Baffin Slope (Aksu and Piper, 1987) suggests that glaciation may have been of rather different character. Overall sedimentation rates are lower than farther south, slope sediments contain a much higher proportion of gravelly ice-rafted detritus, and thick sorted pro-glacial muds and sands appear to be absent. These differences probably reflect lower erosional rates by polar glaciers and a paucity of ice-margin meltwater. It is also possible that glacial ice crossed the continental shelf less frequently than farther south.

The effect of slope processes on ocean basin sedimentation

Turbidites are widespread on the ocean floor during glacial stages (Pilkey *et al.*, 1980; Shanmugan and Moiola, 1982). In mid to low latitudes, this is a consequence of rivers delivering sediment to the shelf break at times of glacially lowered sea level. The greater depth of the shelf break on most glaciated shelves precludes such an explanation for turbidites in glaciated mid to high latitudes, because the shelf break would have remained submerged even at low stands of sea level.

Turbidite sedimentation was rapid in areas such as the Labrador Sea and Laurentian Fan seaward of Wisconsinan ice margins. These turbidite systems are characterized by high muddy levees and long channels floored with coarse sediment. They were fed by turbidity currents generated by slumping of rapidly deposited sediments from glacial meltwater at an ice margin. These turbidity currents were already somewhat sorted; turbidity currents transporting mostly mud deposited and stabilized the levees, whereas flows transporting coarser sediments (particularly those with substantial amounts of gravel) scoured out channels. In contrast, cold ice margins that break up principally by iceberg calving lead to unsorted

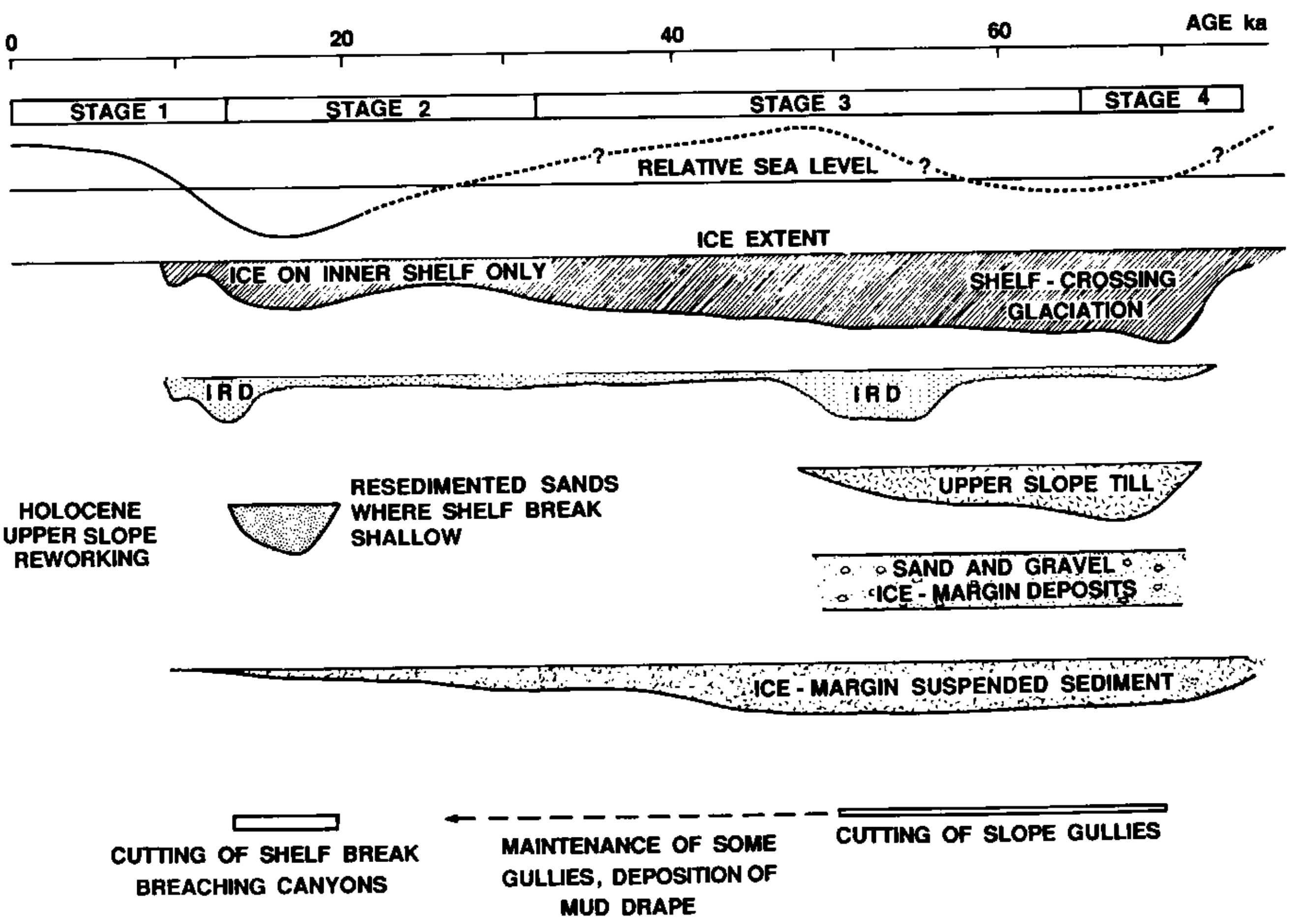

Figure 5 *Cartoon showing the effect of ice margin position and sea level on the sediment facies developed on the Scotian Slope during the Wisconsinan glaciation. Width of patterned bars shows relative importance of a process or facies. Relative sea level based on "eustatic curves" from the global oxygen isotopic record, with correction for ice loading.*

Ice-rafted detritus (IRD) shown as most important during times of rising sea level. Upper slope till restricted to times of maximum ice extent. The associated sand and gravel ice margin deposits led to cutting of slope gullies by turbidity currents. During the Stage 2 maximum lowering of sea level, sands were resedimented from areas of shallow shelf break, and shelf-break breaching canyons were cut. Flux of suspended sediment at the ice margin is shown in approximate proportion to the extent of ice sheets; this sediment was deposited in a drape over previous topography on the continental slope.

coarse sediment deposition over a large area and a lack of channel levee systems, such as is the case in Baffin Bay (Aksu and Piper, 1987).

Summary
Reconnaissance studies of the continental shelves off eastern Canada show that a distinctive suite of ice-margin and pro-glacial sediments accumulated during Wisconsinan, and presumably older Pleistocene glaciations. The most pronounced morphological features result from ice-margin meltwater discharge. A distinctive sediment sequence is developed as ice sheets retreat from the upper slope across the shelf. Deep sea terrigenous sedimentation is strongly influenced by ice-margin processes.

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