ABSTRACT: Large-scale glacial meltwater discharges have long been recognized as important sedimentological agents on the eastern Canadian continental margin. Previous studies in Eastern Valley of Laurentian Fan and Orphan Basin have elucidated aspects of processes and timing of glacial discharges, principally from seismic-reflection profiles and deep-water sidescan sonar. New multibeam bathymetry and piston cores show evidence of important meltwater processes seaward of all transverse troughs on the continental shelf, from Hudson Strait to the Scotian margin. Meltwater cuts broad flat-floored valleys and sculpts residual buttes, depositing thick-bedded gravel and sand turbidites, and builds submarine fans. Based on morphology, a wide range of scales of meltwater discharge may take place. Meltwater is intimately linked with supply of fluid glacial diamict (till) that on gentler slopes (< 2.5°) creates glacigenic debris flows but on steeper slopes breaks up, entrains water, and transforms to create erosive turbidity currents. Three end-member processes are recognized on submarine fans seaward of transverse troughs that were occupied by ice streams: glacigenic debris flows, turbidity-current deposition of channel–levee complexes, and blocky mass-transport deposits resulting from debris avalanches. The relative importance of meltwater appears greater at lower than at higher latitudes, whereas the formation of glacigenic debris flows is dependent on gradient. Pleistocene processes have resulted in slopes that are graded, implying that most sand deposition was on the continental rise.

KEYWORDS: meltwater discharge, turbidity current, turbidite, erosion, channel, levee, mass-transport deposit, glacigenic debris flow

INTRODUCTION

Models of glaciomarine sedimentation models from the 1980s recognized the role of turbidity currents in proglacial settings but did not lead to an organized facies model for proglacial turbidite deposits. Since that time, the role of ice streams has been more widely recognized: they are responsible for the U-shaped transverse troughs on many glaciated shelves (e.g., Shaw et al., 2006). There has also been much debate about the occurrence, magnitude, and lateral extent of subglacial meltwater discharges (e.g., as reviewed by Shaw et al., 2008). It is widely observed that major sediment accumulations occur seaward of transverse troughs. In high latitudes these consist principally of glacigenic debris flows (King et al., 1998), and the term trough-mouth fan has been applied to such deposits (Vorren and Laberg, 1997). At mid-latitudes, thick sequences of turbidites are the predominant component of submarine fans such as Laurentian Fan (Stow, 1981) that lie at the seaward end of transverse troughs. The principal purpose of this paper is to evaluate evidence of subglacial meltwater on the eastern Canadian margin, using
seafloor geomorphological data from multibeam bathymetry, high-resolution seismic-reflection profiles, and cores. Most of our data are from the more proximal parts of the turbidite systems, and only a brief literature review of distal deposits is provided. The findings are used to identify the main processes influencing the architecture of fan deposits seaward of an ice stream, and we comment on how such processes have helped grade the slope across much of the eastern Canadian margin.

BACKGROUND

Geological Setting of the Eastern Canadian Margin

The eastern Canadian margin is a passive continental margin formed by progressive northward rifting of the Atlantic Ocean. Continental shelves are > 100 km wide and are underlain by a wedge of Mesozoic and Cenozoic clastic sedimentary rocks. 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). A series of deep basins (marginal troughs) has been eroded at the landward edge of the Mesozoic–Cenozoic wedge. The mean depth of continental shelves and the depth of the shelf break, both off transverse troughs and off the intervening banks, increases from south to north (Fig. 1). 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 the Scotian Shelf that are less than 100 m deep and were emergent during periods of low sea level.

Fig. 1.—Location map of the Eastern Canadian margin showing mean seabed gradients based on ETOP05 gridded bathymetry (http://www.ngdc.noaa.gov/mgg/global/etopo5.HTML). Contours are from GEBCO charts. Shows location of more detailed Figures 2, 4, 6, 8, and 11; depth of shelf break; and location of major ice streams (arrows). (a)–(g) are locations of sections in Fig. 16. NAMOC = Northwest Atlantic Mid-Ocean Channel. (Modified from Piper and Normark, 2009).
A powerful south- or west-flowing sea-surface current is present close to the continental shelf break all along the southeastern Canadian margin. In the Labrador Sea it is known as the Labrador Current, but it continues to flow around the Grand Banks and along the upper Scotian Slope (Smith and Schwing, 1991). The Labrador Current is most vigorous at times of high freshwater input to the Labrador Sea (Lazier and Wright, 1993). Deep-water circulation forms the Western Boundary Undercurrent (Carter and Schafer, 1983), 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 (Piper, 2005).

Glacial ice reached the shelf edge at the last glacial maximum (LGM) along much of the eastern Canadian margin (e.g., Stea et al., 1998; Piper and Brunt, 2006) but may not have crossed wide shelves such as the Grand Banks since marine isotope stage 6 (Huppertz and Piper, 2009). Acoustically amorphous wedges recognized from seismic-reflection profiles of the upper slope pinch out generally between 500 and 700 mbsl (Fig. 2A, B) and, where sampled, are either not penetrated by a 1 tonne piston corer or return overconsolidated diamict with shear strengths of 60–100 kPa (Fig. 2C; Piper and Brunt, 2006) that Hillenbrand et al. (2005) regarded as diagnostic of lodgement till. These acoustically amorphous wedges are generally termed “till tongues”, but they may differ from similarly named features in continental-
seaward of Hudson Strait, detailed studies by Hesse and his co-workers have made this a type area for the understanding of discharges seaward of ice streams. The fact that the discharge is rich in detrital limestone and dolomite makes it easy to trace in the adjacent ocean. The morphology of the sandy braid plain of the northeastern Labrador Sea was interpreted by Hesse et al. (2001) as evidence for direct hyperpycnal flow of sand-laden meltwater. The continental slope off Hudson Strait is underlain by glacigenic debris flows, the youngest dating from about 30 cal. ka (Rashid and Piper, 2007). The dynamics of fine-sediment deposition on the continental slope and rise from meltwater discharge has been elucidated (Hesse et al., 2004). Sediment lofting from turbidity currents appears an important process on proximal slope areas (Hesse and Khodabakhsh, 2006); hypopycnal plumes associated with meltwater discharge from the Hudson Strait ice stream must be responsible for deposition on the continental shelf, and rafting by icebergs is important (Dowdeswell et al., 1995; Rashid et al., 2003a). Fine-grained carbonate-rich turbidites overlie many Heinrich layers in the Labrador Sea, most notably in Heinrich event 3 (Rashid et al., 2003a, 2003b). Hypopycnal plumes are transported great distances by the Labrador Current, to at least the southwestern Scotian margin (Hundert and Piper, 2008). Plume deposition occurs preferentially immediately down-current from the ice-stream outlet on the upper slope (Hesse et al., 1997), a pattern that has been recognized at other major outlets such as Laurentian Channel (Piper et al., 2007).

Collectively, these studies raise several questions. First, what changing conditions result in the same ice stream at times producing glacigenic debris flows and at times supplying hyperpycnal meltwater that cuts channels and deposits turbidites, as observed by Tripsanas and Piper (2008) for Orphan Basin and Rashid and Piper (2007) for Hudson Strait? Is there geological evidence in deep water as to whether meltwater is supplied to the ice margin as “broad, turbulent floods”, as suggested by Shaw et al. (2008), or as more focussed discharges cutting canyons typically a few kilometers wide, as suggested by the presence of tunnel valleys leading to many submarine canyons on the Scotian margin (Piper et al., 2007, their Fig. 13)?

RESULTS: CASE STUDIES

Introduction

We briefly present several new case studies of depocenters seaward of transverse troughs on the eastern Canadian margin,
for which multibeam bathymetry, seismic-reflection profiles, and cores are available. We also include an assessment of implications of new multibeam bathymetry of the upper Laurentian Fan for the understanding of that otherwise well-known system.

Northeast Fan

Morphology.—

Northeast Fan is the informal name given to the depocenter seaward of the Northeast Channel, on the southwestern Scotian margin (Figs. 1, 4; Robichaud, 2006). Multibeam bathymetry shows that the shelf edge at about 300 mbsl is deeply incised by three submarine canyons. These canyons lead to slope valleys that can be traced across the continental rise in GLORIA sidescan imagery (Hughes Clarke et al., 1992) and eventually lead through the poorly defined “Scotian Channel” to the Sohm Abyssal Plain (Horn et al., 1971).

Seismic Architecture.—

Seismic-reflection profiles show that much of the Northeast Fan between 1500 and 2500 m is underlain by multiple large mass-transport deposits (MTDs; Fig. 5). These have irregular upper and lower surfaces and do not show the lower aspect ratio and smoother bounding surfaces characteristic of glacigenic

Fig. 4.—Multibeam bathymetry (EM-1000 system) of the Northeast Channel transverse trough and conventional bathymetry of Northeast Fan. In southwest of map, GLORIA sidescan imagery from Hughes Clarke et al. (1992). A, B, C are seismic profiles in Figure 5. Dashed lines show continuity of Eastern, Central, and Western valley onto the continental rise, where the valley floor has high backscatter (light color). Continental shelf shallower than 200 m is highlighted by gray tone. On this and subsequent figures, conventional bathymetry has not been corrected for more recent multibeam data, so that contours may not precisely match multibeam morphology.
Debris flows. Western Valley is incised into older Quaternary sediments in its upper reaches where water depths are less than 1800 m, and into MTDs below 2000 mbsl. In contrast, Central and Eastern valleys appear to be largely constructional features below 1400 m water depth. Eastern Valley has well-developed levees that rise 40 m above the valley floor. All valleys are flat-floored in their upper reaches (Fig. 5A). The valleys become narrower as they cross the major MTDs at 1900–2300 mbsl and widen again on the continental rise. Between Eastern and Central valleys, at a sub-bottom horizon tentatively correlated with marine isotope stage (MIS) 6, a zone of high-amplitude reflections ~ 5 km wide occupies a channel (Fig. 5B) and resembles in reflectivity the coarse-grained floor of Eastern Valley of Laurentian Fan (illustrated later as Fig. 10). A similar reflective zone underlies Eastern Valley itself.

**Dawson Canyon**

**Morphology.**—

Dawson Canyon (Fig. 6) is typical of several large canyons on the Scotian Slope (Mosher et al., 2004). Its head indents the shelf...
break. The two unnamed canyon systems 20 and 40 km to the east, which head at about 500 m at the limit of till tongues, have numerous tributary canyons leading to one main canyon; Verrill Canyon to the west also has a similar abundance of tributaries. In contrast, Dawson Canyon has only two small tributary canyons (Ta and Tb in Fig. 6), yet the width of its floor is comparable to that of other canyons in the region (Fig. 6). Morphologically, it appears to have a different origin compared to adjacent canyons, and it resembles canyons on the eastern Scotian Slope that indent the shelf break and align with buried tunnel valleys on the shelf (Piper et al., 2007).

**Cores.**

Late glacial sedimentation in Dawson Canyon has been inferred from a series of cores from terraces. Core 99036-29, from a terrace 75 m above the valley floor, provides a record of turbidity currents that did not spill out over the adjacent 500-m-high intervalley ridge, sampled in core 2000-042-54 (Fig. 7). Chronology for core 54 is provided by Heinrich layer H1 (16.5 cal ka) and the downward termination of supply of red sediment, which is regionally dated shortly after the last glacial maximum at about 19.5 cal ka (Hundert and Piper, 2008). On the basis of sediment color, these markers can be correlated to core 29. Numerous sand–silt–mud turbidites, with alternating silty and muddy laminae, are preserved on the terrace, interbedded with sediment slumped from the valley walls. Detailed grain-size analysis shows that most turbidites are normally graded, but a few show reverse grading at their bases (Fig. 7).

**Laurentian Fan**

**Morphology.**

New multibeam bathymetry from Laurentian Fan clearly images the floor of Eastern Valley (Figs. 8, 9) on which Piper et al. (2007) recognized the 19 ka widespread gravel bed. Eastern
Right-hand levee
2000-042-54

L* black-white
a* red-green

Right-hand canyon wall
1999-036-29

L* black-white
a* red-green

Legend
- Clay
- Silty clay
- Reddish muddy interval
- Slumped sediments
- Clayey silty deposits
- Sandy deposits
- Debris-flow deposits

**Fig. 7.—** Left: Core 54 from the west levee of Dawson Canyon (500 m above valley floor) and core 29 from a low terrace (75 m above valley floor), showing correlation and basis of age model. H1 = Heinrich event 1; LGM = last glacial maximum; Brm b Brm d = marker brick-red mud horizons. The a* spectrophotometry plot was of particular value for correlation: it is a proxy for the abundance of detrital hematite. Right: photographs and grain-size analyses of turbidites in Core 29, showing that most turbidites are normally graded, but with a few horizons with reverse grading at the bases of beds.
Valley of Laurentian Fan is well known from previous sidescan and submersible observations (e.g., Piper et al., 1985; Hughes Clarke et al., 1990). It is unusually wide for a slope valley, tends to narrow rather than widen downslope, has erosional furrows and residual buttes, and is floored by a conglomerate, 1–3 m thick, deposited by a major subglacial meltwater discharge at 19.5 cal ka (Piper et al., 2007). Its form is predominantly erosional. Retrogressive failure of upper slope muds took place in 1929 (Piper and MacDonald, 2002), and large blocks of indurated mudstone are observed overlying a broken cable near the 1200 m isobath (Hughes Clarke et al., 1989).

On the west side of Eastern Valley, the Inter-Valley Divide is an extensive area of eroded Quaternary bedrock between Western and Eastern valleys of Laurentian Fan. It has a dendritic pattern of shallow gullies and canyons cut principally in Lower Pleistocene mudstones. Farther west, seaward of the western part of Laurentian Channel, several broad, relatively straight valleys coalesce near the 3000 m isobath to form Western Valley of Laurentian Fan (Fig. 9). Erosional furrows in these valleys extend all the way upslope to the limit of the survey near the 600 m isobath. These valleys contrast markedly with the deeply incised canyons at the extreme western edge of Laurentian Channel,

Fig. 8.—General map of Laurentian Fan and adjacent areas. Multibeam was acquired with EM-120. White strip is the EEZ of France. Also shows location of Figures 2A, 2B, and 9.
continuing westward to the area off Banquereau (Figs. 8, 9). The upper tributaries of the canyons have V-shaped profiles and sinuous thalwegs that widen downslope. Canyon walls are strongly gullied, in places with a relatively mature dendritic pattern. Elsewhere on the eastern Canadian margin, such canyons are cut into relatively indurated Quaternary sediments and have only a very thin Holocene sediment drape (Piper and Campbell, 2002).

**Distribution of Turbidites.**

The fan valleys are predominantly zones of bypass, but there are numerous turbidites on the Sohm Abyssal Plain (Horn et al., 1971; Benetti, 2006). The major 19 ka gravel bed was substantially eroded by the 1929 turbidity current, which cut thalwegs on both sides of the valley floor (Fig. 10; Hughes Clarke et al., 1990). The 1929 current was initiated by transformation of failures on St Pierre Slope, east of the outlet of Laurentian Channel. Late glacial turbidites, postdating shelf-edge ice retreat, are not recognized in Eastern Valley, but they did flow down Grand Banks Valley from Halibut Channel (Skene and Piper, 2003). Sandy turbidites did not overtop the levees, which are built of mud with silt laminae (Skene and Piper, 2003). The levees themselves are highly asymmetric (Fig. 10; Skene and Piper, 2006).

**Hopedale Fan**

**Morphology.**

Hopedale Saddle marks a regional bulge in the shelf-edge contours (Fig. 11), as a result of seaward progradation of lodgement till (Josenhans et al., 1986) (Fig. 12). Multibeam bathymetry (Fig. 11) shows a series of slope valleys extending seaward from the shelf edge at 400–450 m depth. The two largest valleys derive from the northern edge of the Saddle and are flat floored, but several large slope channels also derive from the central and southern part of the saddle.

**Seismic Architecture.**

The most prominent feature of the seismic architecture is that a major shelf-edge-failure complex, likely dating from about 0.3 Ma (Deptuck et al., 2007), underlies Hopedale Fan (Fig. 13). The

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**Fig. 9.**—Multibeam bathymetry (EM-120) annotated with margins of glacial meltwater channels on upper Laurentian Fan, based in part on Piper et al. (1985) and Shor et al. (1990). White strip is the EEZ of France.
debris field associated with the failure complex covers an area in excess of 28,000 km$^2$ (Deptuck et al., 2007). The positive bathymetric relief generated by some angular slide blocks (up to 6 km wide and > 300 m thick) diverted flows that built Hopedale Fan, and locally formed barriers that promoted the preferential accumulation of sediment on the up-flow sides of blocks. Minor faulting may also be present where younger strata detached above some steeply inclined slide blocks (Figs. 13, 14A, B).

Fig. 10.—Seismic section (40 cu in airgun) across Eastern Valley of Laurentian Fan, showing asymmetric levees and the character of the floor of Eastern Valley. For location, see Figure 9.

Fig. 11.—Multibeam bathymetry (EM-300 system) and conventional bathymetry of glacial meltwater channels on Hopedale Fan. Locations of seismic sections in Figures 12, 13, and 14 and key cores 59 and 60 are also shown. Continental shelf shallower than 300 m is highlighted by gray tone.
The two main northern valleys on the fan have evidence for phases of erosion and of levee widening (Fig. 14A, B). On the continental rise, a broad interval of high-amplitude reflections underlies both valleys and is buried by younger inter-valley levee deposits (Fig. 14B). The levees are highly asymmetric, with consistently higher levees to the south. Unlike on Laurentian Fan, there is a clear levee crest, with strata wedging away from the crest, and cores 59 and 60 from the levees (Fig. 11) contain thin sand beds. The smaller valleys on the southern part of the fan have widened to broad depositional areas on the continental rise at about 2500 m water depth, with inter-valley areas showing growth of sediment waves (Fig. 14C). Praeg and Schafer (1990) showed that similar sediment waves just to the south resulted from turbidite deposition.

DISCUSSION

General Characteristics of Slopes Seaward of Ice Streams

The case studies presented here show that significant depocenters are developed seaward of ice streams that crossed the continental shelf, but the character of those depocenters is quite variable. The deposits show three end-member types: glacigenic debris flows, channel–levee complexes, and blocky mass-transport deposits. The relative importance of each of these three components in different depocenters seaward of ice streams is illustrated graphically in Figure 15A, based on new examples presented in this paper and on examples from the literature. In most depocenters, all three sedimentation processes are active at different times.

1. Glacigenic debris flows (GDFs)

These generally result in progradation of the shelf edge and deposition of GDFs seaward of the entire front of the ice stream.

The most prominent examples are off Hudson Strait (Rashid and Piper, 2007) and in Orphan Basin (Tripsanas and Piper, 2008).

2. Channel–levee complexes.

These are of varying width, commonly with several channels originating at the front of the ice stream (Figs. 4, 9, 11). The channels are flat-floored and, where data exist, are seen to extend to the shelf break, implying that flows that eroded the channels originated from the ice margin. In some systems, similar buried channels cut GDFs, best known in Orphan Basin (Tripsanas and Piper, 2008). The right-hand levee is generally much higher than the left (looking down-flow), especially in the case of major channels on the left sides of ice-stream outlets (Figs. 5B, 10, 14B). Even in Dawson Canyon (Fig. 6), such levee asymmetry is visible in the multibeam bathymetry and confirmed by seismic-reflection profiles (not illustrated). In many cases, seismic reflection profiles show episodes of channel-floor widening, followed by migration of the levee across the channel floor. This is well illustrated for Laurentian Fan by Piper et al. (2007; their Figure 12), but it is also illustrated here by Figure 10. Seaward of Hopedale Saddle, the two distinct northern channels on the upper slope (Fig. 14A) appear to have merged in the subsurface (Fig. 14B), but an inter-valley levee has grown over this old channel floor. Seaward of Halibut Channel, Armitage et al. (2010) have demonstrated growth of an inner levee within a broader slope valley. On Northeast Fan, levees appear to have prograded over the proximal part of a formerly broader Eastern Valley (Fig. 5A).

On the Scotian margin, some major slope channels are eroded back through the shelf break, most prominently on Northeast Fan (Fig. 4). Similar shelf-edge erosion is present at Dawson Canyon (Fig. 6), and the major canyon known as The Gully (Fig. 1) may have a similar origin through repeated erosion by hyperpycnal subglacial meltwater.
Fig. 13.—Line drawing of two composite roughly strike-oriented GI-gun seismic profiles across the Hopedale Fan. Dark gray shaded interval corresponds to the upper blocky MTD in Figure 12. See Figure 11 for line locations.
The two northern channels

Active fault over major failure complex

Broad depositional area at end of small slope valley

Sediment waves

High levee crest

Broad, buried highly reflective valley floor

Major MTD

Fig. 14.—Detailed G1-gun seismic cross sections of Hopedale Fan. For locations, see Figures 11 and 13. Also shows location of cores 59 and 60.
3. Blocky mass-transport deposits (MTDs)

These are quite distinct from GDFs and are an important component of some depocenters. Blocky MTDs on Northeast Fan appear to have filled slope valleys (e.g., the older MTDs beneath Eastern Valley; Fig. 5) or the inter-valley areas (e.g., between Central and Western valleys; Fig. 5). In this case, there may be a relationship between the abundance of MTDs and the deep erosion of the valleys on the upper slope and outer shelf, as deep erosion in the canyon heads may have destabilized the slope, pre-conditioning it for failure of blocky MTDs. Direct chronological evidence for this link is, however, lacking. MTDs are rare on Laurentian Fan; near-surface MTDs (Hughes Clarke, 1990) may be related to the 1929 Grand Banks earthquake, but small deeper MTDs that occupy the proximal parts of channels (Fig. 10) may be similar to those on Northeast Fan. Seaward of Hopedale Saddle (Fig. 12), a large shelf-edge failure produced a major failure complex (Deptuck et al., 2007), perhaps similar to those off the central Baffin Shelf described by Aksu and Hiscott (1989), but with greater displacement. This failure complex appears to pre-date or to have obliterated slope valleys similar to those at the present seabed.

**The Style of Meltwater Supply**

The style of meltwater supply in the systems reported here appears to be quite variable. There is no evidence for the “broad, turbulent floods” suggested by Shaw et al. (2008), except for at the scale of the 5–15-km-wide valley heads on eastern Laurentian Fan (Fig. 9) and ~5-km-wide valley heads at Hopedale Saddle (Fig. 11). More focussed discharges, cutting canyons typically a few kilometers wide, are implied by valley heads on western Laurentian Fan (Fig. 9), valley heads on Northeast Fan (Fig. 4), and the presence of tunnel valleys leading to submarine canyons on the Scotian margin (Piper et al., 2007, their Figure 13). In many transverse troughs, the morphologically largest valley is found seaward of the left-hand (eastern or northern) side of the trough: for example at Northeast Channel (Fig. 4), Laurentian Channel (Fig. 9), Halibut Channel (Fig. 8 and Armitage et al., 2010), and Hopedale Saddle (Fig. 11). This observation is countereuitive, given that the Coriolis force on discharging meltwater would operate in the opposite direction, and we have no explanation for this observation.

At some transverse trough outlets, numerous subparallel small gullies have formed, such as at the “Scotian Gulf” on the central Scotian margin (Piper and Sparkes 1987; Piper, 2000; Hundert and Piper, 2008, their Fig. 3) and at Hudson Strait (Hughes Clarke and Piper, unpublished data). Similar buried gullies are present on the upper slope seaward of Laurentian Channel (Piper and MacDonald, 2002). Such gullies are also described seaward of major transverse troughs from Antarctica (Dowdeswell et al., 2008). From their cross-sectional area such gullies appear to result from relatively small water discharges, and their tendency to die out downslope may be the result of the formation of mid-level density flows containing muddy sediment, of the type interpreted from cores off Hudson Strait by Hesse et al. (2004). In the case of Hudson Strait and the Scotian Gulf, such gullies appear to be erosional forms produced during smaller ice advances.

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**Fig. 15.**—A) Ternary diagram showing relative importance of glacigenic debris flows, subglacial meltwater, and blocky MTDs in the development of submarine fans seaward of transverse troughs that were occupied by ice streams. Some key linkages between the three end-member processes are also shown. B) Plot of characteristic width of upper-slope flat-floored channels (*+) and of the width of transverse troughs (*) showing variation with latitude.
The Controls on Deposit Style Seaward of an Ice Stream

The gradient of the upper slope (Fig. 3) is an important control on the presence of glacialic debris flows (Piper and Normark, 2009). GDFs are restricted to areas in which the gradient of the upper 1000 m of the continental slope is $< 4^\circ$ or $1:14$, such as off Hudson Strait, in Orphan Basin, and off the Scotian Gulf (Fig. 3). In each case, the low slope gradient is a result of overall structural and stratigraphic control on the basin shape. Piper and Normark (2009) suggested that on steeper regional gradients, GDFs would accelerate and entrain ice, transforming almost entirely to turbidity currents. Other factors, particularly grain-size distribution of supplied sediment, could influence this process; the GDFs off Hudson Strait and in Orphan Basin have an important supply of sediment resulting from erosion of shales, but so too do outlets such as Laurentian Channel and Northeast Channel, where GDFs are not found. By its nature, this transformation process is unlikely to leave an unambiguous record. We suggest that the many normally graded turbidites on the low terrace in Dawson Canyon (Fig. 7) and the numerous Late Pleistocene turbidites on Laurentian Fan (Horn et al., 1971; Benetti, 2006) are evidence of such a process.

The discharge of subglacial meltwater and sediment is, however, the main control on deposit style. Large discharges, such as the 19 ka discharge to Laurentian Fan (Piper et al., 2007), are clearly erosional (Hughes Clarke et al., 1990, their Figure 5) and appear to be responsible for the main geomorphological features of the large flat-floored valleys. The 19 ka event deposited a 3-m-thick gravel layer on the floor of Eastern Valley of Laurentian Fan. Similarly, highly reflective flat-floored valleys, commonly buried by younger inner-leeve sediments, are found on Northeast Fan (Eastern and Central valleys, Fig. 5A), Halibut Valley (Armitage et al., 2010), and the main northern valley off Hopedale Saddle (Fig. 14B); they are interpreted to result from similar major discharge events. The 19 ka event on Laurentian Fan also delivered large amounts of mud, a portion of which moved southwestward in a hypopycnal plume (Piper et al., 2007) and a portion of which was either supplied hypopycnally or settled to produce a thick dilute turbidity current that deposited evenly across the highest (900 m) levee (Skene and Piper, 2003). Preferential deposition on the western levee (Fig. 10) was likely principally the result of the Coriolis force on the dilute flow, as argued in detail by Piper and Savoye (1993) for the Var fan, but would also have been favored by the southwestern trajectory of the hypopycnal plume in the Labrador Current. A similar process is inferred for the development of asymmetric levees elsewhere on the margin (Hesse et al., 1997).

Various lines of evidence suggest that in addition to the large outburst floods that carve the major valleys, smaller meltwater discharges occur at ice margins. In Orphan Basin, three meltwater channels of different sizes and at different stratigraphic levels cut the stack of glacialic debris flows dating from around the last glacial maximum (Tripsanas and Piper, 2008). The slope gullies at Hudson Strait and the Scotian Gulf suggest small discharges, as discussed above. The inversely graded bases to a few turbidites on the Dawson Canyon terrace, suggestive of hypopycnal flow (Mulder et al., 2003), do not occur preferentially in the thickest turbidite beds (Fig. 7) and thus suggest relatively small flows.

Estimating the relative amounts of meltwater between different ice outlets is limited by the paucity of data and the likely variability in the magnitude and duration of meltwater discharges. The relative volumes of plume sediments and the rates of plume sedimentation immediately downstream from transverse troughs provide one method of estimating the total volume of water that was discharged. On this basis, Hudson Strait and Laurentian Channel appear to generate the greatest volume of plume sediments, with outlets on the Labrador Shelf and around Newfoundland of secondary importance (Piper, 2005). The width of flat-floored slope valleys probably scales with peak meltwater discharge (Piper and Normark, 2009); on this basis, the largest meltwater hyperpycnal flows are found on Laurentian Fan (Fig. 15B), and flows seaward of Hudson Strait appear relatively unimportant, particularly when compared with the size of the ice stream (Fig. 15B). Figure 15B suggests that the peak discharge of meltwater may diminish with increasing latitude and hence greater amounts of cold-base ice. Topographic barriers to ice-stream flow, such as occur at Cabot Strait in Laurentian Channel and at the outlet of Hudson Strait, may also play an important role in ponding subglacial meltwater.

The stratigraphic record makes it clear that not all turbidites in slope valleys cut by major outburst floods are of ice-margin or meltwater origin. Turbidites that postdate ice retreat from near the shelf edge are found on Northeast Fan (Robichaud, 2006), on Laurentian Fan via Halibut Channel (Skene and Piper, 2003; Armitage et al., 2010), and in Orphan Basin (Tripsanas et al. 2008). Some, such as in Orphan Basin and the 1929 turbidite on Laurentian Fan, resulted from transformation of sediment failure. Others may result from storm resuspension of sand on the outer shelf, such as inferred for Holocene turbidites in Dawson and Logan canyons on the Scotian Slope (Piper, 2005). On the Dawson Canyon terrace, at least the upper few meters of core 29 (Fig. 7) accumulated after ice retreated from the shelf edge. Most turbidites in this core show only normal grading (Fig. 7); those stratigraphically lower may have evolved from transformation of glacialic debris flows and those higher up from storm resuspension of outer shelf sand, as argued more generally by Piper (2005). Turbidity currents resulting from these other mechanisms may play a role in erosion of submarine canyons, such as those that deeply incise Western Valley on Northeast Fan (Fig. 4). The presence of shelf-cutting canyons, in areas where there is active sand transport on the shelf, appears responsible for some postglacial turbidites at Northeast Fan, Dawson Canyon, and Halibut Canyon. In contrast, where the shelf break is deeper (Fig. 1), as in Laurentian Channel, Trinity Trough, Hopedale Saddle, and seaward of Hudson Strait, postglacial turbidites are rare or absent.

The distribution of the various systems in Figure 15A suggests that there is a balance between progradation of the shelf edge by lodgement till (as for example in Hopedale Saddle), in some cases also with glacialic debris flows (as off Hudson Strait and in Orphan Basin), and erosion of the shelf edge by major subglacial meltwater outbursts. Where progradation is least and erosion greatest, as on Northeast Fan, The Gully, and the eastern Scotian Slope fed by tunnel valleys (Piper et al., 2007), the deep incision of meltwater valleys on the slope promotes the failure of blocky debris flows, which are a common component of Northeast Fan (Fig. 5) and are widespread on the eastern Scotian Rise (Piper and Ingram, 2003). Overall, the evidence for deep incision of meltwater valleys is greatest at lower latitudes on the Scotian margin, whereas progradation by lodgement till is more prominent in the higher latitudes of the Labrador margin.

**Dominance of “Graded” Slopes off Eastern Canada**

On continental slopes off eastern Canada, dip profiles parallel to the sediment transport direction commonly produce a smooth concave-upward pattern, where the gradient is steepest near the shelf edge and gradually diminishes towards the continental rise (Fig. 16). Such slopes are referred to as “graded” (Prather, 2003). Only some slopes with low enough gradients to allow accumula-
tion of GDFs, like the Orphan Basin slope, generate a slightly convex-upward slope that is slightly above grade (Fig. 16). Although the steepness of the present-day upper slope and the depth of the continental rise varies along the eastern Canadian margin (Figs. 1, 16), in most settings the slope outboard from ice streams lacks downslope morphological variations, such as alternating lower-gradient steps or ponds and higher-gradient ramps. Such morphological features are common on many other margins where the modern slope deforms in response to loading and deformation of salt (e.g., Plio-Pleistocene slope in the central Gulf of Mexico; Prather et al., 1998), detachment above a weak layer (e.g., gravity sliding above overpressured shale on the Niger Delta slope; Pirmez et al., 2000; Deptuck et al., this volume), or lithospheric plate movements (e.g., NW Borneo; Ingram et al., 2004; and offshore Colombia; Romero et al., this volume).

Despite the mix of initiating processes in canyon heads along the eastern Canadian margin (Piper and Normark, 2009), sediment gravity flows triggered through the failure of unconsolidated till or the direct supply of glacial meltwater were efficient mechanisms for generating graded slopes along much of the eastern Canadian margin. This is true even in settings like the Scotian margin known to be underlain by allochthonous salt (e.g., Fig. 17). For example, the Late Tertiary slope near Dawson Canyon was characterized by prominent subcircular bathymetric highs associated with salt diapirs and bathymetric lows associated with mini-basins (Fig. 17B). The slope was probably strongly influenced by gradient changes associated with salt deformation, with localized depocenters forming on the slope where salt tongues and sheets were actively loaded (Fig. 17B). Bulls-eye patterns on time thickness maps through Miocene and Pliocene strata corroborate this interpretation. Other than along the axes of isolated canyons, deformation of the Late Tertiary slope appears to have outpaced the depositional and erosional processes needed to grade the slope. In contrast, the Pleistocene to recent slope is much more erosional, with a high density of canyons that removed underlying intervals of Miocene and Pliocene strata with contemporaneous deposition of strata on intercanyon highs. Profiles down canyon axes as well as on the adjacent aggradational slope between canyons are dominantly graded (Fig. 16).

The change from an ungraded Late Tertiary slope to a graded modern slope, combined with the increased density of canyons on the modern seafloor (compare Figs. 17A and B) appears to result from two processes. Lowered sea level in the Early Pleistocene led to frequent emergence of the shelf and development of numerous upper-slope gullies (Piper et al., 1987). In the mid to late Pleistocene, the periodic advance and retreat of shelf-crossing glaciers (Piper et al., 1994) resulted in rapid continental erosion, efficient supply of sediment to shelf break, and thus numerous ways in which turbidity currents could be initiated (Piper and Normark, 2009). Differences in style between Late Tertiary and Late Pleistocene slope valleys (Fig. 17) point to differences in the style, frequency, or magnitude of the flow processes.

The_PRO_ rate of substrate deformation relative to the rate of erosion and deposition from submarine sediment gravity flows

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**Fig. 16.** Chart showing the dominance of graded slopes along the eastern Canadian margin. Transect locations are shown in Figure 1. Downslope changes in seafloor morphology from the Niger Delta, Gulf of Mexico, and northwest Borneo are shown for comparison.

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Pirmez et al. (2000); Prather et al. (1998); Sylvester et al. (this volume); Ingram et al. (2004); Mosher and Piper (2007)
influences whether or not a smooth graded slope profile is possible (Steffens et al., 2003). Graded slopes do not favor storage of sand and gravel anywhere except along canyon axes and on the lower-gradient continental rise. This appears to be the case for large segments of the modern eastern Canadian margin. High rates of fine-grained sedimentation resulting from along-slope redistribution of channel overspill or advection of plume sediments by the south-flowing Labrador Current, and its continuation around the Grand Banks and Scotian Shelf, would also have smoothed over slope irregularities that existed in the Late Tertiary.

CONCLUSIONS

1. Major sediment depocenters form seaward of transverse troughs that were occupied by ice streams at glacial maxima.
2. Glacialic debris flows formed by direct flow of till down the continental slope are found only on low gradients; elsewhere they are inferred to transform into turbidity currents.


4. Slope valleys cut by meltwater are conduits for turbidity currents initiated by other processes, and these flows may erode a narrow thalweg and/or deposit inner levees.

5. Erosion of the outer shelf by subglacial meltwater promotes failure and debris avalanches, which deposit blocky mass-transport deposits.

6. Sediment depocenters seaward of transverse troughs can be classified according to the relative importance of glacialic debris flows, channel–levee complexes, and blocky mass-transport deposits.

7. Despite the range of glacialic processes that shape the seascape off eastern Canada, graded slopes dominate the eastern Canadian margin, even in areas with mobile substrates. This indicates that the Pleistocene and Holocene processes that eroded the slope along canyons and accumulated sediment on inter-canyon ridges outpaced the processes that deformed the slope. The graded slope implies that most sand deposition is on the continental rise.

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