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Major Quaternary sediment failures on the east Scotian Rise, eastern Canada[1]

David J.W. Piper and Stephen Ingram

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Abstract: Sparse, single-channel, seismic-reflection and swath-bathymetric data are integrated with industry, multichannel, seismic-reflection profiles to define the late Pliocene and Quaternary geological framework of the east Scotian Slope and Rise, and to investigate major sediment failures on the Rise. Chronology is based on correlation with dated sections on the Laurentian Fan and at the Tantallon M-41 well site. The late Cenozoic of the east Scotian Slope is similar to the central Scotian margin east of Verrill Canyon, except that there is less intercanyon sediment. Major sediment mass-transport events have occurred with an average recurrence interval of 0.25 Ma since the late Pliocene. A large failure on the continental rise at 0.15 Ma resulted in widespread failure of almost 10^3 km^3 of proglacial sediment in slabs hundreds of metres thick.

Résumé : Des données éparses de sismique-réflexion monocanal et de bathymétrie par secteurs sont intégrées à des profils de sismique-réflexion multicanal recueillies par l'industrie pour définir le cadre géologique du Pliocène tardif et du Quaternaire de la partie orientale de la plate-forme et du glacis Néo-Écossais, ainsi que pour étudier les ruptures majeures survenues dans les sédiments du glacis continental. La chronologie est basée sur des corrélations avec des coupes datées du cône Laurentien au puits Tantallon M-41. Les dépôts du Cénozoïque tardif du talus Néo-Écossais oriental sont semblables à ceux de la partie centrale de la marge Néo-Écossaise à l'est du canyon Verrill, sauf qu'ils renferment moins de sédiments déposés dans des canyons. Des épisodes importants de transport en masse des sédiments sont survenus à un intervalle de 0,25 million d'années depuis le Pliocène tardif. Une importante rupture survenue sur le glacis continental il y a 0,15 million d'années a engendré l'effondrement généralisé de près de 10^3 km^3 de sédiments proglaciaires en plaques de plusieurs centaines de mètres d'épaisseur.

INTRODUCTION

Sparse, single-channel, seismic-reflection profiles on the east Scotian Rise (Fig. 1), south of Banquereau, show that several mass-transport deposits ('debris flows'), tens to hundreds of metres thick, were deposited throughout the late Cenozoic. Piper et al. (1999) correlated these seismic-reflection profiles to the Laurentian Fan in order to derive a chronology for the mass-transport deposits. These authors did not have sufficient data to do more than speculate on the style and triggering mechanism for the failures.

Several seafloor blocks have recently been leased for hydrocarbon exploration on the east Scotian Slope south of Banquereau, so understanding the origins of the enormous mass-transport deposits has become more pressing. Under an agreement between TGS-Nopec Geophysical Company and the Geological Survey of Canada, commercial-confidential industry multichannel seismic lines shot in 1998 over the area were made available for interpretation. These data have significantly improved the understanding of mass-transport deposits on the east Scotian Rise. The authors have also benefited from access to confidential swath bathymetry acquired by WesternGeco.

EAST SCOTIAN SLOPE

The east Scotian Slope off Banquereau has a mean gradient of 4° and is highly dissected by canyons. Three major canyons have incised landward of the shelf break: Haldimand Canyon, Shortland Canyon, and The Gully, which separates Sable Island Bank from Banquereau (Fig. 1). Intervening canyons head seaward of the 200 m isobath and are probably similar to the smaller canyons on the central Scotian Slope described by Pickrill et al. (2001).

Conventional bathymetric profiles, seismic-reflection profiles, and sparse multibeam bathymetric data show that, between 200 and 2000 m, the seafloor is highly dissected (Fig. 2). Intercanyon ridges are sufficiently eroded that flat tops to the ridges are extremely rare, except on the ridge west

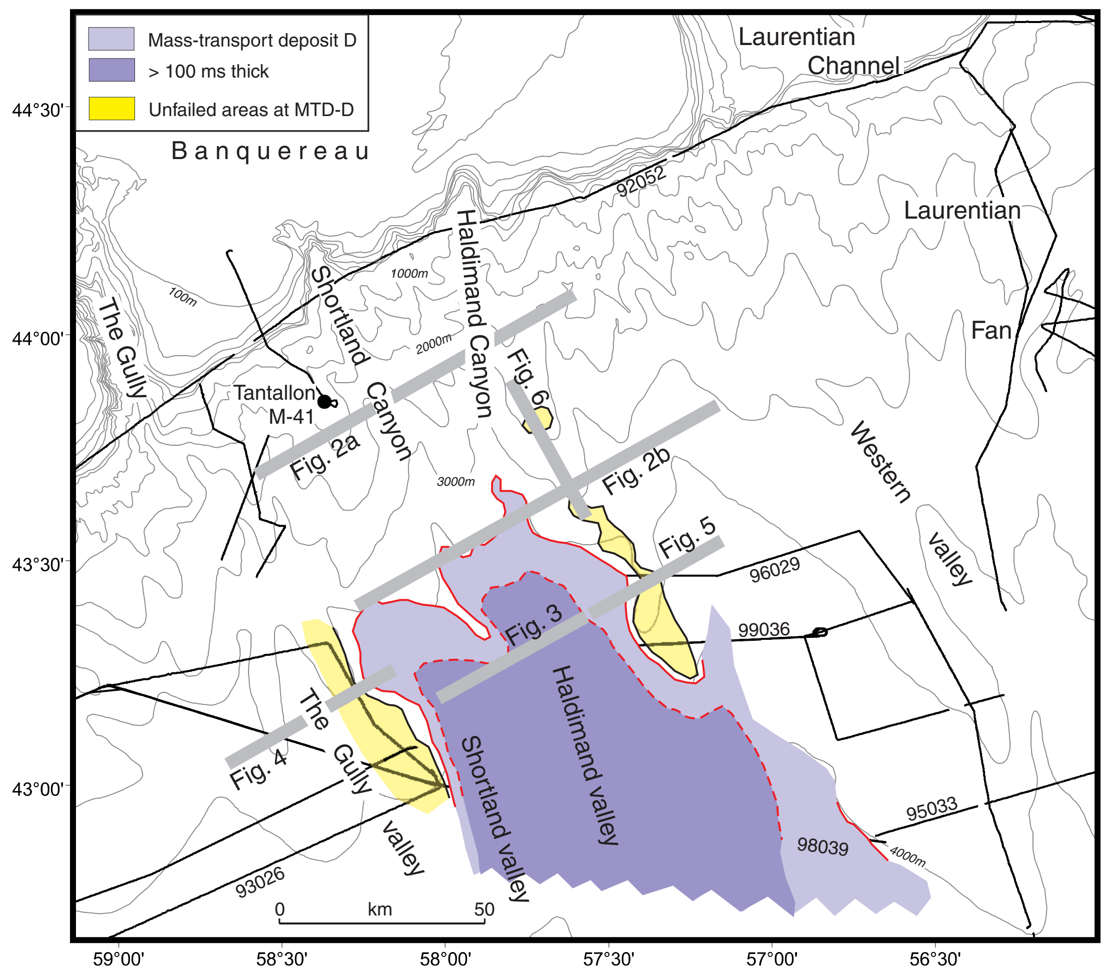

__Figure 1.__ Location map of the east Scotian Slope and Rise, showing key Geological Survey of Canada–Atlantic seismic lines (thin black lines) and TGS-Nopec lines (thick grey lines) illustrated in Figures 2 to 6. Also shows locations of Tantallon M-41 well and failure related to mass-transport deposit D.

of Shortland Canyon where the Tantallon M-41 well is located; this ridge resembles those on the central Scotian Slope reported by Pickrill et al. (2001). Numerous side gullies extend up the canyon walls, creating a topography similar to the badlands of western North America. The floors of the smaller canyons appear to consist principally of debris-flow deposits; the large canyons have incised thalwegs that appear to be sandy.

STRATIGRAPHY OF THE EAST SCOTIAN SLOPE AND RISE

TGS-Nopec line 93-100, a long strike line in about 4000 m water depth, was used as a reference line in order to establish a regional type stratigraphy for the continental rise (Fig. 3). Four key horizons, crimson, pink, green, and orange, were defined on this line. A fifth horizon, mauve (between green and orange), was defined farther west, on line 109 (Fig. 4).

The crimson horizon marks the regional boundary between parallel, high-amplitude reflection packets above and fuzzy, discontinuous reflections below. This pattern is similar to the change in character at horizon L on the Laurentian Fan (Uchupi and Austin, 1979), tentatively interpreted as mid-Pliocene age by Piper and Normark (1989). Crimson can be traced to the Tantallon M-41 well, where it corresponds to an unconformity, with late Pliocene overlying Miocene, immediately below the base of the casing. The pink and orange horizons can be correlated to the Laurentian Fan through seismic lines from Geological Survey of Canada–Atlantic (GSCA) cruise 96029, as discussed by Piper et al. (1999), and are respectively equivalent to horizons A (late Pliocene) and O (marine isotope stage 6, 0.15 Ma).

On the upper slope, a long, single-channel, seismic-reflection strike line (GSCA cruise 92052) near the 500 m isobath shows features similar to those south of Sable Island Bank, to the west of The Gully (Fig. 1). In water depths of less than 500 to 700 m, a thick, acoustically incoherent section overlies well stratified sediment. The contact between the two acoustic facies is interpreted elsewhere on the Scotian Slope as dating from marine isotope stage 12 at about 0.5 Ma (Piper et al., 2002). The upper incoherent facies includes glacial till and probably sandy prodeltaic outwash deposits, and appears to thicken eastward. The resistant glacial till is probably responsible for preventing many of the canyon heads from extending right up to the edge of the continental shelf.

DISTRIBUTION AND CHARACTER OF MASS-TRANSPORT DEPOSITS

Major mass-transport deposits elsewhere in the world that have been drilled by the Ocean Drilling Program are recognized in seismic-reflection profiles as a packet of acoustically incoherent, relatively transparent reflections, commonly with an irregular upper surface (Piper et al., 1997). The bases of such deposits are commonly step like and may show pronounced linear grooves (Posamentier et al., 2000). Studies of three-dimensional seismic-reflection data from the Gulf of Mexico and elsewhere show that some such mass-transport deposits are semi-autochthonous, with irregular slide blocks that have been translated only a few kilometres terminating in complex toe thrusts (H. Posamentier, pers. comm., 2002, following Prior et al., 1984).

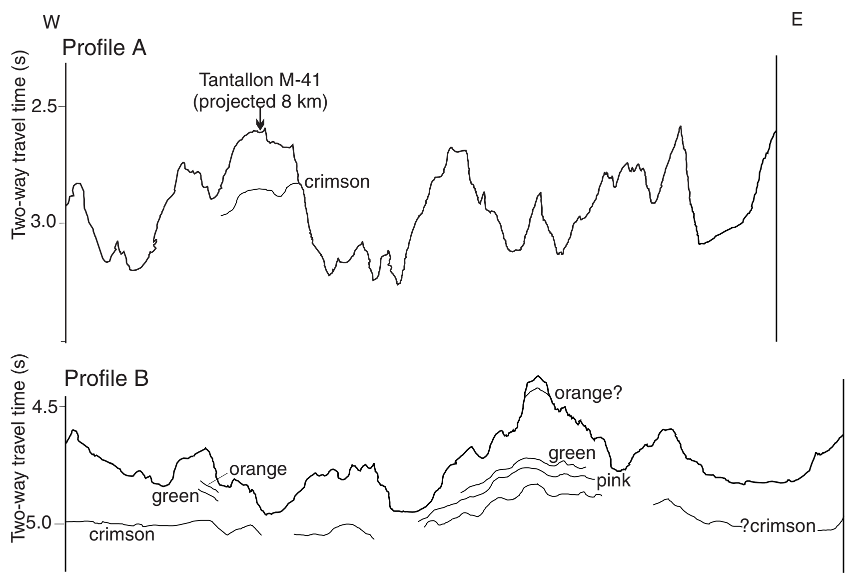

Figure 2. *Line drawings of two strike seismic lines showing typical bathymetry of east Scotian Slope. Also shown is the position of the late Pliocene-Miocene unconformity (crimson horizon) in the Tantallon M-41 well in profile A, and the crimson, pink, green, and orange horizons, where they can be traced from the Scotian Rise.*

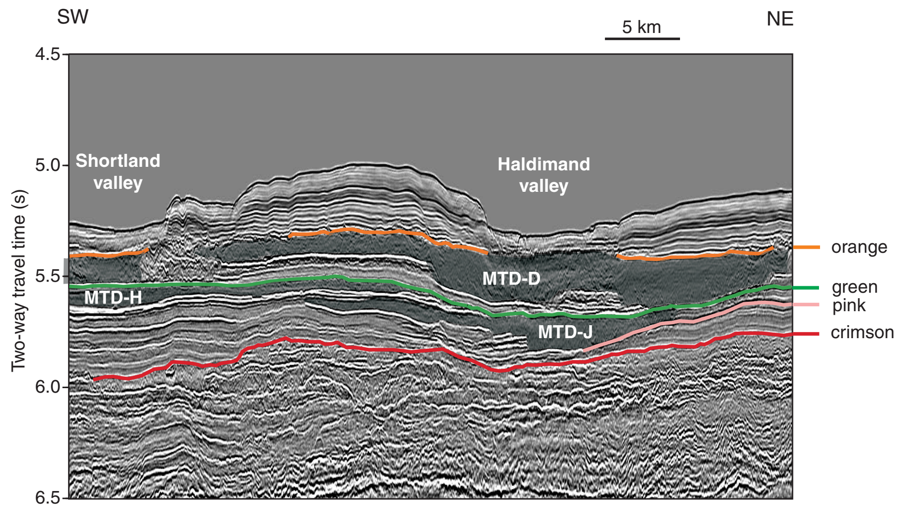

Figure 3.

Multichannel seismic-reflection strike profile through Haldimand valley, showing key stratigraphic horizons and mass-transport deposits.

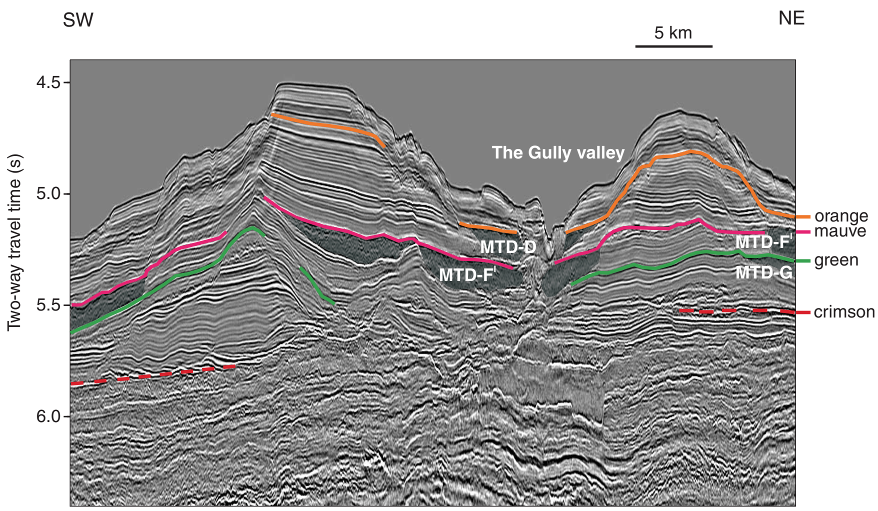

Figure 4.

Multichannel seismic-reflection strike profile through The Gully valley, showing key stratigraphic horizons and mass-transport deposits.

In the sector of the east Scotian Rise illustrated in Figure 3, three large mass-transport deposits are visible above the crimson horizon. The pink horizon shows rather irregular relief above crimson, apparently defining a broad submarine valley (Haldimand valley, a continuation of Haldimand Canyon). Younger stratified units onlap this broad valley form. Mass-transport deposit J (MTD-J) fills this old valley form, eroding the younger units in a step-wise manner in the southwest and cutting down to pink in the northeast. In the southwest, a thin stratified packet overlies MTD-J and is overlain by a thin mass-transport deposit (MTD-H) that is directly overlain by the green horizon. Haldimand valley appears to have remained an actively eroding sediment conduit, because green directly overlies MTD-J, with no intervening sediment deposition. Thirty five kilometres east of Haldimand valley (Fig. 5) is thick accumulation of stacked mass-transport deposits. One deposit immediately underlies the green horizon and may thus correlate with MTD-H. Another (MTD-K) lies between pink and crimson.

In Haldimand valley, MTD-D has locally eroded down to the green horizon and is directly overlain by the orange horizon (Fig. 3). It can be traced westward 60 km to the edge of the eastern levée of The Gully valley (Fig. 4). It is the thickest mass-transport deposit observed, being 200 ms thick in places. It is also recognized in a line from GSC cruise 98039, 40 km farther south (Fig. 1), where it is 150 ms thick (Piper et al., 1999, Fig. 5). To the east of Haldimand valley, the package of stratified sediment between the green and orange horizons is 750 ms thick, including two thin mass-transport deposits (Fig. 5, MTD-E and MTD-F). The mauve horizon corresponds approximately to MTD-F. To the west, the green to orange section is 400 to 750 ms thick on the levées of The Gully valley (Fig. 4). Farther west, away from valleys, the green to orange section is at least 350 ms thick. The paleoscarp that is draped by the orange horizon and MTD-D is 700 ms (525 m) high east of Haldimand valley (Fig. 5) and 300 ms (225 m) high at The Gully valley levée. Not all of this thickness of missing sediment was involved in the formation of MTD-D because, at least in the west, two thin mass-transport deposits (MTD-F', MTD-G) are preserved, with MTD-G cutting down locally to the green horizon. A single continuous reflection separates MTD-G and MTD-F', which, in places, is separated by as much as 100 ms of stratified sediment from the base of MTD-D (Fig. 4). Mass-transport deposit G appears to correlate stratigraphically with the mauve horizon, which is an unconformity surface on the levées of The Gully valley (Fig. 4). Above this unconformity, the axis of The Gully valley shifted 10 km eastward.

Key horizons can be traced up-dip on the intervalley ridge east of Haldimand valley (Fig. 6). The crimson horizon marks a pronounced change in reflection character. Horizons crimson, pink, and green can be traced upslope to near the 2500 m isobath, where the degree of dissection by canyons is so severe that little seismic correlation in the Quaternary section is possible (Fig. 2). The mauve horizon is 200 to 300 ms above green. Above this level, failure and complete evacuation of valley-side sediment is common. At 400 to 500 ms above green is a major unconformity on highs. Thickness of sediment above this unconformity suggests that, in places, it may correspond to orange, but in other places is younger. Where valley-side sediment has been evacuated above mauve, the thickness of overlying sediment is also consistent with evacuation taking place immediately prior to the orange horizon.

Dip lines south of the Tantallon M-41 well show a reasonably continuous section from crimson to green, but then major erosional removal of sediment between the orange and green horizons. The crimson horizon outcrops about half-way down the canyon walls near Tantallon M-41 (Fig. 2), and only the wider intercanyon ridges preserve a visible stratigraphy, which is probably quite discontinuous. In particular, much of the section between the green and orange horizons is likely missing. The GSCA, high-resolution airgun, seismic-reflection profiles across the ridges show quite a complex history of cut and fill.

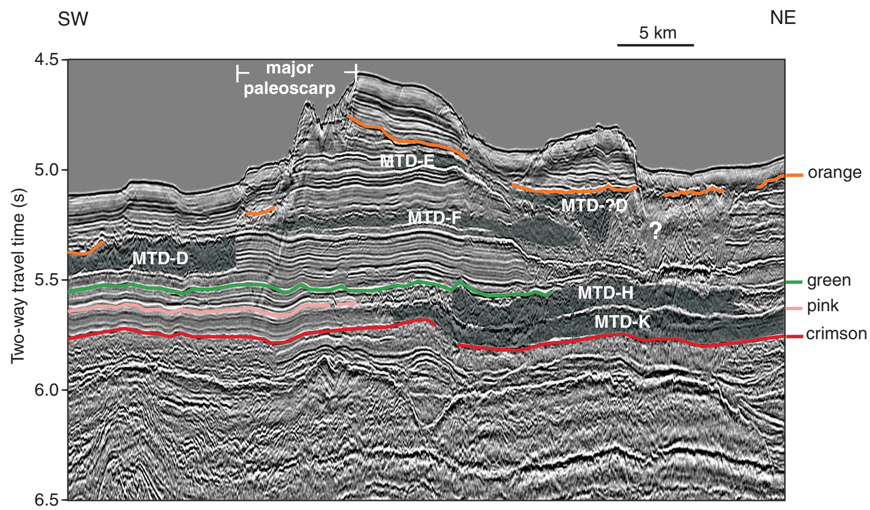

Figure 5.

Multichannel seismic-reflection strike profile east of Haldimand valley, showing key stratigraphic horizons and mass-transport deposits.

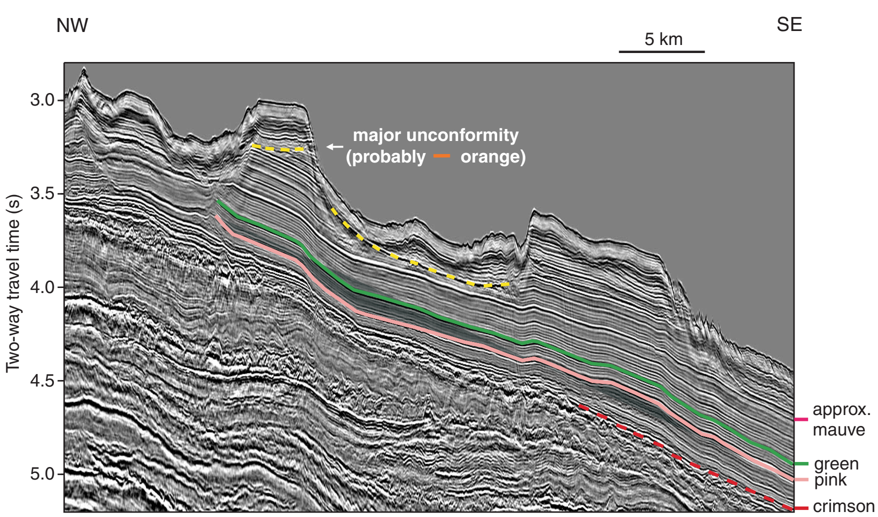

Figure 6.

Multichannel seismic-reflection dip profile along the eastern 'levée' of Haldimand valley, showing key stratigraphic horizons and mass-transport deposits.

DISCUSSION

The late Cenozoic geological history of the east Scotian Slope and Rise revealed by the new data is broadly consistent with the regional model proposed by Piper and Normark (1989). The late Pliocene crimson horizon marks the onset of widespread turbidite deposition on the continental rise, disconformably overlying Miocene and early Pliocene hemipelagic sediment that was influenced by the deep western boundary undercurrent. Both Haldimand and The Gully valleys were initiated as erosional features at or near the crimson horizon, and The Gully valley shows prominent levées (Fig. 4). Development of turbidite channels on the continental rise is presumably related to falling eustatic sea level in the late Pliocene as northern hemisphere ice sheets developed. On the Atlantic margin of the United States, Mountain and Tucholke (1985) recognized a regional unconformity ('Merlin') that they ascribed to intensification of bottom-current circulation in the late Miocene. In the Labrador Sea, however, bottom circulation decreased in intensity and sedimentation rate increased substantially in the late Pliocene, at about 2.5 Ma (Srivastava et al., 1987; Myers and Piper, 1988). The authors therefore suggest that the change in sedimentation style on the east Scotian Rise is of similar age.

Piper et al. (1994, 2002) have argued that voluminous glacial ice first crossed the Scotian Shelf in isotopic stage 12 (0.5 Ma), excavating the Laurentian Channel. Such an event would be expected to have a marked influence on sedimentation on the east Scotian Rise, given the importance of plume discharge from the Laurentian Channel during shelf-crossing glaciation (Skene and Piper, 2003). Based on stratigraphic thicknesses on the Laurentian Fan (Piper et al., 1999), this event corresponds approximately to the mauve horizon. In The Gully valley, mauve marks a major shift in channel position shortly before MTD-F'. On the upper Rise (2500–3500 m), failure of valley-side sediment is much more common above mauve than between mauve and green (Fig. 6). Sedimentation rates at the Tantallon M-41 well site during discharge of plumes from the Laurentian Channel between approximately 17 000 and 14 000 BP was about 4 m/ka , in contrast to 1.2 m/ka on the central Scotian Slope near the Shubenacadie H-100 well site (Mosher et al., 1989). Sediment thickness above the orange horizon on the upper east Scotian Rise is approximately double that in similar water depth above the horizon interpreted to be of similar age on the central Scotian Rise (hazel reflector of Gauley, 2001). These high sedimentation rates reflect proximity to the major glacial discharge through the Laurentian Channel.

Mass-transport deposit D on the east Scotian Rise is larger than previously described Quaternary failure events on the Scotian margin. The volume of MTD-D up-dip from the section shown in Figure 3 is 200 km^3, with a further 200 km^3 between the locations of Figure 3 and GSC line 98036 (Fig. 1); its extent farther downdip is unknown. The wide canyons and cut-and-fill features on the intercanyon highs indicate that some of this large volume of sediment is likely related to the extreme dissection of the continental slope. The step-like erosional base of the mass-transport deposit (Fig. 3) and the hundreds of metres of 'missing' sediment between the green and orange horizons (Fig. 3, 6), however, indicate that much of this mass-transport deposit was derived from sediment failure on relatively low slopes on the continental rise. The volume of 'missing' sediment on the continental rise is estimated as 800 km^3. This enormous failure event took place at about 0.15 Ma and released more than ten times as much sediment as the 1929 Grand Banks earthquake on the upper slope. It therefore likely created a severe tsunami. On valley walls on the continental rise, the entire section of proglacial plume sediment failed, whereas preglacial sediment was also removed in Haldimand valley, perhaps by a bulldozing effect along glide planes of fine sand turbidite beds. A large passive-margin earthquake was the likely trigger for such a widespread failure (cf. Mosher et al., 1994).

Most other mass-transport deposits have volumes an order of magnitude less than MTD-D, and for none other is there evidence of such a great thickness of 'missing' sediment. For example, MTD-J (Fig. 3), with a volume of 30 km^3 updip from the position of the section shown in Figure 3, locally cuts out 100 ms thickness of underlying sediment, but regionally there is no evidence for mass evacuation of sediment between green and pink on the continental rise. Such volumes of sediment may well have been derived from failure on the continental slope. Similarly, shallow mass-transport deposits above orange, reported by Piper et al. (1999), are likely derived from the continental slope. Approximately 10 mass-transport deposits with volumes greater than 10 km^3 are recognized above the crimson horizon updip from position of the section shown in Figure 3, suggesting a mean recurrence interval of 0.25 Ma.

The east Scotian Slope presents similar geohazard challenges to hydrocarbon exploration and development as those described by Pickrill et al. (2001) from those parts of the central Scotian Slope with abundant canyons. These authors suggested that there is no evidence for Holocene sediment failure on the central Scotian Slope. Unconsolidated surficial sediments appear to have failed on slopes of greater than 8° near the Tantallon M-41 well site (Piper, 2001). Canyon walls exposing more consolidated sediment are likely stable (Piper and Campbell, 2002). Sediment failure may have occurred more frequently during the last deglaciation, as a result of either load-induced seismicity or melting of gas hydrates as bottom waters warmed (Gauley, 2001). The presence in the past of major failures involving sediment slabs hundreds of metres thick means that strength properties of proglacial plume sediments should be evaluated against stresses induced during exploration and production, including excess pore pressures resulting from loss of well control. Sedimentation rates in proglacial sediments are higher on the east Scotian Slope than elsewhere on the Scotian margin, and Piper (2001) found that sediment strength in the upper 20 m of sediment was considerably lower at the Tantallon M-41 well site than near Shubenacadie H-100 on the central Scotian Slope.

CONCLUSIONS

Depositional processes and, consequently, depositional architecture on the eastern Scotian margin changed at 2.5 Ma, with the onset of continental-margin turbidite sedimentation, and at 0.5 Ma, with the onset of shelf-crossing glaciation. Major mass-transport deposits have occurred with an average recurrence interval of 0.25 Ma since the late Pliocene. A particularly large event on the continental rise at 0.15 Ma resulted in widespread failure of almost 10^3 km^3 of proglacial sediment in slabs hundreds of metres thick. These proglacial sediments appear to be more readily susceptible to failure than were older turbidite and hemipelagic sediments.

The basic architecture of the east Scotian Slope is similar to other parts of the Scotian margin east of Verrill Canyon, except that erosion of canyons has removed more intercanyon sediment. Shelf-breaching canyons have sandy thalwegs, whereas canyons heading on the upper slope are mostly floored with debris-flow deposits. Risk of sediment failure in shallow proglacial sediment is higher than elsewhere on the Scotian Slope, as a result of higher glacial sedimentation rates.

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