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Authors' addresses

***D.J.W. Piper* (*dpiper@nrcan.gc.ca*)**
Geological Survey of Canada
1 Challenger Drive
P.O. Box 1006
Dartmouth, Nova Scotia B2Y 4A2

***K. Gould* (*kathleengould@hotmail.com*)**
Department of Geology
Saint Mary's University
Halifax, Nova Scotia B3H 3C3

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Late Quaternary geological history of the continental slope, South Whale Subbasin, and implications for hydrocarbon development, southwestern Grand Banks of Newfoundland[1]

D.J.W. Piper and K. Gould

Piper, D.J.W. and Gould, K., 2004: Late Quaternary geological history of the continental slope, South Whale Subbasin, and implications for hydrocarbon development, southwestern Grand Banks of Newfoundland; in Geological Survey of Canada, Current Research D-1, 13 p.

Abstract: The Quaternary geological framework and geohazards on the Southwest Grand Banks Slope are interpreted from 100 line kilometres of seismic-reflection profiles and five piston cores. Stacked tills deposited from grounded ice extend to 300 m b.s.l., with flow tills farther seaward. Radiocarbon dates and Heinrich layers provide chronology for piston cores. Canyons were eroded during maximum ice advance. Proglacial sediments form the upper 100 m of the slope, unconformably overlying Tertiary strata on the middle slope and mass transport deposits on the lower slope. Sediment failure has a recurrence interval of approximately 10 000 years, comparable with elsewhere on the southeastern Canadian margin.

Résumé : Le cadre géologique du Quaternaire et les géorisques sur la partie sud-ouest du talus continental des Grands Bancs sont interprétés à partir de 100 km linéaires de profils de sismique-réflexion et cinq carottes prélevées au carottier à piston. Des tills empilés, déposés par de la glace échouée, s'étendent jusqu'à 300 m sous le niveau de la mer alors que des tills flués se prolongent encore plus loin vers le large. Des datations au radiocarbone et des couches de Heinrich permettent d'établir une chronologie pour les carottes. Les canyons ont été érodés pendant le pléniglaciaire. Les 100 m supérieurs du talus se composent de sédiments proglaciaires, lesquels recouvrent en discordance des strates tertiaires sur le talus moyen et des dépôts de mouvement de masse sur le talus inférieur. L'intervalle de récurrence des ruptures survenues dans les sédiments est d'environ 10 000 ans, ce qui est comparable aux observations effectuées ailleurs sur la marge continentale sud-est du Canada.

[1] Contribution to the Program of Energy Research and Development (PERD) project 532211. Geological Survey of Canada Project X-27.

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INTRODUCTION

The South Whale Subbasin (Fig. 1), located on the southwestern Grand Banks of Newfoundland, recently has been leased for hydrocarbon exploration. Part of the basin underlies the continental slope, in the area around DesBarres Canyon. This study examines the geophysical properties of seafloor sediment and assesses the risk of sediment failure on the continental slope in this area. It expands previous work by Marsters (1987) on geotechnical properties of sediments at the Narwhal F-99 well site, drilled in 1986, and by Pass et al. (2000), who interpreted the late Cenozoic geological framework from seismic-reflection profiles.

METHODS AND DATA

Piston cores and Huntec® DTS (deep-towed seismic) sparker subbottom profiler data were collected on the 2001-043 Geological Survey of Canada cruise on *CCGS Hudson*. One older piston core, MD95-2031, was re-examined for chronostratigraphic correlation. Cores from that cruise typically show 200% extension in the upper 4 m of sediment (Skene and Piper, 2003). Each unsplit core was run through a Geotek multisensor track device to measure bulk density, P-wave velocity, and magnetic susceptibility at a resolution of 1 cm. Discrete P-wave-velocity and shear-strength measurements were taken at 10 cm intervals where possible on split cores. Colour was measured using a Minolta Spectrophotometer at 5 cm intervals on the split core face. Measurements are expressed in terms of the L, a, and b values (ASTM E308-85 and ASTM E1164-02). The Huntec DTS sparker system was towed about 100 m below the sea surface and paper copies of the profiles were interpreted.

Throughout this paper, ages are given in radiocarbon years. Reported dates are conventional ^{14}C ages with 0.4 ka reservoir correction.

REGIONAL SETTING AND BATHYMETRY

The continental slope of the South Whale Subbasin forms part of the Southwest Grand Banks Slope (Fig. 1). The adjacent Grand Banks of Newfoundland experienced glaciation at times in the Quaternary and shallower banks were transgressed during rising sea level after the global last glacial maximum (Slatt, 1977; Fader and Miller, 1986; Miller, 1999). An unusual outer shelf mud belt, the Tail of the Bank mud, accumulated in the early Holocene (Fader and Miller, 1986).

DesBarres Canyon is a complex canyon with several tributary heads that cut back into the continental shelf beyond the regional trend of the shelf break. To the northwest, canyons head in 400–600 m b.s.l. (metres below sea level) and do not incise the upper slope and shelf break. The most prominent is informally named ‘Narwhal canyon’ for the nearby wildcat well.

SEISMIC STRATIGRAPHY

Quaternary seismic stratigraphy from airgun profiles

The outer continental shelf and upper slope north of DesBarres Canyon is substantially deformed by salt tectonics, with the location of seafloor gullies controlled by faults (Fig. 2). Strata interpreted as Quaternary are offset by faults and acoustically incoherent glacial sediment has been ponded against fault-bound horsts (Fig. 2). The modern seafloor shows an inflection point at about 300 m water depth, but is

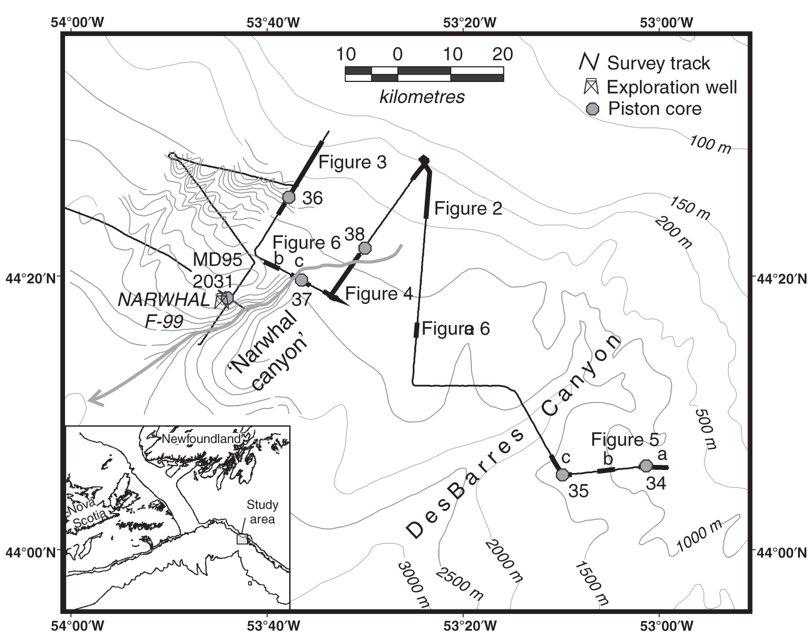

Figure 1.

Location map showing the continental slope of the South Whale Subbasin and location of piston cores and illustrated seismic profiles. Generalized bathymetry from Canadian Hydrographic Service charts, detail from Pass et al. (2000); grey arrow shows position of ‘Narwhal canyon’.

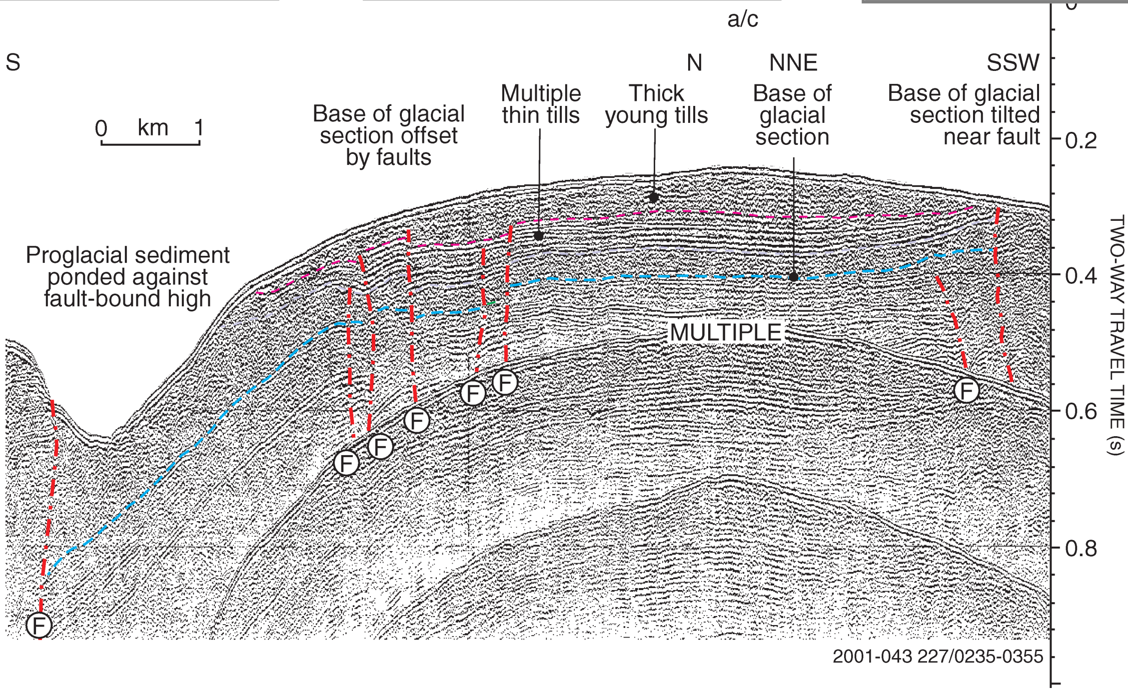

Figure 2. *Seismic reflection profile showing salt tectonic deformation on the outer shelf and upper slope. Outer shelf stratigraphy is based on the more detailed interpretation in Figure 3. (F) = fault.*

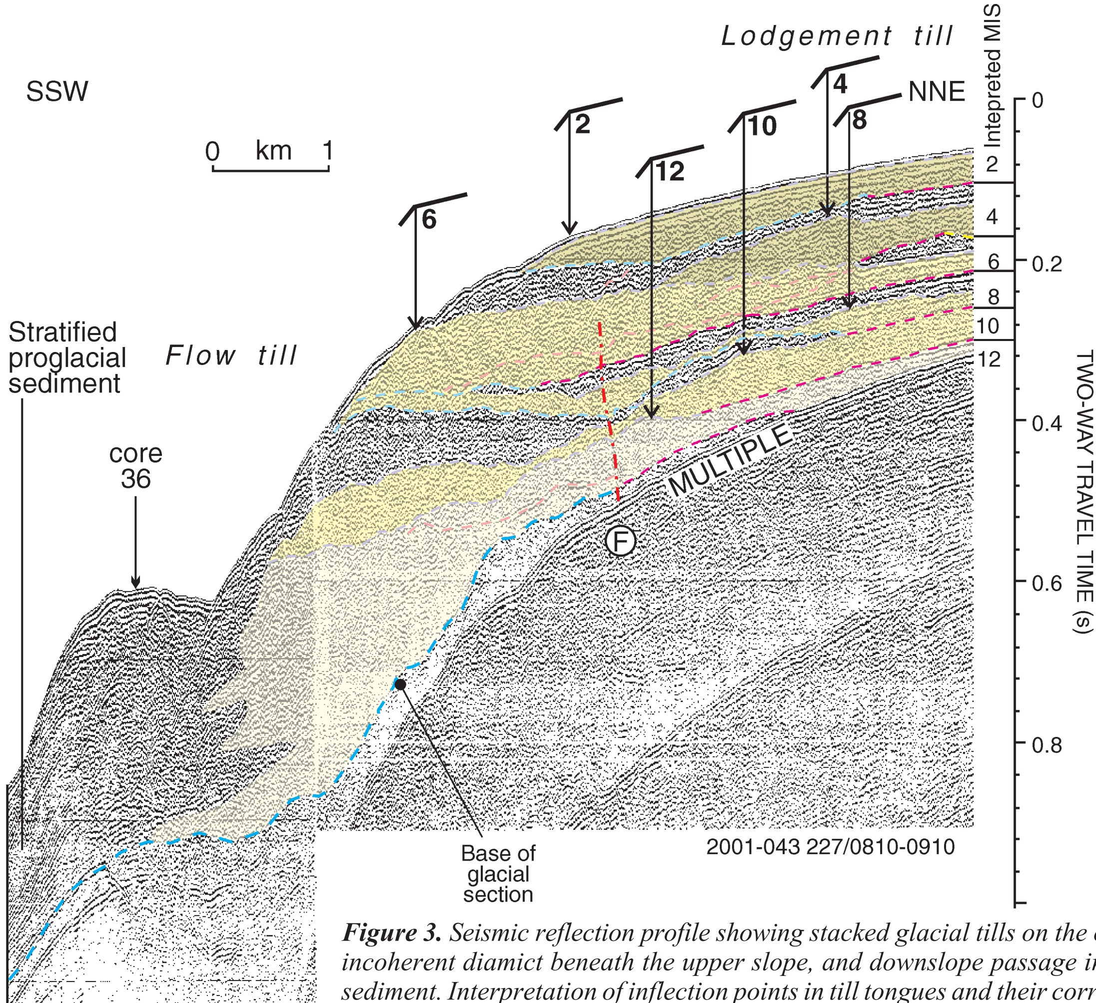

Figure 3. *Seismic reflection profile showing stacked glacial tills on the outer shelf, acoustically incoherent diamict beneath the upper slope, and downslope passage into stratified proglacial sediment. Interpretation of inflection points in till tongues and their correlation with marine isotope stages (MIS) 2-12 is discussed in text. Base of glacial section is tentatively correlated with the 'blue' reflection of Pass et al. (2000) in Figure 4.*

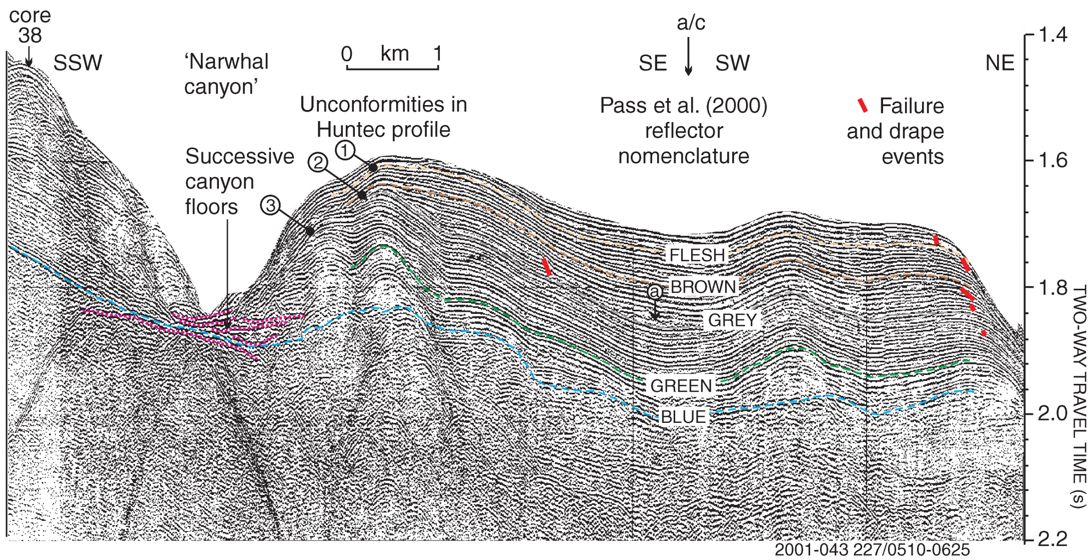

Figure 4. *Seismic reflection profile on midslope near the Narwhal F-99 well showing seismic reflections of Pass et al. (2000); canyon-cutting event identified as sediment drapes unconformable over failure scarps; and broad canyon-floor reflectors.*

underlain by acoustically incoherent sediment to water depths of 650 m, that then pass laterally into stratified proglacial sediment (Fig. 3). Multiple stacked subsurface tills are recognized on the outer shelf, in areas of net subsidence, showing paleo-inflection points similar to the modern seafloor (Fig. 3). The deepest inflection point is 300 m deeper than the inflection point at the present seafloor. The base of the deepest till horizon passes downslope into a major unconformity surface on the middle slope that corresponds approximately to the "blue" reflection of Pass et al. (2000) (Fig. 4).

Northwest of DesBarres Canyon, airgun seismic profiles from the middle and lower slope correlated with the stratigraphic section defined by Pass et al. (2000) near the Narwhal well site (Fig. 4). Well stratified draping reflectors characterize the 150 ms above the 'blue' reflection. Below 'blue' are several erosion surfaces and acoustically incoherent strata interpreted as mass-transport deposits. Some large buried failure horizons can be recognized in the upper stratified section above the 'blue' reflection (e.g. 'a' in Fig. 4). On the flanks of both DesBarres and 'Narwhal' canyons, intervals of canyon wall failure alternate with intervals of continuous sediment drape over the canyon wall (Fig. 4), and these intervals can be regionally correlated.

High-resolution seismic stratigraphy of the upper 100 m of seabed

No Huntec sparker data are available from shallower than 700 m b.s.l. southeast of DesBarres Canyon. At 700–750 m b.s.l., reflectors are generally subparallel, but three irregular unconformities are recognized ('gold', 'purple', and 'brown' in Fig. 5), that become conformable in deeper water. The shallowest unconformity, 'gold', is penetrated by core 34.

Stratigraphic markers can be traced downslope along the flanks of DesBarres Canyon to water depths of about 1300 m b.s.l., around core site 35. The presence of buried scarps and erosional hiatuses suggests that there has been a history of failure on steep slopes on the flanks of the canyon. On a small levee of a tributary gully to DesBarres Canyon, at 1300 m b.s.l., the generally draped sediment succession shows subtle erosional unconformities, the youngest being at or close to the seafloor (Fig. 5c).

Upslope from the Narwhal well site, at 10–25 ms subbottom on the mid-slope, a draped sediment packet overlies locally flat-lying erosion surface, with high amplitude irregular reflectors, correlative scarps on steeper slopes, and mass-transport deposits in fault-bound depressions (Fig. 6). A deeper erosion surface is also overlain by mass-transport deposits and an overlying sediment drape. The seismostratigraphic section in the area near the Narwhal well can be indirectly correlated with that shown in Figure 6 and shows a major erosion surface, related to erosion of the wall of 'Narwhal canyon', at about 30 m subbottom.

PISTON CORES

Core 35, from a broad ridge immediately south of DesBarres Canyon at 1326 m b.s.l., has the longest continuous stratigraphic section (Fig. 7). It contains two prominent beds rich in detrital carbonate (Heinrich layers), recognizable from the high spectrophotometer L* values and peaks in magnetic susceptibility measurements. The shallower layer at 2.8 m is interpreted as H1 on the basis of correlation with dated cores from the Narwhal well site (Piper and Skene, 1998) and the deeper layer at 6.0 m corresponds to H2. A mud-clast conglomerate, interpreted as a debris-flow deposit occurs just above 9.0 m, corresponding to a horizon with the erosional

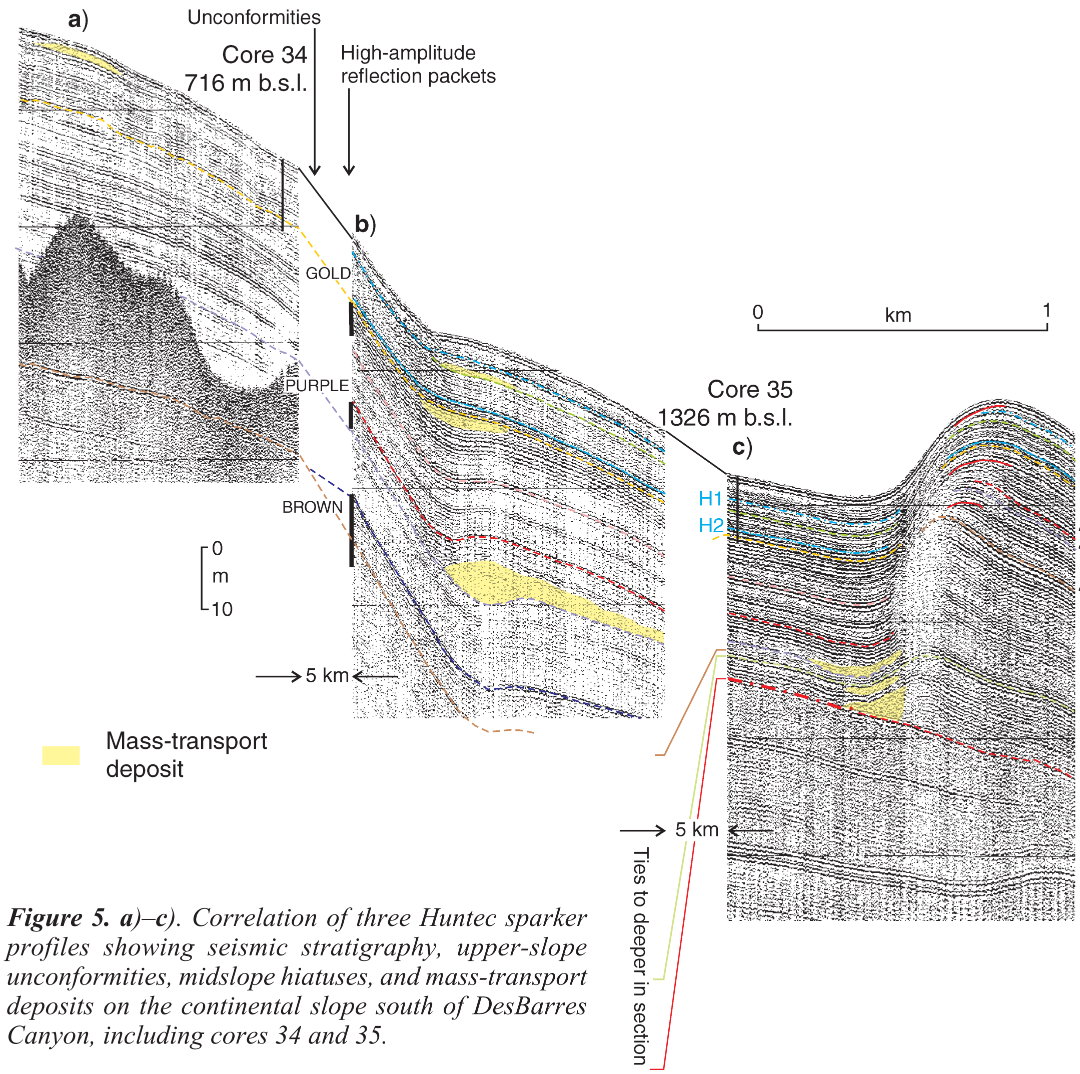

Figure 5. a)–c)*. Correlation of three Huntec sparker profiles showing seismic stratigraphy, upper-slope unconformities, midslope hiatuses, and mass-transport deposits on the continental slope south of DesBarres Canyon, including cores 34 and 35.*

unconformity ('gold', Fig. 5) in the Huntec sparker profile. Core 34, upslope on the same ridge at 716 m b.s.l., shows a similar section to core 35, except that H2 is not present (Fig. 8). At about the same stratigraphic horizon, there is a mud-clast conglomerate which contains carbonate-rich clasts, interpreted as the slumped equivalent of the H2 layer. Between H1 and H2, peaks in the a* values as well as two layers rich in granules correlate between the two cores. Shear strength is locally very low in the interval below the interpreted H2 horizon, probably corresponding to material at or immediately below the unconformity observed in the Huntec sparker profile.

In core MD95-2031, from a ridge near the Narwhal well site (Fig. 8, 9; *see also* McCarthy and Mudie (1998)), the top of which appears to be stretched during the coring process, H1 is at 10.2 m and the oldest radiocarbon age, 15.25 ka, is from 14.0 m downcore. The base of the core is at 26 m and H2 is not recognized. The muddy sediment contains 10–30% sand from 8 m to 22 m subbottom, interpreted to correspond to times of turbidity current flow down the adjacent 'Narwhal canyon'. If turbidity current generation is essentially controlled by eustatic sea-level variations, then the standard isotope curve can be used (with some caveats: Shackleton (1987)) to estimate the age when sea level was similar to 13 ka as about 24.5 ka. This chronology is consistent with the observed thickening of the seismic stratigraphy from core 35 (Fig. 5) to this region (Fig. 6).

Cores 36 to 38 were taken upslope from the Narwhal F-99 well and thus complement cores reported by Pass et al. (2000). Core 36 at 585 m b.s.l. penetrated an upper slope unconformity at about 5.5 m subbottom, represented by a hard deformed mud (shear strength 82 kPa), interpreted as an iceberg-scoured surface from the Huntec sparker profile (Fig. 6, 8). The overlying section is interpreted as younger than H1. The top 2.5 m of mud show a gradual increase in bulk density and uniform L* colour values that decrease abruptly at 2.5 m. A similar pattern is seen at 0.7 m in core 34 and 1.0 m in core 35. The sandy mud unit at 2.5–2.7 m is correlated with the sandy unit at 4.5–5.0 m in MD95-2031, dated at 9.8 ka (Fig. 9).

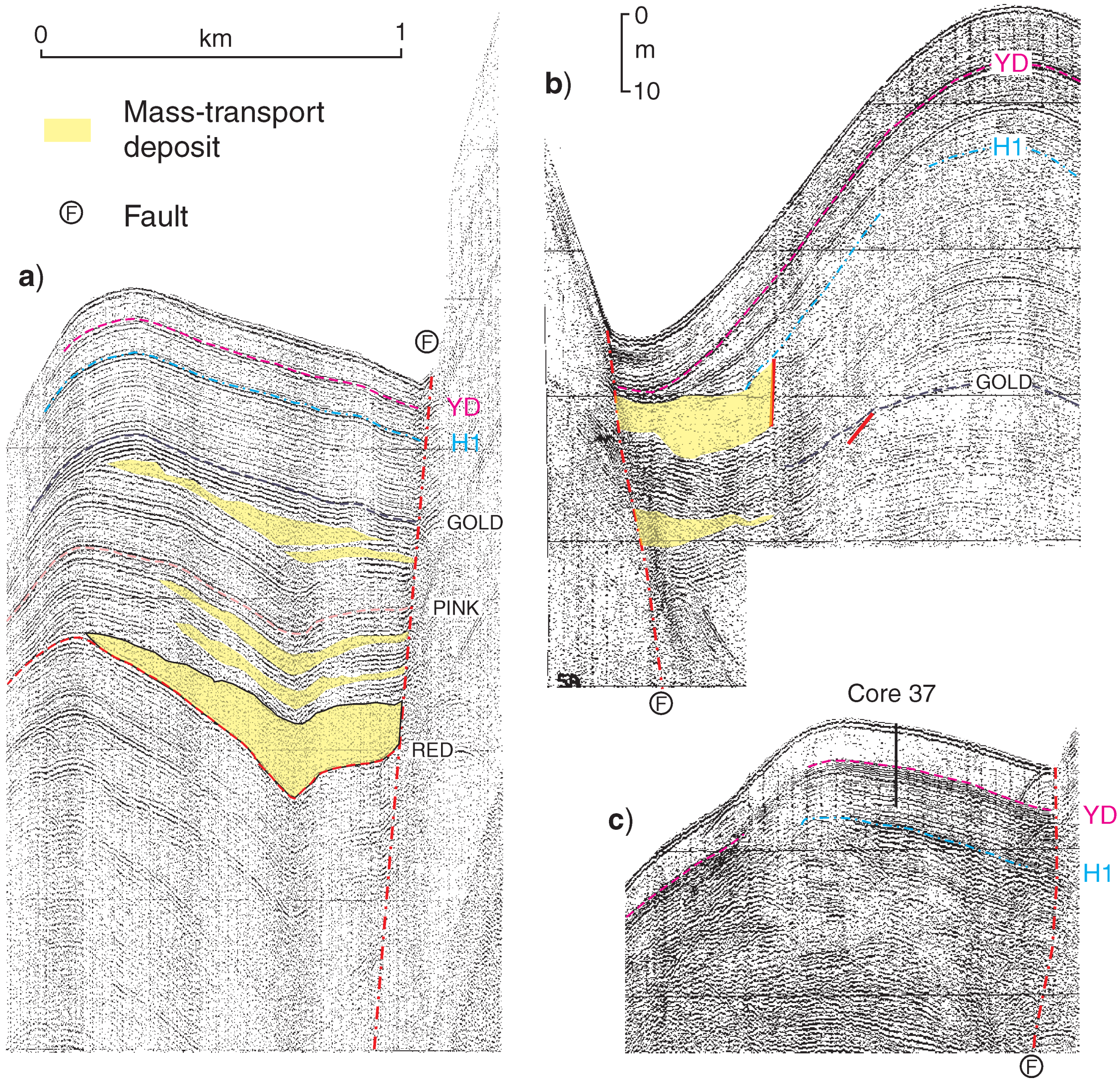

*Figure 6. Huntec sparker profiles northwest of DesBarres Canyon showing **a)** series of mass-transport deposits at foot of fault scarp; **b)** two major failures and mass-transport deposits recorded in a fault-bound depression; and **c)** seismic stratigraphy at core 37. YD = Younger Dryas reflection, H1 = Heinrich 1 reflection.*

Core 37 at 1535 m b.s.l. is located on a terrace 86 m above the 'Narwhal canyon' floor and also does not appear to penetrate H1. Between 0.4 m and 2 m of sediment is missing from the core top. The marker in L* values and bulk density occur at 3.3 m downcore and corresponds to an abrupt change in acoustic facies in the Huntec sparker profile. The Huntec profile also shows an unconformity at about 15 m subbottom. Core 38 at 1033 m b.s.l. sampled a section that is similar to that in core 37 (Fig. 8).

DISCUSSION

Correlation between the upper and lower slope

Because of salt tectonics and gullying, stratigraphic correlation between the upper slope and the lower slope is difficult. Upslope from the Narwhal site, the base of the outer shelf glacial section appears to correspond to a major erosion surface on the middle slope and the base of well stratified sediment (at 'blue') on the lower slope. At the time that the mass-transport deposits below the 'blue' reflection were accumulating, the middle and probably upper slope were sites of erosional bypass.

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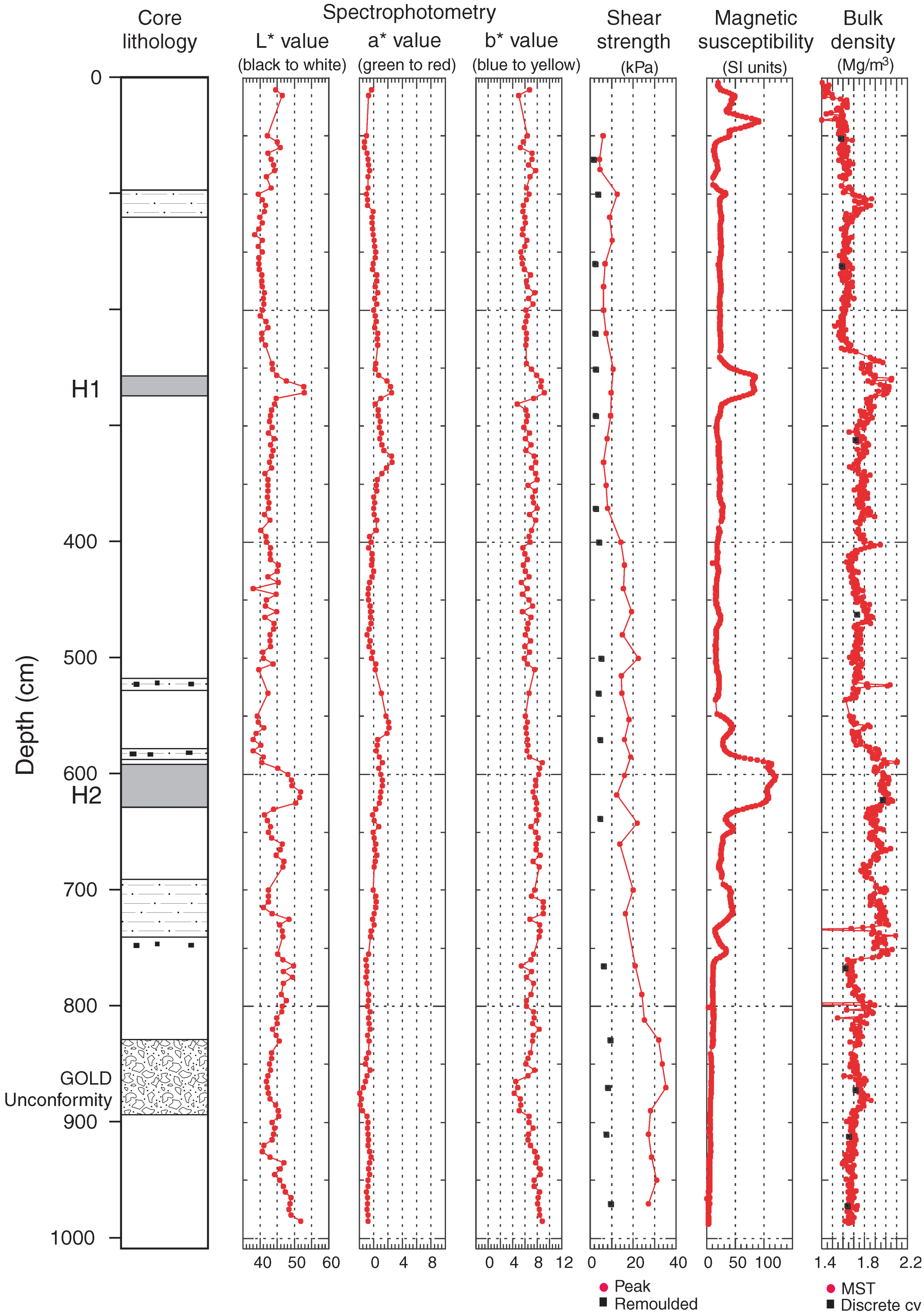

Figure 7. Detailed core log of core 35.

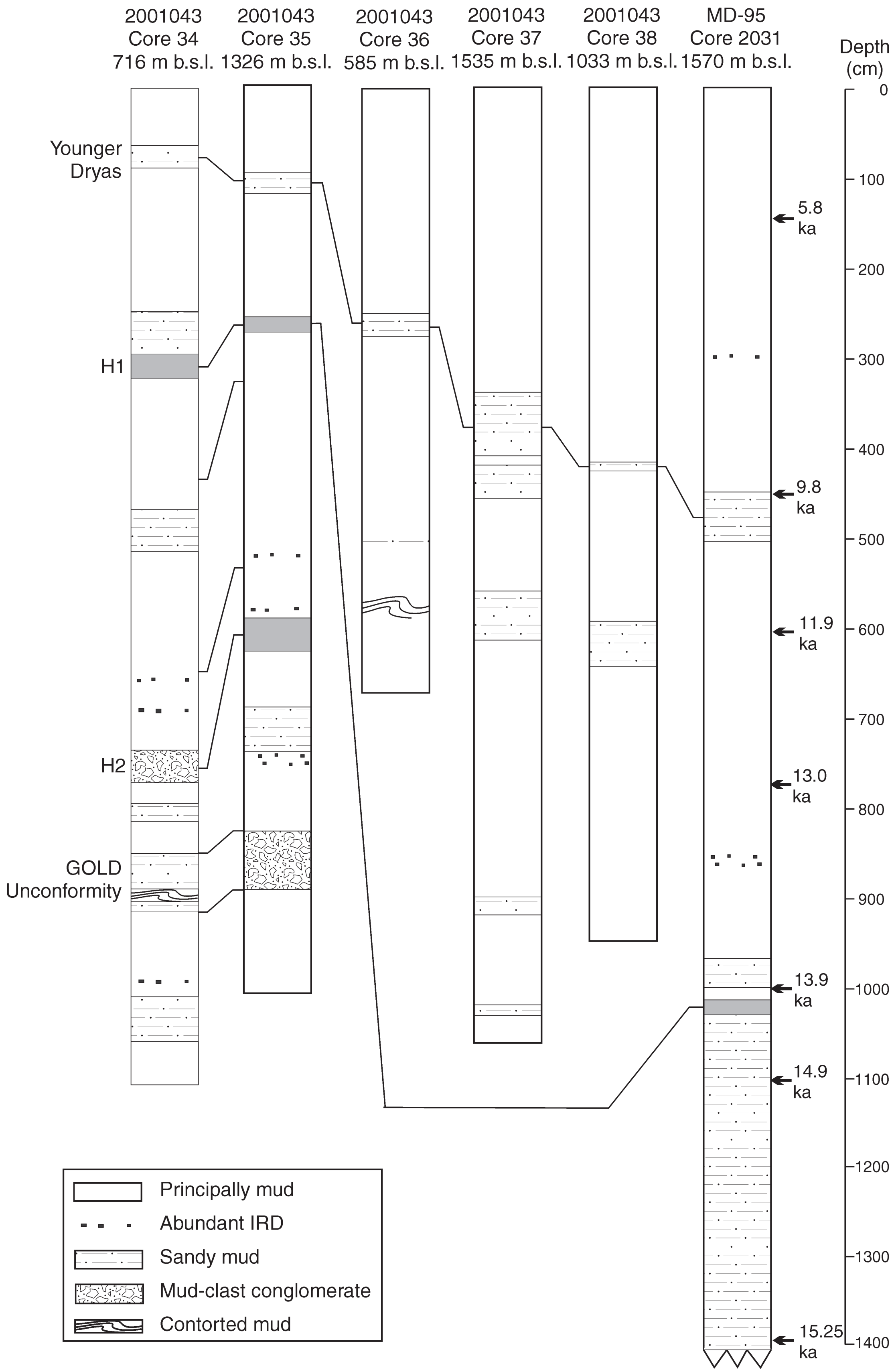

Figure 8. *Summary correlation of all cores.*

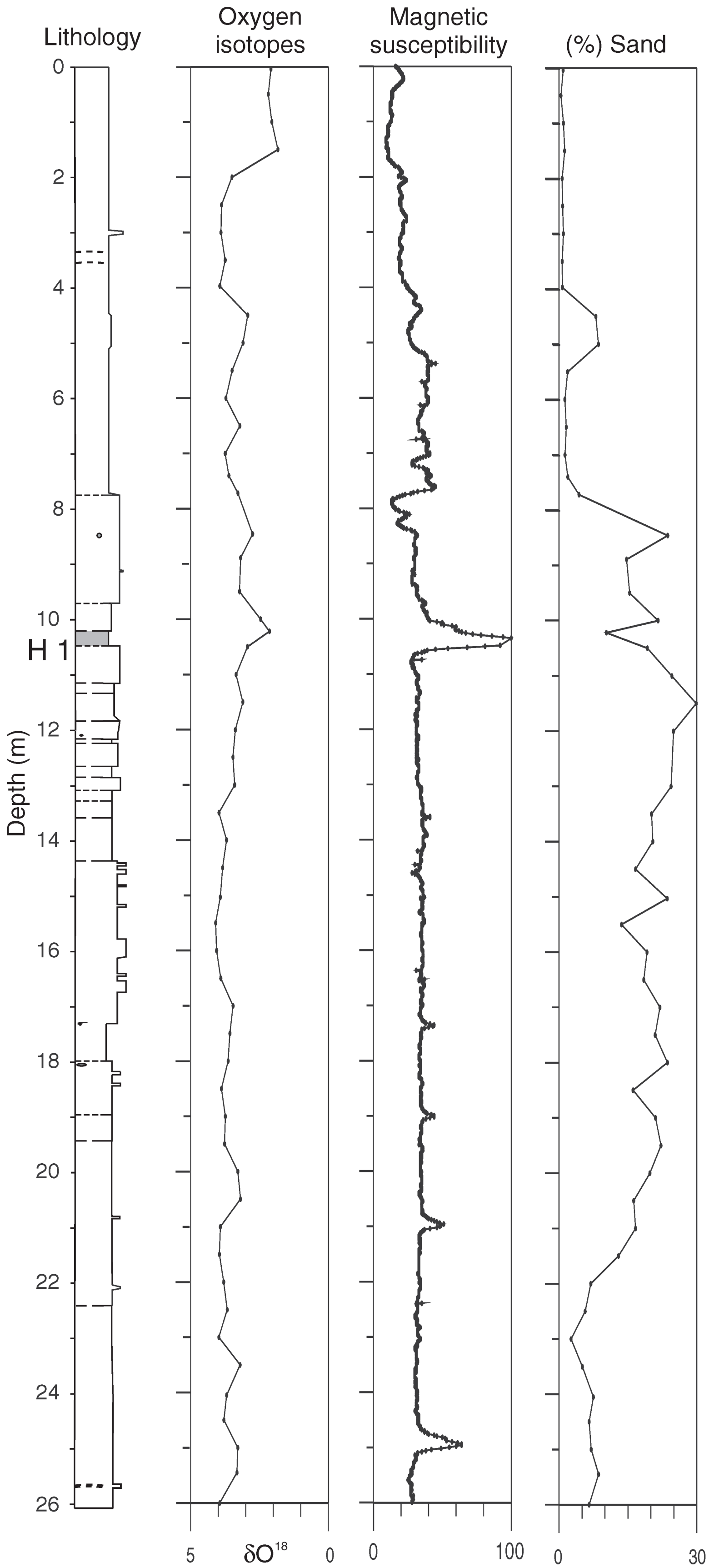

Figure 9.

Downcore log of core MD95-2031.

Deposition of glacial till on the outer shelf and upper slope

Glacial till units, recognized as acoustically incoherent stacked layers on the outer continental shelf, show a planar dipping upper surface to an inflection point on the outer shelf. Beyond this they show a more irregular upper surface, dipping more steeply, to about 650 m, where the acoustically incoherent sediment passes into stratified sediment. A similar pattern was recognized by Pass et al. (2000, their Fig. 8) 100 km to the northwest near Haddock Channel. By analogy with observations on the Norwegian shelf (e.g. King et al., 1998), we interpret the outer shelf inflection point as the limit of grounded ice and deeper water incoherent deposits as flow tills deposited in front of the ice. These flow tills were ponded downslope against fault-bounded salt-cored horsts (Fig. 2). Locally, a morainal mound is developed at the seaward edge of the planar grounding surface near the inflection point (inflection points 4, 10, and 12 in Fig. 3).

The possibility that the 'flow till' is an iceberg-turbated proglacial sediment is rejected. The unconformity at core site 36 that stopped penetration of the corer has an irregular surface typical of iceberg scouring and its age is approximately equivalent to H1, when 'armadas' of icebergs were transported by the Labrador Current. In Flemish Pass, located 700 km more proximally in the Labrador Current, scours to 510 m b.s.l. have widths of 25–40 m and depths of 1–2 m, whereas large scours to depths of 700 m b.s.l. are probably older (Piper and Pereira, 1992). Scour dimensions at core site 36 resemble those of the large scours at Flemish Pass; however, most of the 'flow till' section lacks coherent reflections, unlike intervals of iceberg-scoured sediment on eastern margin of the Grand Banks (Toews, 2003). The western margin of the Grand Banks is unlikely to have experienced iceberg scouring for as long as the eastern Grand Banks, because of the progressive warming of the Labrador Current.

Age of the stacked till deposits can be speculatively assigned (Fig. 3) on the assumption that each major unit corresponds to a glacial marine isotopic stage (cf. Piper et al., 2002), using the evidence of terrigenous flux to ODP site 1063 on the Bermuda Rise (Giosan et al., 2002) that greatest sediment delivery was likely in MIS 2, MIS 6, MIS 10, and MIS 12. In this case, the grounding line in MIS 2, MIS 6, and MIS 12 extended farther seaward than in MIS 4, MIS 8, and MIS 10, consistent with the global ice-volume estimates for these glacial stages (Shackleton, 1987). This interpretation places an age of 0.5 Ma for the base of the glacial section and of reflection 'blue' on the lower slope, consistent with the middle Pleistocene glacial history of the Grand Banks inferred by Piper et al. (1994).

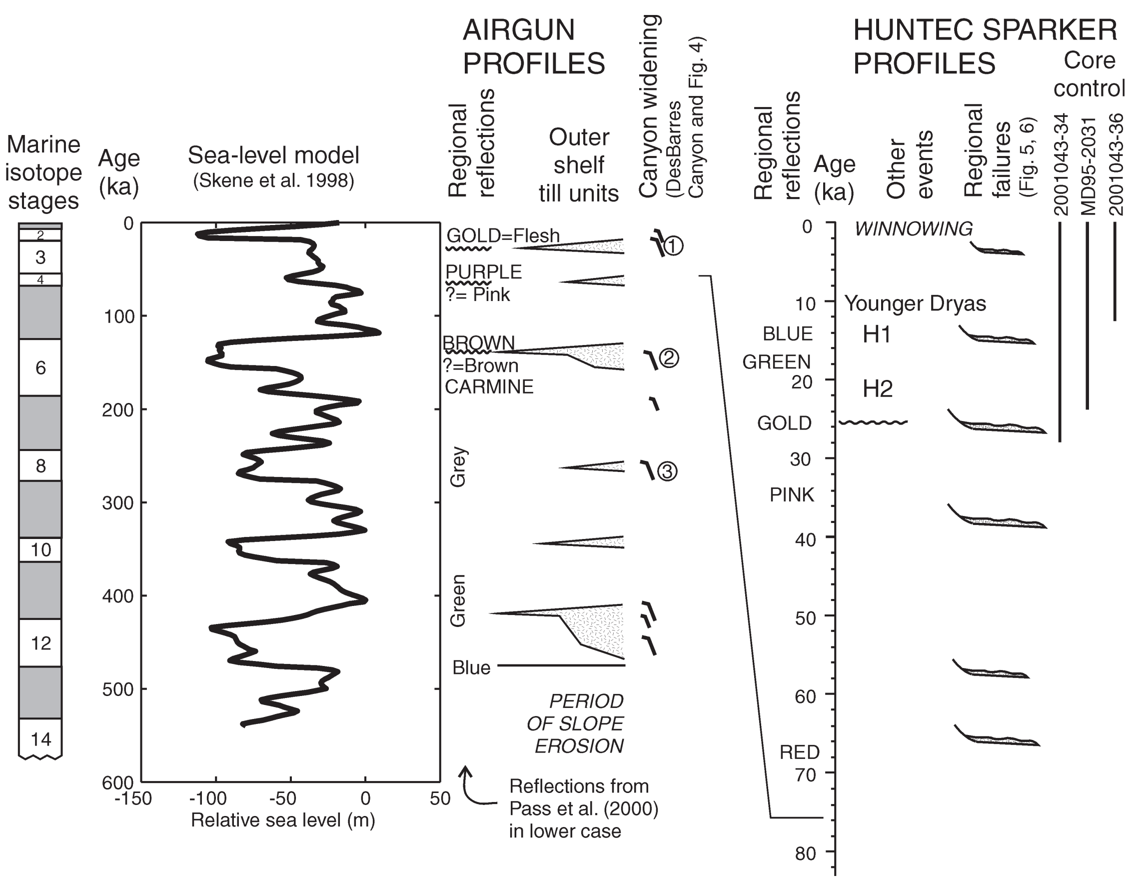

Figure 10. Summary of interpreted Quaternary chronology on the continental slope of the South Whale Subbasin.

Extrapolated chronology for the high-resolution seismic stratigraphy

A widespread unconformity (gold, Fig. 5) occurs in the Huntec records just below H2, i.e. dating from about 25 ka (Fig. 10). There are two possible explanations: that it is due to failure triggered by a random passive-margin earthquake, or that it is in some manner related to the maximum extent of late Wisconsinan glacial ice, which Piper and Campbell (in press) interpreted as being about 25 ka on the continental slope above Flemish Pass. The erosional surface on the upper slope (Fig. 5), with little channel-like features, is more difficult to explain as resulting from an earthquake than from an ice margin, where it might result from hyperpycnal water discharge, ice surge, or iceberg scouring. In core 34, deformed sediments immediately underlie the unconformity. Erosion of the walls of 'Narwhal canyon' just below the limit of penetration of core MD95-2031 has a similar extrapolated age. Less erosion took place in the interval from 24.5–13 ka, when sandy turbidity currents passed through the channel.

South of DesBarres Canyon, near core 35, sedimentation rates back to H2 appear reasonably uniform between glacial and interglacial periods. Extrapolation of sedimentation rates in Figure 5b, where there is no evidence for loss of sediment by failure, suggests an age of 70 ka for the 'purple' and 110 ka for the 'brown' reflectors, corresponding to unconformities on the upper slope. These two unconformities are thus correlated with the MIS 4 and the end of the MIS 6 glaciations (Fig. 10).

At 1300 m b.s.l., on the low levee in Figure 5c, units of draped sediment alternate with units of condensed sediment, the youngest being of Holocene age and similar to Figure 10 of Piper and Campbell (2002). Extrapolation of sedimentation rates suggests that the older condensed horizons date from about 40 ka and during MIS 5 (85–125 ka).

Upslope from the Narwhal well (Fig. 6), the shallowest erosion surface and corresponding debris-flow deposit has an extrapolated age corresponding to the erosion surface and failure deposits just below H1 southeast of DesBarres Canyon (Fig. 5). The deeper erosion surface and debris-flow deposits may thus correlate with those a little way below H2 southeast of DesBarres Canyon.

Based both on cores and seismic correlation, the late Pleistocene to Holocene sediment section appears to be almost twice as thick near the Narwhal well site as in the corresponding water depth southeast of DesBarres Canyon (cf. Fig. 5, 6). Several processes may have been active here. First, the unusual Tail of the Bank mud points to significant early Holocene mud accumulation on the outer shelf southeast of DesBarres Canyon. Second, the northwestward-flowing Slope Current, a continuation of the Labrador Current, may cause sediment winnowing on topographic highs, such as inferred in Figure 5c. Third, DesBarres Canyon may have been a major input point for both glacial meltwater in the late Pleistocene and fluvial sediment in the earliest Holocene, both of which would form plumes that would drift northwestward in the prevailing current. The unusual thickness continues into the Holocene section, which is up to 4 m thick, compared with less than 1 m on much of the Scotian Slope. The Younger Dryas is marked by a distinctly sandy interval in the cores, with 5–10% sand in MD95-2031. This sand could have originated from storms off the Grand Banks (analogous to the interpretation of Piper and Fehr (1991) for the Scotian Shelf) or from winnowing by the Labrador Current. We prefer the former hypothesis because recent work by Mackie (in press) has shown that in Flemish Pass the Labrador Current was weak during the Younger Dryas.

Regional correlation of slope failures and their causal factors

The stratigraphic occurrence of regional failures (Fig. 4–6) is summarized in Figure 10. The mean recurrence interval for the reasonably well dated interval is approximately 10 000 years. The correlation of infrequent failures from near the Narwhal site (Fig. 6) to southeast of DesBarres Canyon (Fig. 5) suggests a regional trigger, presumably earthquakes, for many failures.

The triggers for slope failures on the eastern Canadian continental margin have been recently reviewed by Piper et al. (2003). They concluded that there was little evidence for salt tectonics triggering more frequent failures and that the chronological correlation of most abundant failures with deglaciation suggested that many failures were triggered by earthquakes associated with glacial unloading. In the area studied, steep slopes associated with salt tectonics appear to be favoured locations for failure (e.g. Fig. 6a, b), but the recurrence interval of approximately 10 000 years is no greater than on parts of the Scotian Slope little affected by salt tectonics (Piper et al., 2003).

Canyon widening events

Some canyons show a wide, highly reflective canyon floor that has been partly buried by younger sediment (e.g. upper 'Narwhal canyon', Fig. 4) and episodic canyon wall erosion events covered by a drape of younger sediment (e.g. southeast wall of upper 'Narwhal canyon', Fig. 4). No precise correlation with till tongues is possible with the available data; however, the youngest erosional event in 'Narwhal canyon' appears to be a little older than H2. It approximately corresponds to the erosional surface and failures at the 'gold' horizon southeast of DesBarres Canyon, which correlates with the mid-late Wisconsinan ice maximum on the Grand Banks. Canyon erosion is presumably the result of large subglacial discharges of water, similar to those inferred by Piper and MacDonald (2002) on the upper slope off Laurentian Channel. Extrapolation of sedimentation rates (e.g. in Fig. 4) indicates that more deeply buried channel widening events could correspond to glacial MIS stages 4 and 6. Such a process might account for the correlation of mass-transport deposits with glacial advances in canyons on the middle Scotian Slope noted by Piper et al. (2002).

Significance of Heinrich layers

Heinrich layers provide a rapid method of correlating and dating cores. Their presence in these cores indicates transport by the Labrador Current of carbonate-rich ice-rafted and meltwater sediment derived from Hudson Strait (Rashid et al., 2003).

Heinrich layer H2 is not present in core 34, but at the equivalent horizon is a slumped body of carbonate-rich mud. Unlike other Heinrich layers in cores 34 and 35, this slumped horizon does not have a characteristic high magnetic susceptibility and in this regard resembles proximal Heinrich layers off Hudson Strait (Rashid et al., 2003). High magnetic susceptibility is characteristic of crystalline Precambrian rocks derived principally from Greenland or Baffin Island and is most prominent in the central North Atlantic Ocean (Grousset et al., 1993). This suggests that the H2 equivalent in core 34 was deposited from the innermost part of the Labrador Current that lacked mixing with icebergs derived from Precambrian shields. It may have been close to shelf-fast sea ice, which locally prevented deposition of Heinrich layers on the upper Labrador Slope (cores 92-1 and 92-2; Rashid (2002)). A similar process may have prevented deposition of H2 in MD95-2029, or its deposition may have been diluted by turbidite sedimentation in this core.

The occurrence of H2 as a slump in core 34 supports evidence elsewhere that Heinrich layers fail preferentially compared with other sediment on the upper slope, perhaps because of rapid deposition or massive iceberg scouring. Carbonate-rich turbidite deposits are particularly abundant on the floor of Flemish Pass (Piper and Campbell, in press) and carbonate turbidite deposits on the Sohm Abyssal Plain probably result from slumping of Heinrich layers on the Grand Banks margin (Piper and Hundert, 2002).

IMPLICATIONS FOR HYDROCARBON EXPLORATION AND DEVELOPMENT

Shallow drilling conditions on the Southwest Grand Banks Slope are dominated by proglacial sediments in the upper 100 m, overlying thick mass-transport deposits on the lower slope and an erosional unconformity over Tertiary strata on the upper slope. This proglacial style of sedimentation is similar to that previously reported for Flemish Pass (Piper and Campbell, in press), Salar basin (Toews, 2003), and much of the Scotian Slope (Mosher et al., in press), although the geotechnical properties of muds are likely related to source and thus specific to this area. Sediment failure has occurred in the past, with a recurrence interval of the order of 10 000 years, comparable with that elsewhere on the southeastern Canadian margin (Piper et al., 2003). The active salt tectonics creates local steep fault scarps, but otherwise does not appear to have geohazard significance.

CONCLUSIONS: QUATERNARY GEOLOGICAL HISTORY

This study provides a conceptual framework for interpreting Quaternary sedimentation on the Southwest Grand Banks Slope. Sedimentation on the slope is strongly influenced by salt tectonics. Stacked tills deposited from grounded ice extend to 300 m b.s.l. and beyond that flow tills were deposited on the upper slope to at least 600 m b.s.l. A consistent chronostratigraphic interpretation has been developed for Quaternary sediments from radiocarbon and Heinrich event chronology in piston cores and from the systematic pattern of stacked tills. Canyon erosion took place preferentially at times of maximum ice advance, whereas winnowing of topographic highs occurred preferentially during interglacial conditions.

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