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Surficial geology of the Scotian Slope, eastern Canada

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Abstract: Sediment type on the upper 5 cm of seafloor has been mapped on the Scotian Slope using core samples, acoustic backscatter in sidescan sonar and multibeam bathymetry, observations from submersibles, and high-resolution acoustic profiles. The upper slope is underlain by overconsolidated till with iceberg pits and scours, overlain in water depths of <300 m by mobile fine sand in the east and sand and gravel in the west. Muddy fine sand occurs on canyon heads and floors to water depths of about 1000 m. Mudstone outcrops on some canyon walls, with intervening terraces with mud and locally sand deposits. Intercanyon ridge crests <800 mbsl have surface-winnowed sand; similar sand occurs locally on ridge crests to depths of 1500 mbsl. Even low hills in deep water may have winnowed sandy mud at the seabed. The deeper continental slope is generally floored with bioturbated mud changing to foraminifer-rich mud beyond 3000 mbsl. These observations on sediment distribution are important for understanding biological habitat and assessing modern seafloor reworking by currents.

Résumé : On a cartographié les types de sédiments déposés dans les 5 cm supérieurs du talus Néo-Écossais en se basant sur des échantillons de carottes, des données de rétrodiffusion acoustique par sonar à balayage latéral et de bathymétrie multifaisceaux, des profils acoustiques à haute résolution et des observations effectuées à partir de submersibles. La partie supérieure du talus se compose de till surconsolidé comportant des fosses et des marques d'affouillement formées par des icebergs. Dans des eaux de moins de 300 m de profondeur, ce till est recouvert de sable fin mobile dans la partie est du talus Néo-Écossais et de sable et de gravier dans la partie ouest. Du sable fin boueux recouvre le fond et le plancher des canyons jusqu'à des profondeurs d'eau d'environ 1 000 m. Du mudstone affleure sur certaines parois de canyon. Les terrasses intermédiaires sont recouvertes de boue et, par endroits, de dépôts de sable. À moins de 800 m sous le niveau de la mer, le sommet des crêtes entre les canyons est recouvert de sable vanné; du sable similaire se rencontre par endroits sur les sommets des crêtes jusqu'à des profondeurs pouvant atteindre 1500 m sous le niveau de la mer. On peut même trouver de la boue sableuse vannée sur les collines peu élevées en eau profonde. Le talus continental plus profond est généralement recouvert de boue bioturbée passant à de la boue riche en foraminifères au-delà de 3000 m sous le niveau de la mer. Ces observations sur la répartition des sédiments sont importantes pour comprendre l'habitat biologique et évaluer le remaniement par les courants du plancher océanique moderne.

INTRODUCTION

In preparing geological maps of the seabed, decisions have to be made as to what information to display. As on land there is commonly a distinction between soil type and underlying bedrock, so in the marine environment the upper 5 cm of sediment is commonly different, both in texture and physical properties, from the average material in the upper few metres. This is particularly the case where the seafloor is eroded during extreme oceanographic and geological events.

Canadian seabed mapping has generally been based on acoustic tools that image the upper few metres of the seabed and provide less information on the actual seafloor. As a result, most published maps (e.g. King, 1970) show seafloor outcrop of glaciogenic and postglacial formations. These formations are only a general predictor of material at the sediment–water interface. In contrast, maps based principally on grab samples, such as the United States Geological Survey series on the American continental shelf (e.g. Ross, 1970), provide more direct information on the sediment–water interface, but little information on subsurface materials. Both types of information are important to different user communities: for example, the fishery requires information on seafloor sediment type whereas pipeline and other seabed structure planning requires information on subsurface materials.

Recent advances in survey technology, particularly the availability of multibeam bathymetry and backscatter tools, have revolutionized our ability to map the seabed. Whereas older long-range sidescan sonar systems commonly averaged over the upper few metres of sediment (e.g. GLORIA [Gardner et al., 1991]; SeaMARC I [Piper et al., 1985]), high-frequency sounding systems provide backscatter information from the upper metre of sediment (Todd et al.,1999; Shaw and Courtney, 2000).

We have produced a preliminary seafloor geology map of the Scotian Slope (Fig. 1) in response to demand from industry clients, regulators, and public-interest groups. This map is based on a wide range of reconnaissance data. Deep-water multibeam and backscatter information is publicly available for the area of The Gully. The GSC is co-owner of industry-confidential multibeam bathymetric data on parts of the Scotian Slope, and we have used segments of that information that have appeared in the public domain (i.e. in papers by Pickrill et al. [2001] and Gauley [2001]). Along-track 3.5 kHz

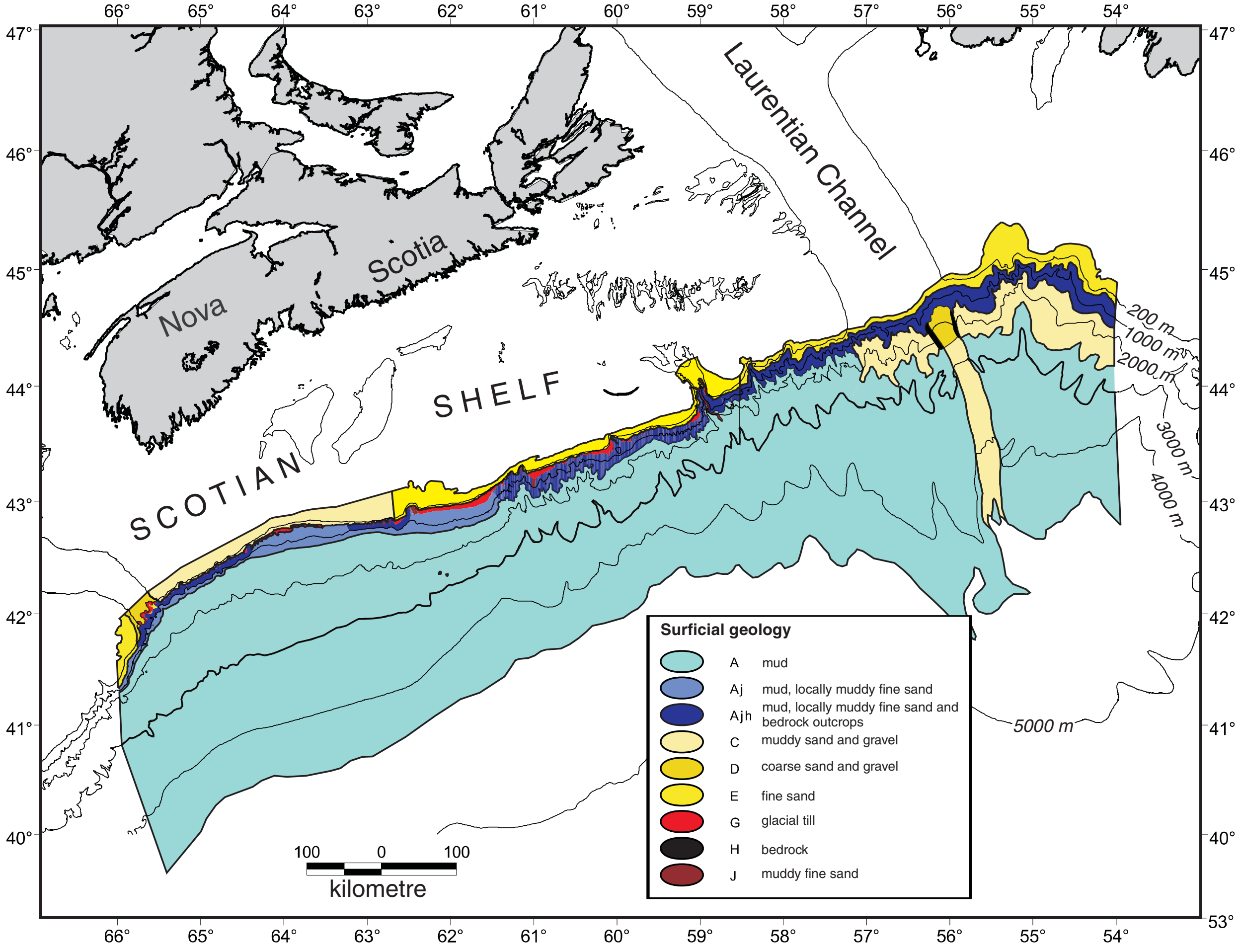

Figure 1. Preliminary map showing seafloor sediment type for the Scotian Slope.

profile interpretations (Campbell, 2000) and sparse deep-water high-frequency sidescan data (Baltzer et al., 1994; Piper, 2001) provide additional acoustic information on seabed conditions. Core-top samples and grab samples, together with sparse bottom photographs and observations from submersible and remotely operated vehicle dives (Hill et al., 1983; Hughes Clarke and Frobel, 1987; Mayer et al., 1987; Hughes Clarke et al., 1989; Campbell, 2001) provide direct information on sediment type at the seafloor. In recent years, we have collected specific seabed samples to investigate local variability in seafloor sediment type. Here we report the results of these studies (Fig. 2).

The seabed sediment types that we have distinguished (Table 1) are modified from a classification proposed by Roff et al. (in press) for evaluation of benthic habitat on Canadian continental shelves.

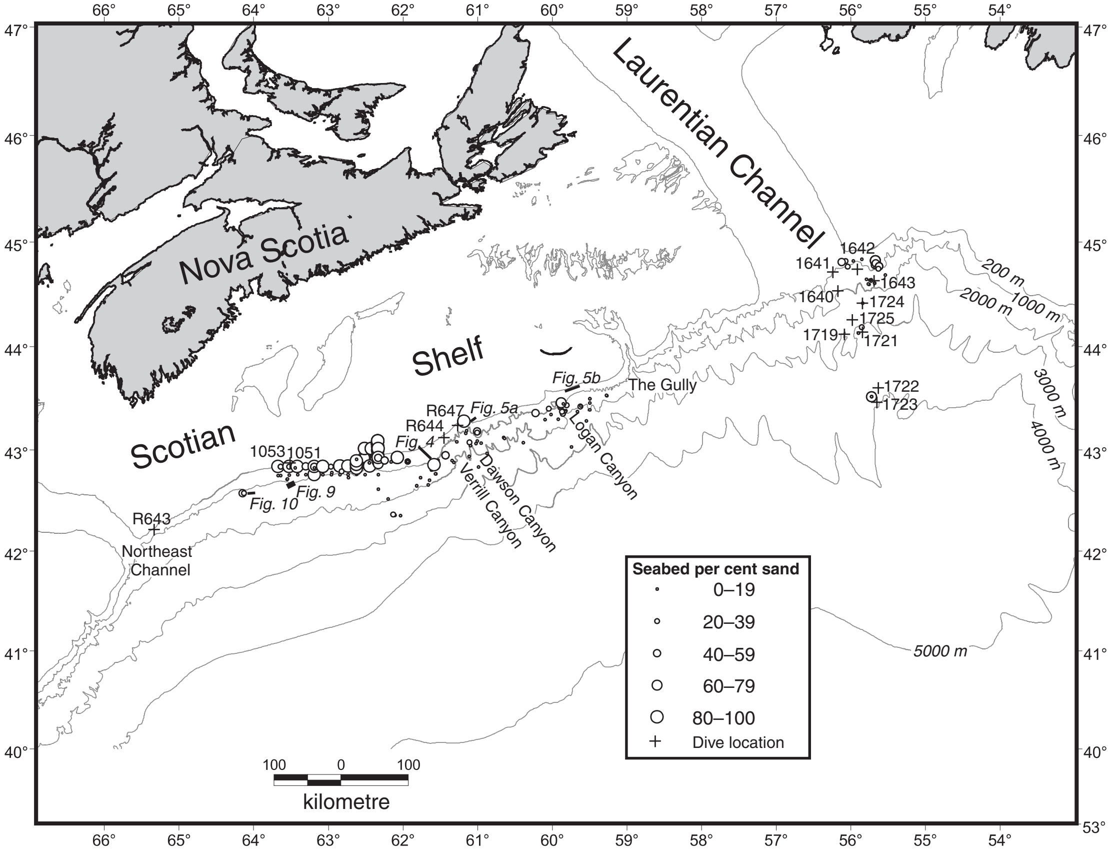

Figure 2. Percentage sand in seafloor samples from box cores and good quality gravity cores. Map also shows location of other figures in this report and of submersible and remotely operated vehicle dives discussed in this report.

Table 1. Classification of seabed sediment types.

Type	Sediment type	Occurrence	Notes
A	Mud	Widespread >600 mbsl	
Aj	Mud, locally muddy fine sand	Upper parts of gullied slope, western Scotian Slope	High local heterogeneity of substrate
Ajh	Mud, locally muddy fine sand and bedrock outcrops	Upper parts of canyons, eastern Scotian Slope	High local heterogeneity of substrate
C	Muddy sand and gravel	Upper western Scotian Slope, 300–100 mbsl	
D	Coarse sand and gravel	Northeast Channel	May include some fine sand, but no mud
E	Fine sand	Upper eastern Scotian Slope, 300–100 mbsl	No mud
G	Glacial till	Upper slope 300–500 mbsl	Poorly sorted sediment, but may have veneer of gravel (type F)
H	Bedrock	Locally on steep canyon walls	Not regionally mapped
J	Muddy fine sand	Upper parts of some canyons, intercanyon ridges, and other winnowed highs	Fine sand and silt, <25% clay

UPPER SLOPE

Smooth upper slope

The seafloor gradient increases at the shelf break at 80 to 160 mbsl to gradients of 1.1° to 3.3° on the upper slope. Most areas of the upper slope, to about 500 mbsl, have a relatively smooth morphology (Fig. 3). In water depths of 250 to 500 mbsl, Pickrill et al. (2001) have shown the widespread presence of relic iceberg pits and scours, recognizable from multibeam bathymetry and from bathymetric and seismic profiles (Fig. 3, 4). In shallower water, these pits and scours become progressively more muted (Fig. 3), suggesting that they are filled by modern sediment. Locally, sand waves in 200 to 250 mbsl confirm the presence of abundant modern sediment (Pickrill et al., 2001), and high-resolution seismic-reflection profiles show the presence of a veneer of sandy sediment (Piper, 2001, Fig. 7.11). Sparse cores and grab samples (including the study of Hill and Bowen, 1983) show that on the eastern Scotian Slope the upper slope sediment is predominantly sand, but that west of latitude 62°50′W, surficial sediment comprises sand and gravel.

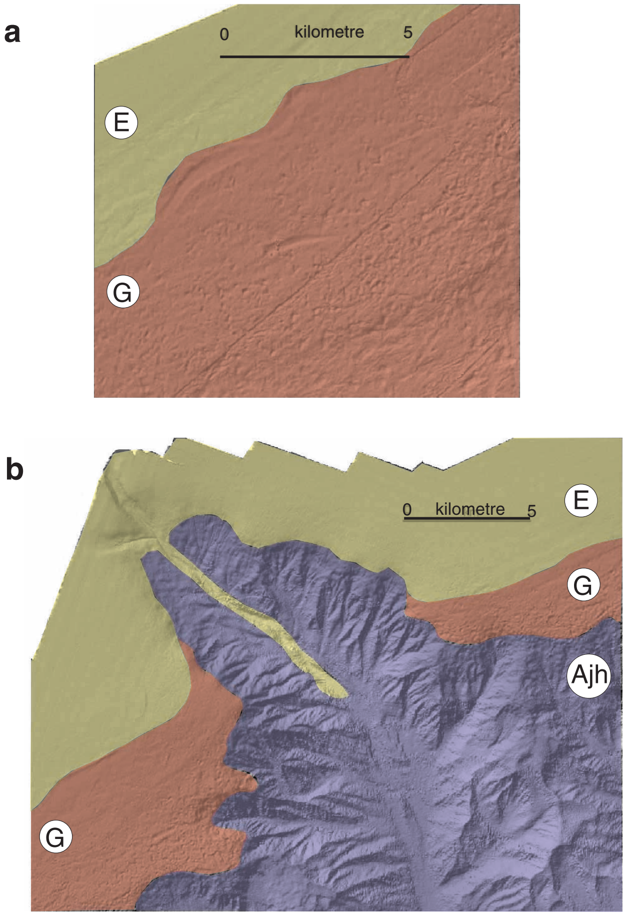

***Figure 3.** Sediment texture maps overlain on multibeam images of the upper slope (*modified from *Pickrill et al., 2001). **a**) west of Dawson Canyon, **b**) head of Logan Canyon. E = fine sand; G = glacial till; Ajh = mud, locally muddy fine sand and bedrock outcrops*

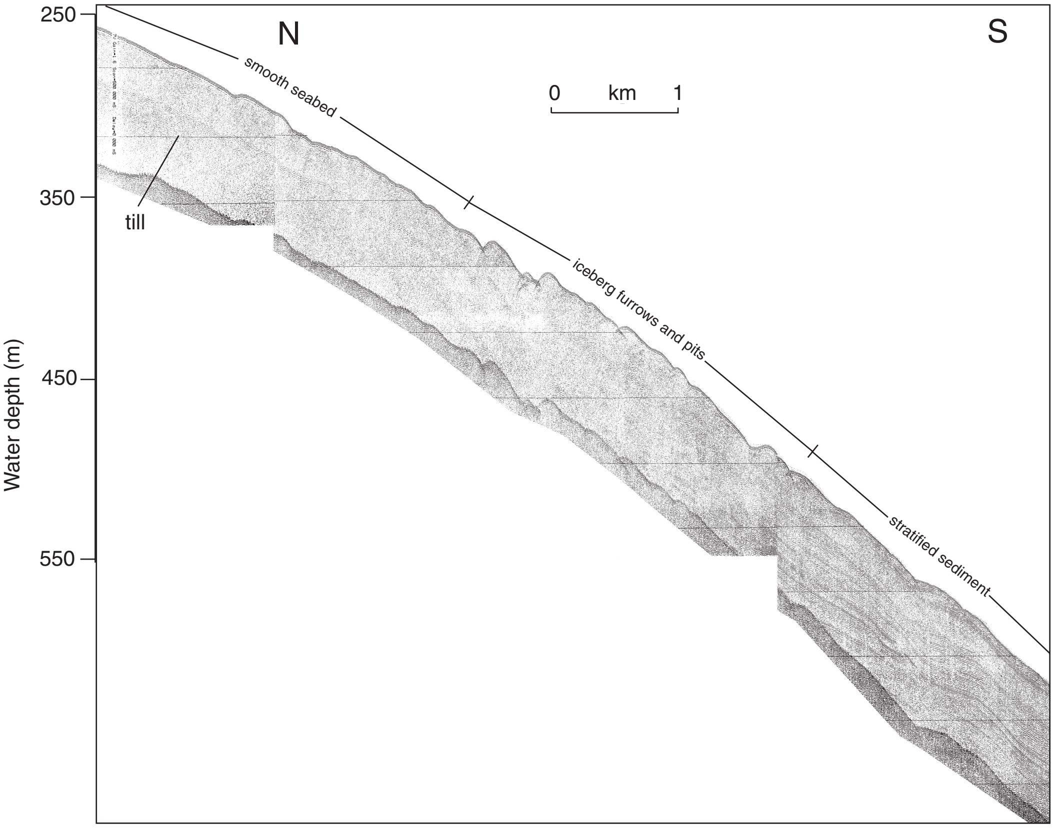

Figure 4.

Huntec DTS profile showing downslope passage from sand on upper slope through iceberg furrows and pits to stratified muddy sediment, across seabed similar to that illustrated in Figure 3b.

Submersible dives (*Pisces* 1051 and 1053: *see* Fig. 2) on the upper slope at latitude 63°25′W (Hill et al., 1983) were carried out on *Pandora* cruise 81050. Only hand-held camera shots are available from these dives, together with intermittent hand-held black and white video on dive 1053 and a detailed dive log. The dives ran from muddy deposits in 600 m water depth to silty sand with scattered gravel in 500 m water depth and then upslope to low ridges of large boulders, common patches of boulders and gravel, with sand in intervening areas. The boulder ridges may represent the winnowed berms of iceberg scours (*see* Fader, 1989). One dive traversed up the axis of a small slope gully, which had sandier sediment, more garbage, and more biogenic disturbance than adjacent slope areas. *ROPOS* dive R643 near Northeast Channel followed a 2.5 km transect up an upper slope ridge, then crossed moderately irregular seabed. The upper slope ridge was predominantly covered with medium sand. The irregular seabed was also dominated by sand, with local concentrations of gravel including boulders and shelly hash.

Sidescan sonar images of the deeper parts of the upper slope confirm the presence of iceberg pits and scours, which become progressively more obscured by mud deposits beyond about 400 mbsl where the upper slope continues smoothly into the middle slope (Fig. 3a). Seismic reflection profiles (Fig. 4) and cores suggest that the area with pits and scours is underlain by overconsolidated till (Mosher et al., 1989; Piper, 2001). Insight into likely sediments is based on deep-water shelf areas of till heavily scoured and pitted by icebergs. In Avalon Channel (Fader, 1989), submersible observations show that berms consist of boulders and troughs of pits and scours consist of sorted gravel. *Pisces* dive 1653 on the upper Labrador Slope (Josenhans and Barrie, 1989) found similar sediments on iceberg-scoured seabed. Sparse sampling on the Scotian Slope suggests that gravel may be less abundant than off Newfoundland and Labrador and that weathered muddy till outcrops with pockets of sand predominate.

Canyon heads

The heads of the larger canyons that incise the outer continental shelf, such as Logan and Dawson canyons, have a relatively smooth seabed (Pickrill et al., 2001) (Fig. 3b), and sparse Huntec DTS sparker lines indicate that a drape of sand occurs in these canyon heads (Fig. 5).

New observations from the remotely operated vehicle *ROPOS* from 470 to 350 mbsl in the head of Dawson Canyon (dive R647) show local outcrops of well bedded mudstone over the entire depth range. Most of the seabed is mud, but locally rare gravel and sand are found near the outcrops, suggesting that they may be eroding out of the bedrock walls of the canyon. At least one outcrop appeared to be a pebbly mudstone or diamict (dive R644) (Fig. 6b). One 50 cm boulder was noted at 413 mbsl, with scour around it.

Deeper water canyon heads, typically at 400 to 600 mbsl, have been imaged by multibeam bathymetry (Pickrill et al., 2001) and SAR high-resolution sidescan (Baltzer et al., 1994). At the head of the Albatross canyons (Baltzer et al., 1994), in water depths of 536 to 761 m, push cores and cone penetrometer showed a 30 cm thick surface fine silty sand that was thicker in small channels. Sidescan backscatter and deep-towed subbottom profiler suggest that this sediment type is widespread in the canyon heads here. Whether any outcrops are present in the steep headwalls is uncertain.

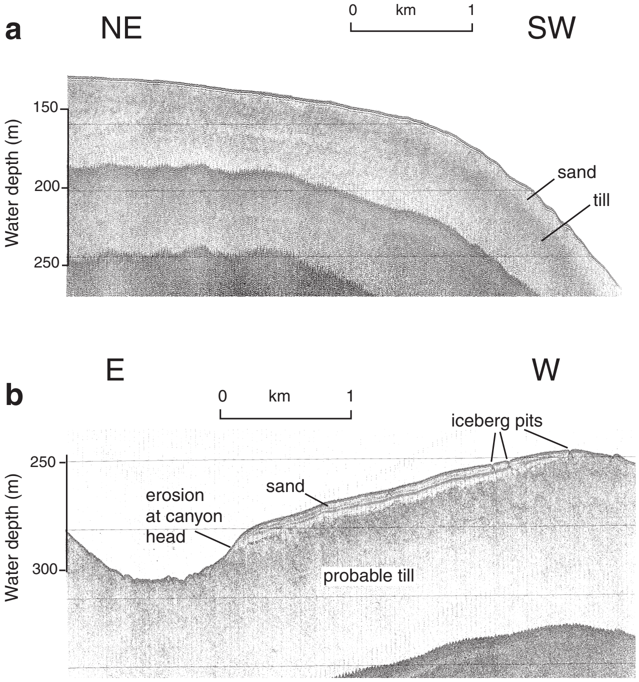

*Figure 5. Huntec profiles showing surficial sand near canyon heads. **a**) Sands on the flanks of the head of Dawson Canyon; **b**) sands on the flank of an unnamed canyon near Logan Canyon showing erosion on the floor of the canyon head.*

CANYONED SLOPES

Side walls of canyons

The side walls of canyons have a ridge-and-gully topography originally illustrated by Piper et al. (1985) from SeaMARC sidescan sonar, but now more clearly revealed by multibeam bathymetry (Pickrill et al., 2001) and illustrated in Figure 7a from The Gully. The seabed character of such topography is best known in the inner part of The Gully, where submersible observations (Amos, 1989) show subvertical rock faces of partly lithified mudstone and shale alternating with flatter areas on which recent sediment has accumulated. Similar inferences can be made from Campod bottom photographs (G. Fader, pers. comm., 2002) and detailed bathymetric records obtained during dredging of fresh blocks of mudstone (D.J.W. Piper, unpub. cruise rept., HU 88-010, 1988).

Ridge-and-gully topography has also been investigated from submersible dives on the Laurentian Fan. *Pisces* dives 1640 to 1643 are reported in detail by Hughes Clarke et al. (1989). Continuous video and hand-held photographs were

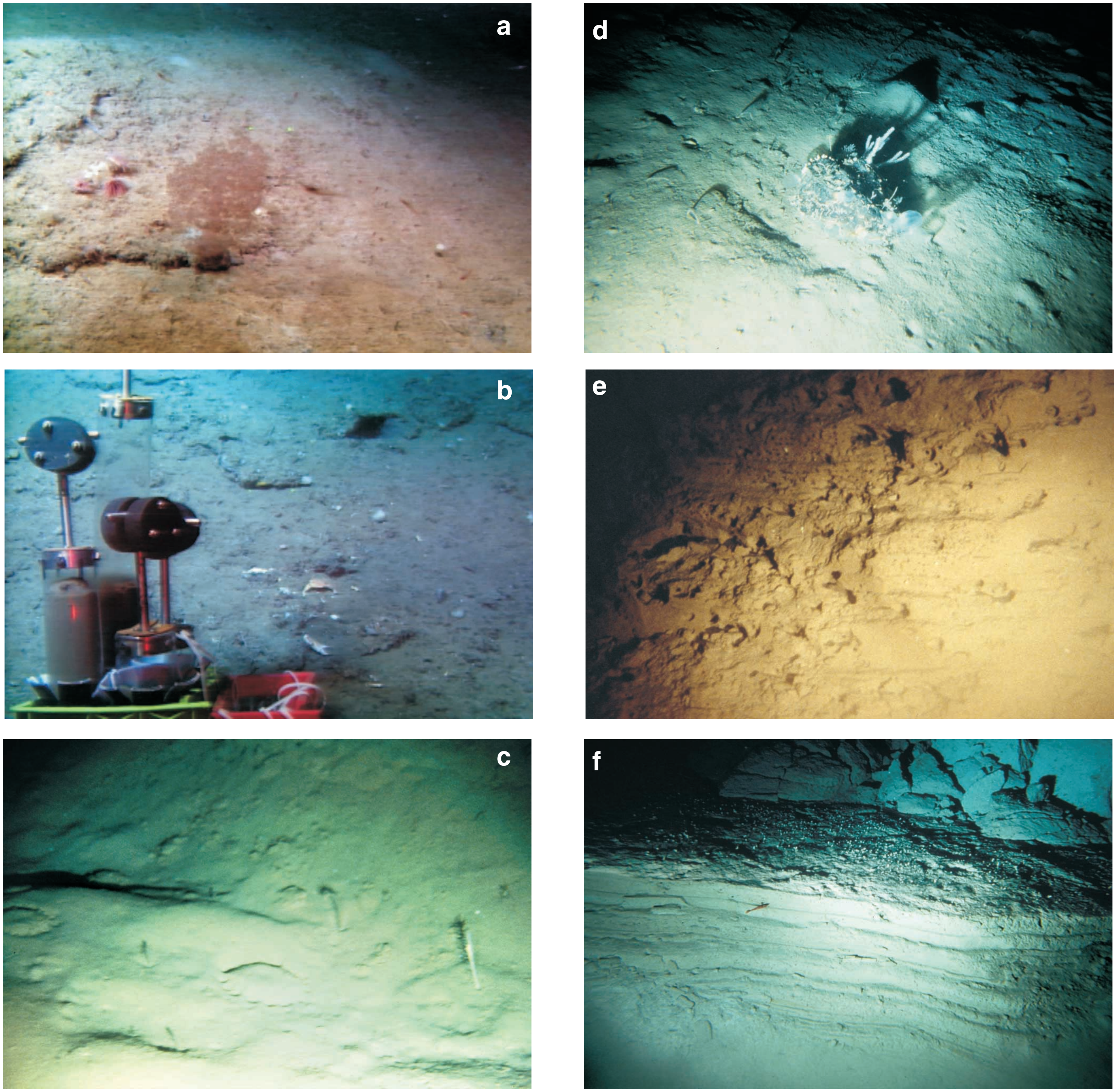

Figure 6. *Photographs of canyon walls from ROPOS (a, b) and DSV Alvin (c–h).* ***a****) Dive R647, near the head of Dawson Canyon showing bioturbated seabed;* ***b****) dive R644 at the headwall of a small canyon west of Verrill Canyon showing outcropping diamict (possibly till);* ***c****) dive 1719, gully on canyon wall;* ***d****) dive 1719, isolated cobble on gullied canyon wall;* ***e****) and* ***f****) dive 1723, fresh outcrops, terrace, and talus eroded by 1929 turbidity current.*

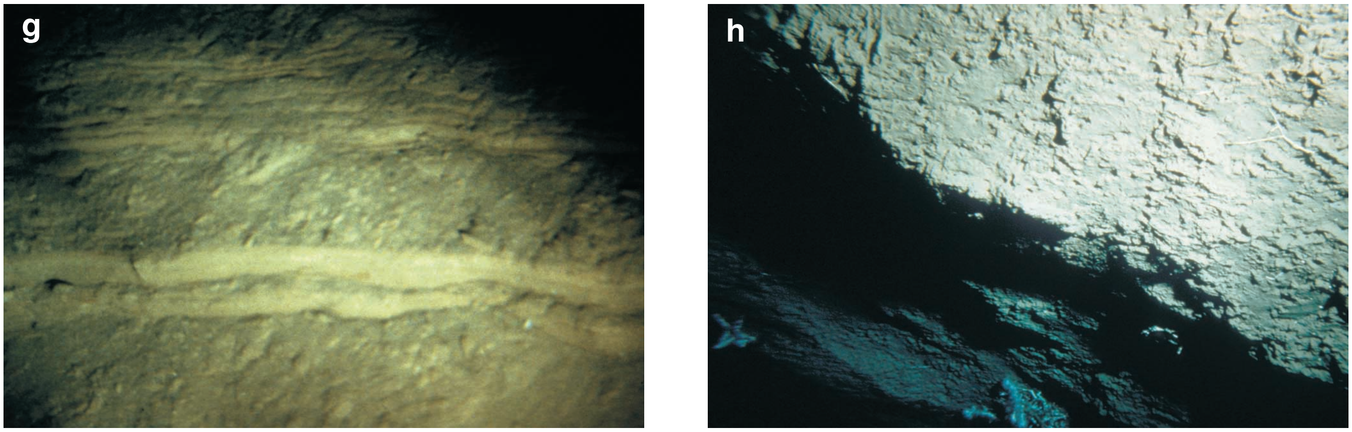

***Figure 6.** **g**) and **h**) dive 1723, bioturbated outcrop in ridge-and-gully topography on canyon wall.*

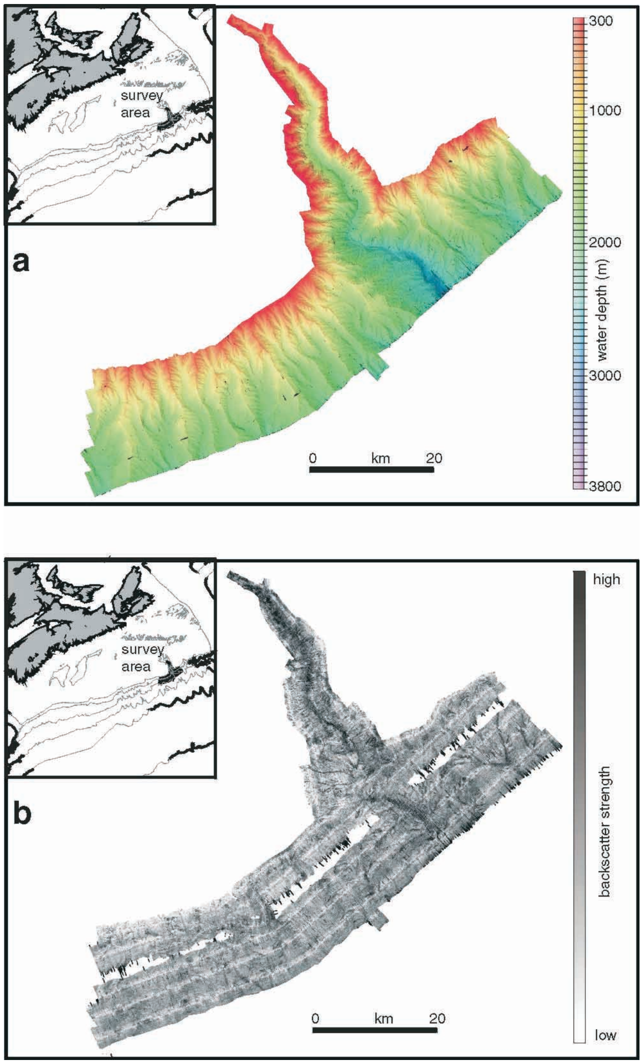

***Figure 7.** **a**) Multibeam image of the outer part of The Gully canyon, showing the multibeam character of ridge-and-gully terrain. **b**) Backscatter image of part of the same area, showing higher backscatter on canyon floors.*

obtained on all dives. Most dives are located on deep-water sidescan imagery. Dive 1641 started at 1250 m in the head of the Eastern Valley of the Laurentian Fan. It then climbed a steep valley wall between 1000 and 860 mbsl consisting of a series of ridges with outcropping scarps 1 to 5 m high and into an area of ridge-and-gully topography up to 700 mbsl, where scarps 1 to 7 m high in mudstone alternated with flatter terraces generally covered with mud, but with sand and gravel where unconsolidated coarse beds were eroding out. The dive then crossed smooth upper slope and investigated fresh headscarps that failed during the 1929 'Grand Banks' earthquake (Piper et al., 1999). Dive 1642 crossed the floor of St. Pierre Valley, a slope valley, at 1620 mbsl, went up the steep valley wall with gullies and spurs and abundant outcrop, and then crossed a series of muddy ridges and depressions resulting from failure or creep in 1929, at about 1200 mbsl. Dive 1643 crossed a major rotational slump at 1600 mbsl, and investigated the erosion of rotated blocks, the character of a gully, and the nature of the headscarp.

The floor of Eastern Valley is unique on the southeast Canadian margin because of vigorous erosion and gravel supply in late glacial times, which created fields of gravel waves on the floor, and the passage of the 1929 'Grand Banks' turbidity current, which eroded the lower valley walls and reworked a lot of late glacial sand. *Alvin* dives 1720 to 1725 were all on the valley floor in 2500 to 4000 mbsl and are located on Seabeam multibeam bathymetry (Shor et al., 1990). Continuous video and hand-held camera shots were obtained during the dives. Dive 1719, in the tributary Central Valley, ran from the valley floor (about 2950 mbsl) up a freshly eroded terraced valley side to older ridge-and-gully topography and then to a flat crest on top of the ridge (about 2750 mbsl), with a mean gradient of 12°. The eroded valley side had continuous scarps of mudstone decimetres to metres in height, with intervening terraces covered with bioturbated mud. Fresh talus blocks were seen below some scarps, but sand or gravel were absent. The ridge-and-gully topography had fewer, less continuous outcrops, generally highly bioturbated surficial sediments (Fig. 6c), and rare, highly bioturbated talus blocks. At least one outcrop consisted of pebbly mudstone; scattered pebbles and shell hash were seen near some outcrops and rare cobbles (perhaps relic ice-rafted detritus) were seen (Fig. 6d).

Dive 1721 also started on the valley floor at about 3000 mbsl, crossed some freshly eroded higher areas, and ended on older ridge-and-gully topography at 2800 mbsl. In the freshly eroded area, presumably a result of the 1929 turbidity current, scarps 3 to 4 m high in grey mudstone appeared to be actively retreating by local failure and shedding blocky talus. The ridge-and-gully topography had only rare outcrop, generally of mudstone, but locally sorted sand and gravel were seen on the seafloor, probably derived from weathering of an outcrop. Locally, a terraced morphology was developed, with low scarps at the top of each step and a few highly bioturbated talus blocks.

Dive 1723 started on a valley floor at about 4000 mbsl, rose to 3770 mbsl up a series of freshly eroded scarps and intervening talus slopes (Fig. 6e, f) with a mean gradient of 18°, and then onto a more bioturbated valley slope of about 13° with about 3% weathered outcrop and some ridge-and-gully topography. On this upper slope, some outcrops were steep and relatively fresh, with some bioturbation (Fig. 6g, h), and some had sand and gravel weathering out. Hackly weathered outcrop in which bedding planes could be picked out only as mesotopographic features were common. The dive terminated at about 3300 mbsl. This dive experienced some strong currents and noted moating around blocks on the lower valley wall. On the upper bioturbated valley slope, current-winnowed cobbles were common. Observations on the upper part this dive, with scattered outcrops unaffected by the 1929 turbidity current, are probably a good analogue for some of the steeper canyon walls at over 1000 mbsl on the eastern Scotian Slope. The observations on St. Pierre Valley walls, with a 15° slope at 1600 to 1200 mbsl, are probably also quite relevant, although the degree of erosion and steepening that occurred in 1929 on these valley walls is uncertain. Observations of ridge-and-gully terrain on *Pisces* dive 1641 and *Alvin* dives 1719 and 1721 are probably also relevant to the less steep canyon walls and ridges on the Scotian Slope. In many of these areas, irregular patches of gravel are seen at the seabed, apparently eroded out of underlying strata that are blanketed by Holocene sediment and a bioturbated 'soil'. Local dropstone boulders are also seen.

Canyon floors

Cores from canyon floors suggest that in water depths greater than 1000 m, the floors consist of mud. At the foot of steep canyon walls, local winnowing and scour may produce sandy sediments, as was observed locally on *Alvin* dive 1723 at about 4000 mbsl in the Eastern Valley of the Laurentian Fan. In shallower water, few data are available. Multibeam backscatter near The Gully (Fig. 7b) shows higher backscatter in some canyon floors to about 1000 mbsl. Observations in canyon and gully heads such at Albatross and *Pisces* dive 1053, discussed above, show that silty sand is present in the upper parts of canyons. Samples at the head of Dawson Canyon recovered surface sand at 650 mbsl. We therefore tentatively show silty sand on canyon floors to water depths of about 1000 mbsl.

Ridge crests

Core samples from ridge crests between canyons commonly show a surface layer of winnowed fine sand. This is seen most spectacularly in cores from the Tantallon M-41 wellsite at 1500 mbsl, where trigger-weight cores have 5 to 20 cm of fine sand overlying muds (Piper, 2001, Fig. 8.6). In other areas, cores at this water depth recovered surface muds, but in water depths of less than 800 mbsl, surface sand is ubiquitous in ridge-crest cores.

SMOOTHER SLOPES AND CONTINENTAL RISE

General seabed conditions

Over most of the continental slope in water depths greater than 1000 m and in many shallower water areas, the seabed consists of bioturbated mud with a sand content of less than 5%. On the basis of core studies and bottom photographs, such mud occurs not only on well stratified seabed, but also on channel floors, on channel walls, and on debris-flow deposits. On the continental rise below about 3000 mbsl, seafloor sediment consists principally of muddy foraminiferal ooze (Berry and Piper, 1993)

Winnowing on low topographic features

The exception to this widespread distribution of mud at the seabed in deep water is found on the top of some positive topographic features. The presence of winnowed sand on intercanyon ridges has been noted above. Winnowed sand or sandy mud has been found in several detailed studies of much smaller topographic features, where a 13 to 14 ka marker horizon of distinctive brick-red sediment occurs at less than 0.5 m subbottom, compared to more normal subbottom depths of 1 to 3 m (Piper and Skene, 1998). For example, on the crest of a hill that rises 40 m above the regional seafloor at 2414 mbsl on the upper continental rise, a box core showed surface sandy mud with 39% >63µm (<4 ϕ) (Fig. 8) and the 13 to 14 ka marker at 20 cm depth. The crest of a low mud diapir at 820 mbsl showed high backscatter in high-frequency sidescan sonar, and cores and geotechnical probes revealed a surface layer of fine sand, whereas the flanks of the diapir have surface mud (Fig. 9).

We carried out a detailed study of this effect across a shallow channel at 1050 mbsl (Fig. 10) on the west Scotian Slope, taking box cores on the channel floor (core 1), on a low rise west of the channel (core 4), and on a 30 m high ridge east of the channel (core 3). A Stacor (core 2) was taken at the same site as core 1 to provide a longer stratigraphy. Brick-red mud units b and d of Piper and Skene (1998), dated at 13 and 14 ka, are found in cores 2 and 3 and thus provide a chronological context for the study. Surface sediment in core 3 is muddy fine sand (41% <4 ϕ: Fig. 8) a few centimetres thick overlying grey silty mud and brick-red mud unit b at 12 cm. The thin muddy sand thus appears to represent the entire Holocene section. In cores 4 and 1, a 3 cm thick sandy mud (25% <4 ϕ) unit also occurs at the top of the core, overlying silty mud with rare sand. Adjacent core 2 shows that the brick-red mud unit b occurs at 35 cm depth. This transect thus shows that Holocene winnowing takes place preferentially on low ridges, but that at 1050 mbsl sandy mud is quite common at the seafloor.

CONCLUSIONS

A variety of datasets have been combined to produce the first map of the Scotian Slope showing the character of the top 5 cm of seabed sediment. Glacial till outcrops on the upper slope, overlain by fine sand on the outer eastern Scotian Shelf. Muddy fine sand is found in the floors of canyons on the middle slope and on intercanyon ridges and other isolated highs. Canyon walls have sparse outcrops of mudstone. The remainder of the seabed is covered by clay and silt.

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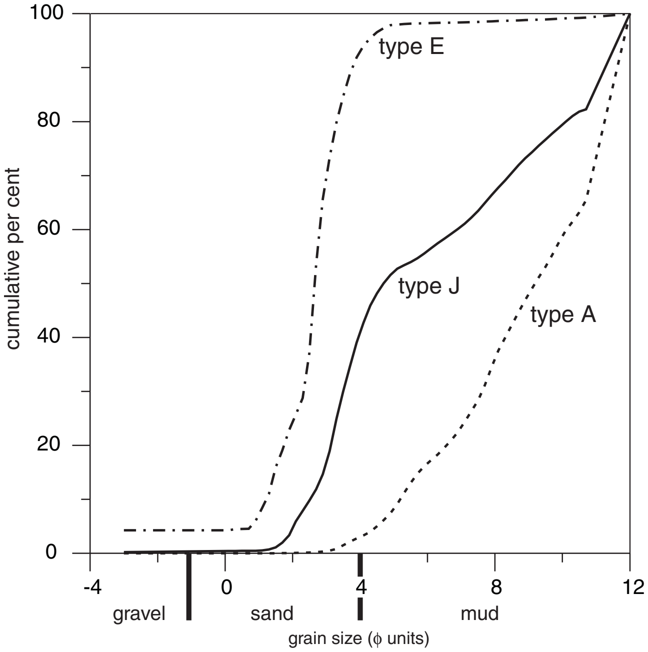

Figure 8. Grain-size analyses of selected seabed samples of sand and muddy sand. type A = mud; type E = fine sand; type J = muddy fine sand

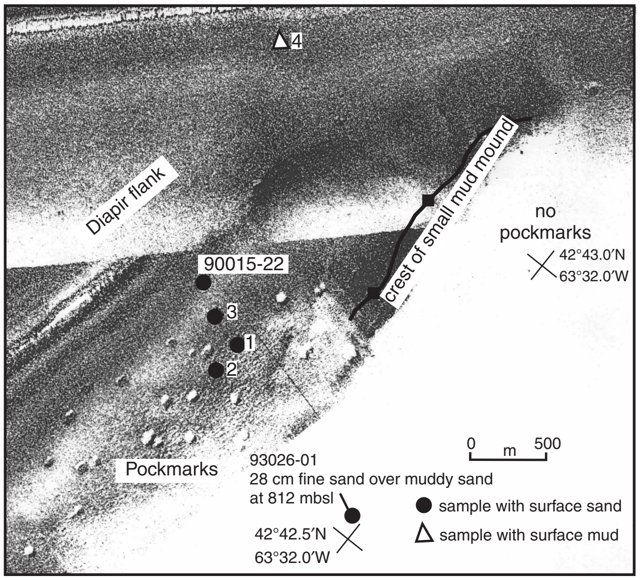

Figure 9. SAR high-resolution sidescan image of mud diapir on the western Scotian Slope showing distribution of surface samples. Numbers refer to cores.

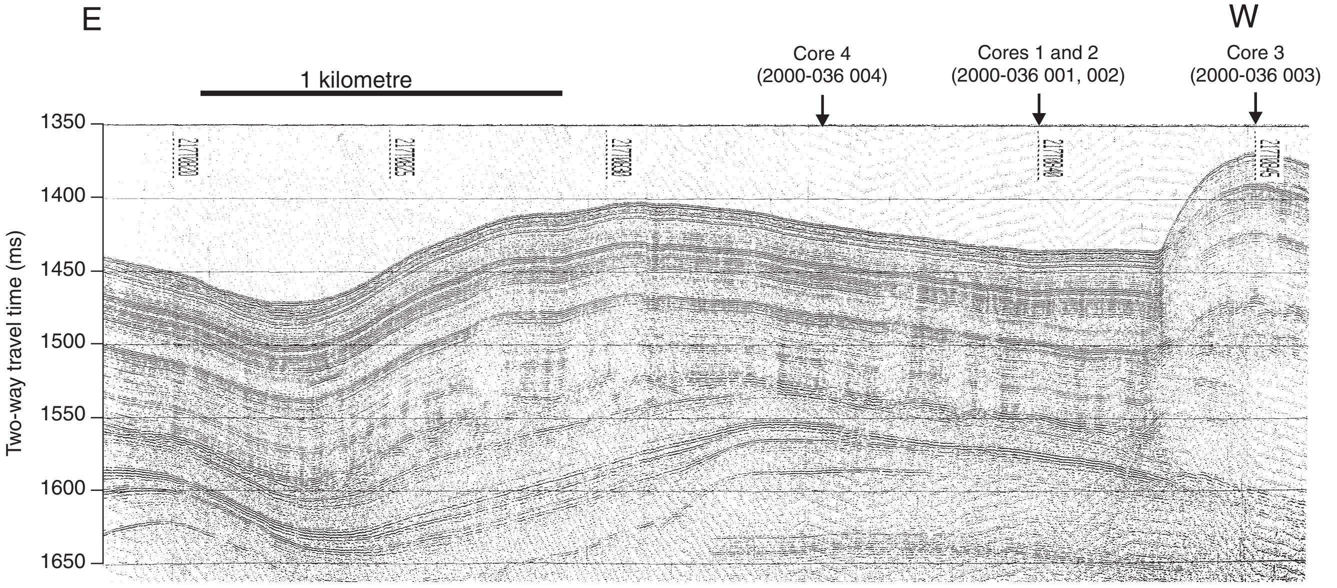

Figure 10. Huntec profile through local high and valley on the middle Scotian Slope, showing Holocene core sections.

Chevron-Texaco Canada Ltd., who funded the acquisition of the commercial-confidential multibeam data reported by Pickrill et al. (2001) and facilitated the add-on program of publicly accessible multibeam surveys in The Gully, funded by the Geological Survey of Canada, the Department of Fisheries and Oceans, and Sable Offshore Energy Inc. Multibeam bathymetry surveys of the western Scotian Slope were carried out in collaboration with Clearwater Fine Foods Inc. *ROPOS* surveys were funded principally by NSERC, with contributions from the Geological Survey of Canada. Andrey Kostylev carried out the study of cores reported in Figure 10. We thank Jim Collins, Vladimir Kostylev, and Paul Hill for useful discussions.

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