Late Quaternary slumps and debris flows on the Scotian Slope

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ABSTRACT

The Scotian Slope just west of Verrill Canyon was surveyed using the Sea MARC I deep-towed sidescan-sonar system, high-resolution seismic-reflection profiles, and 25 piston cores.

The generally smooth continental slope has a gradient of ~2.5°. It is crossed by 2 small valleys that are 1 km wide and 100 m deep. Much of the sea bed shows evidence of surficial sliding that removed 10–20 m of sediment, and the slide scars give the sea bed a steplike morphology. From the 600-m isobath to ~1,800 m, there extend 2 zones of disturbed sediment. These disturbed zones have the rough surface and transparent acoustic character previously regarded as characteristic of debris flows, but sidescan-sonar images and cores suggest that they are principally rotational slide deposits, with true debris flows at their distal limits. Streamlined erosional depressions near the downslope edge of the debris flows cut both the flow and sediment farther downslope. These may have been produced by a turbidity current associated with the debris flows. Sorted coarse sand in piston cores provides further evidence of current activity. This widespread sediment failure on relatively low slopes was probably the result of a large earthquake that can be dated from cores as occurring between 5000 and 12000 yr B.P.

INTRODUCTION

Many parts of the continental slope off eastern Canada are covered by Quaternary sediment as much as 1 km thick. A large part of this sediment may have accumulated close to ice margins, and the morphologic variability of this continental slope attests to the variety of erosional and sedimentation processes that have been active. In this study, we describe the surficial sediments and sea-bed morphology of a 50 by 50 km area of the Scotian Slope (Fig. 1), which is shown on small-scale bathymetric maps to have a smooth surface not dissected by canyons. Such smoothness is typical of much of the western part of the Scotian Slope (Hill, 1983), whereas the eastern part of the Scotian Slope is deeply incised by submarine canyons (Stanley and Silverberg, 1969; Stanley and others, 1972).

The purpose of the study was to identify the range of sediment-instability features present in this type area and to determine their age and origin.

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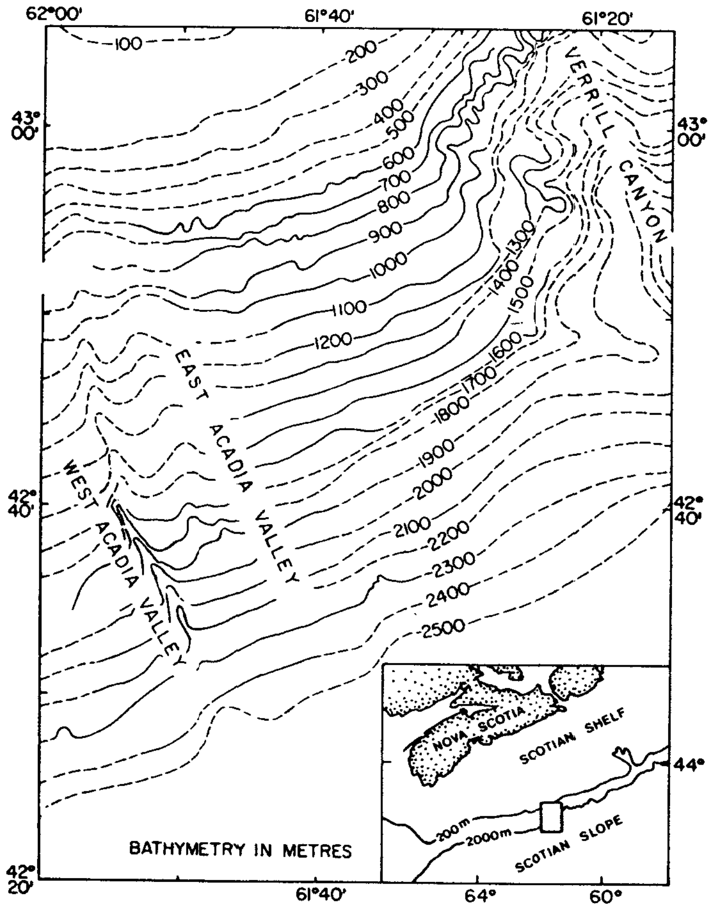

Figure 1. Bathymetry of the study area (v = 1,463 m sec^{-1}) based on 12-kHz and 3.5-kHz profiles in Figure 2 and Sea MARC sonographs. Dashed lines indicate areas without sidescan control. Inset shows general location on the Scotian Slope.

Data

The principal source of data for this study was a Sea MARC I midrange sidescan-sonar survey. Orthorectified, digitally processed images were obtained of ~1,500 km^2 of sea bed from water depths of 500 to 2,500 m and compiled in a mosaic (Piper and others, 1983). The Sea MARC I System also acquired 250 line km of sub-bottom profiles from

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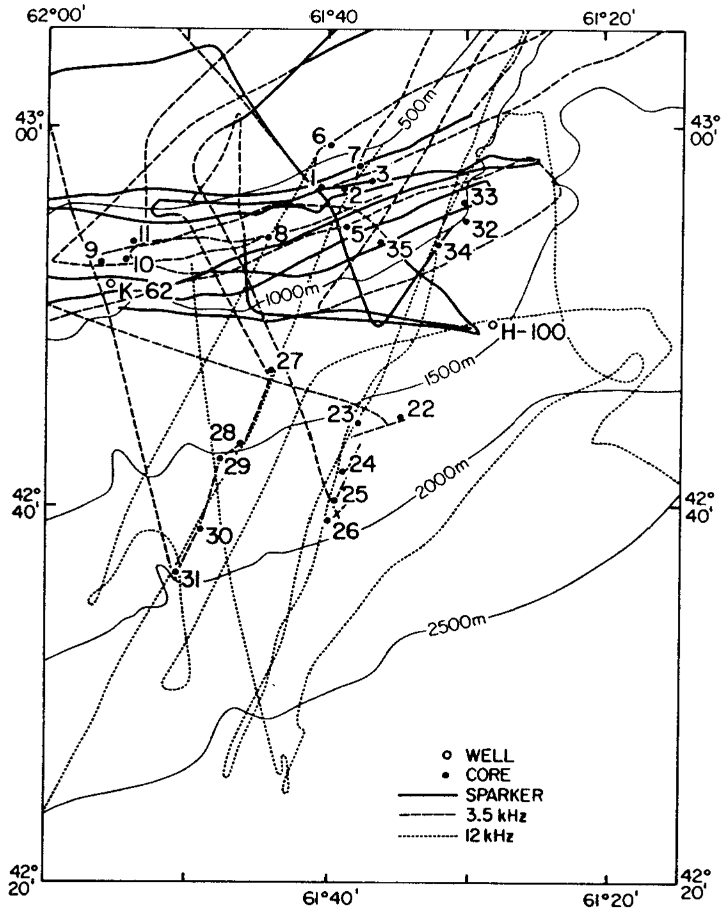

Figure 2. Map showing data available within the study area. Sea MARC fish track is shown in Figure 4.

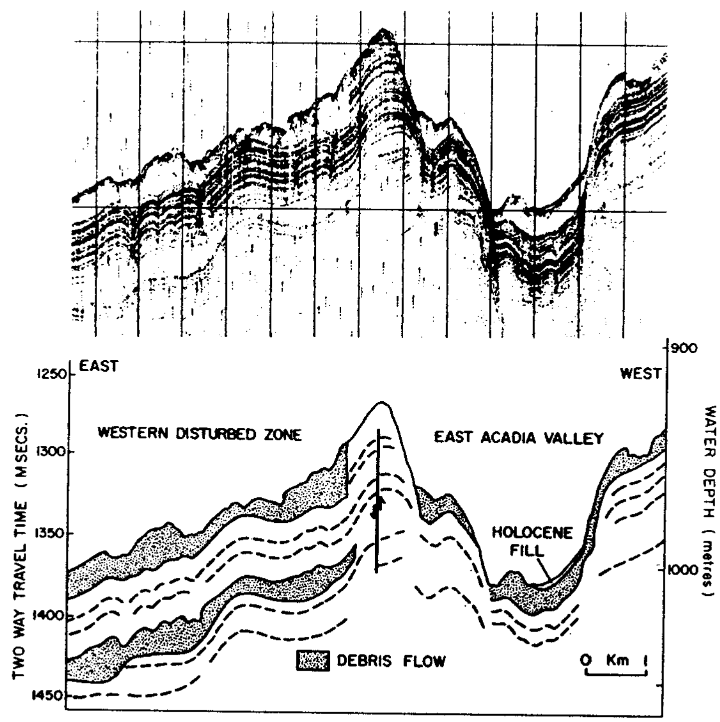

Figure 3. V-fin sparker profile of part of the western disturbed zone and East Acadia Valley, showing the generally draped sediment configuration and the distribution of surface and subsurface disturbed-sediment zones.

a 4.5-kHz transducer mounted on the neutrally buoyant vehicle, towed approximately 300 m off the sea-floor. Details of the Sea MARC I System are given by Ryan (1982) and Kosalos and Chayes (1983). Ship navigation was by Loran-C and transit satellite; instrument positions were estimated using acoustic ranges from the ship and wire-out measurements.

In water depths to 800 m, the Sea MARC data were supplemented by 250 line km of high-resolution seismic-reflection profiles (Fig. 2), acquired using the Nova Scotia Research Foundation v-fin 250j sparker system towed at ~100 m below the water surface (Bidgood, 1974). Additionally, 600 line km of hull-mounted 3.5-kHz profiles, several hundred kilometres of 12-kHz profiles, and 25 piston cores were obtained.

Terminology

We follow Nardin and others (1979) and Cook and others (1982) in using *slide* as a general term for a shear failure along discrete shear planes and *slump* as a slide in which the mass of material moves as a unit or as several subsidiary units along one or several curved slip surfaces, usually with backward rotation of the mass.

The term *debris-flow deposit* is used for sediment inferred to have flowed as granular solids mixed with water in response to the pull of gravity (Middleton and Hampton, 1976) and *slump deposit* for sediment transported predominantly in a slump. We use *disturbed zone* as a descriptive term for areas of characteristically rough sea bed lacking internal reflectors on acoustic profiles and interpreted to consist of either slump or debris-flow deposits.

Bathymetry

A bathymetric map of the area, based on our surveys, is shown in Figure 1. The shelf break occurs at ~250 m water depth. The upper slope down to ~400 m is relatively smooth, but from 400–800 m it is cut by short gullies typically ~1 km wide and 10–50 m deep. To the east, Verrill Canyon sharply indents the shelf break and deeply incises the continental slope. The western part of the slope is crossed by 2 smaller valleys (East and West Acadia Valleys) ~1 km wide and 100 m deep. Elsewhere, the slope is generally smooth, with a gradient of ~2.5°.

GEOLOGICAL OBSERVATIONS

In general, our high-resolution profiles show little acoustic penetration on the uppermost slope to approximately the 450-m isobath. Between 450 m and 650 m depth, acoustic penetration increases to reveal well-stratified sediments cut by an erosional sea bed with local relief of 1–3 m. East of Verrill Canyon, in water depths of 140 to 200 m, well-stratified sediment as much as 15 msec thick is underlain by material with a uniformly dense reflectivity pattern of incoherent reflections that King (1980) recognized as the acoustic characteristics of till. Both lithologies are cut unconformably by the present sea floor (Piper and Wilson, 1983). The till may extend downslope to the 450-m isobath.

Seismic-reflection profiles show that near-surface sediments on the middle and lower slope are evenly stratified over much of the study

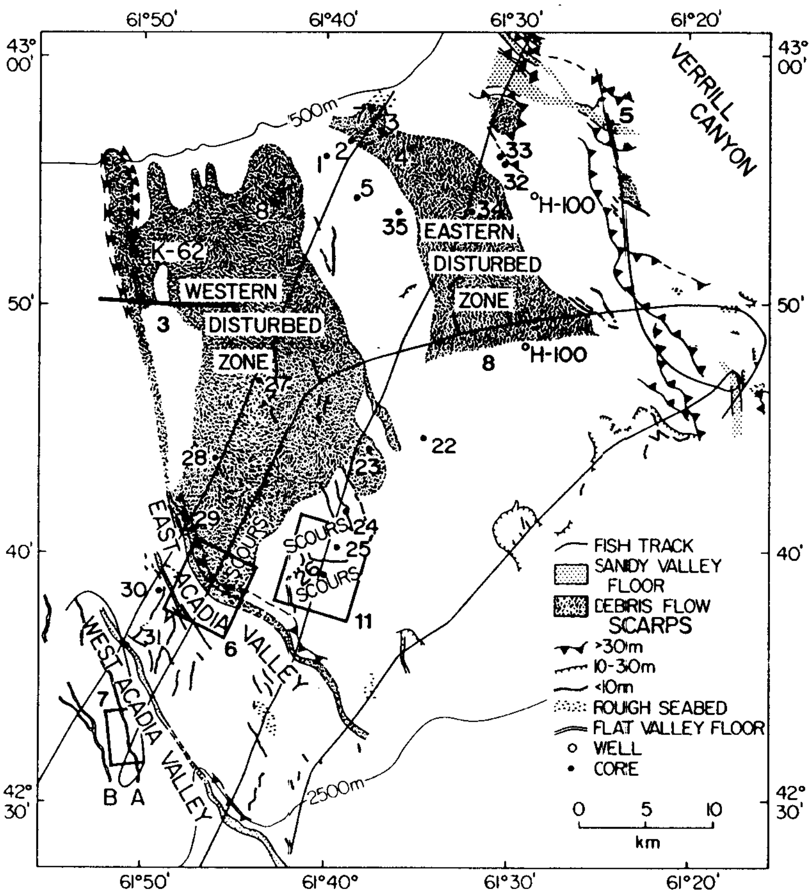

Figure 4. Morphologic map illustrating features seen in Sea MARC sidescan images, Sea MARC fish track, location of cores, and location of more detailed figures.

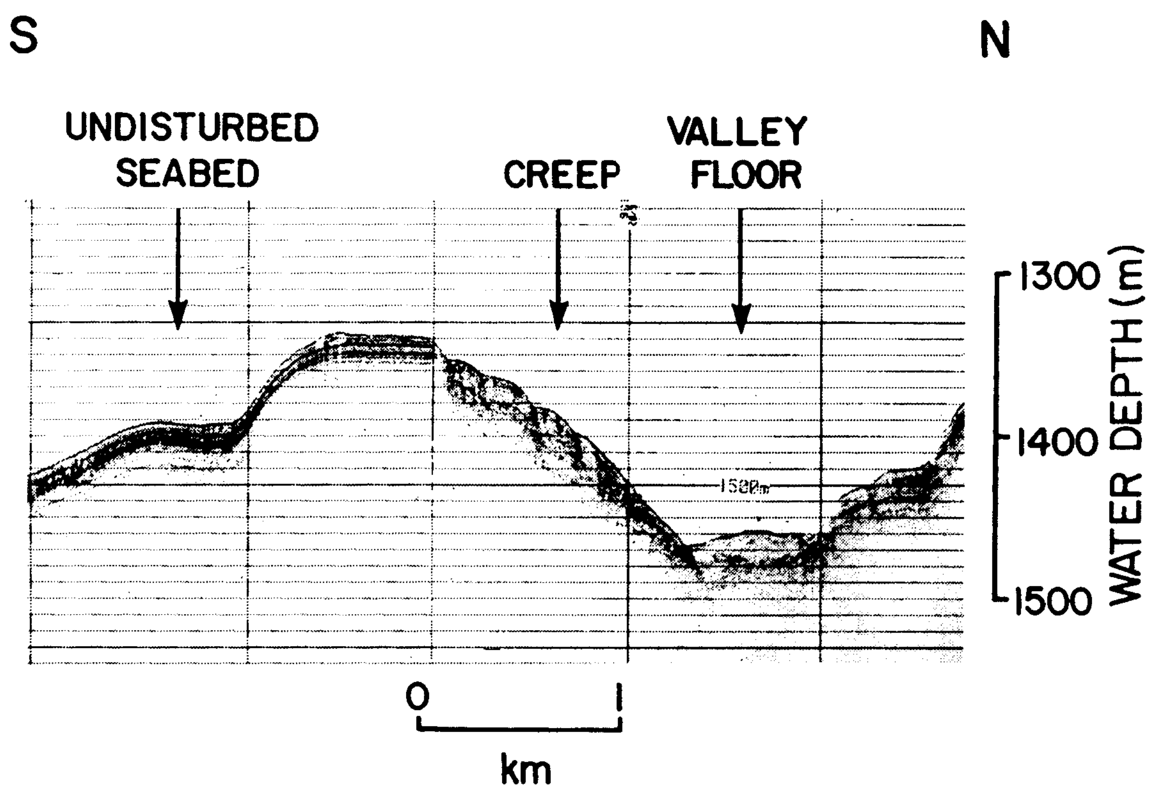

Figure 5. 4.5-kHz sub-bottom profile showing inferred creep deformation on the side of Verrill Canyon.

area. V-fin sparker profiles having as much as 100 msec sub-bottom penetration show that individual reflectors can be correlated throughout the area over distances of tens of kilometres (Fig. 3). Sediment thickness between correlatable reflectors decreases linearly by ~50% from 500 m to 1,300 m water depth.

Valleys

In the head of Verrill Canyon, between water depths of 700 and 950 m, Sea MARC images show a series of flat-floored valleys separated by steep, sharp-crested ridges some 150–300 m high and 0.5–1.5 km wide

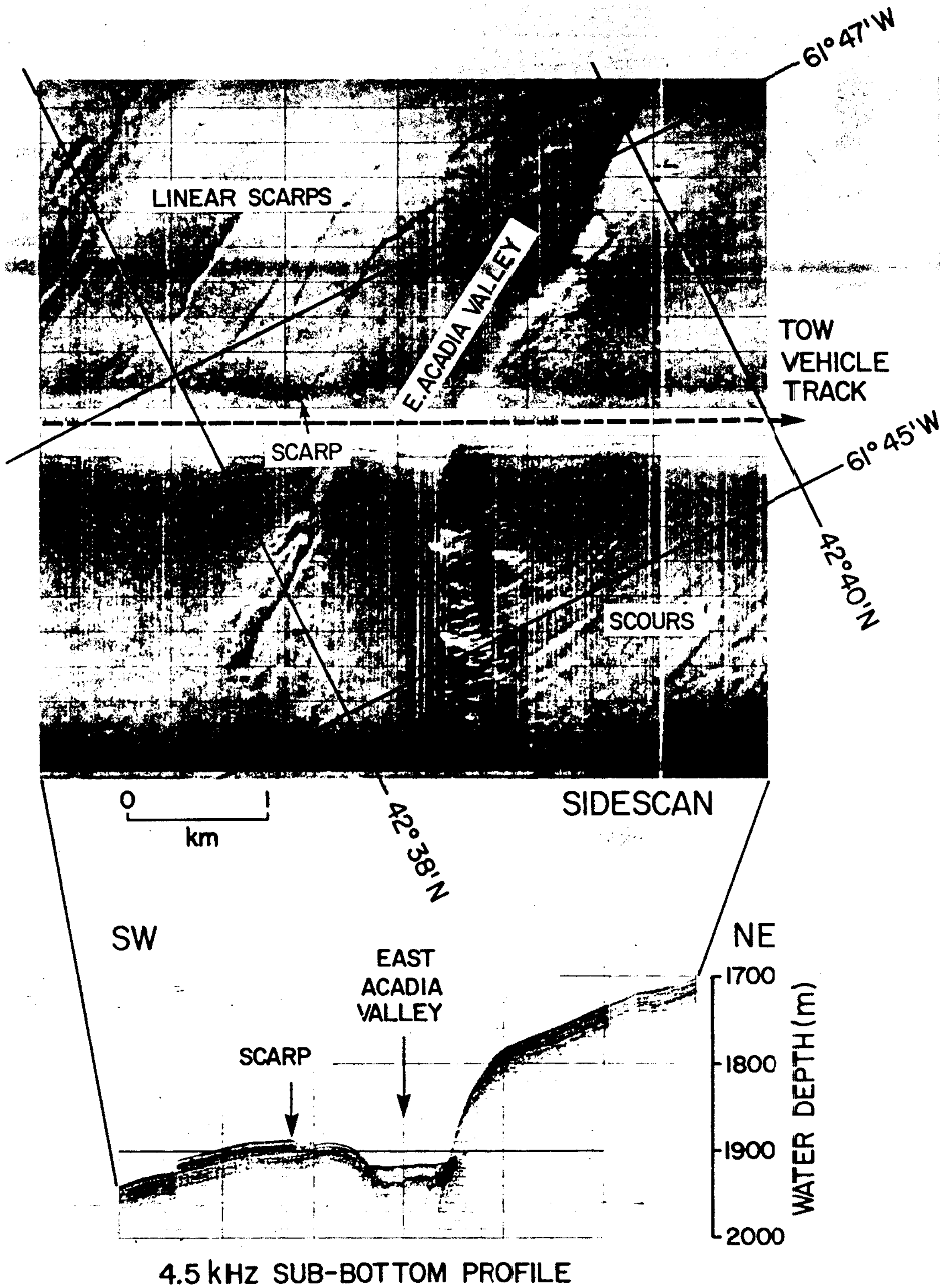

Figure 6. Sidescan image showing East Acadia Valley, linear scarps in area of sediment detachment to the southwest, and elongate scours to the northeast. Corresponding 4.5-kHz sub-bottom profile shows 10–20 m of debris in valley axis and prominent scarps southwest of valley.

(Fig. 4). Sidescan images indicate that the valleys are fed by side gullies as much as 1 km long that extend up to the crest of the ridges. Similar intercanyon ridges have been found both on the Atlantic slopes of Europe (Kenyon and others, 1978; Belderson and Kenyon, 1976) and on the middle-Atlantic slopes of the United States (Farre and others, 1983). In slightly deeper water, stratified sediments on the flanks of Verrill Canyon show shallow folds, similar to those inferred by Hill and others (1983) to result from creep (Fig. 5).

Both West Acadia and East Acadia Valleys have somewhat sinuous courses and asymmetric cross sections over much of their lengths. Their eastern walls are steep and 50–150 m high, whereas they have low levees ~1 km wide with a crest 20–50 m above the valley floor on their western side. The floor of the West Acadia Valley appears highly reflective on sidescan and subbottom records, as if floored with sand. In most crossings of the East Acadia Valley, such as that illustrated in Figure 6, there is ~15-m-thick fill that is acoustically nonstratified and semitransparent.

To the west of the West Acadia Valley, 3, gently sinuous, narrow channels with 1- to 4-m-high levees are mapped (2, identified as A and B, are shown in Fig. 4). These channels are 50–100 m wide and 1–3 m deep (Fig. 7). The sharply defined shadow from the wall seen in sidescan images suggests that the margins are steeper than 15°. The narrow channels parallel the major valleys rather than feeding into them. They consist of straight

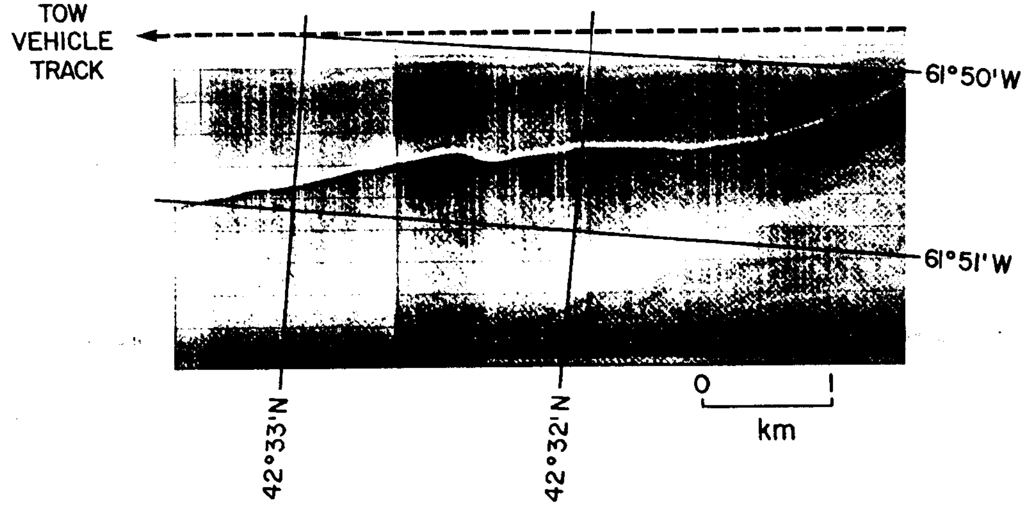

Figure 7. Sidescan image of small channel southwest of West Acadia Valley.

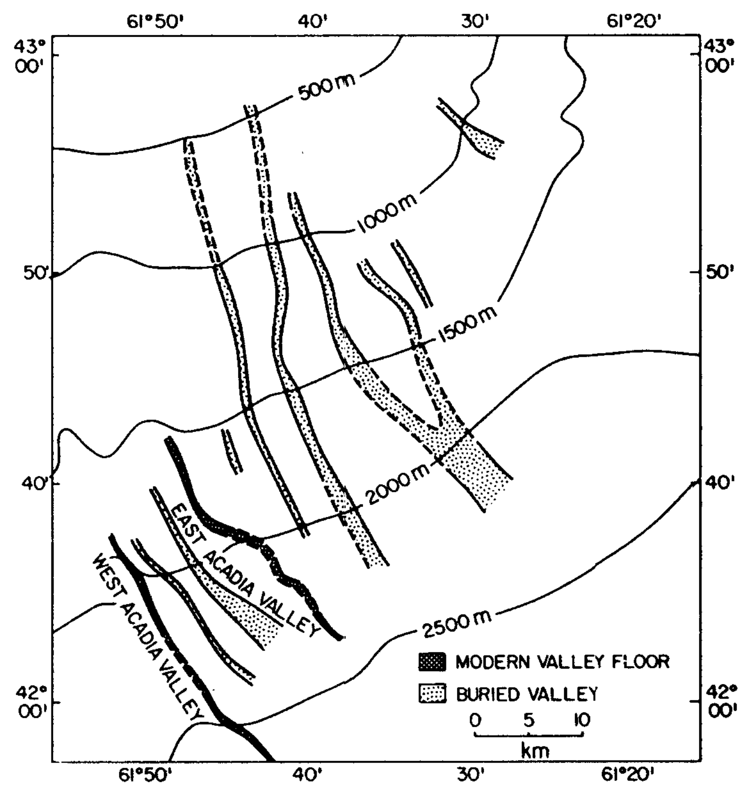

Figure 8. Distribution of buried valleys at 40–70 msec sub-bottom depth.

segments 2 to 3 km long; relatively sharp bends; and broader, more sinuous turns. Their origin is not clear.

Sub-bottom profiles below ~1,000 m water depth show a set of leveed valleys, hundreds of metres wide, buried beneath tens of metres of stratified sediment. They are parallel and spaced ~3 km apart (Fig. 8).

Scarps

Large, arcuate scarps occur in the southeast part of the study area (Fig. 4). Some of these large, arcuate scarps appear localized along the system of buried valleys shown in Figure 8. Another scarp, 50–150 m high, is U-shaped in plan view (4 km wide, 10 km long) and appears to have a small valley leading to its upstream end. It may be a tributary of Verrill Canyon or possibly an elongate retrogressive slide (Prior and Coleman, 1982).

Sea MARC data also show sets of steplike escarpments 3–20 m high in many areas in water depths of 700–2,500 m (Fig. 4). The scarps are generally relatively linear, and most face downslope and are parallel or subparallel to contours. The back-scatter energy of these areas appears nearly constant in sidescan images (Figs. 6, 9). The 4.5-kHz subbottom profiles show a 1- to 2-m-thick uppermost transparent drape over the steps that is not resolvable in journal reproductions.

On average, 10 m of well-stratified sediment has been removed downslope from steplike escarpments in the area studied east of East Acadia Valley, corresponding to a total volume of 3.5×10^9 m^3 of missing stratified sediment (Fig. 10).

Disturbed Zones

Acoustically transparent sediment 5–15 m thick overlies the detachment surfaces in the 2 areas of widespread removal of stratified sediment. The surface of this upper deposit is rough, with hyperbolic reflectors (Figs. 3, 9). The eastern of these disturbed zones, some 5 km wide, is located just west of Verrill Canyon (Fig. 4). It is separated by a 5-km-wide area of undisturbed, stratified sediment from the 15-km-wide western zone, which extends to East Acadia Valley (Fig. 3).

The disturbed zones are thickest (>15 m) on the upper slope near the mouths of steep, upper-slope gullies than open out in ~800 m water depth (Fig. 10). Tongues of sediment extend downslope from these gullies and gradually thin downslope. The disturbed zones infill and mask some shallow valleys and also overlie steplike escarpments similar to those exposed at the sea bed (a in Fig. 9). In places, the margins of the zones are confined by scarps; elsewhere, they gradually thin at their margins. The western disturbed zone appears to have spilled over into the East Acadia Valley (Fig. 5) and thins out downslope at about the 1,800-m isobath. The thickness of disturbed-zone sediment overlying the detachment surface is nearly the same as, but slightly less than, that of the sediment missing from the stratified sequence (Fig. 10).

The surface roughness of the disturbed zone varies with local relief. Over topographic highs where the disturbed zone is thin, the surface often

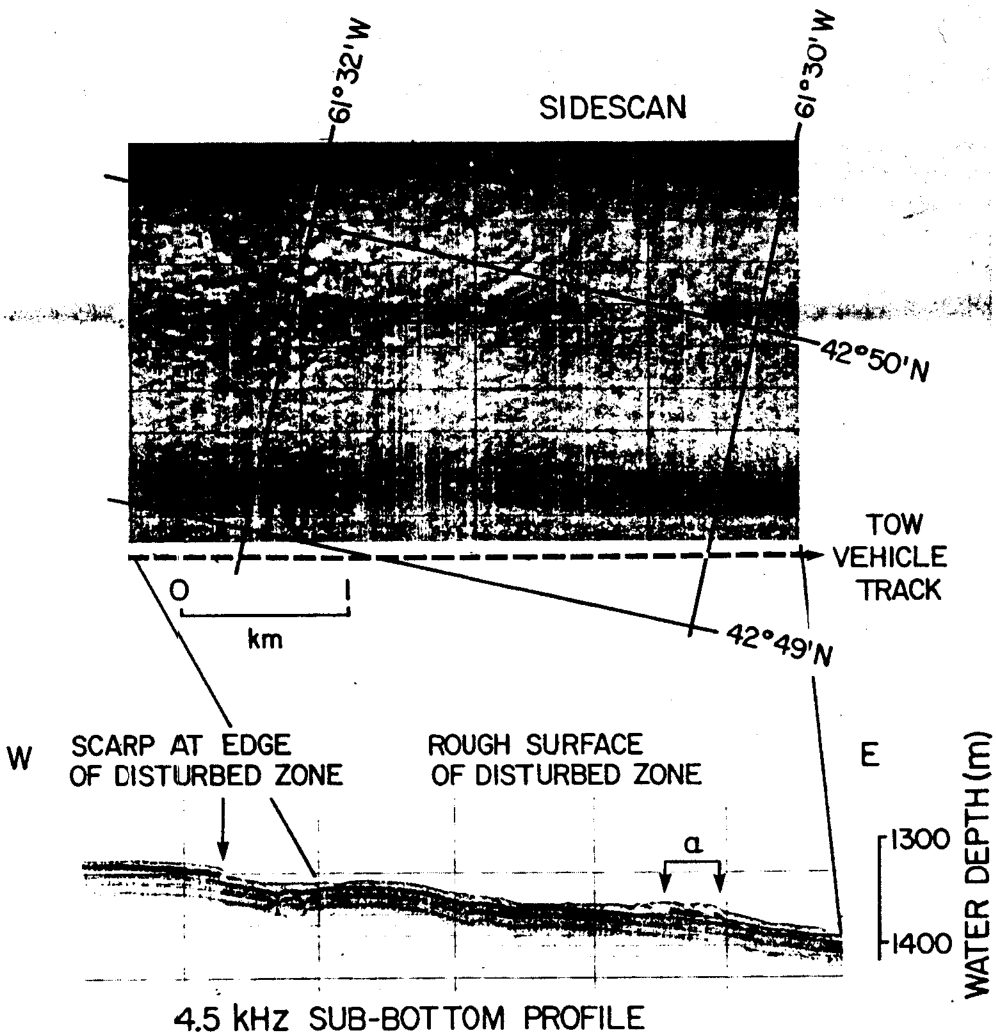

Figure 9. Sidescan image and corresponding 4.5-kHz sub-bottom profile of part of eastern disturbed zone. The sidescan image shows a pattern of subparallel ridges arising from low-relief, hummocky topography. On the sub-bottom profile, hyperbolae generated from the upper surface imply considerable surface roughness. Disturbed sediment varies in thickness from <1 m to 15 m. At "a" in sub-bottom profile, a remnant of acoustically stratified slope strata is surrounded on top and two sides by disturbed sediment.

appears smooth. The most common surface features in water depths of <1,400 m are, however, sets of long, sinuous, subparallel ridges (Fig. 9). Typically, they are 1–2 m high, with a wavelength of 50 m. They generally are parallel to contours; at margins of the disturbed zones, they tend to swing around and become subparallel to the margin of the disturbed zone. They are thus concave downslope, in contrast to the pressure ridges described by Prior and others (1983) that are convex downslope. These ridges appear similar to those visible in aerial photographs of regressive rotational slumps, for example, those in unstable Pleistocene clays of the St. Lawrence Lowland, Canada (LaRochelle and others, 1970). The sediment cut by and underlying the disturbed zones has a well-stratified draped configuration, maintaining almost constant thickness over topographic highs and lows (Fig. 3). The gently undulating character of these reflectors appears to be inherited from the surface of a buried disturbed zone at 50 msec subbottom (Fig. 3) or from an even deeper horizon.

The sea floor immediately downslope from the western disturbed zone is marked by groups of closed, downslope-trending, streamlined erosional depressions (Fig. 11). Their plan-view size and shape vary considerably, but everywhere they have flat floors and are only a few metres deep. The largest ones are >2 km long and 700 m wide, and the smallest identifiable are <10 m wide. Length to width ratios range from 20 to <2, with 4 being most common. Their margins at the upslope and downslope ends are generally pointed, but some show subrounded to complexly indented patterns. Several of the streamlined depressions display two erosional levels in their floor, with one closed depression within another. The thin downslope edge of the western disturbed zone appears to have been cut by the depressions.

CORE CONTROL

Lithostratigraphy

A local stratigraphic sequence was established in cores from undisturbed sea bed (Fig. 12). Cores were taken from the foot of erosional steps where the absence of surficial sediment allows a composite stratigraphic sequence to be extended to a subbottom depth of 25 m, and 7 lithostratigraphic units were distinguished. Unit 1 at the surface is composed of olive-gray, bioturbated, silty mud that varies between 0.5 and 2 m in thickness (Fig. 13) and appears to fill topographic depressions. Unit 1 overlies resedimented, muddy sands and gravelly, sandy muds (unit 2) that are similar to those described by Hill (1984, 1985) from 100 km to the west. Below this, unit 3 is principally bioturbated, hemipelagic, sandy mud, including ice-rafted debris. Bioturbated and laminated gray muds are found in unit 4, over a still deeper sequence of predominantly brown sediments (units 5–7).

Most cores from the disturbed zones (Fig. 13) or from areas of

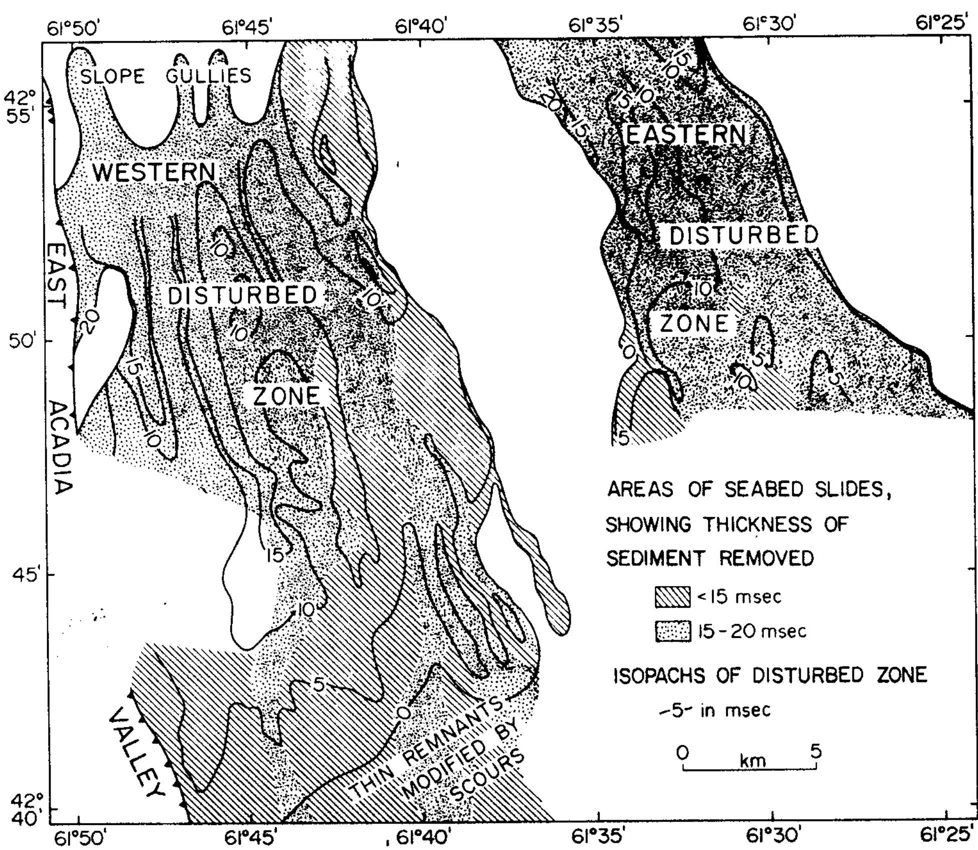

Figure 10. Isopach map of disturbed sediment, in milliseconds. The original sub-bottom depth of undisturbed strata beneath the disturbed zone is also shown.

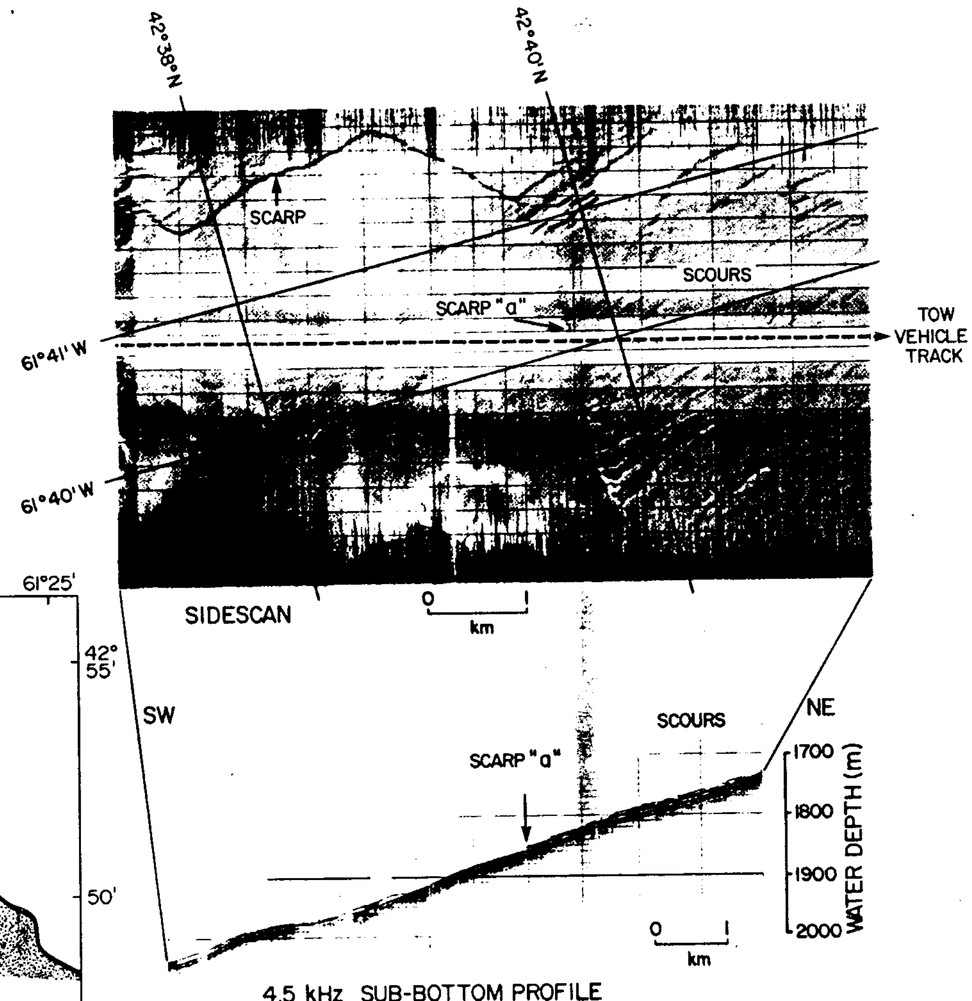

Figure 11. Sidescan image and corresponding 4.5-kHz sub-bottom profile showing streamlined erosional depressions interpreted to be scours, downslope from western disturbed zone. Note that depressions are truncated at the headwall (scarp "a") of a large bedding-plane slide.

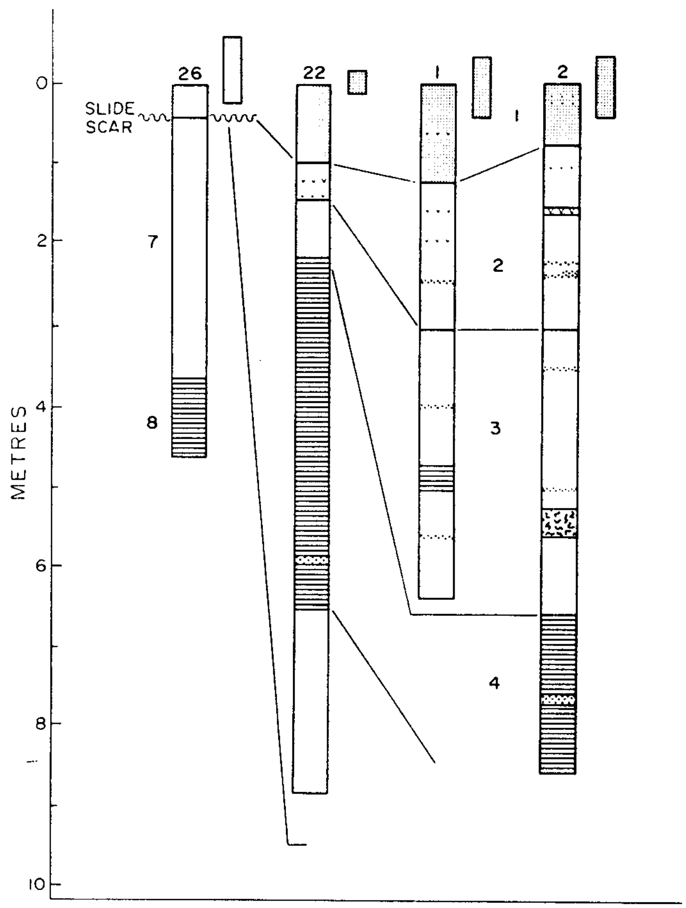

Figure 12. Schematic lithostratigraphy of selected piston cores in undisturbed sediment. For location, see Figure 4. Key to symbols in Figure 13. Numbers 1–8 indicate lithostratigraphic units. Cores 2, 1, and 22 are undisturbed autochthonous sediment and show downslope thinning of stratigraphic units. Core 26 is from a slide scar and contains sediment originally ~20 m sub-bottom.

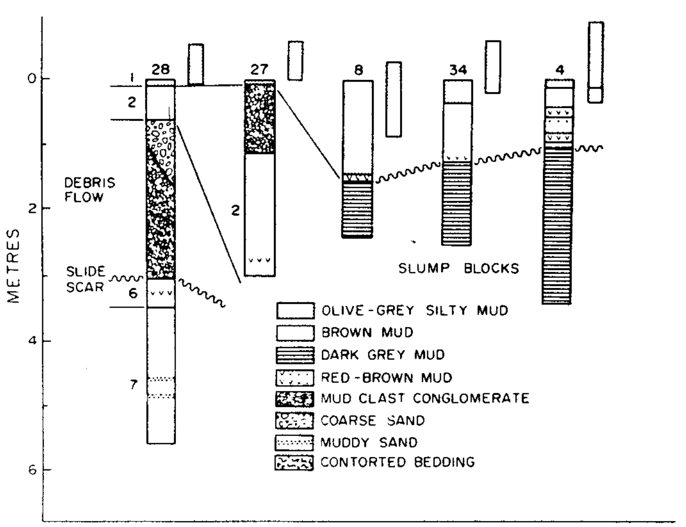

Figure 13. Schematic lithostratigraphy of cores from disturbed-sediment zones, showing proximal (core 4) to distal (core 28) changes in the character of allochthonous sediment.

steplike eroded sea bed (for example, in core 26 in Fig. 12) contain sediments of units 1 and 2 that rest disconformably on more highly consolidated material. All cores from the main disturbed zones in <1,000 m water depth either penetrated only units 1 and 2 or collected only short samples of subhorizontally bedded, stiff, gray muds (some with silty laminae) similar to unit 4. In core 27, from the central part of the western disturbed zone (Fig. 4), a thin (<1 m) debris-flow deposit of highly deformed clay clasts is found within unit 2, overlying the acoustically distinct main disturbed zone. Core 28, from near the southern edge of the western disturbed zone (Fig. 4), contains a gravelly, sandy mud with mud clasts, interpreted as the distal part of a true debris flow, overlain by a few tens of centimetres of sorted, coarse sand (Fig. 13). The mud with clasts is interpreted as a debris-flow deposit; the coarse sand was the only sorted sand bed more than a few centimetres thick that was recovered in any of the 25 cores.

Age of the Sediments

In core 1 (Fig. 14), the change from unit 1 to unit 2 is marked by an increase in cold-water fauna, including sinistral *Neogloboquadrina pachyderma* and *Elphidium excavatum* f. *clavata*. Farther west, at longitude 63°15′W, Hill (1981) found a similar faunal change in slope sediments for which 3 ^{14}C dates suggest an age between 5,000 and 8,500 yr. At ~5 m depth in core 1, in unit 3, a transported mollusk shell gave a ^{14}C age of 12,000 yr.

DISCUSSION

General Evolution of the Study Area

A well-stratified, 0.7 km-thick prograding sequence of sediments accumulated on the continental slope throughout the Quaternary, except in the vicinity of Verrill Canyon, where sediment is thinner and there is a complex history of cut-and-fill events (D.J.W. Piper, unpub. data). We have detailed information only about the upper 100 m of this prograding

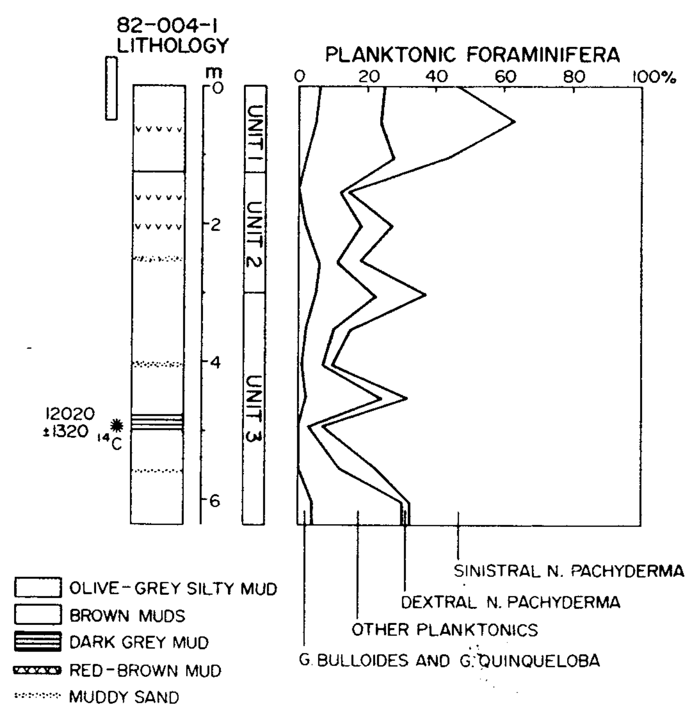

Figure 14. Lithology and planktonic foraminifera of core 1.

sequence. At ~40 m sub-bottom on the upper slope, there is an irregular surface that appears to be the top of an older disturbed-sediment zone (Fig. 3). At a similar stratigraphic level on the mid-slope, there is a series of gullies (Fig. 8). Later sediments appear evenly draped over this surface, and its morphology carries through to the sea bed. Only East and West Acadia Valleys have maintained themselves over time as distinct valleys, having erosional valley walls and levees. The draped morphology of the slope probably reflects rapid sedimentation from an ice-margin plume (Swift, 1985).

The northeastern part of Verrill Cañyon that was examined in detail shows sharp, crested ridges dissected by side gullies that are believed to indicate long-term headward erosion through a variety of mass-wasting processes (Farre and others, 1983).

Origin of the Steplike Topography and Disturbed Zones

The steplike escarpments are scarps from which bedding-plane slides have detached. The disturbed zones and the semitransparent fill of East Acadia Valley represent some of the detached material, and more may be located in ~3,000 m water depth on the lower slope and upper rise (Swift, 1985).

The proximal parts of the disturbed zones are interpreted as complex rotational slumps (Fig. 15). Their acoustic characteristics are identical to those of debris flows described by previous workers (for example, Embley, 1976, 1982). Cores, however, recovered tilted but continuous sequences of stiff mud, overlain by thin, muddy sand beds. Our acoustic data show no internal structure in the disturbed zone, suggesting that the tilted blocks are small or have dips of >15°. Tilted blocks less than 50 m in breadth would give so much scattering as to appear acoustically transparent in most high-resolution seismic profiles. Surface ridges (Fig. 9), concave downslope, are similar to those seen in retrogressive rotational slumps on land. No large slump scars have been recognized on the upper slope that might be sources of the sediment in the disturbed-sediment zones. The volume of the acoustically transparent disturbed-zone sediment is similar to the volume of stratified sediments inferred to have been removed in the same areas.

We conclude from these observations that most of the acoustically transparent sediment was derived locally from the stratified sequence by sediment failure without significant downslope transport. Farther downslope, there is a thinner surface deposit of debris-flow and turbidite sediment that we argue is associated with this failure.

The distal part of the disturbed zone lacks surface ridges and shows slight stratification in some acoustic profiles. Cores recovered conglomerates of highly deformed, small, muddy blocks. These have the characteristics of debris flows.

The acoustically semitransparent fill of East Acadia Valley downslope from the limit of the western disturbed zone is also interpreted as a debris-flow deposit, possibly a downslope extension of the western disturbed zone. The situation is similar (although on a smaller scale) to that on the middle Mississippi fan where the main channel is filled by units interpreted as channelized debris flows (Kastens and Shor, 1985). It seems likely that a pre-existing channel beneath a debris flow would concentrate flow, and that a channelized portion of the flow would extend downslope beyond the main deposit. A more local source for debris in the channel is also possible. Immediately west of the channel on the image in Figure 6, the open slope is sculpted by numerous thin (>15 m), bedding-plane sediment-detachment scarps. It is likely that at least some of the channel fill comes from these adjacent slides.

The streamlined erosional depressions near the downslope margin of the western disturbed zone are probably scours produced by a powerful downslope current. The association of the depressions in groups, their elongate downslope shape, and sharply defined bounding walls seem to preclude a simple downslope-sliding mechanism of formation. Normark and others (1979) described erosional flute-shaped depressions on Navy Fan with horizontal dimensions similar to those of our elongate depressions. The depressions observed on the Scotian Slope, however, are generally shallow, flat-floored, and pointed at both ends, whereas the Navy Fan mega-flutes appear to be scaled-up relatives of bedding-plane flute marks commonly observed in ancient rocks. The streamlined form and group association suggest that the Scotian Slope depressions were eroded by downslope-traveling currents that selectively scoured easily eroded sediments. When a more resistant stratum was reached, erosion spread laterally, producing flat floors. When erosion breached this level, depressions within depressions resulted.

The timing of this scouring relative to the upslope slumping is uncertain. The scour occurred during or after debris-flow deposition, because parts of the thin downslope limit of the western disturbed zone are scoured. In one area, however, a field of scours appears to have been removed by a subsequent bedding-plane slide (at scarp "a" in Fig. 10). Faint lineations cross both the scoured and unscoured areas. It is possible that a single event triggered a slump and debris flow, followed by turbidity current scour, followed by local sliding and continued downslope current flow.

The sediments of unit 2, which immediately overlie or form part of the disturbed-sediment zone (recognized acoustically), include thick-bedded muddy sands and thin-bedded graded sands of the type interpreted by Hill (1984) as debris flows and turbidites. The sorted coarse sand in core 28 is unique in the cores from the region and is probably a proximal

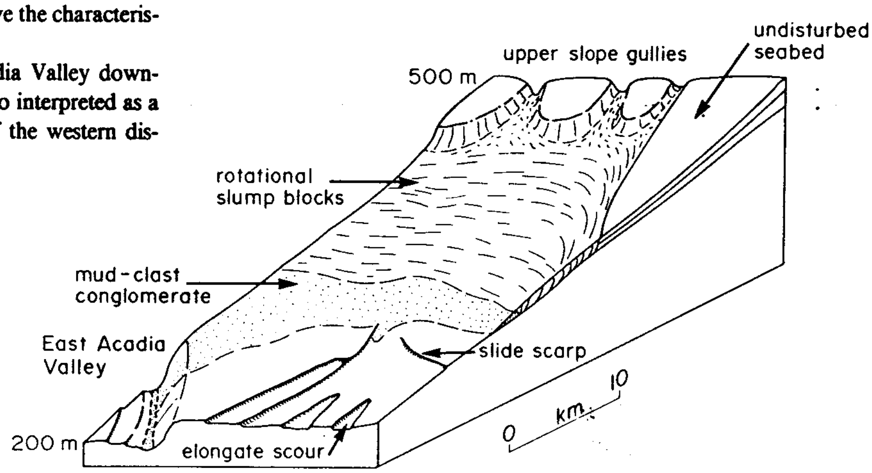

Figure 15. Schematic model showing sediment facies developed on the Scotian Slope near Verrill Canyon.

turbidite. Turbidites are common on the continental rise below the study area (Piper, 1975; Stow, 1981), although we have insufficient core coverage to demonstrate any specific correlations. Hampton (1972), on theoretical grounds, predicted that some subaqueous debris flows should transform into turbidity currents. Our study area may record a transition from slumping through debris flows to turbidity currents, as he proposed.

Age and Cause of the Sliding and Debris Flows

Sediment units 1 and 2 overlie the disturbed zones, and unit 1 overlies the steplike slide scarps. Unit 2 was probably genetically related to the sliding and may have accumulated very rapidly. The resedimented shell dated at 12,000 yr B.P. (core 1, unit 3) places a maximum age on the sliding, whereas the faunal change near the base of unit 1 dated between 5000 and 8500 yr B.P. by Hill (1981) provides a minimum age.

Seismic-reflection profiles show that disturbed-sediment zones and sliding of surface sediment are not frequent events within the stratigraphic sequence of the study area. The slide-detachment scarps and the disturbed zones are both surface features, which are usually covered by <2 m of younger sediment that, although found in cores, is generally not detectable on 3.5-kHz profiles. Bedding-plane slides occur over an area of at least 50 × 50 km, in water depths of 800 to 2,500 m, and on gradients as low as 2.5°. Preliminary geotechnical analysis of cores (E. Hivon and K. Moran, 1984, perso commun.) shows that under static conditions the sea-bed sediments , stable on slopes in excess of 15°. This sliding is, therefore, not the re..ılt of oversteepening by valley undercutting. The water depth of the slides indicates that they are not triggered by cyclic loading by storm waves on the upper slope. Although Hill and others (1983) suggested that creep may lead to sediment detachment, there is no apparent reason for this process to be restricted in time and space, and evidence for active creep is seen at only one locality (Fig. 5). The sliding, consequently, is most probably seismically triggered. The continental margin off eastern Canada is an area of rare large-magnitude earthquakes (Basham and Adams, 1982). The geographic extent of sediment slides in the Verrill Canyon area is similar to that around the 1929 Grand Banks earthquake epicenter (Piper and others, 1985), suggesting that the two earthquakes that triggered the slides were of similar magnitude.

CONCLUSIONS

Between 5000 and 12,000 yr B.P., a large earthquake appears to have caused widespread surface sediment failure over an area 50 km by 50 km on the Scotian Slope west of Verrill Canyon. The upper 10–20 m of sediment failed over large areas, leaving steplike escarpments. Much of this sediment formed two acoustically distinct disturbed-sediment zones that thin downslope. Rotational slumping involving little downslope transport was probably the dominant mechanism, although some true debris-flow deposits occur distally. Turbidity currents developed from these debris flows and scoured the lower parts of the debris flows and the sea bed beyond them.

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