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Abstract: The style of Quaternary sedimentation on the central Scotian Slope near the Shelburne G-29 well is interpreted from seismic reflection profiles. Three types of shelf-edge ice margin produced different styles of sediment accumulation in the later Quaternary on the slope. 1) Ice margins of ice streams persisted for many thousands of years at the shelf edge and resulted in active sedimentation of coarse, channelled deposits, and debris flows. 2) Seaward of outer shelf banks, ice advance onto the upper slope was short lived and sedimentation was dominated by fallout from ice-margin plumes. 3) Under intermediate conditions, ice advance deposited upper slope till and subglacial meltwater cut gullies, but active sedimentation seaward of a broad ice front was lacking. These ice-margin facies overlie an early Quaternary prodeltaic margin and a major debris-flow deposit. The Quaternary sediments are offset by slope-parallel faults that have provided pathways for mud diapirs.

Résumé : Des profils de sismique-réflexion nous permettent d’interpréter le style de la sédimentation survenue au Quaternaire dans la partie centrale du talus Néo-Écossais, à proximité du puits Shelburne G-29. À la bordure de la plate-forme continentale, trois types de marges glaciaires ont produit des styles de sédimentation différents sur le talus continental vers la fin du Quaternaire. (1) Des marges glaciaires de courant glaciaire ont persisté pendant plusieurs milliers d’années à la bordure de la plate-forme continentale et la sédimentation active qui leur était associée a produit des dépôts grossiers de chenaux et des dépôts de coulée de débris. (2) Au large des bancs de la plate-forme continentale externe, l’avancée de la glace sur la partie supérieure du talus continental a été de courte durée et la sédimentation y était dominée par les retombées de panaches de marge glaciaire. (3) Dans des conditions intermédiaires, l’avancée glaciaire a déposé du till sur la partie supérieure du talus continental et l’eau de fonte sous-glaciaire a découpé des vallées, mais il n’y avait pas de sédimentation active au large d’un vaste front glaciaire. Ces trois faciès de sédimentation de marge glaciaire recouvrent une marge prodeltaïque du Quaternaire inférieur et un dépôt majeur de coulée de débris. Les sédiments du Quaternaire sont déplacés par des failles parallèles au talus continental qui ont permis la mise en place de diapirs de boue.

INTRODUCTION

The Scotian Shelf (Fig. 1) has the classic morphology of a glaciated continental shelf (Shepard, 1972), with a series of overdeepened basins on the mid-shelf and a discontinuous line of shallow banks on the outer shelf, separated by deeper-water troughs. The basins and troughs were excavated by major glacial streams from the Appalachian Ice Complex (Grant, 1989; Piper et al. 1990). Glacial ice extending to the edge of the continental shelf played a major role in mid- to Late Pleistocene sedimentation on the Scotian Slope (Piper, 1988). The style of proglacial sedimentation on the continental slope is an important control on slope stability (Piper and Sparkes, 1987; Mosher et al., 1994; Mulder and Moran, 1995), which in turn is a significant constraint for hydrocarbon exploration and production on the Scotian Slope.

The study area lies on the continental slope seaward of three major shelf basins — Emerald, LaHave, and Roseway basins (Fig. 1). A broad outer shelf trough lies seaward of Emerald and eastern LaHave basins and a narrower trough seaward of western LaHave and Roseway basins, separated by LaHave Bank, and bounded to the east by Emerald Bank and the west by Baccaro Bank (Fig. 2). Seismic-reflection profiles from the study area have been interpreted to infer the Quaternary evolution of the continental slope.

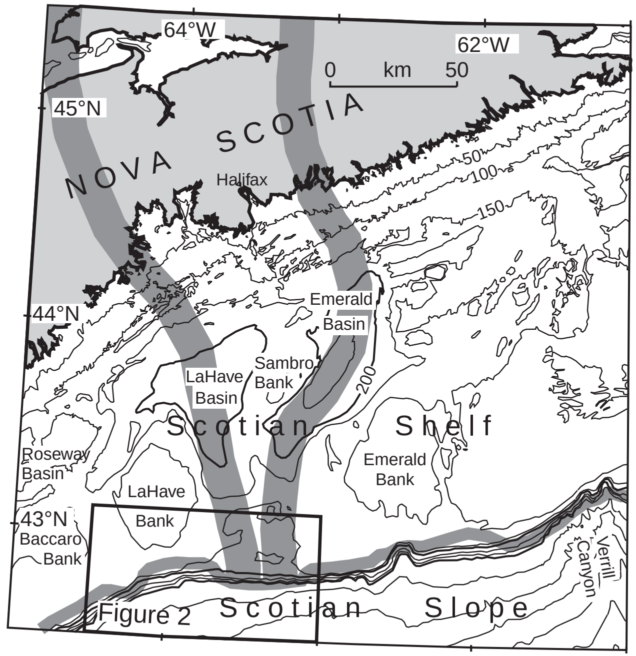

*Figure 1. General map of Nova Scotia and the Scotian Shelf showing location of the study area (Fig. 2 box). Grey line at shelf edge represents late Wisconsinan ice margins (*after *Stea et al., 1998); thick grey bars represent position of ice streams (*after *Grant, 1989).*

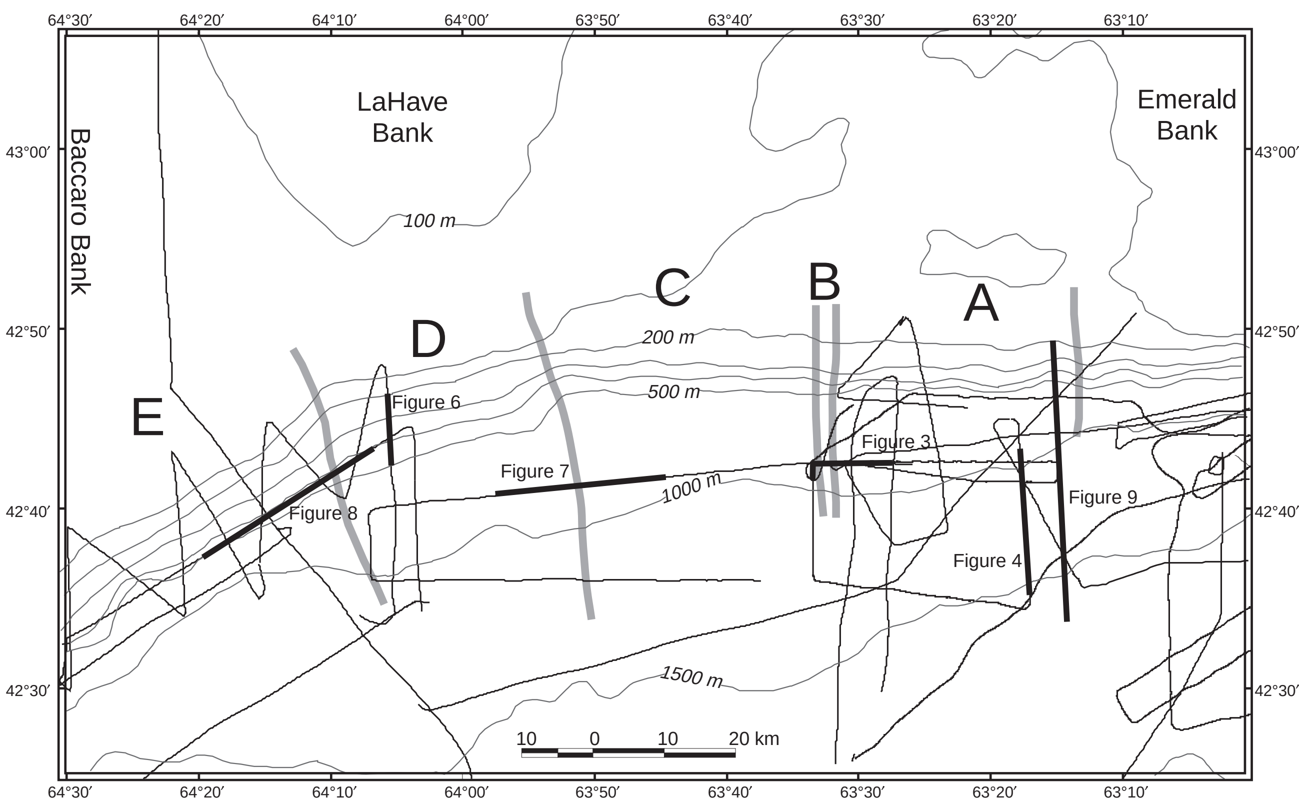

Figure 2. Map of study area showing seismic track lines and location of illustrated figures. 'A' to 'E' are zones discussed in text.

The near-surface seismic stratigraphy and sedimentology of the eastern part of the area was studied in detail by Hill (1981, 1983, 1984) and Piper and Sparkes (1987). Gipp (1996) interpreted the near-surface seismic stratigraphy of the western part of the area. The stratigraphic pick on the base of the Quaternary at the Acadia K-62 well to the east (Piper et al., 1987) has been correlated to the study area using industry seismic-reflection profiles (Piper and Sparkes, 1990). The acquisition of new seismic reflection profiles on *CCGS Hudson* cruise 99-036 in August 1999 has provided new insight into the evolution of the continental slope in this area.

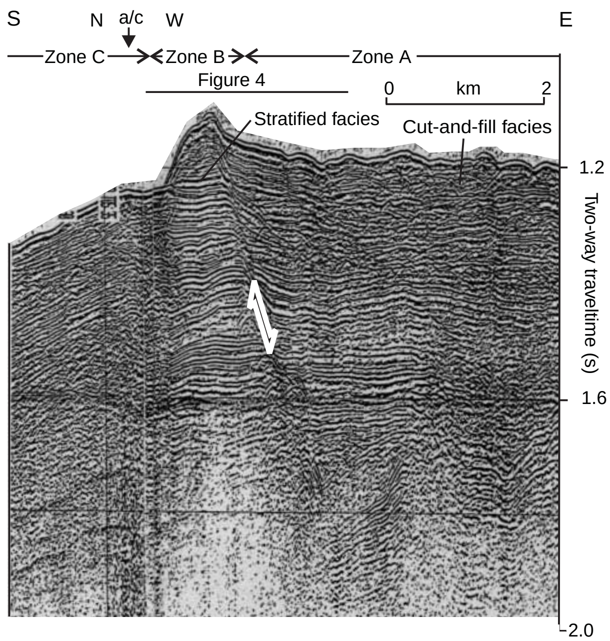

Figure 3. *Seismic reflection profile along strike in 900 m water depth in zones A–C, showing facies, stratigraphy, and faulting. Two 40 cubic inch sleevegun source, cruise 99-036.*

METHODS

Seismic reflection profiles have been collected over the past 20 years, principally using a 40 cubic inch airgun or sleeve gun. The 1999 profiles were collected with two 40 cubic inch sleeve guns. Navigation prior to 1991 was by Loran C and since that time by GPS.

SEISMIC INTERPRETATION

Interpretation of seismic reflection profiles on the upper continental slope indicates that five different acoustic facies can be distinguished.

1. Well stratified facies are characterized in airgun seismic by continuous, subparallel, or locally mounded reflections (Fig. 3). The continuous subparallel reflections are also visible in higher resolution seismic systems, such as the Huntec DTS^{TM} sparker (Fig. 4). Piston cores show that this facies near surface consists of stratified proglacial muds (Piper and Sparkes, 1987).

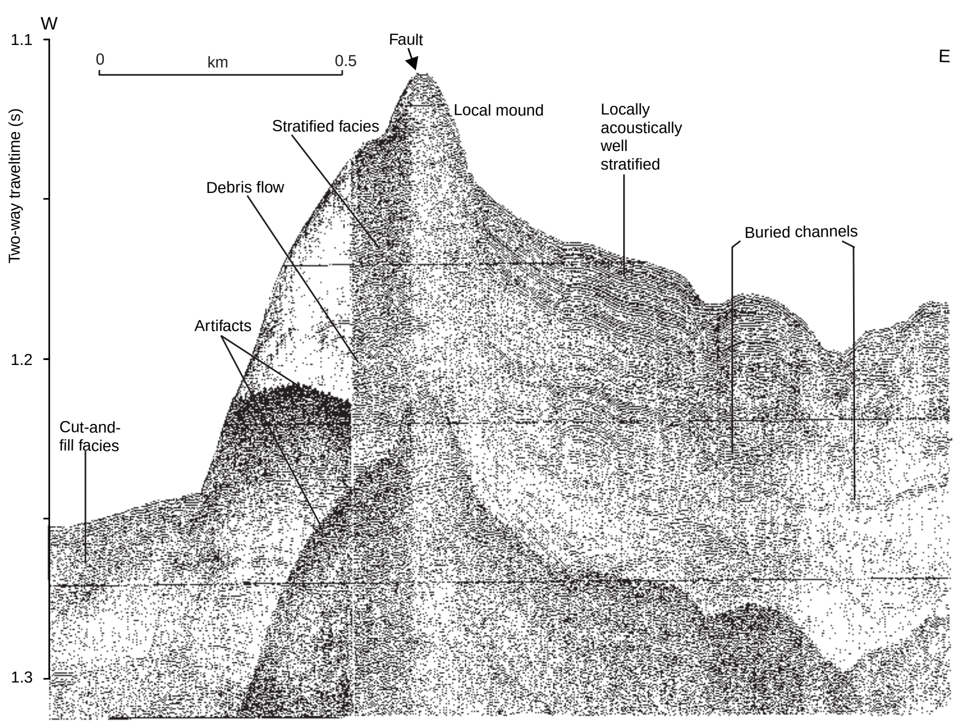

Figure 4. *Huntec DTS^{TM} sparker high-resolution seismic profile of part of the section in Figure 3 showing greater seismic resolution of facies, cruise 99-036.*

2. Cut-and-fill facies are characterized in airgun seismic by discontinuous reflector segments commonly dipping at opposing low angles, with some more continuous reflectors. High-resolution sparker data (Fig. 4; *see also* Piper and Sparkes, 1987) show intervals of continuous parallel reflectors alternating with intervals with the seismic character of debris flows and channel-filling sands, an interpretation confirmed by cores (Hill, 1984) and sidescan sonar imagery (Piper and Sparkes, 1987).
3. The irregular stratified facies in airgun seismic is intermediate between the two facies discussed above. It consists of some continuous planar to gently mounded reflections interbedded with intervals or areas of more discontinuous reflections (Fig. 5). The lithologies present are probably an alternation of those found in the two facies above.
4. Debris-flow facies is characterized in airgun seismic by acoustically incoherent intervals with rare internal reflections, commonly a rough upper surface returning hyperbolic diffractions, and commonly a depression-filling geometry (Fig. 5). This facies may include debris-flow deposits *sensu stricto*, debris avalanches, and rotational slumps.
5. Till and proglacial facies, characterized in airgun seismic by incoherent reflections and short discontinuous reflections (Fig. 6), occurs only on the upper slope to water depths of about 600 m. This facies resembles the

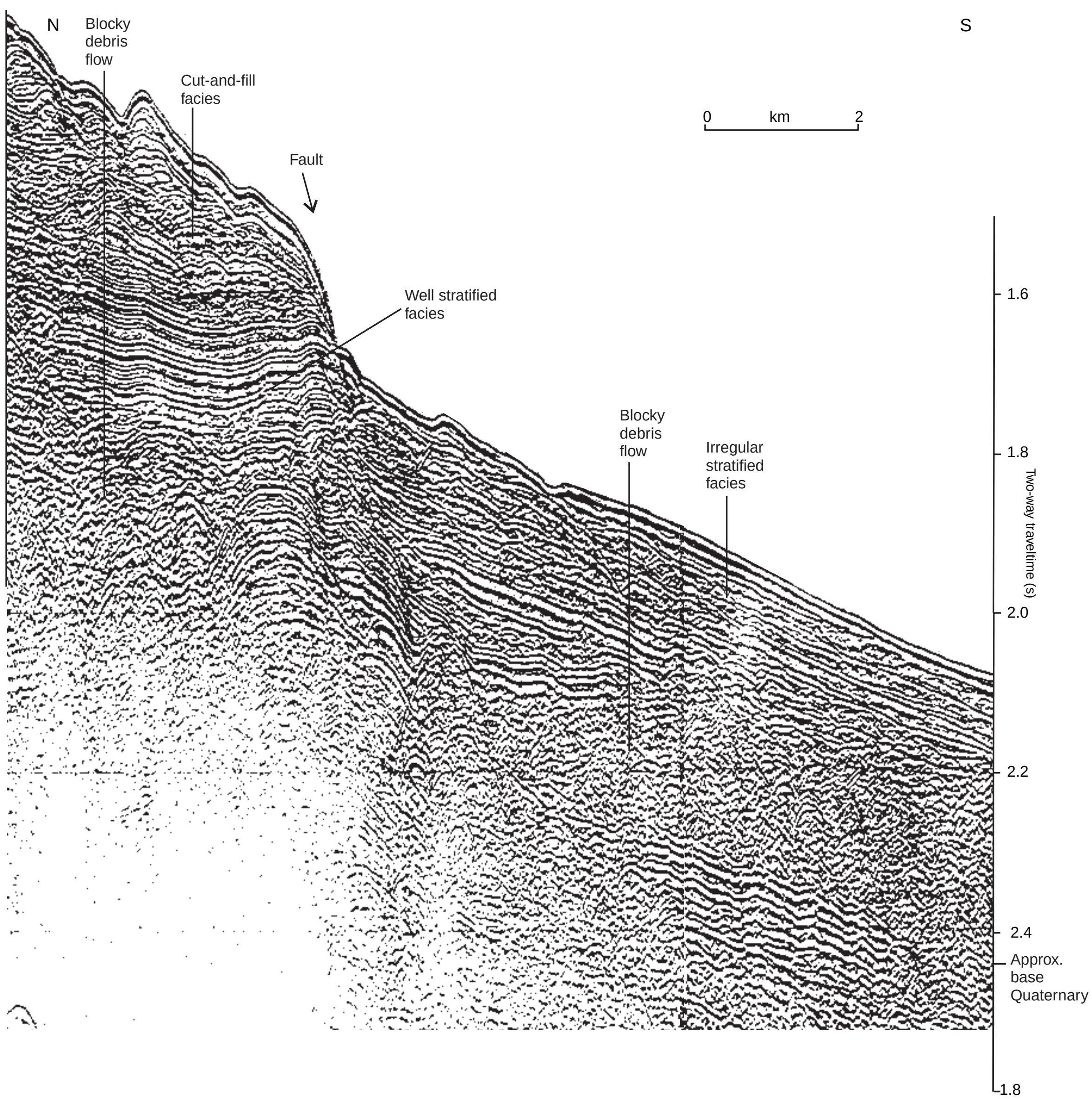

Figure 5. *Seismic reflection profile down dip in zone A, showing facies, stratigraphy, and faulting. Two 40 cubic inch sleevegun source, cruise 99-036.*

"incoherent wedges" recognized by Mosher et al. (1994) on the upper slope to the east and interpreted as glacial diamict, perhaps interbedded with proglacial coarse-grained sediments. This facies passes downslope into well stratified facies (Fig. 6).

Five zones with differing Quaternary stratigraphies can be recognized on the continental slope between Emerald Bank and Baccaro Bank. In zone A on the middle slope (Fig. 5), 200 ms of shallow cut-and-fill facies overlies 200 ms of well stratified facies. This rests on top of a blocky debris-flow unit also about 200 ms thick, overlying more than 200 ms of well stratified facies. The basal Quaternary marker (correlated from the Acadia K-62 well, Piper and Sparkes (1990)) is near the top of this lower well stratified facies. In about 1250 m water depth, there is an apparent slope-parallel normal fault across which the stratigraphy is offset by about 200 ms. This fault corresponds downslope to the east-west scarp of Piper and Sparkes (1987). The blocky debris-flow facies is developed only locally on the footwall of this fault. The debris flow and the overlying well stratified facies overlie, probably unconformably, a somewhat deformed sequence of stratified facies that may represent substantially older sediments.

Zone B is a narrow strip of well stratified facies at least 700 ms thick, apparently fault bounded on its eastern side (Fig. 3), at the western end of zone A. It appears to correspond to the entire Pleistocene section to the east, including the upper cut-and-fill facies. Some individual reflectors appear to correlate through with small offset across the fault.

In zone C, 300–400 ms of shallow cut-and-fill facies overlies more than 200 ms of well stratified facies (Fig. 7). The eastern (Fig. 3) and western (Fig. 7) margins of the zone are abrupt, apparently erosional, and persistent through time.

In zone D, the near-surface sediments on the mid-slope are well stratified (Fig. 7) and thicken westward from 200 ms in the east to 350 ms in the west. They are underlain by 500 ms thickness of shallow cut-and-fill facies interbedded with irregular stratified facies (Fig. 7). On the upper slope, till and proglacial facies appear to be the lateral equivalent of the upper well stratified facies and overlie cut-and-fill facies (Fig. 8). The till and proglacial facies passes downslope into well stratified facies (Fig. 6), with the till bodies wedging out downslope in a manner similar to those near Verrill Canyon (Mosher et al., 1989).

The best data for zone E is on the upper slope (Fig. 8), where 200–250 ms of till and proglacial facies overlies 500 ms of well stratified facies that appear to be the lateral equivalent of the shallow cut-and-fill facies in deeper water in zone D. Several generations of partially filled gullies cut the upper slope and were interpreted by Gipp (1996) as discharge routes for subglacial meltwater. On the mid-slope, rather poor quality data shows more than 300 ms of irregular stratified facies.

A rather similar continental slope architecture appears to be present east of zone A, with upper slope till and proglacial facies passing downslope into stratified facies, both cut by gullies and small canyons partially filled with cut-and-fill facies. An industry seismic dip line (Fig. 9) cuts obliquely

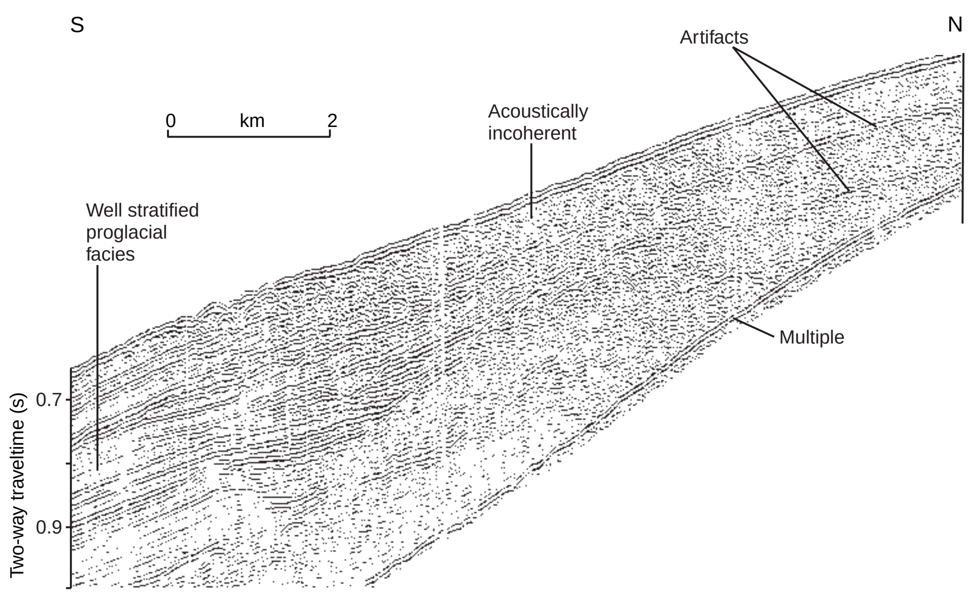

***Figure 6.** Seismic reflection profile down dip in zone D, showing incoherent acoustic facies corresponding to till passing downslope into well stratified acoustic facies, corresponding to proglacial plume fall-out deposits. One 40 cubic inch airgun source, cruise 90-002.*

through such a gully. The facies interpretation of the near-surface parts of this seismic profile is based on intersecting airgun seismic lines. The till and proglacial facies unconformably overlies a series of progradational shelf-edge clinoforms that pass downslope into irregular stratified facies. Seismic correlation suggests that the base of this clinoform packet is of approximately basal Quaternary age.

The prominent fault in Figure 5, with an apparent throw of about 150 m, can be traced in seismic reflections profiles to both the west and east. To the west, it corresponds to the east-west escarpment mapped by Piper and Sparkes (1987). To the east, it appears to split into two strands that can be followed into the industry seismic line of Figure 9. This profile shows that there might be a corresponding deep-seated fault

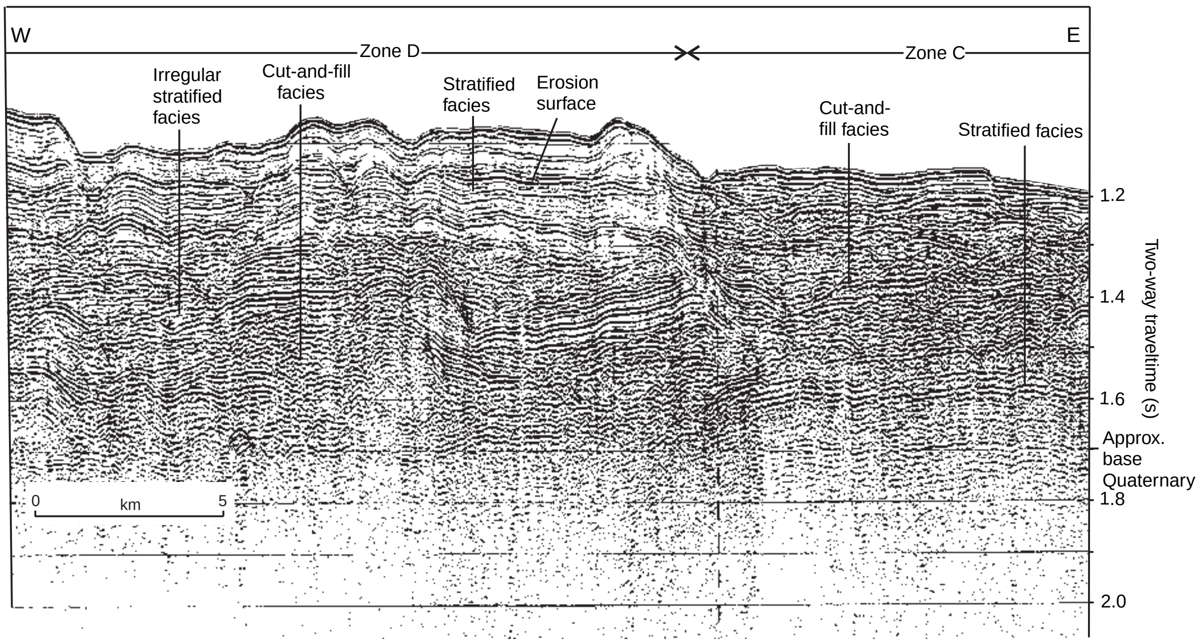

Figure 7. *Seismic reflection profile along strike in 900 m water depth in zones C and D showing facies and stratigraphy. One 40 cubic inch sleevegun source, cruise 90-015.*

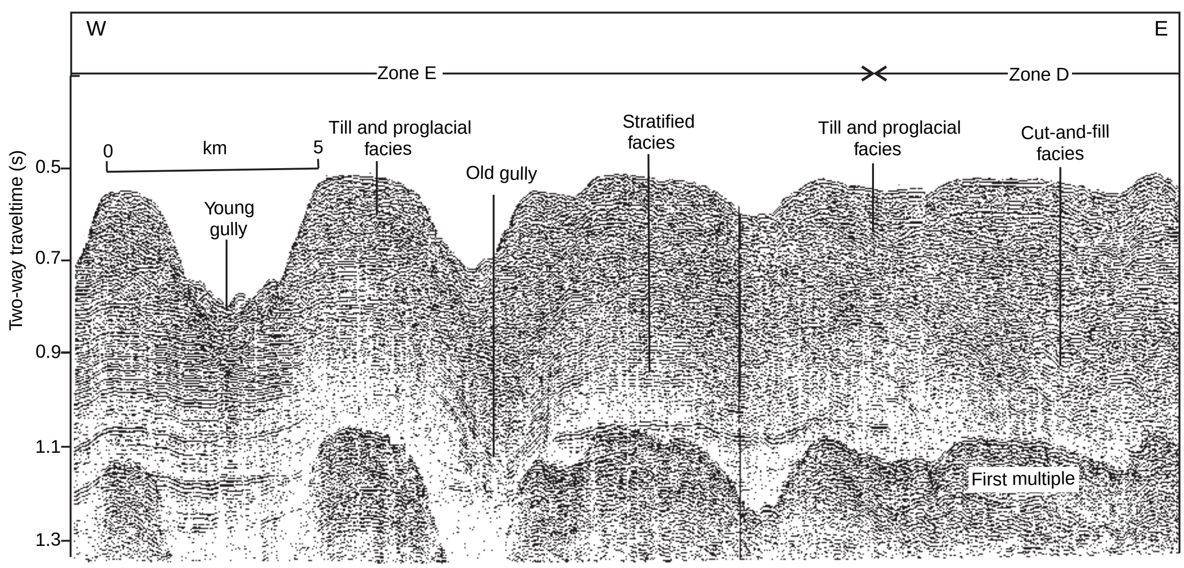

Figure 8. *Seismic reflection profile along strike in 400 m water depth in zones D and E, showing gullies cutting till and proglacial facies overlying well stratified facies in zone E whereas in zone D, till and proglacial facies lack gullies and overlie cut-and-fill facies. One 40 cubic inch airgun source, cruise 90-002.*

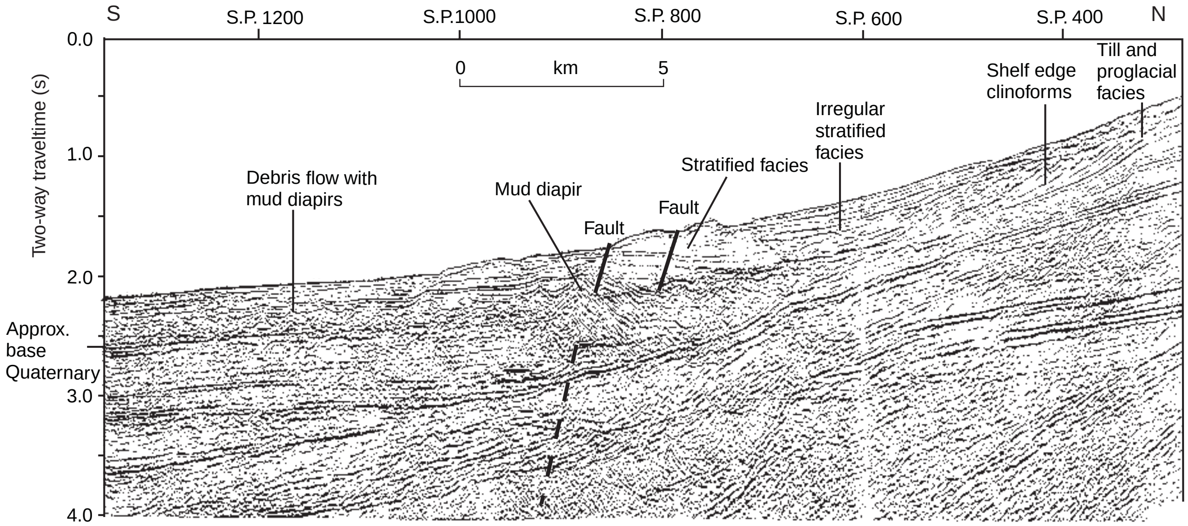

__Figure 9.__ Industry multichannel seismic reflection profile down dip from the eastern end of zone A, showing late Cenozoic stratigraphy and facies. Petrocanada line 3416-82P courtesy Canada– Nova Scotia Offshore Petroleum Board.

with a small throw, correlative with the deep-seated fault inferred from the offset in strata beneath the debris-flow horizon in Figure 5. However, some of the apparent motion in Figure 9 appears related to differential movement of sediment overlying the major debris flow. A mud diapir appears to have developed from the debris-flow horizon along the southern fault strand.

DISCUSSION

Later Quaternary glacial facies

The cut-and-fill facies is found in approximately the upper half of the Quaternary section in zones A and C, seaward of the inferred major ice outlet between LaHave and Emerald banks. The near-surface sediments in this area have been interpreted as resulting from ice-margin supply of diamict and subglacial meltwater laden with sediment, overlain by plume fall-out deposits as ice retreated back into Emerald Basin (Hill, 1984; Piper and Sparkes, 1987; Gipp, 1994). The seismic profiles presented here suggest that such depositional conditions persisted for about half the Quaternary. Similar seismic facies are recognized seaward of Laurentian Channel (Piper and Normark, 1989), another major ice outlet on the Scotian margin, where shelf-edge ice persisted for many thousands of years (Piper and Skene, 1998).

In zone D, seaward of LaHave Bank, the correlative section in the upper half of the Quaternary is generally well stratified, with a draped morphology over subsurface irregularities developed at a prominent erosional horizon. Upslope, this facies passes into the till and proglacial facies. This style of sedimentation is very similar to the area near Verrill Canyon described by Mosher et al. (1989), where ice reached the upper slope for only a few short intervals (10^2–10^3 years) in the later Quaternary and sedimentation was dominated by fall-out of sediment from distal proglacial plumes.

In zone E, the upper Quaternary section is marked by gullies deeply incised into till and proglacial facies, typically 150 m deep and spaced every 3–5 km. The till and proglacial facies passes downslope into irregular stratified facies. Similar gullies are absent in zone D. In zones C and A, previous studies have shown gullies on the upper slope that are shallower (a few tens of metres) and more closely spaced (0.5–1 km) (Hill, 1983; Piper and Sparkes, 1987).

This variation in upper slope facies in the later Quaternary suggests that three types of ice margin were present in the study area. Zones A and C had the most dynamic and coarsest sediment supply, including common debris flows and small channels filled with sand. They lie seaward of the largest basins on the Scotian Shelf suggesting that ice streams through Emerald Basin and eastern LaHave Basin reached the edge of the shelf for prolonged periods and were responsible for the active style of sedimentation in these zones. On the shelf, these two ice streams would have been separated by Sambro Bank; the narrow zone of well stratified sediment in zone B corresponds to a dead-ice area in the lee of Sambro Bank.

In zone D and probably also in the area east of zone A, ice reached the upper slope only occasionally and for short periods. Sedimentation was dominated by plume fallout of fine-grained sediments, in the case of zone D probably derived from the major ice outlet of zones A and C.

Conditions in zone E appear to have been intermediate between the active ice streams of zones A and C and the rare ice of zone D. Dip lines show thicker till units and thinner stratified proglacial sediments than in zone D, suggesting greater duration of ice reaching the shelf edge, but there is generally no evidence for vigorous downslope movement of sediment over a broad ice front, in contrast to zones A and C. The deeply incised gullies suggest that focused subglacial meltwater supply was important at times (Gipp, 1996), in contrast to zone D, and presumably transported coarse sediment into deeper water.

The preglacial earlier Quaternary

In zones A and C, the cut-and-fill facies represents only about half the Quaternary section and overlies well stratified facies. East of zone A, till and proglacial facies unconformably overlie early Quaternary clinoforms interpreted as shelf-edge deltaic sediment, passing downslope into well stratified and irregular stratified facies. Similar and correlative prodeltaic conditions are inferred from the well stratified facies in the lower Quaternary section in zones A and C. Mosher et al. (1989) recognized a similar transition from glacial to prodeltaic facies on the Scotian Slope in the Verrill Canyon area, at about the same stratigraphic level. Piper et al. (1994) demonstrated that the glacial excavation of Carboniferous sediments in the Laurentian Channel glacial trough took place during isotopic stage 12, at about 450 ka. The first shelf-crossing ice streams through Emerald and LaHave basins are probably of similar age. Prior to that, upland glaciation in the Appalachians would have fed proglacial rivers (Piper et al., 1994) but glacially lowered sea levels would have promoted shelf-edge progradation. A cut-and-fill facies is developed in zone D at this stratigraphic level, which might indicate that the main axis of river progradation was in this zone. The relationship of such progradation to LaHave Bank is unclear, because of a lack of suitable seismic data in the area.

Implications for slope sediment stability

Several features visible in seismic reflection profiles suggest considerable past instability on the continental slope in this area. Small debris flows are recognized in areas of cut-and-fill facies. A large blocky debris flow near the base of the Quaternary section (Fig. 5) appears to have been remobilized in places into mud diapirs (Fig. 9). The small mound on the fault at the edge of eastern edge of zone B (Fig. 4) also appears to be a mud diapir. The scale of faulting in the Quaternary section (Fig. 5) is startling and appears related to mobility of and differential subsidence on the early Quaternary debris flow, although mobility may be aided by deep-seated faults with a relatively small throw (Fig. 9). Although the ‘block’ of stratified facies in Figure 9 appears to be allochthonous, regional seismic reflection profiles suggest that this is an illusion and it is an autochthonous facies development somewhat analogous to zone B (Fig. 3).

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