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Quaternary Geology of three selected transects of the continental slope off eastern Canada

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Atlantic Geoscience Centre

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QUATERNARY GEOLOGY OF THREE SELECTED TRANSECTS OF THE CONTINENTAL SLOPE OFF EASTERN CANADA

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GEOLOGICAL SURVEY OF CANADA OPEN FILE ****

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This Open File consists of a lightly edited work term report by a Co-op student. It describes the Quaternary marine geology of transects of the continental slope off La Have Basin, near Logan Canyon, and at the Tail of the Banks. The work was supported by PERD under project 6.3.2.6 (Sediment stability on continental slopes - D.J.W. Piper).

ABSTRACT

Data from three transects of the continental slope off Nova Scotia and Newfoundland has been investigated as part of an ongoing synthesis of slope instability by the Geological Survey of Canada. Single and multichannel airgun seismic were used to establish a Cenozoic setting for late Quaternary sedimentation as well as to attempt furthering ties to previously developed stratigraphies. High resolution Huntec DTS sub-bottom profiler, 3.5 kHz bottom profiler data and available piston cores were used to investigate surficial geology.

From analysis and preliminary interpretation of the transects, a sedimentary model defining the morphologic constraints of late Quaternary sedimentation is proposed. The factors of slope morphology include depth of shelf break, slope gradient, and pre-existing topography. Depth of shelf break controls sediment delivery to the slope given glacial-eustatic sea level changes and ice margin conditions. The magnitude of the slope gradient controls sediment failure or retention on the slope. Pre-existing topography supplies the baseline from which glacial induced processes can be separated from background processes. Initial evaluation of the model included its application to the areas investigated -- Logan Canyon, La Have Slope, and Tail of the Banks.

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1.0 INTRODUCTION

1.1 Background

The continental slope off Eastern Canada has been the site of hydrocarbon exploration for approximately ten years. In general, the region is poorly known with data existing for small, selected areas only. Extent and variability make comprehensive mapping of the slope impractical. Therefore, selected areas are studied which hopefully encompass the range of slope variability.

By far the most thorough data sets exist for regions of the slope where hydrocarbon exploration has been focused (Hill, 1984; Piper et al., 1985; Piper, Normark, and Sparkes, 1987; Piper and Sparkes, 1987; Piper and Normark, 1989). Less intensive study has been carried out in areas of secondary interest, investigating the degree of slope variability.

In examining slope variability, a fundamental goal is hazard assessment (in relation to hydrocarbon exploitation and deep-sea cable routes). Research into hazard assessment primarily focuses on the causes of slope instability. Processes interpreted from various locations along the Eastern Canadian slope can then be related to the areas of primary interest in hydrocarbon exploration.

1.2 Purpose

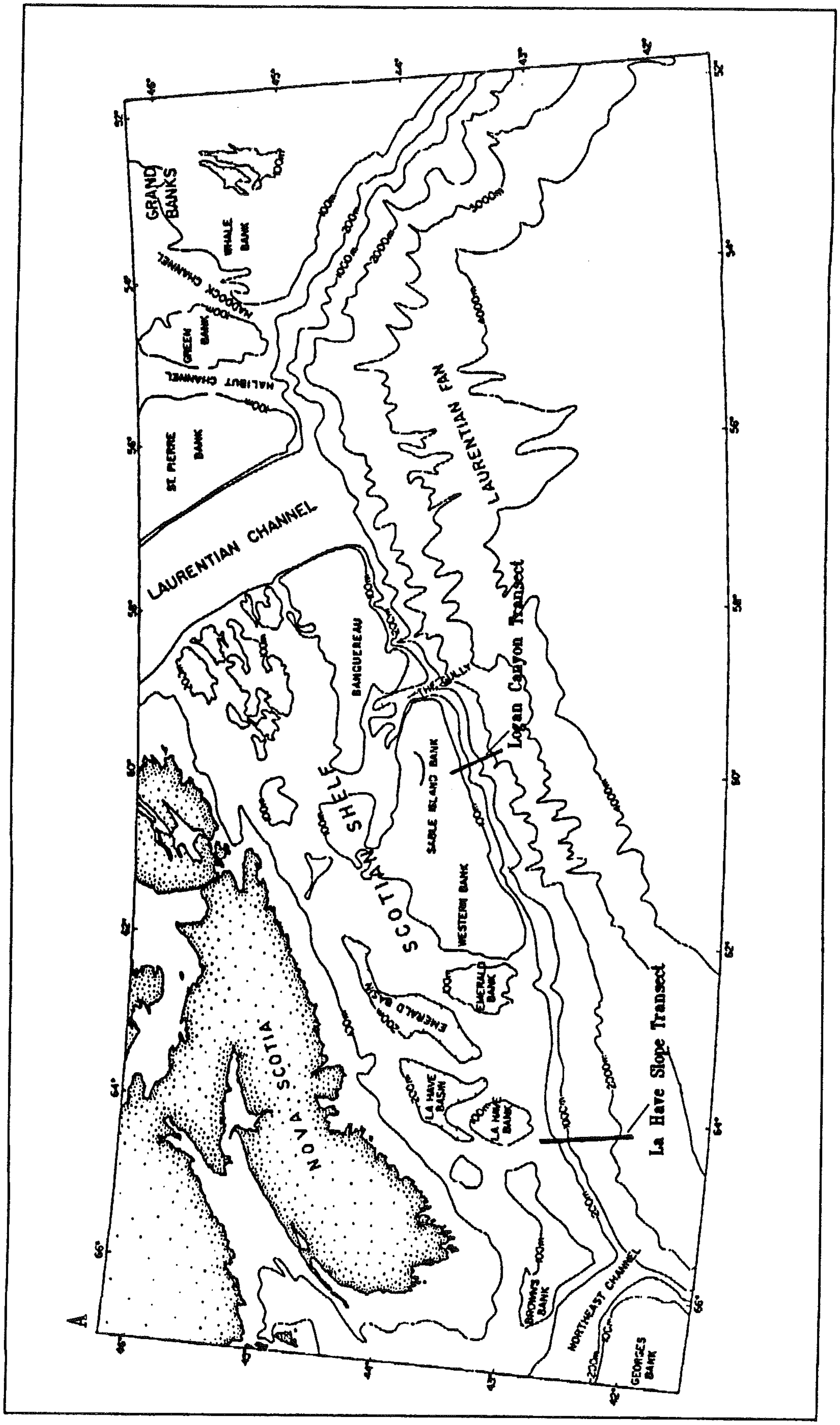
A synthesis of available data from the continental slope off

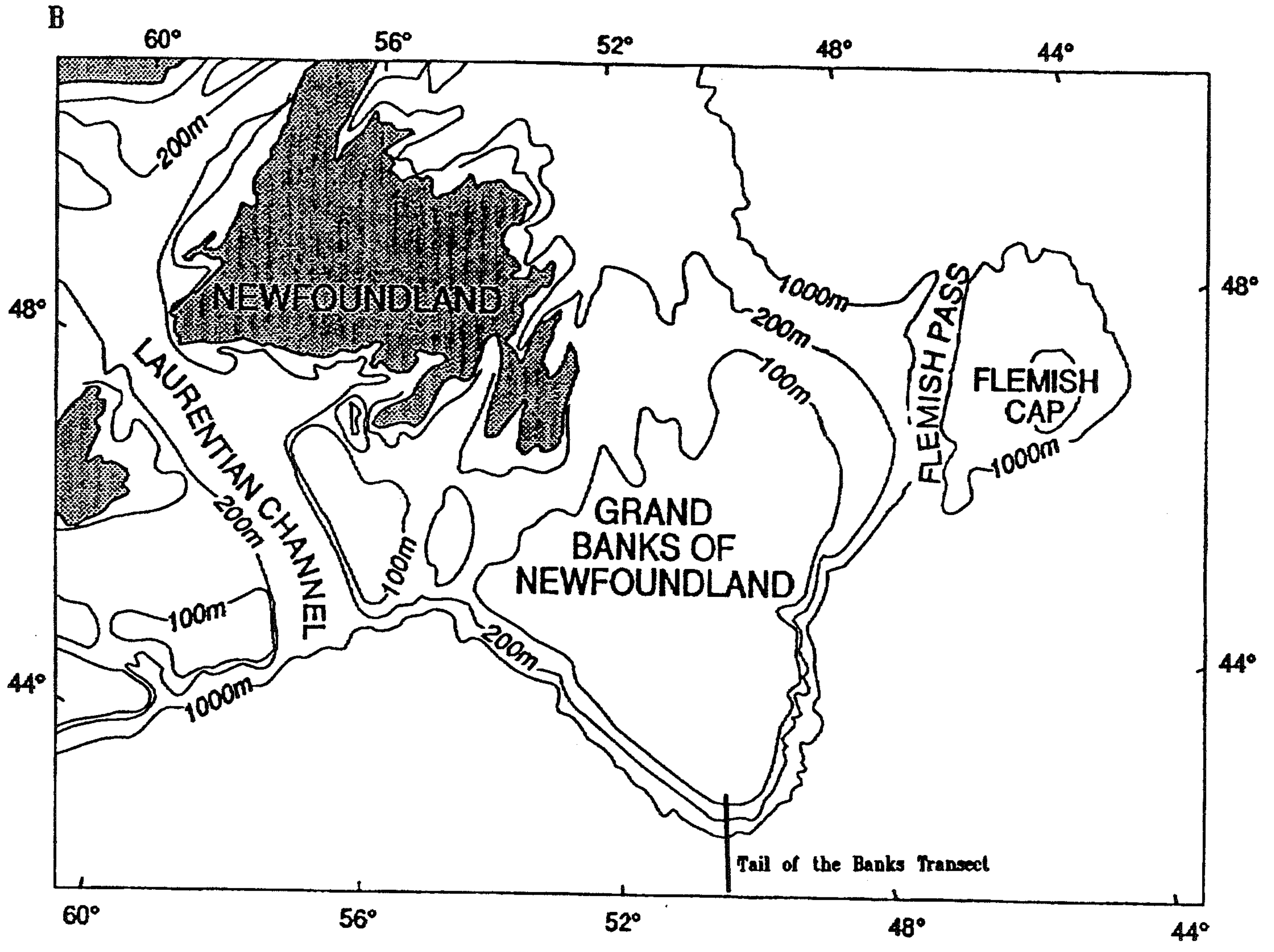
Nova Scotia and Newfoundland is part of an ongoing project of the Geologic Survey of Canada. This project organizes the data into downslope transects which are interpreted using available single channel airgun seismic, Huntec DTS high resolution sub-bottom profiler, 3.5 kHz profiler, and core data. This paper provides the preliminary interpretation of three transects -- the slopes off Sable Island Bank (Logan Canyon area), East La Have/Emerald Basins (La Have Slope), and the Tail of the Banks (Figure 1.1). In addition, a sedimentary model is proposed defining the constraints of slope morphology on late Quaternary sedimentation. The factors of slope geometry are primarily depth of shelf break, slope gradient, and pre-existing topography. This model was then applied to the three transects to evaluate its potential in explaining the observed Quaternary sedimentation.

1.3 Methods

The data used is principally from cruises of CSS HUDSON (87-003, 87-008, 88-010) and CSS DAWSON (90-002) sponsored by the Atlantic Geoscience Centre. Descriptions of the Cenozoic seismic setting were made from available single channel and multichannel airgun seismic. Surficial geology was investigated using Huntec DTS (Deep Tow System) high resolution sub-bottom profiler records, 3.5 kHz bottom profiler records, and available piston cores.

Figure 1.1. Regional maps of the Eastern Canadian continental slope showing location of study areas: A) Logan Canyon and La Have Slope study areas; and B) Tail of the Banks study area. Bold lines denote transect location.


A
GRAND BANKS
WHALE BANK
HADDOCK CHANNEL
GREEN BANK
HALIBUT CHANNEL
ST. PIERRE BANK
LAURENTIAN CHANNEL
LAURENTIAN FAN
BANQUEREAU
THE GULLY
Logan Canyon Transect
SABLE ISLAND BANK
SCOTIAN SHELF
WESTERN BANK
EMERALD BANK
EMERALD BASIN
NOVA SCOTIA
LA HAVE BASIN
LA HAVE BANK
La Have Slope Transect
BROWNS BANK
NORTHEAST CHANNEL
GEORGES BANK
100m
200m
1000m
2000m
3000m
4000m
46°
45°
44°
43°
42°
52°
54°
56°
58°
60°
62°
64°
66°


B
60°
56°
52°
48°
44°
48°
44°
NEWFOUNDLAND
LAURENTIAN CHANNEL
200m
100m
1000m
GRAND BANKS OF NEWFOUNDLAND
FLEMISH PASS
FLEMISH CAP
1000m
200m
100m
Tail of the Banks Transect

2.0 DATA BASE

Table 1 summarizes the source and extent of the data used in this study. Table 2 summarizes the AMS radiocarbon dates determined for selected cores.

Table 1: Data Base Summary

Geographic Area	Cruise(s)	Seismic Available	Core Data Available
Logan Canyon	87-003	Huntec DTS Airgun	Physical properties X-radiography
	88-010	Huntec DTS Airgun	
La Have Slope	90-002	3.5 kHz Airgun	X-radiography 5 radiocarbon dates
Tail of the Banks	87-008	3.5 kHz Airgun	Physical properties X-radiography 1 radiocarbon date

Table 2: AMS Radiocarbon Dates

Core	Depth (cm)	Age	Lab Number
87-008-006	437	38 750 ±1010	Beta 34301 ETH 6053
90-002-004 TWC	48	10 790 ± 90	TO-2033
90-002-004	109	13 190 ± 110	TO-2034
90-002-004	118	13 350 ± 160	TO-2035
90-002-004	263	14 240 ± 120	TO-2036
90-002-004	580	14 350 ± 120	TO-2037

Except for the 90-002 cruise on CSS DAWSON, the data was collected by the CSS HUDSON, all using equipment supplied by the

Atlantic Geoscience Centre. In general, the transect coverage included 3.5 kHz sub-bottom sounder data, Huntec DTS (deep-tow system) high resolution sub-bottom profiler data, and single channel 40 cubic inch airgun seismic.

3.0 PRESENTATION OF TRANSECTS

The three transects form a subset of the transects that will be presented by Piper et al. (in prep.). They were selected on the basis of varying sedimentation styles for a comparison of slope morphology in the late Quaternary. Analysis of each transect followed a fairly standard procedure including: 1) preparation of an interpretative line drawing presenting an airgun seismic profile to illustrate the late Cenozoic setting on the continental slope; 2) visual core description, X-radiography, and measurement of physical properties in available cores; and, 3) relating sub-bottom profiler data (3.5 kHz or Huntec DTS) to the lithologic sequences in cores thereby making a broader analysis of the late Quaternary sedimentation possible.

The transects have seismic coverage to various water depths. To allow for a standardized approach in the naming of morphologic regions on the slope, the following conventions have been adopted. The upper slope refers to the region between the shelf break and 300-400 m water depth. The middle slope extends from the upper slope to 1000 m water depth. The lower slope covers depths greater than 1000 m and continues to the usually abrupt decrease in the slope gradient at the upper rise. The upper rise is normally the downslope limit of data collection.

3.1 Logan Canyon Transect

Logan Canyon is a major bathymetric feature on the Central Scotian slope, approximately 220 km off Nova Scotia, seaward of Sable Island Bank (Figure 3.1). Piper and Normark (1989) presented a seismostratigraphy of the area. McLaren (1988), working on the shelf off Sable Island, describes the area as a prograding delta-like slope. The transect lines run both to the northeast and southwest of Logan Canyon, providing the opportunity to examine localized variations in slope morphology.

The shelf break at Logan Canyon is abrupt and occurs at 110 to 120 m water depth. The downslope topography (Figure 3.2 and 3.3) is dominated by a series of submarine canyons beginning at 350 to 450 m water depth and continuing to the lower slope (seen in Figure 3.3 from the southeast side of the study area only). The gradient of the middle to lower slope averages 4.9 degrees. The upper rise flattens to a 1.15 degree gradient with only minor relief along the transect line in comparison to the middle slope.

Figure 3.1. Map showing data distribution and bathymetry of the Logan Canyon study area. Bold lines denote seismic profiles, dots refer to core locations.

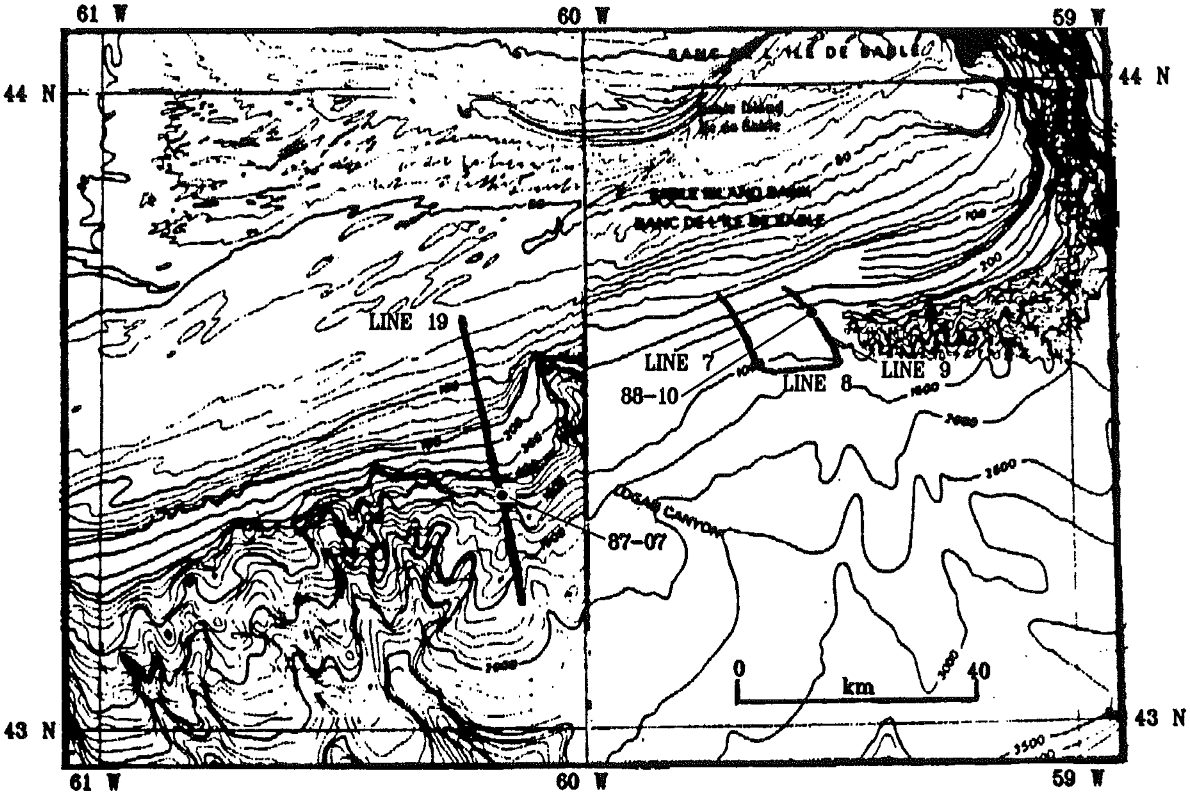

61 W
60 W
59 W
44 N
43 N
BANC DE L'ILE DE SABLE
Sable Island
Île de Sable
SABLE ISLAND BANK
BANC DE L'ILE DE SABLE
LINE 19
LINE 7
LINE 8
LINE 9
88-10
87-07
LOGAN CANYON
50
100
200
1000
1500
2000
2500
3000
3500
0
km
40

Figure 3.2. Line drawing of dip airgun seismic profile from the northeast side of study area (88-010 lines 8 and 9).

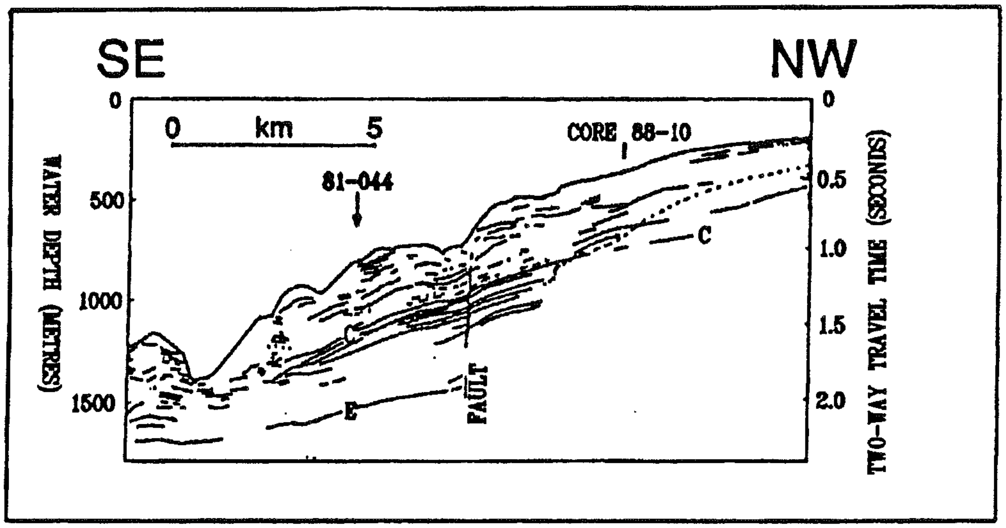
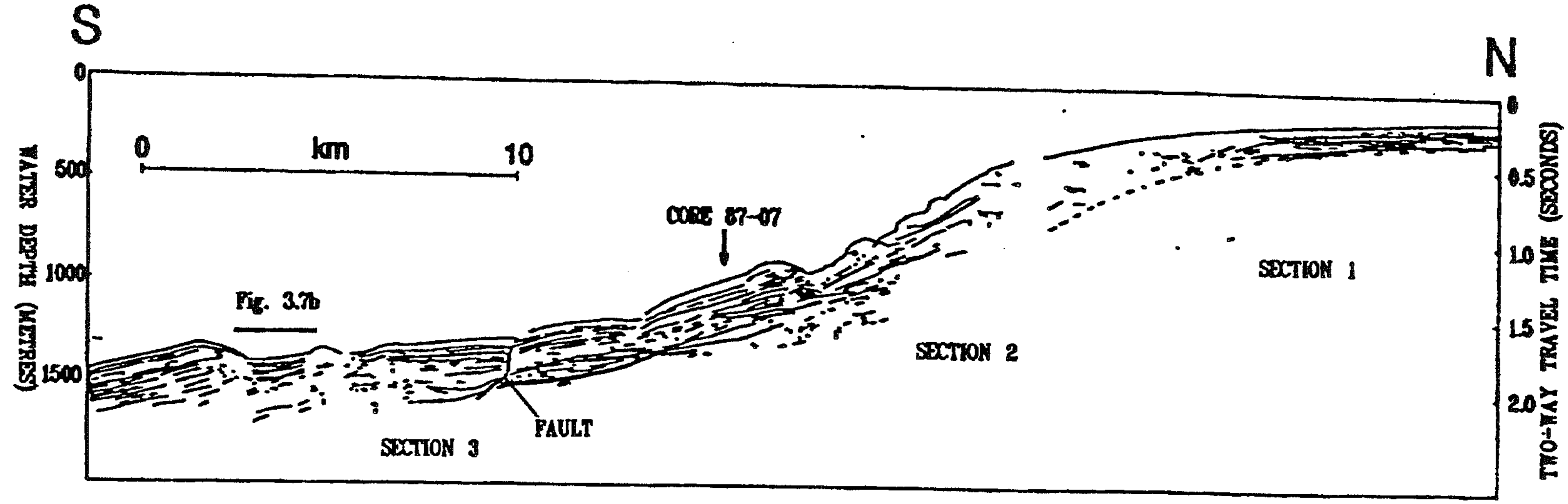

SE
NW
0
500
1000
1500
WATER DEPTH (METRES)
0 km 5
81-044
CORE 88-10
C
E
FAULT
0
0.5
1.0
1.5
2.0
TWO-WAY TRAVEL TIME (SECONDS)

Figure 3.3. Line drawing of dip airgun seismic profile from the southwest side of study area (87-003 line 19).


S
N
0
500
1000
1500
WATER DEPTH (METRES)
0
0.5
1.0
1.5
2.0
TWO-WAY TRAVEL TIME (SECONDS)
0
km
10
CORE 87-07
Fig. 3.7b
SECTION 1
SECTION 2
SECTION 3
FAULT

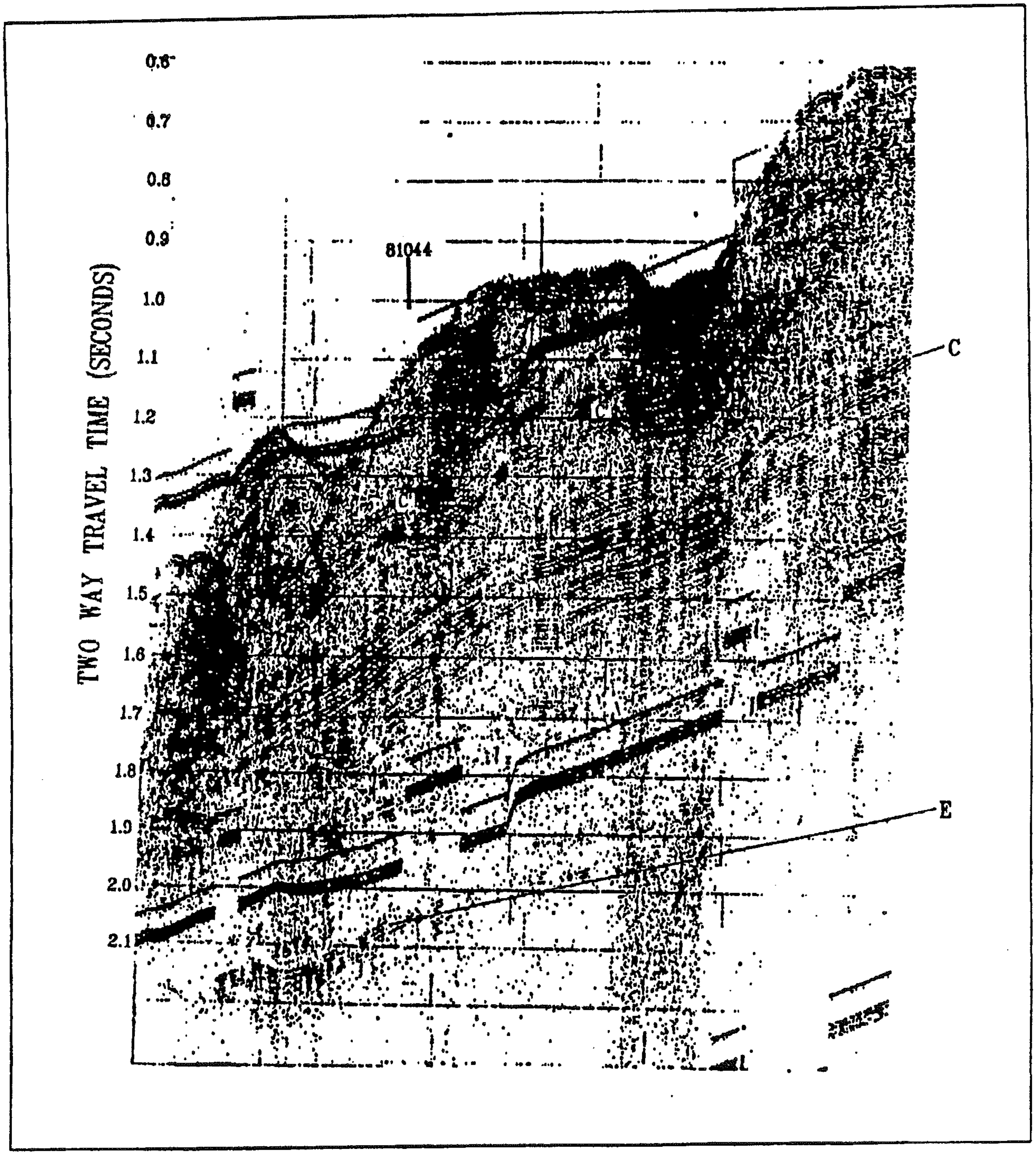
3.1.1 Cenozoic Seismic Setting

Airgun seismic data from the northeast side of the study area consists of two dip lines running from the outer shelf to the middle slope. A connecting strike line runs between the 1100 m and 1200 m isobaths.

Figure 3.2 depicts a line drawing of the airgun seismic from the northeasternmost dip profile (Fig. 3.1). Processed multichannel seismic in the area has been correlated to the Triumph P-50 well-site by low resolution industry seismic and to the Shubenacadie-Acadia area on the basis of reflector character (Clifford, 1986; Piper and Normark, 1989). Reflectors C and E, from the stratigraphy developed by Piper and Normark (1989), were identified in the dip seismic profiles and traced upslope. Piper and Normark (1989) identified the C Horizon as basal Quaternary and E as mid-Pliocene.

Reflector C appears to separate the section into two acoustic facies. Above C, the outer shelf to upper slope is underlain primarily by amorphous reflectors; however, there are several indistinct forset reflectors, possibly linked to paleoshelf breaks. The Quaternary reflectors underlying the middle slope canyon topography tend to be short and discontinuous, giving the impression of alternating transparent and acoustically well-stratified reflectors (Figure 3.4). This alternation results, in part, from the migration of buried

Figure 3.4. Airgun seismic profile from northeast side of the study area, showing the alternation of transparent and well-stratified acoustic facies.


TWO WAY TRAVEL TIME (SECONDS)
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0
2.1
81044
C
C
C
E

valleys, with stratified facies filling some valleys.

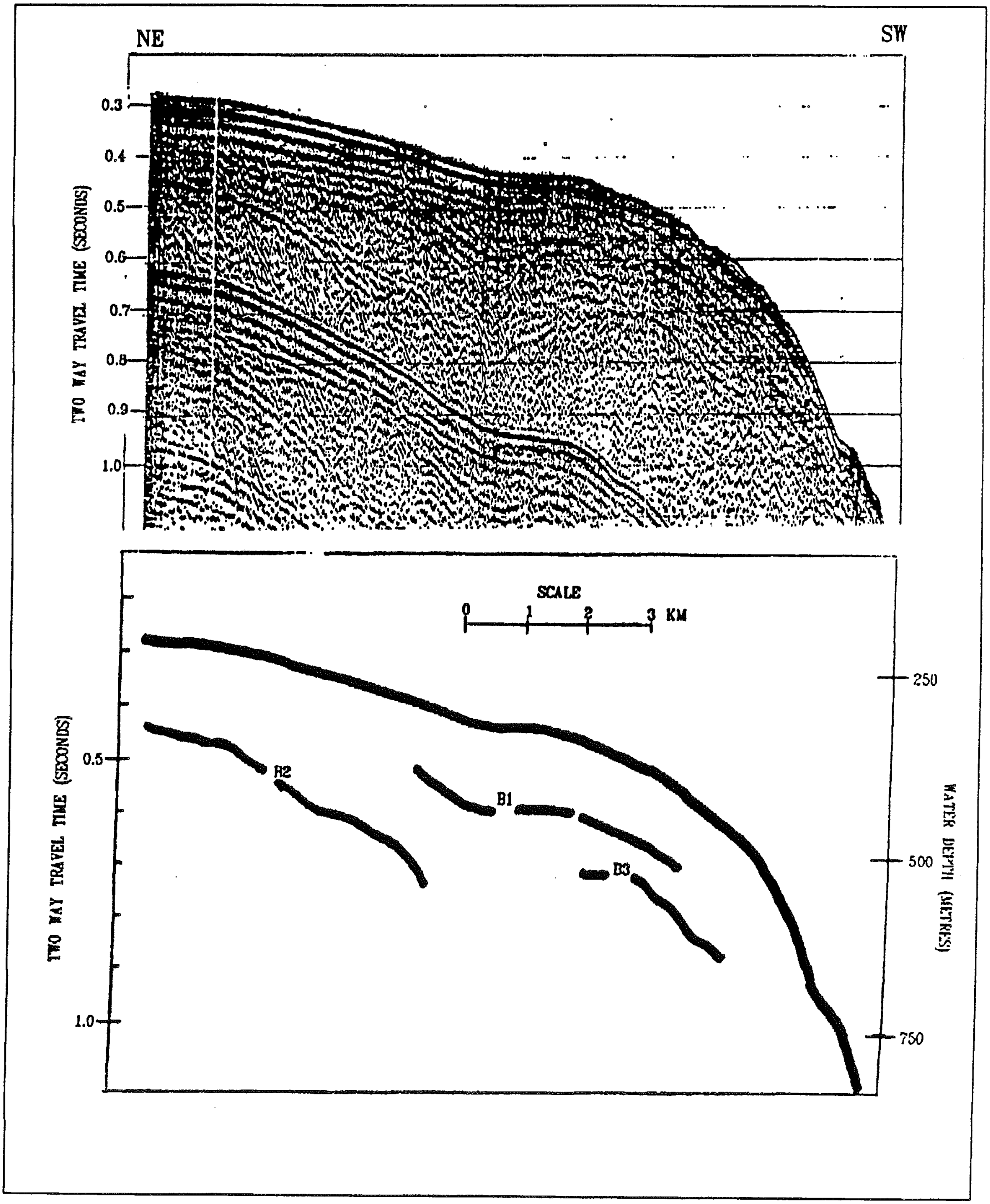
Tracing of the C horizon upslope is hampered by the presence of deep gullies which distort reflector continuity. It is therefore uncertain whether reflector C correlates to the hummocky relief surface (C'in Figure 3.4) or to the top of the acoustically well-stratified reflectors (C in Figure 3.2 and 3.4).

Below C, the late Tertiary sequence has packets of parallel, high amplitude, continuous reflectors, which appear discontinuous only at depth where insufficient seismic energy has penetrated.

The entire sequence is cross cut by a vertical fault which extends from the near-surface through the mid-Pliocene marker. The fault appears to mark the site of a series of buried valleys extending downsection to just above reflector C.

The paleoshelf breaks seen in Figure 3.2 are more readily apparent in Figure 3.5. In this area, 85-036 water gun records interpreted by McLaren (1988) depict two regional horizons which

Figure 3.5. Airgun seismic profile and line drawing from northeast side of study area (88-010 line 7) showing probable paleoshelf breaks. A pattern of progradation and aggradation can be seen going from B2 to B3 to B1. Reflector B1 is tied to the R2 reflector described by McLaren (1988).


NE
SW
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
TWO WAY TRAVEL TIME (SECONDS)
SCALE
0
1
2
3 KM
250
500
750
WATER DEPTH (METRES)
B2
B1
B3
0.5
1.0
TWO WAY TRAVEL TIME (SECONDS)

bound sequences of forset reflectors coming to the outer shelf from Sable Island Bank. R2, the lower regional marker in McLaren (1988), correlates to reflector B1. Taking these "terrace-type" reflectors as paleoshelf breaks, their orientation suggests a progradational then aggradational shelf break sequence.

Figure 3.3 presents the airgun seismic from the southeast side of the study area. Ties to the regional stratigraphy developed by Piper and Normark (1989) were not possible because of the lack of suitable seismic profiles from this area.

Because sub-bottom reflectors lacked significant continuity for a rigorous stratigraphic discussion, the profile was divided into three laterally distinct sections: 1) outer shelf to shelf break; 2) the chaotic to stratified transition on the upper to middle slope; and, 3) the stratified lower slope to upper rise.

The outer shelf to shelf break (section 1) is characterized by continuous reflectors from the outer shelf passing laterally into increasingly discontinuous reflectors. Short, steeply inclined reflectors are abundant, delineating probable channel cuts when seen in conjugate pairs and erosional cuts when singular. Reflections of increasingly discontinuous character become abruptly chaotic just seaward of what appears to be a major buried valley underlying the present-day shelf break.

The upper to middle slope (section 2) encompasses the zone in which the chaotic reflectors of the upper slope gradually give way to the increasing stratification underlying the middle slope. The middle slope is cut by several gullies and underlain by acoustically well-stratified reflectors. As the topography becomes irregular, the sub-bottom acoustic character between gullies appears to become continuous and well-stratified.

Section 3 includes the acoustically well-stratified sediments of the lower slope to upper rise. These reflectors appear to be bounded by hyperbolics which are possibly related to paleogully-cutting events. One hyperbolic set appears to be a fault which extends to base of the section, tending to flatten out at depth. Within the section there is a periodic transition between transparent and stratified units; but, it is seen to a much lesser extent than on the northeastern side of the study area.

Records from the northeast and southwest sides of the study area tend to show little local variation in seismic character. Both sides of the study area are cut by major submarine canyons which distort reflector continuity by producing hyperbolics. In some cases, reflectors traced on the inter-gully ridges are cut by the gullies; though, in most cases, hyperbolic diffractions make it impossible to determine if reflectors outcrop or drape the gully walls. Faults are seen in both, although it is unlikely that the fault in Fig. 3.2 cutting the middle slope is the same fault as that in Fig. 3.3, which cuts the upper rise. Of note, also, is a westward thickening of near-surface sediments implied by variation in the depth of R2. From a depth of 17 m (23 ms) sub-bottom in the Huntec DTS record from line 9 (88-010), R2 deepens to approximately 200 m sub-bottom in the airgun seismic from line 7 (Figure 3.5).

The Cenozoic setting at Logan Canyon appears to be dominated by thick accumulations of sediment through the Quaternary which have been incised by canyon cutting events. Due to the depth of the shelf break at Logan Canyon, glacial lowstands of sea level would have produced an emergent shelf break. Glacially derived sediments would, consequently, have been delivered directly to the slope with melt water events probably cutting the observed canyons. Sedimentation on the locally high relief inter-gully ridges would have been continuous as is suggested by their acoustically well-stratified nature. In addition, the alternation of transparent and well-stratified reflectors is a possible record of variations in glacial-derived sediment delivery. The acoustically transparent zones (probably representing muds; Droz and Bellaiche, 1985) would represent hemipelagic sedimentation during times of weakened glacial-fluvial input (?because of glacial retreat). The acoustically well-stratified reflectors (probably alternating sands and muds;

Droz and Bellaiche, 1985) would represent sediments dominated by coarser grained glacial-fluvial material (?because of glacial advance).

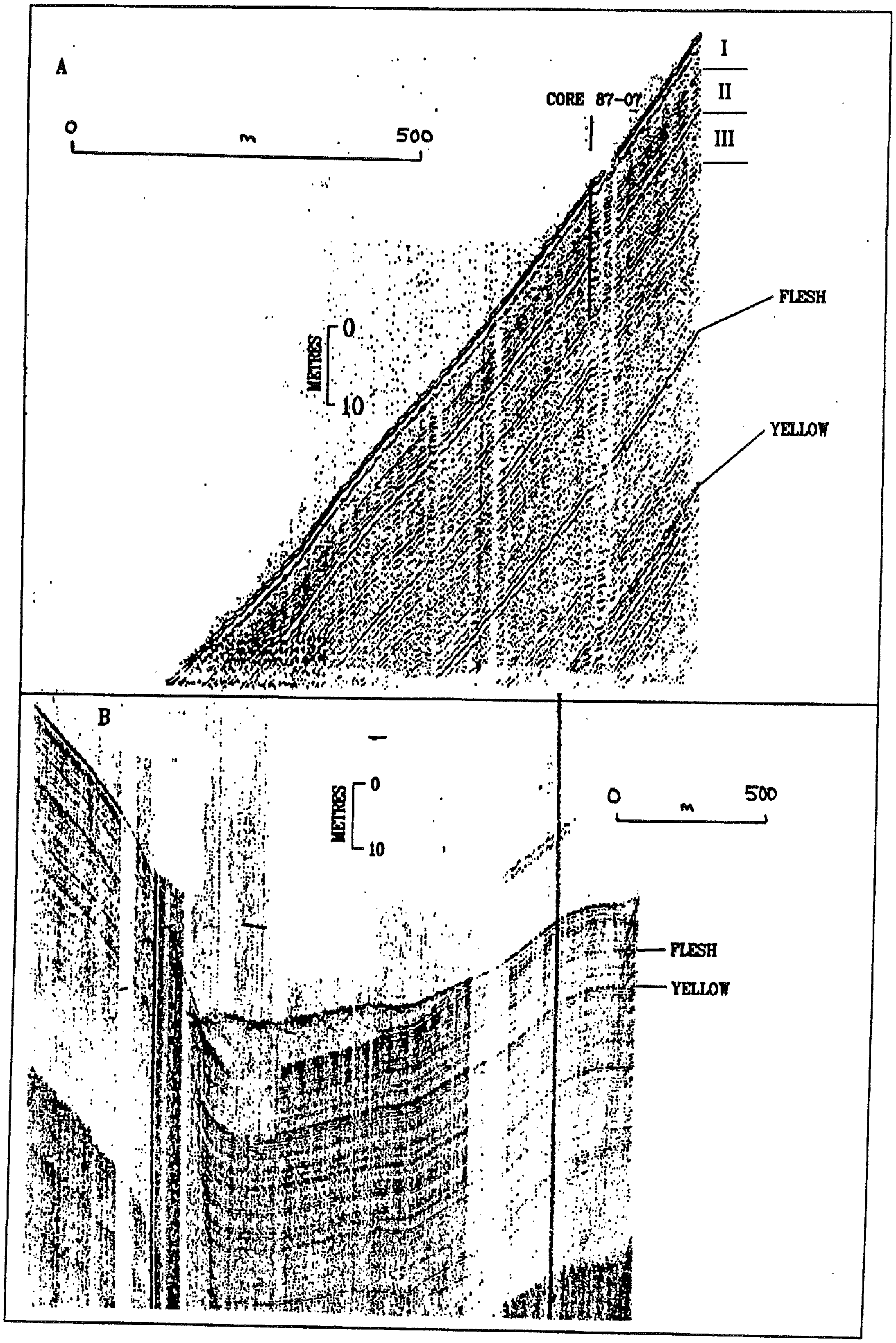
3.1.2 Surficial Geology

Near-surface Seismic: Huntec DTS

The limited Huntec DTS data available on the northeast side of Logan Canyon area depicts an irregular reflector 23 ms sub-bottom in the vicinity of the shelf break. This reflector ties to the R2 marker in McLaren (1988). It can be traced downslope to 350 m water depth and is overlain by an acoustically amorphous unit. Huntec DTS records on the outer shelf to upper slope also show a highly reflective ("hard-bottom") sea bed which has probable iceberg scours to water depths of at least 300 m.

On the southwest side of the study area Huntec records are more extensive with good quality data existing from the lower slope to upper rise, corresponding to section 3 of the airgun seismic presentation. Two correlable reflectors are defined in the Huntec profile in the vicinity of Core 87-003-007 (Figure 3.6a). Below the yellow horizon regularly stratified reflectors can be traced throughout the record. These reflectors and those above yellow trend toward an upslope thickening. The Huntec profile does not show any reflector pairs deviating significantly from this trend. Above yellow, two relatively recent gully cutting events are seen on the lower slope which cross-cut the flesh reflector (Figure 3.6b). The gully fill is distinctly amorphous.

Figure 3.6. Huntec DTS profiles from the southwest side of the study area. A) Huntec DTS profile in the vicinity of core 87-003-007. Seismic horizon I is the surficial transparent unit; horizon II is the well-stratified reflectors; horizon III is the appears to be amorphous with sporadic strong reflectors. B) Huntec DTS profile showing possible gully-cutting on the upper rise with amorphous fill at the surface of this gully (?debris flow).


A
0
m
500
CORE 87-07
I
II
III
METRES
0
10
FLESH
YELLOW
B
METRES
0
10
0
m
500
FLESH
YELLOW

In general, the surficial geology reinforces the acoustic observations made from the airgun record. Sediments tend to be acoustically well-stratified on the lower slope to upper rise.

Cores

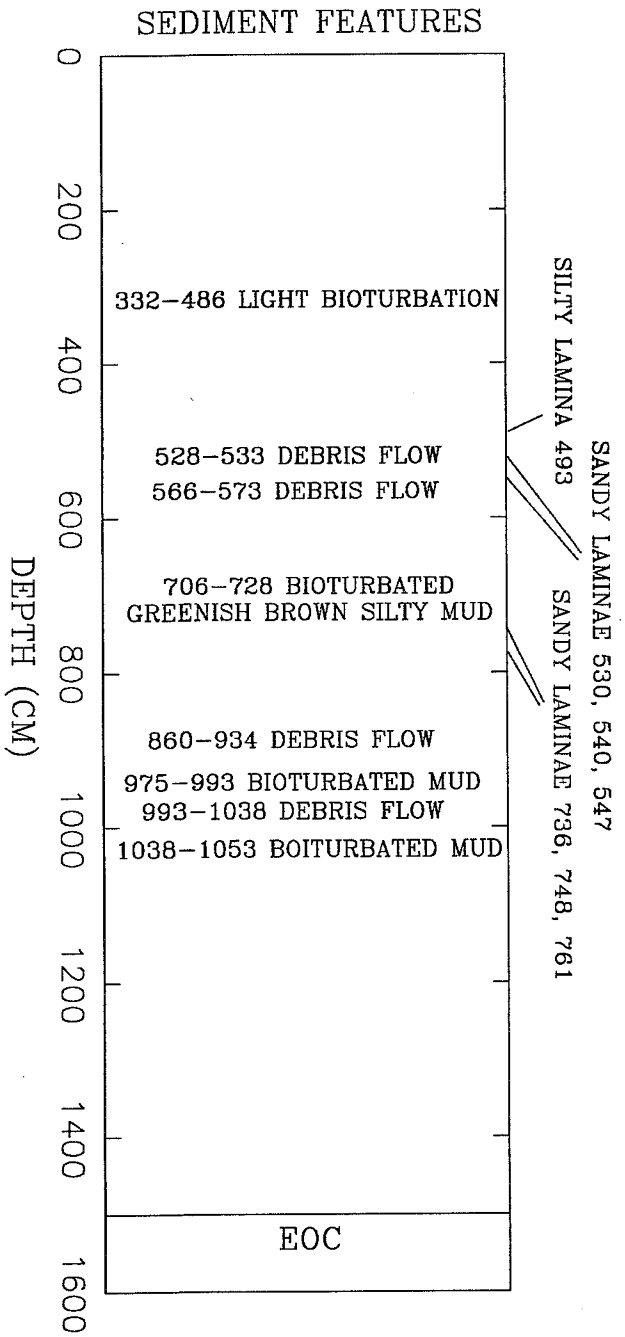
Two cores provide lithologic control of the surficial geology. Core 88-010, collected in 345 m water depth, appears to have subsampled an amorphous seismic unit. Coring retrieved 73 cm of sand.

Core 87-003-007 was collected in 920 m water depth on the lower middle slope. Figure 3.7 presents a summary core description with velocity and bulk density measurements. Coring retrieved 1500 cm of muds and silty muds though the basal 394 cm were suspected to be flow in.

The trigger weight core consists of structureless olive-grey mud similar to the lithology at the top of the piston core, though exact correlation is not possible. In the piston core these olive-grey muds continue to a depth of 400 cm where they are underlain by a lightly bioturbated grey-brown mud with silty laminae. Below 523 cm, three lithologic units are distinguished: 1) coarse grained graded beds with varying amounts of mud; 2) red-brown muds with abundant clay clasts, sporadic pebbles and some sandy laminae; and, 3) bioturbated greenish brown silty mud.

Figure 3.7. Summary core description of 87-003-007.

SUMMARY CORE DESCRIPTION
CORE 87-003-007



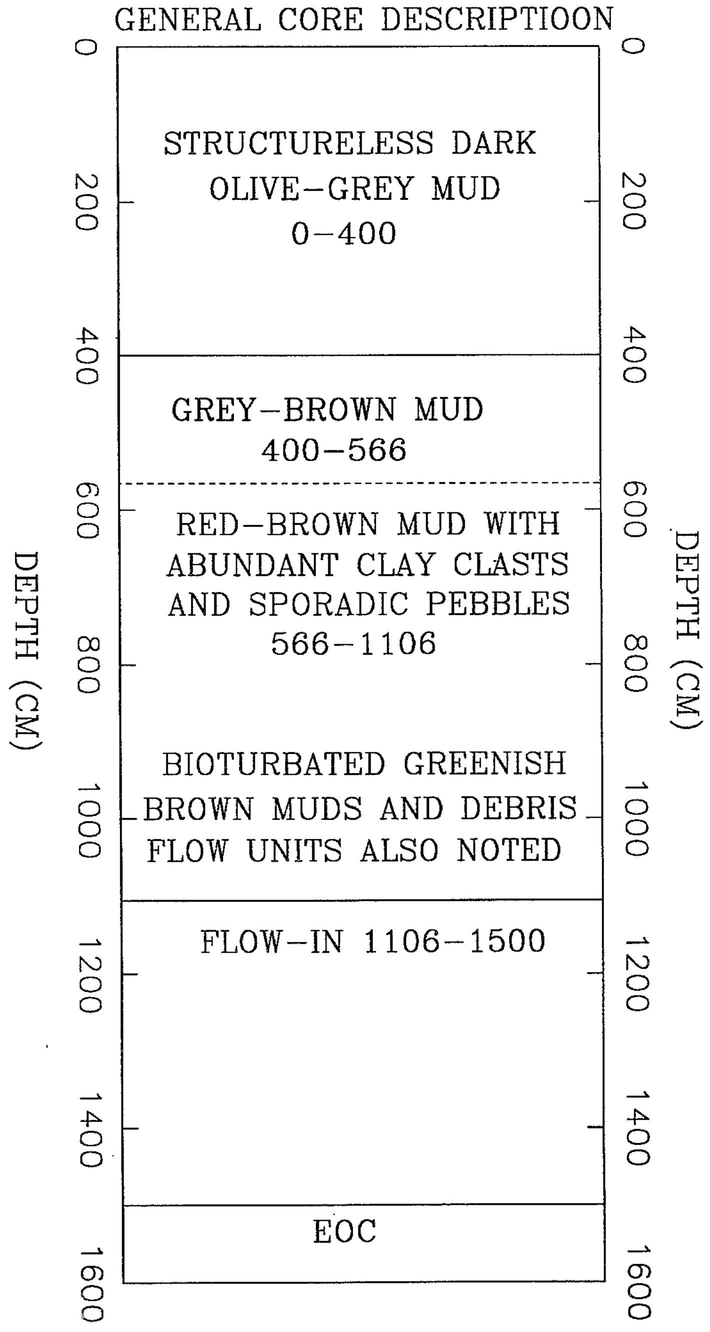


Table 3 and Figure 3.8 summarize and illustrate the downcore distribution of facies, respectively.

Table 3: Description of Lithofacies: Logan Canyon transect

Facies A: olive-grey mud --
    1) without ice-rafted detritus
    2) with ice-rafted detritus

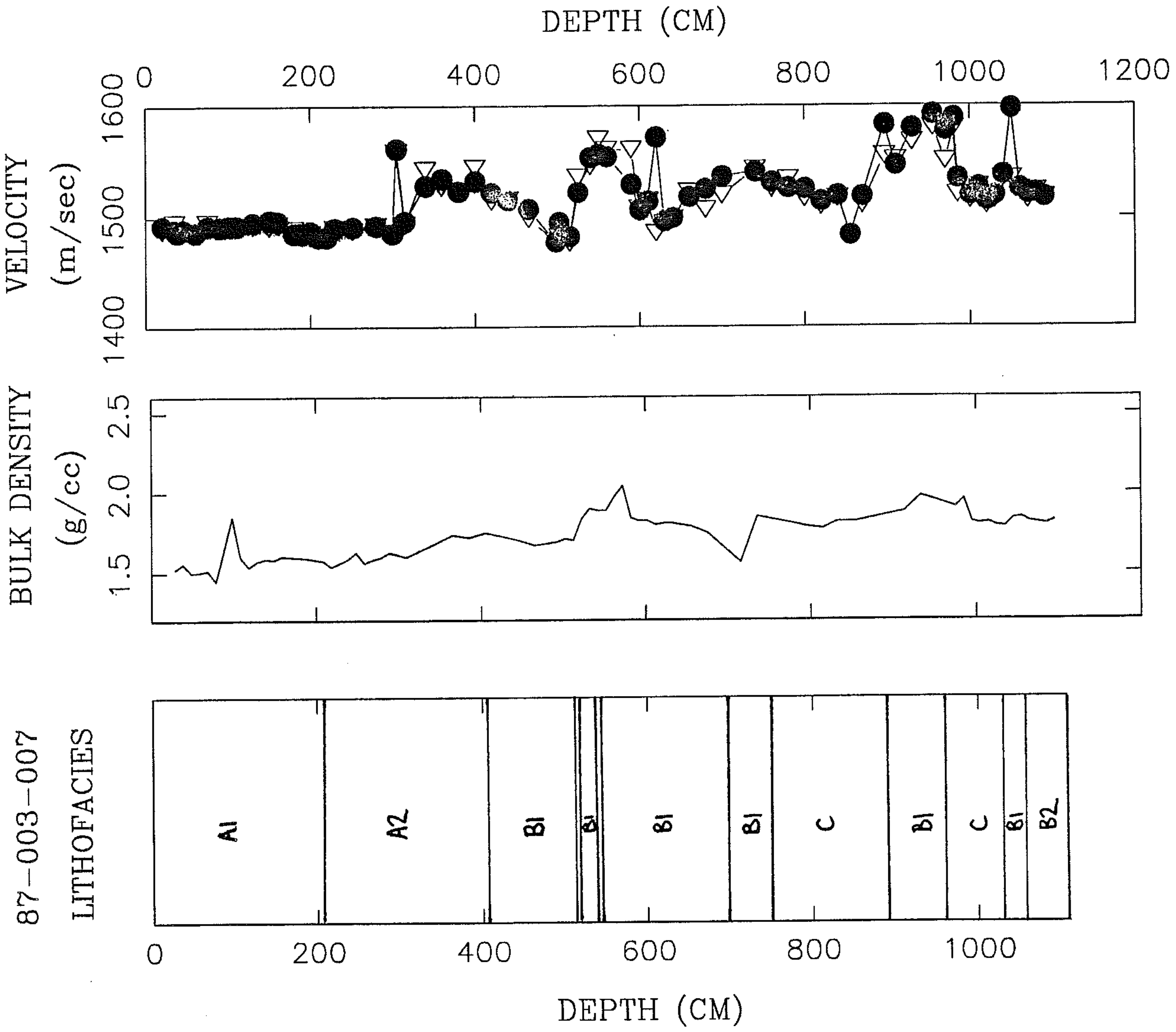
Facies B: brown bioturbated muds having some silty or sandy laminae and scattered ice-rafted detritus
    1) greenish to greyish brown
    2) reddish brown

Facies C: coarse-grained graded beds with varying amounts of interbedded mud, typically red-brown.

Facies A1 correlates to the extensive olive-grey Holocene muds on the Scotian Slope described by Hill (1984). This facies is thought to represent ambient sedimentation during the present interglacial. It is found at the top of the core and remains distinct from the other facies.

Facies A2 is the glacial equivalent of A1. Facies A2 most probably represents ice-distal conditions during the end of the last glaciation when icebergs would have been abundant from the break up of the continental ice sheet.

Figure 3.8. Downcore distribution of lithofacies in core 87-003-007 with selected physical properties. Facies are defined in Table 3.


DEPTH (CM)
0
200
400
600
800
1000
1200
VELOCITY
(m/sec)
1400
1500
1600
BULK DENSITY
(g/cc)
1.5
2.0
2.5
87-003-007
LITHOFACIES
A1
A2
B1
B1
B1
B1
C
B1
C
B1
B2
0
200
400
600
800
1000
DEPTH (CM)

Facies B1 most likely originates from glacial-fluvial sediment delivery to Logan Canyon. The brownish colour of the facies is probably a result of ice-marginal conditions -- sediment being supplied by glacial erosion of the Carboniferous red beds in Nova Scotia (Hill, 1984).

Facies B2 is most likely similar to B1 except that the concentration of reddish glacially-derived sediment is higher. If one can suggest that olive-grey muds are continuously supplied to the area then facies B1 is less red because of greater dilution. The reddish brown nature of facies B2 then suggests its deposition was primarily episodic, not allowing for dilution.

Facies C is characterized by graded coarse-grained beds. They are inferred to be debris flows (Aksu, 1984), though evidence remains inconclusive.

Facies B1, B2, and C are interbedded in the lower half of the core (Fig. 3.8). This suggests there were periodic changes in sediment provenance and/or the depositional mechanism. Deciding whether a change in provenance or depositional mechanism is the predominant cause of the interbedding hinges upon the episodic nature of facies B2 and C (?debris flows). If facies B2 can be considered as a concentrated form of the same source as facies B1 (suggested above), then it is most likely episodic.

Consequently, variations in depositional mechanism would have caused the interbedding, most of the accumulated sediments being quickly deposited by event deposition.

If facies B2 and C can be considered episodic then at a depth of 523 cm in the core, there is a major break in the nature of sedimentation on the lower slope at Logan Canyon. Above this horizon, sediments appear to be regular hemipelagic; whereas, below this horizon, debris flow deposition greatly influences sediment accumulation.

Using velocity and bulk density to predict reflections, the core can be placed in the Huntec record. Lithologic control effectively extends through three seismic units (labelled I, II, and III in Figure 3.6). The peak in bulk density and velocity at approximately 520 cm in the core (first occurrence of facies C) was tied to the base of the of the acoustically well-stratified unit. Seismic unit I is the upper transparent unit which correlates to facies A1. Seismic unit II is acoustically well-stratified and contains Facies A2 and B1. Seismic unit III is acoustically amorphous with periodic strong reflections which correlates to the interbedding of Facies B1, B2, and C.

Reflectors from the core site terminate upslope at a crest formed by the middle slope canyon cutting. Downslope, the reflectors are lost passing into an increasingly transparent zone as the slope gradient decreases.

3.2 La Have Slope Transect

The data collected by the CSS DAWSON in April 1990 (90-002) represents the first attempt to assemble a regional geologic framework on the La Have Slope off Browns and La Have Bank (Figure 3.9). Consequently, the regional surficial geology and seismic stratigraphy are poorly known.

The bathymetry on the La Have Slope shows a lack of deep canyons, in contrast to the Logan Canyon area and elsewhere on the continental slope (Uchupi and Swift, in press). However, smaller-scale bathymetric features, especially downslope channels, are found.

The slope geometry at La Have is characterized by a deep water shelf break (150 to 170 m water depth). There is no significant inflection point which marks the outer shelf to upper slope boundary. The outer shelf very gradually steepens to the upper slope which has an average gradient of approximately 2.4 degrees (Figure 3.10).

Figure 3.9. Map showing data distribution and bathymetry on the La Have Slope off Browns Bank. Bold lines denote seismic profiles. Dots refer to core locations.

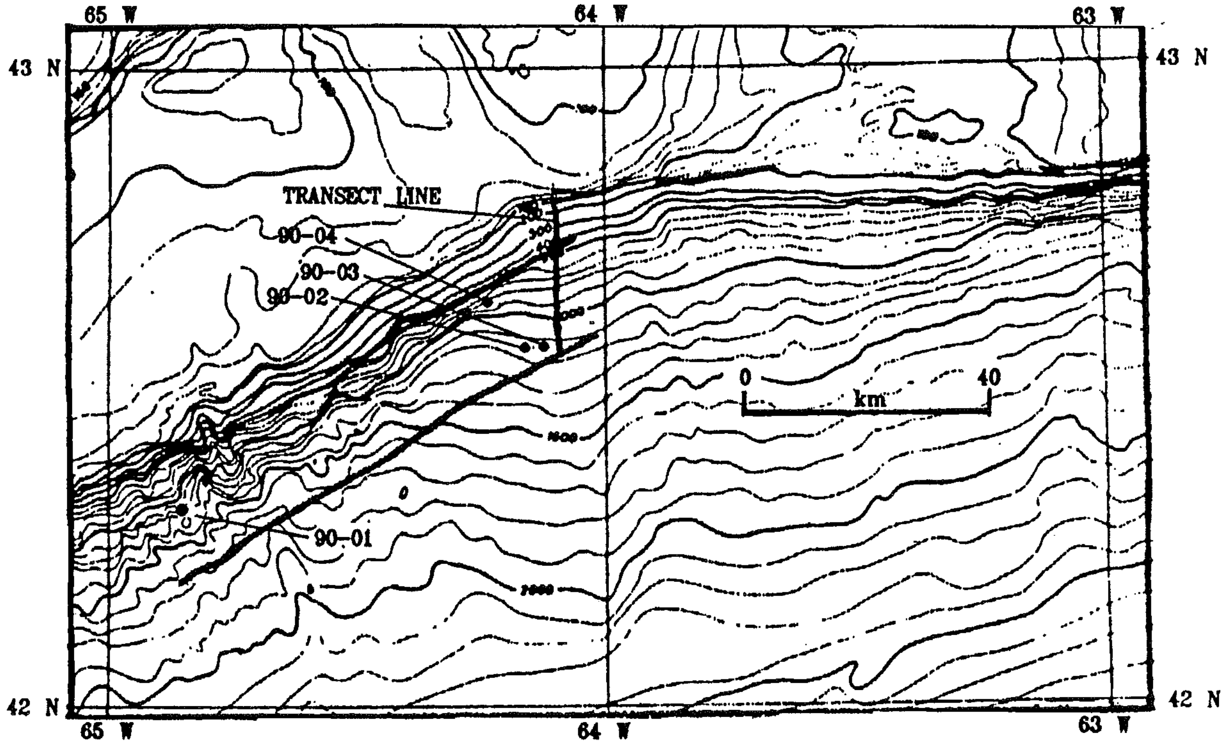
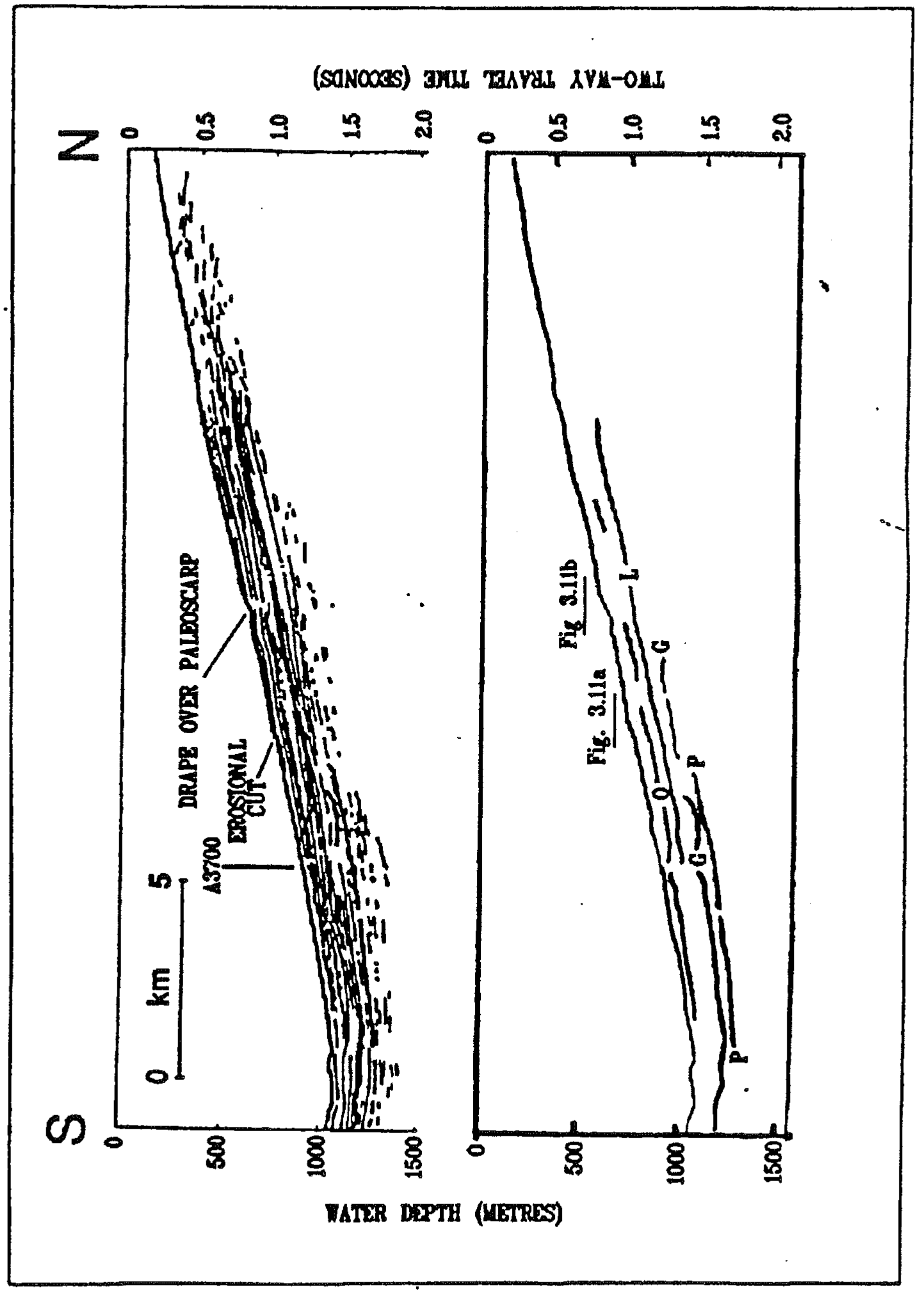

65 W
64 W
63 W
43 N
43 N
TRANSECT LINE
90-04
90-03
90-02
0
40
km
1500
90-01
2000
42 N
42 N
65 W
64 W
63 W

Figure 3.10. Line drawing of dip airgun seismic from La Have Slope. Annotations refer to interpretations of 3.5 kHz profiler data shown in Figure 3.11. A3700 refers to an industry seismic line which crosses the profile.


S
N
0 km 5
A3700
EROSIONAL CUT
DRAPE OVER PALEOSCARP
TWO-WAY TRAVEL TIME (SECONDS)
0
0.5
1.0
1.5
2.0
WATER DEPTH (METRES)
0
500
1000
1500
Fig. 3.11a
Fig. 3.11b
L
G
O
P
G
P

The topography along the transect is smooth with minor sea floor relief at about 500 m water depth. Two erosional cuts appearing to be recent and paleoscarps (noted in Figure 3.12) are the only other significant breaks in the sea floor morphology. Topography along strike tends to be gentle in the vicinity of the transect line. To the west, the strike seismic profile shows large channels (typically 300-350 m deep) running downslope. These channels tend to shallow downslope; the next strike seismic line downslope shows little evidence of such a varied bathymetry.

3.2.1 Cenozoic Seismic Setting

Figure 3.10 is a line drawing representation of a dip airgun seismic profile from La Have Slope. Several continuous reflectors identified in the record help to divide the stratigraphy into distinct units. Even with the proximity of the Shelbourne well-site and available multichannel seismic profiles, ties to a regional stratigraphy were not possible. Reflectors traced in industry seismic (tied to the Shelbourne well-site) were too deep to be transferred onto the single channel seismic profile.

Four correlable horizons are distinguished in the airgun record: P=pink, G=green, L=lavender, and O=orange. The sequence below pink consists of flat-lying discontinuous reflectors; a character which continues downsection to the limits of airgun resolution. The green reflector has substantial relief and appears to be associated with development of several levee-like features.

Overlying green is the lavender horizon which marks a major unconformity. The unconformity was identified by its onlap of overlying reflectors. However, much of the surface is not characterized by onlap, appearing as part of a continuous upsection sequence. Above this horizon and continuing upsection to the orange marker, erosional cuts, minor unconformable relationships, and broad channel cuts appear common.

Orange marks the return to regularly and acoustically well-stratified sediments. Sediments above the orange horizon, for the most part, mimic the topography of the sea floor.

In the vicinity of the shelf break/upper slope a prominent amorphous zone seems to intertongue with the well-defined reflecting sequences. Such behaviour is analogous to the amorphous wedges at Verrill Canyon described by Mosher et al. (1988).

Erosional events causing unconformities dominate the Cenozoic setting on the La Have Slope. At least some of these erosional events appear as probable slump events (producing near-surface scarps). These events are typically overlain by draping reflectors. This would suggest that the history of the upper part of the section is a balance between hemipelagic or pelagic sedimentation and erosion. Such behaviour is not seen at the green horizon where levee development would imply the lack of erosional processes.

3.2.2 Surficial Geology

Near-surface Seismic: 3.5 kHz

The seismic investigation of the surficial geology was limited by the lack of continuous near-surface reflectors. A summary interpretation of 3.5 kHz sub-bottom profiler data is included with the line drawing (Fig. 3.10). Besides the probable iceberg furrows, the scarps are the major surficial features along the transect (Figure 3.11). Along strike, downslope channels with levee formations are prominent (Figure 3.12). Also of note is a surficial debris flow seen to the west of the transect line (Figure 3.13).

Figure 3.11. Dip 3.5 kHz profiles showing major surficial features annotated in Figure 3.10. A) recent erosional cut possibly related to slumping. B) Draping reflectors over a buried erosional cut possibly related to a slump event.

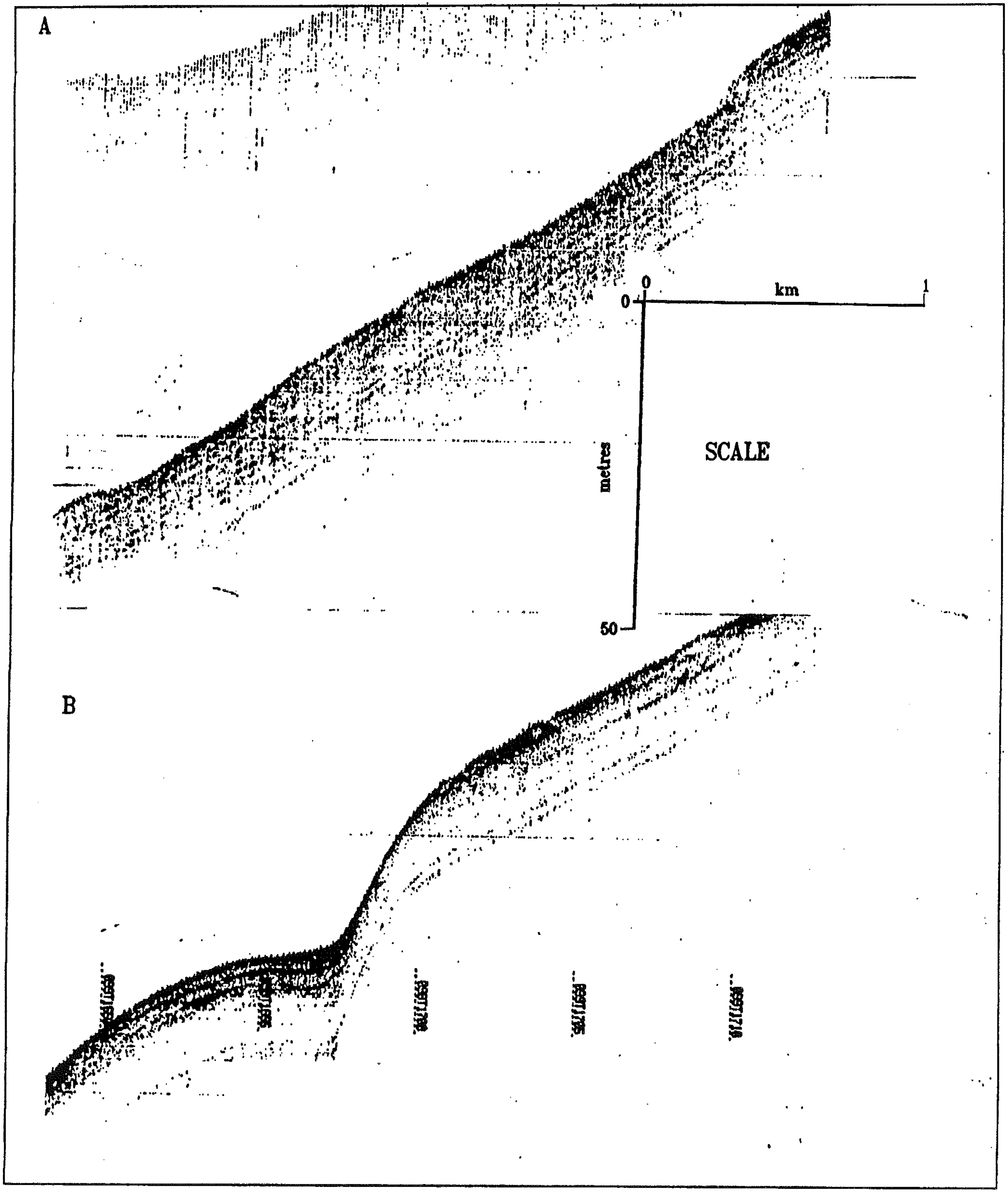

A
0
km
1
0
metres
50
SCALE
B
0657/1650
0657/1655
0657/1700
0657/1705
0657/1710

Figure 3.12. Strike 3.5 kHz profile showing levee and channel development on La Have Slope.

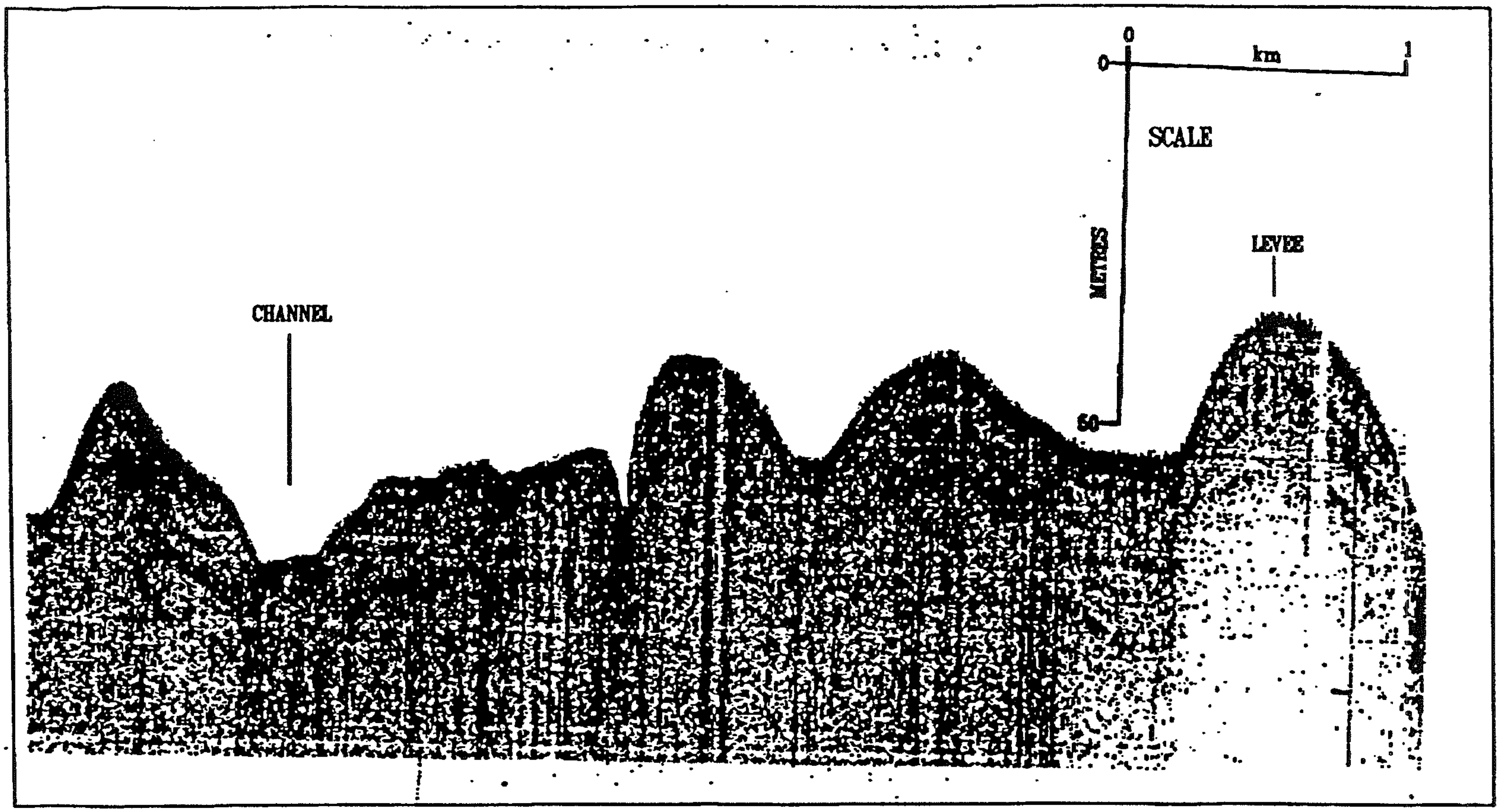
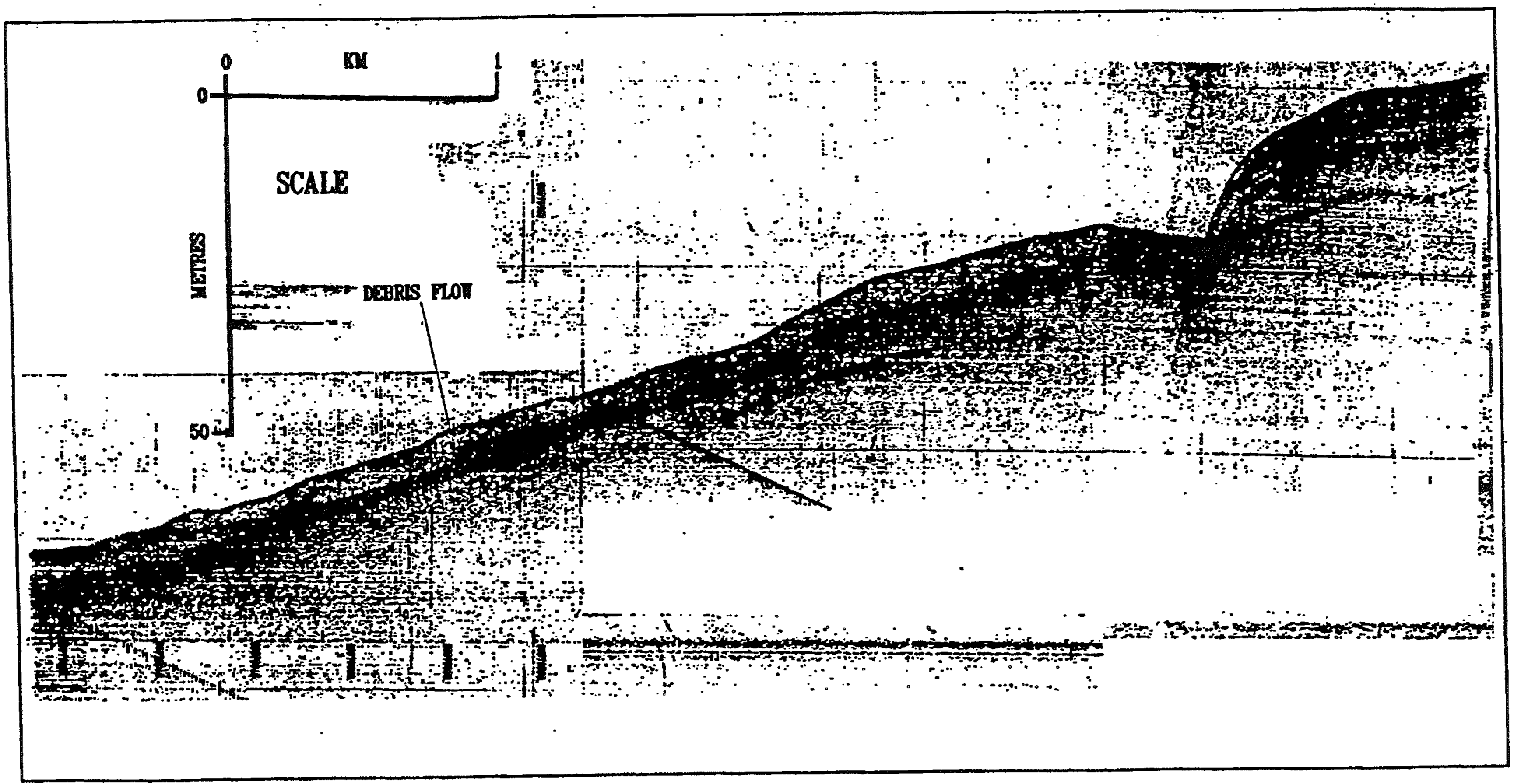

0
0
km
1
SCALE
METRES
50
LEVEE
CHANNEL

Figure 3.13. Strike 3.5 kHz profile showing a surficial debris flow located west of the line shown in Figure 3.10.


0
KM
1
0
SCALE
METRES
DEBRIS FLOW
50

Cores

Four Benthos piston cores provide lithologic control of the surficial geology. Cores 002, 003, and 004 run approximately along the transect line. Core 001 is located 60 km west of core 003 in similar water depths. Core collection data is found in Table 4.

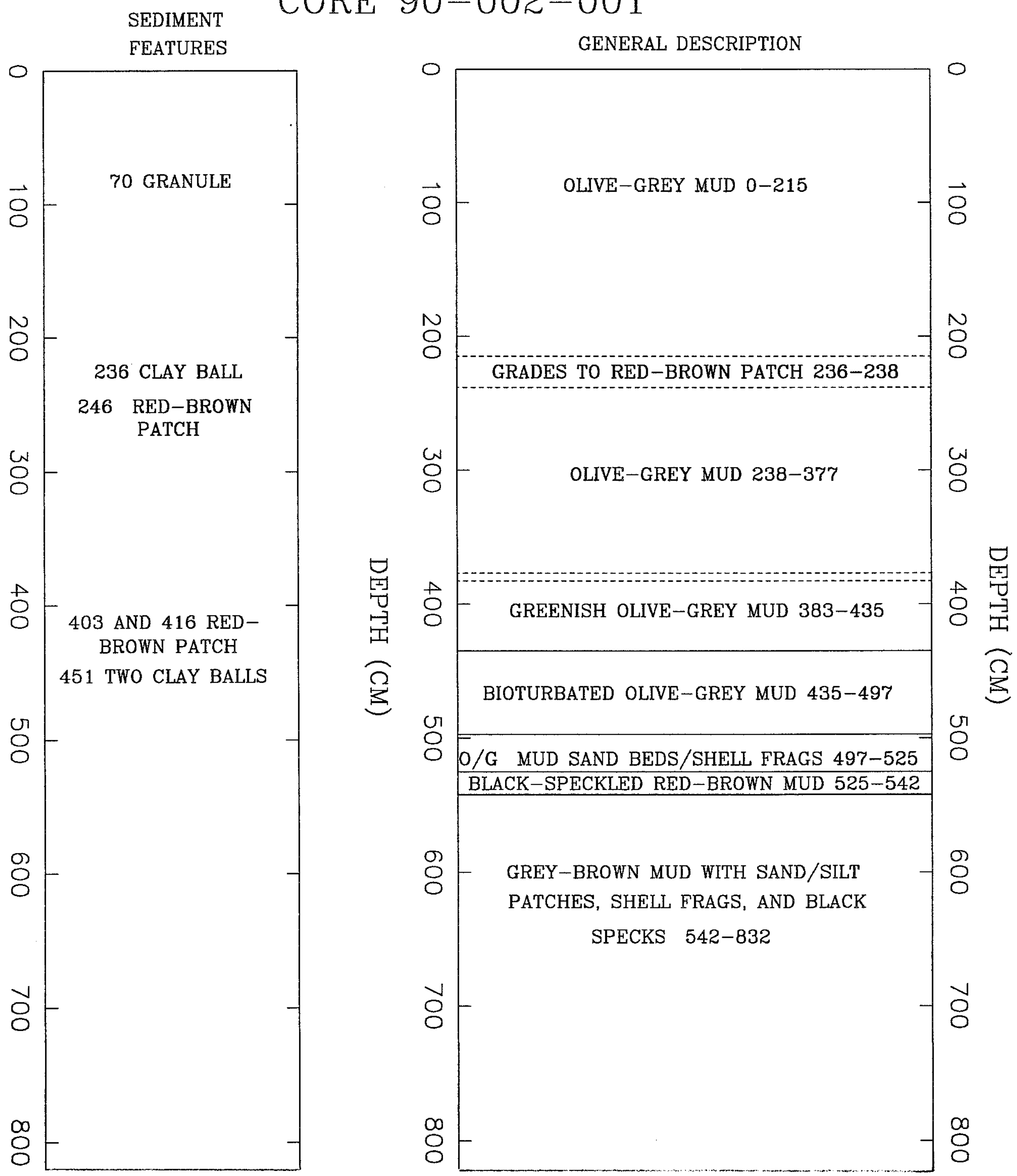
Table 4: Collection data for cores in the La Have Slope area

Core	Location	Water Depth (m)	Total Length (cm)
001	42 19.18N 64 50.87W	1117	832
002	42 34.03N 64 08.84W	1042	512
003	42 34.00N 64 07.00W	1040	551
004	42 38.78N 64 13.73W	629	585

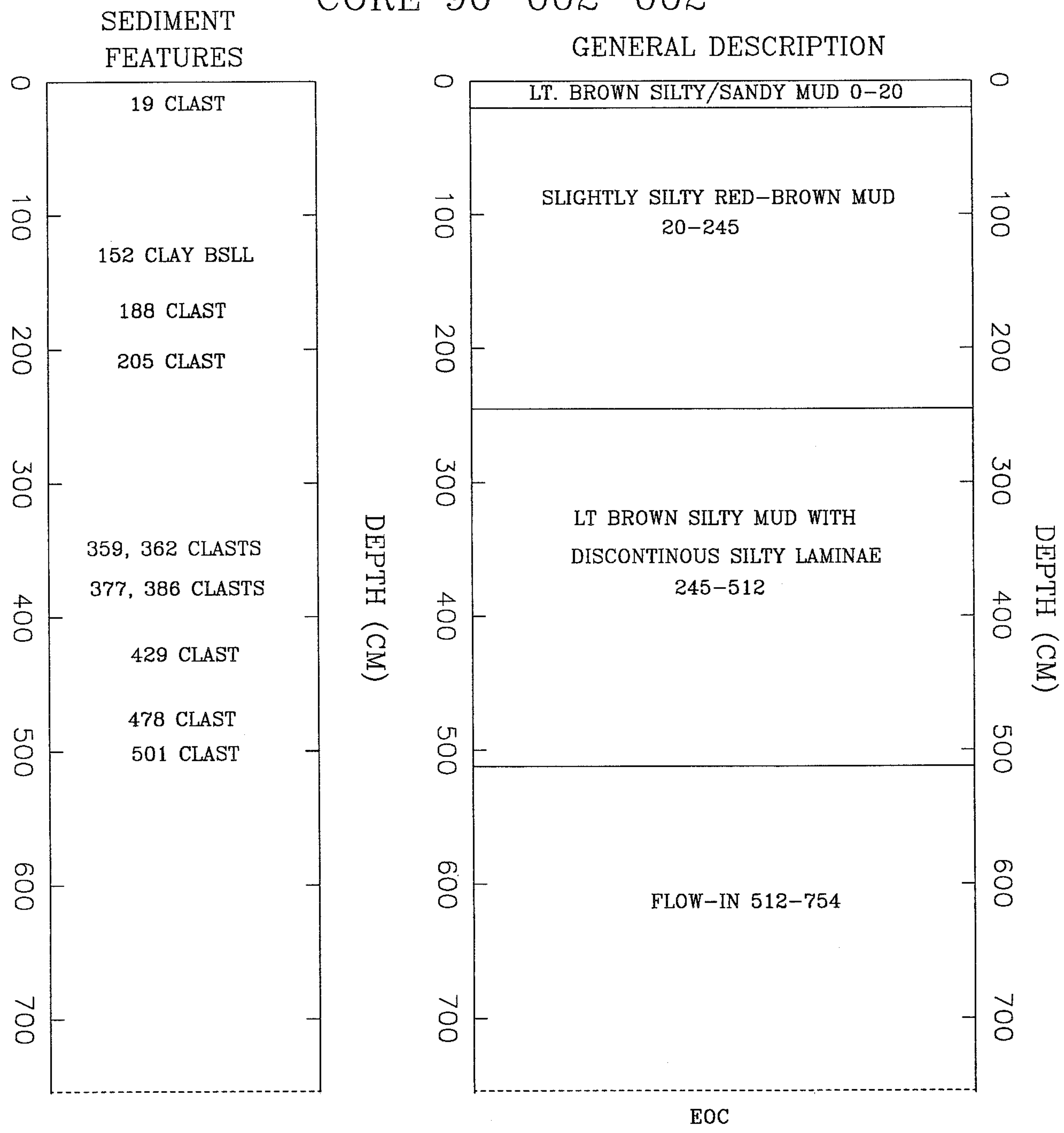
Figures 3.14a-d present summary descriptions of the four cores. Figure 3.15 illustrated the downcore distribution of the lithofacies (summarized in Table 5) and a tentative correlation between the cores. Since core 001 is somewhat removed from the other three, correlation with it is extremely uncertain.

Figure 3.14. Summary descriptions of cores from La Have Slope: A) core 90-002-001; B) core 90-002-002; C) core 90-002-003; D) core 90-002-004.

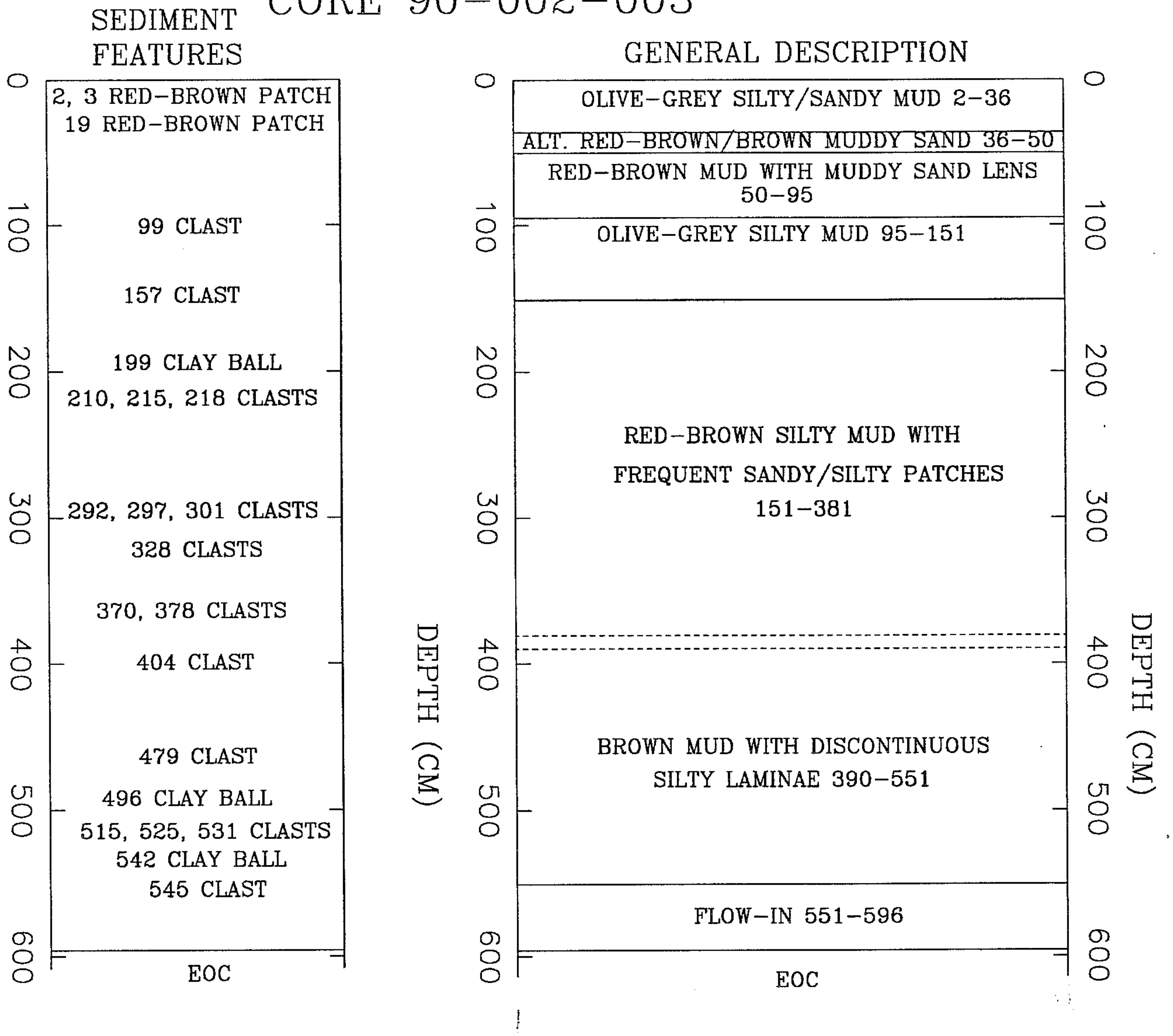
SUMMARY CORE DESCRIPTION
CORE 90-002-001



SUMMARY CORE DESCRIPTION
CORE 90-002-002



SUMMARY CORE DESCRIPTION
CORE 90-002-003



SUMMARY CORE DESCRIPTION
CORE 90-002-004

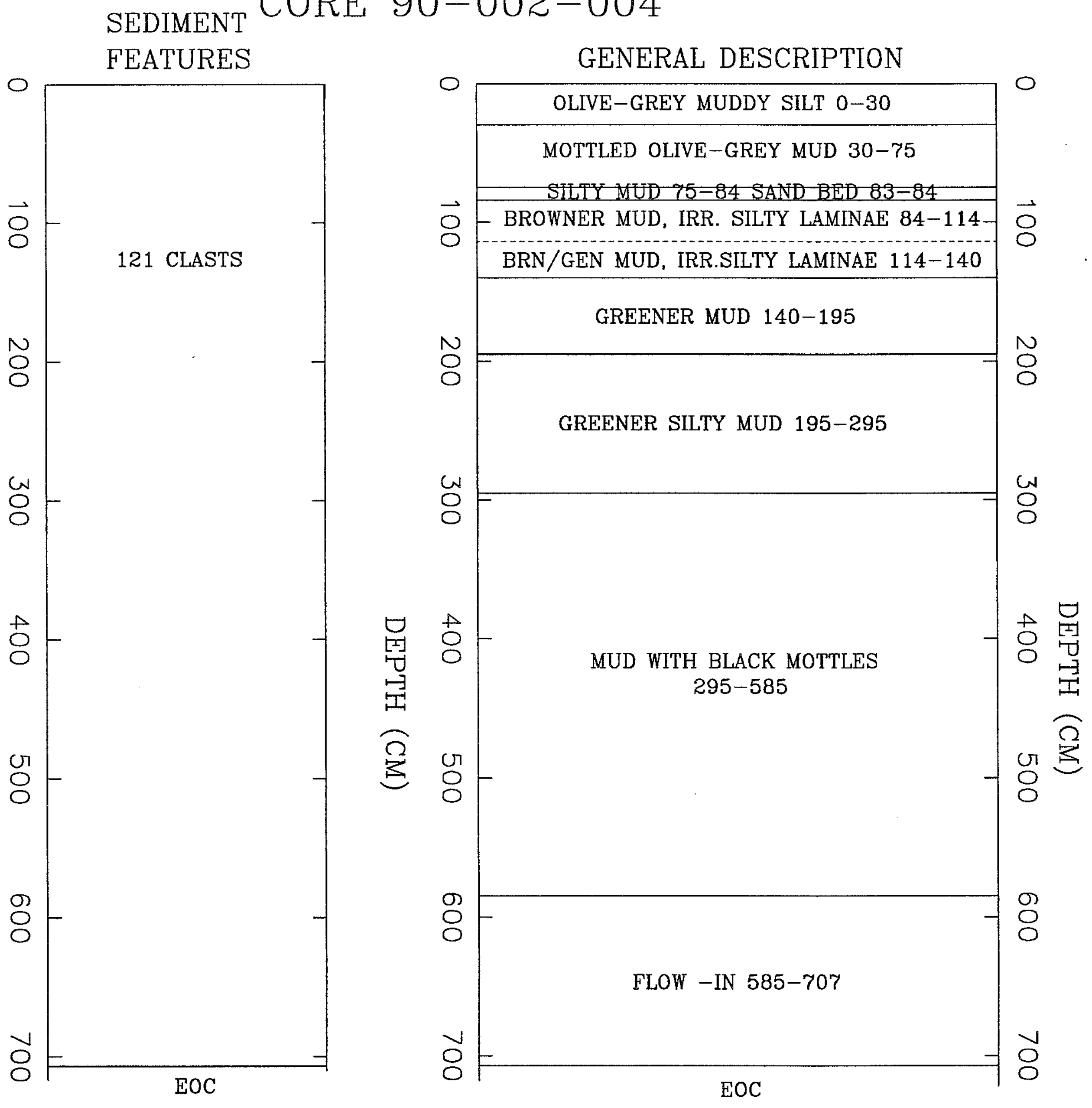


Figure 3.15. Downcore distribution of lithofacies in cores from La Have Slope and a tentative correlation. Location of C-14 dates in core 90-04 is also given.

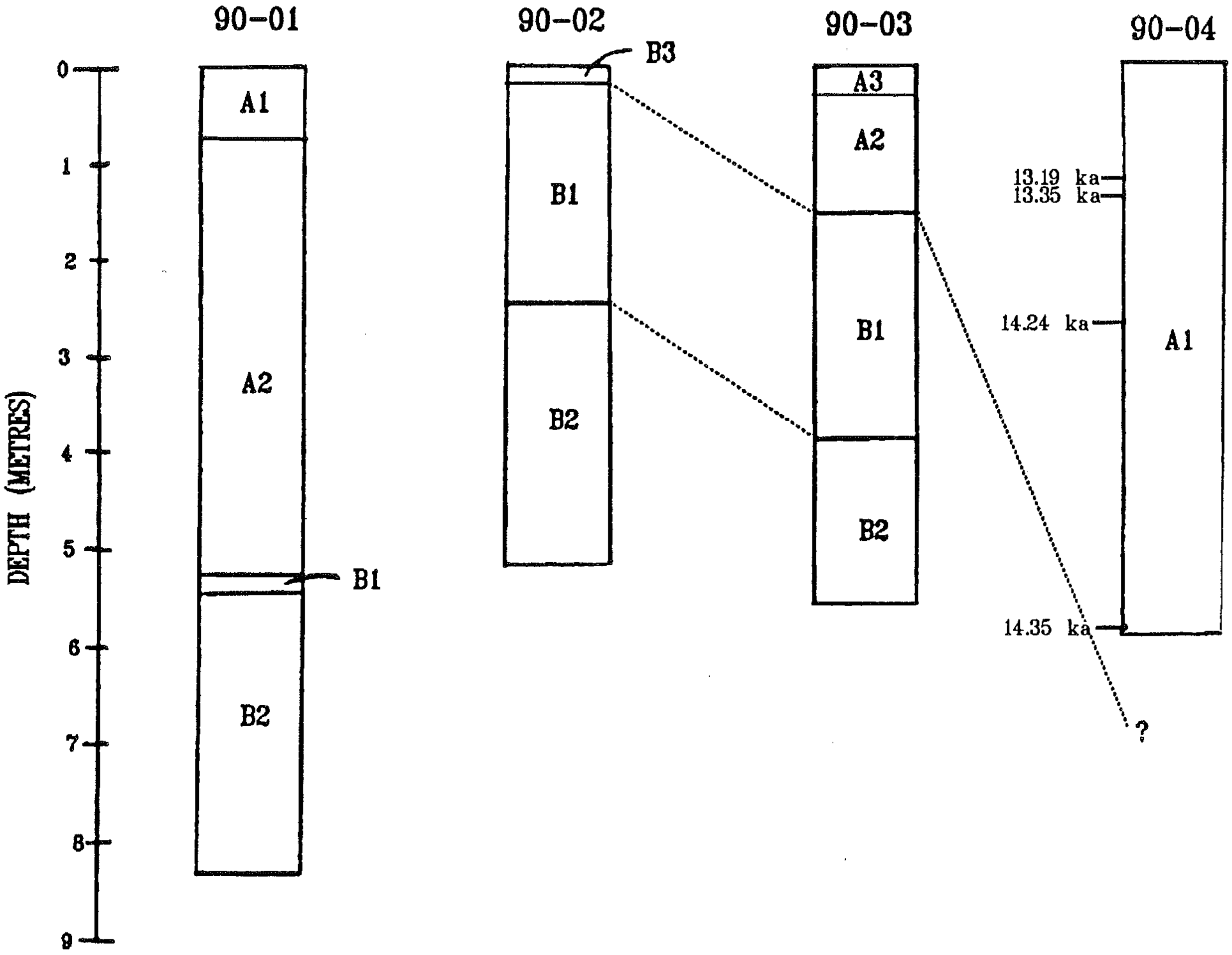

90-01
90-02
90-03
90-04
DEPTH (METRES)
0
1
2
3
4
5
6
7
8
9
A1
A2
B1
B2
B3
B1
B2
A3
A2
B1
B2
13.19 ka
13.35 ka
14.24 ka
14.35 ka
A1
?

Table 5: Description of Lithofacies: La Have Slope transect

Facies A: olive-grey to green mud with varying amounts of silt and sand --
- 1) without ice-rafted detritus
- 2) with ice-rafted detritus
- 3) muddy sands or sandy muds

Facies B: brown silty mud with abundant pebbles
- 1) light brown with black mottles and/or discontinuous silty laminae
- 2) reddish-brown sediments
- 3) structureless light brown mud

Facies A1 and A2 are equivalent to facies A1 and A2 from Logan Canyon. However, facies A1 and A2 have infrequent red-brown beds no more than 2 cm thick usually occurring as patches. These beds are normally thought to represent storm-induced redeposition of older deposits (?facies B2). Facies A3 appears to represent Holocene reworking. The origin of the sands seen in core 003 is speculative; but, they could represent the redeposition (? by turbidity currents) of glacially derived sands thought to be widespread on the outer shelf to upper slope (King, 1970; Drapeau and King, 1972).

Facies B1 and B2 are again equivalent to B1 and B2 from Logan Canyon. The laminae of facies B1 at La Have Slope tend to be discontinuous, unlike the Logan Canyon equivalent. Discontinuity appears to have been caused by bioturbation. Facies B3, a structureless brown mud, occurs at the top of core 002 only. Core 002 subsamples the top of a prominent levee on the lower slope. Facies B3 may then represent the reworking of facies B1 with resuspension and deposition of the fine-grained component on the levee.

Core 001 is represented by facies A1, A2, and B1. The occurrence of A2 near the top of the core suggests that this core subsamples an older horizon than the other cores. Core 001 is directly seaward of Browns Bank while cores 002, 003 and 004 lie seaward of the channel that separates Browns and La Have Bank (Fig. 3.9). Consequently, sediment delivery to core 001 is thought to be at a lower rate than the other cores.

The correlation between core 002 and 003 (Figure 3.15) is based on the occurrence and stratigraphic positions of facies B1 and B2. Facies B2 is especially distinct in appearance thus facilitating the correlation. The correlation between core 003 and 004 implies the absence of a thick olive-grey unit in core 003. Two explanations are proposed: 1) recent slumping; or, 2) condensed upper sequence in core 003. The 3.5 kHz reflectors cannot be traced to the core site though there is an upslope trend toward the thickening of a near-surface transparent unit. If such a unit can be correlated to the olive-grey muds in core 004, then arguing that core 004 is an expanded unit (or core 003 is a condensed sequence) appears reasonable. The radiocarbon dating indicates a rapid sedimentation rate of 5 m/ka which further suggests that core 004 is expanded. A surface scarp is seen in the 3.5 kHz between the two core sites, so that the absence of a thick olive-grey sequence (facies A1) in core 003 might result from recent slumping of the near-surface sediment. It is most reasonable to suggest a combination of the two suggested explanations -- increased sedimentation on the middle slope causing failure due to unstable sediment loading and/or oversteepening.

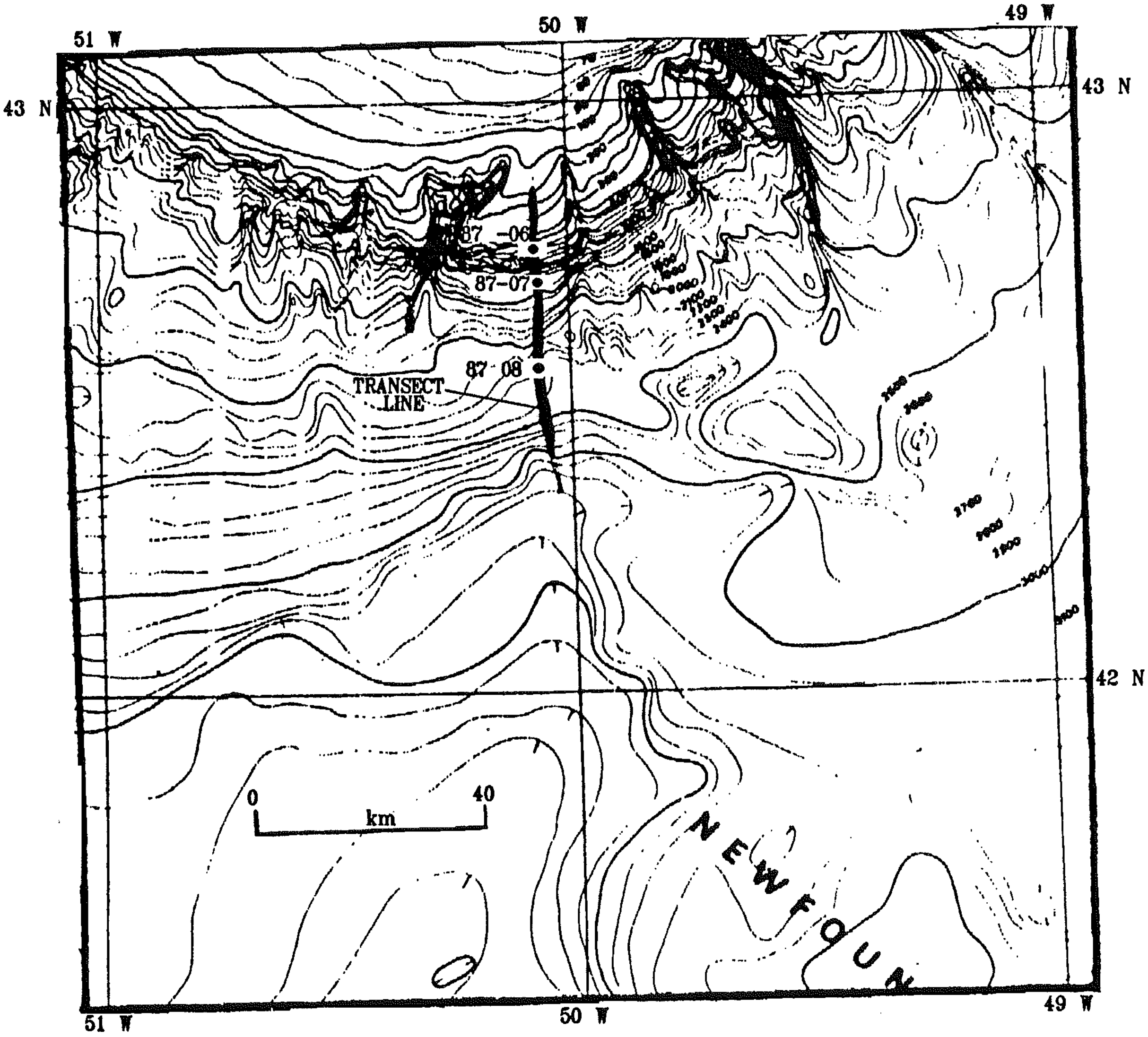
Lithologically, core 001 is similar to the other cores. Since it is far removed from the other cores and in a different deposition setting, correlation without age control is not possible.

The surficial geology of the La Have Slope transect is generally smooth with erosional cuts, downslope channels, and levees being the only significant features. Sediments appear to thicken rapidly upslope as suggested by the correlation of cores 003 and 004. The cores tend to lack obvious episodic facies, primarily consisting of the hemipelagic sediments. The abundant evidence of bioturbation is further evidence for the paucity or lack of turbidites or other episodic facies.

3.3 Slope off Tail of the Banks Transect

The slope off Tail of the Banks has been studied just east of Denys Canyon; however, little data is available (Figure 3.16). Existing records include a dip airgun seismic profile and three LCF (Long Coring Facility) piston cores. The action of bottom

Figure 3.16. Map showing data distribution and bathymetry at the slope off Tail of the Banks.


51 W
50 W
49 W
43 N
42 N
87 -06
87-07
87 08
TRANSECT LINE
0
40
km
NEWFOUN

currents play a major role in the Quaternary sedimentation at this study area. The slope off Tail of the Banks is also distinguished by having a steep gradient --approximately 6.6 degrees.

From an abrupt shelf break at 90 to 100 m water depth, the topography of the downslope transect is predominantly smooth down to 1840 m water depth. Deeper than this, the topography is irregular apparently due to gullies. At 2700 m water depth, the slope gradient quickly flattens to almost horizontal.

3.3.1 Cenozoic Seismic Setting

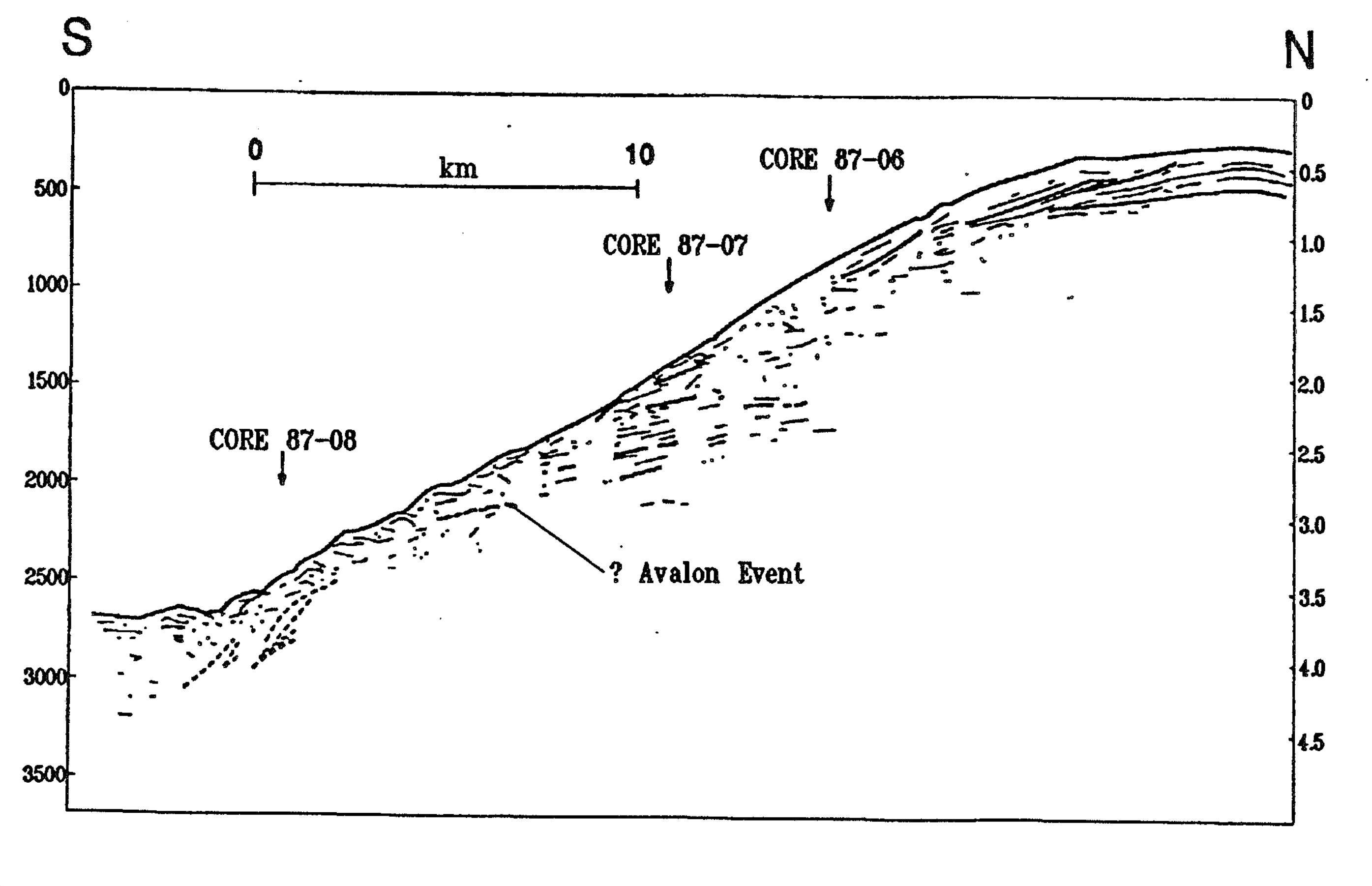
Tail of the Banks is far-removed from any controlling well-site. Ties to a regional stratigraphy are therefore not possible. Multichannel airgun seismic in the vicinity was used, however, to place the Avalon Event in the available single channel dip airgun seismic profile. Though the Avalon Unconformity is a deep event on the Grand Banks, it shallows quite rapidly eventually appearing to outcrop on the middle slope (Grant and McApline, 1990). A basal Miocene marker traced from the Jaeger A-49 well-site on the shelf merges with the underlying Avalon marker landward of the outer shelf. Sediments seen overlying the Avalon marker are therefore presumed to be post-Oligocene; whereas, underlying sediments are late Cretaceous.

Figure 3.17 is a line drawing representation of the single channel airgun seismic profile. Reflectors underlying the outer shelf to upper slope transition appear in unconformable relationships. Each angular relationship becomes steeper downslope, mimicking the seafloor gradient. The least inclined of these reflectors are traced from the outer shelf. These are overlain by a steeper set of reflectors at the shelf break which cross-cut the outershelf reflectors. The shelf break reflectors are in turn overlain by cross-cutting reflectors which underlie the upper slope. This unconformity has a broadly concave upward shape and a similar unconformity is seen further downslope.

Underlying the unconformity sequence are flat-lying reflectors which occur at approximately the same sub-bottom depth along the transect line. However, these flat-lying reflectors trend toward shallowing downslope. They possibly represent control of bedding plane orientation by the flat-lying Avalon Unconformity. The progradation of the continental shelf over this event is recorded by the horizontal nature of the overlying reflectors. The transition between flat-lying reflectors and the sequence of unconformities (which mimic the seafloor gradient) possibly represents the transition between progradation of the shelf and building of the present day slope.

The near-surface sediments in water depths of >1840 m have a chaotic pattern of reflector relationships, abruptly different from the patterns described upslope. These sediments appear dominated by gully-cutting. Side-echoes in the record hamper any further comments on the lower slope acoustic stratigraphy.

Figure 3.17. Line drawing of a dip airgun seismic profile from the slope off Tail of the Banks (87-008).


S
N
0
500
1000
1500
2000
2500
3000
3500
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
0
km
10
CORE 87-06
CORE 87-07
CORE 87-08
? Avalon Event

3.3.2 Surficial Geology

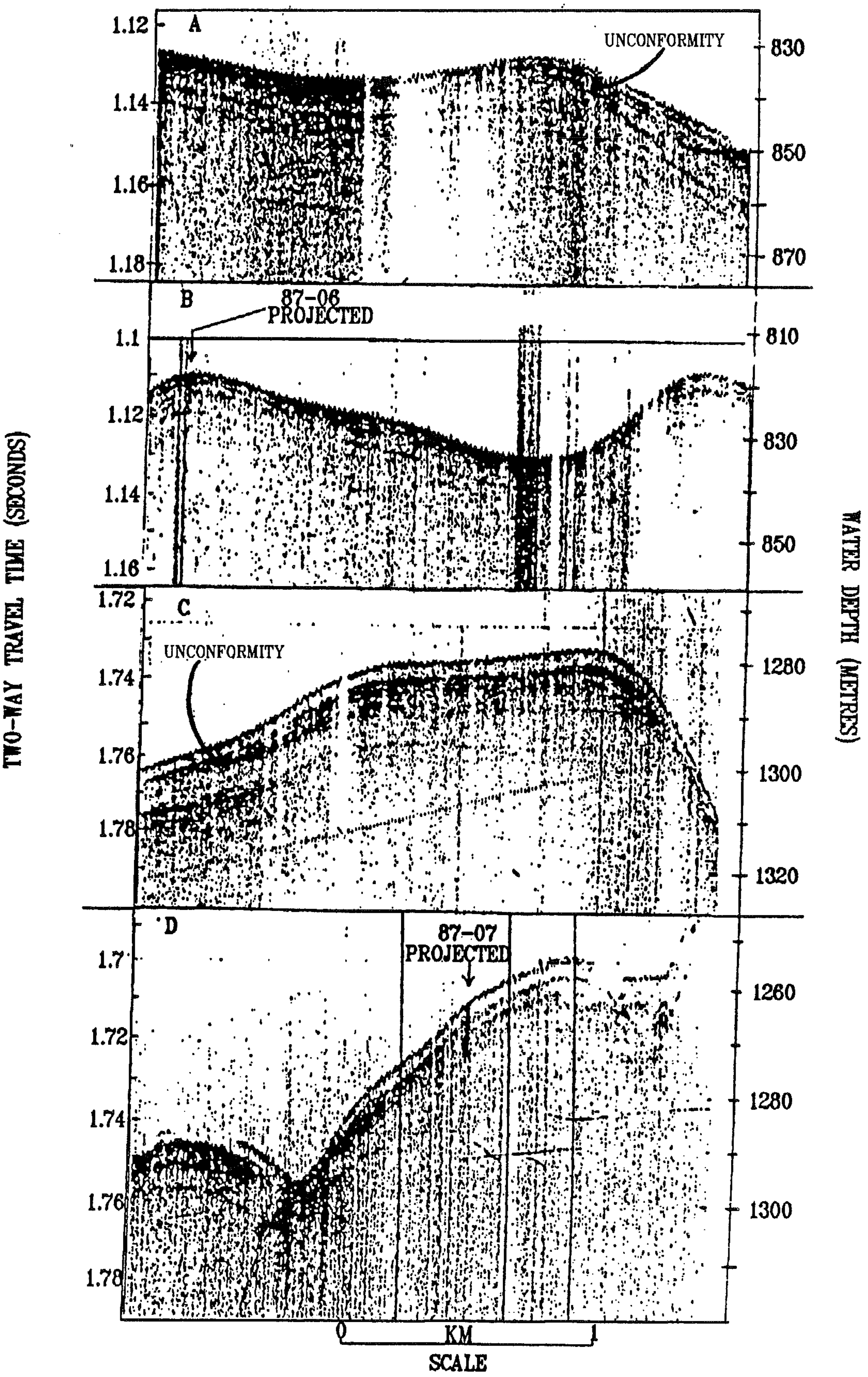
Near-surface Seismic: 3.5 kHz

Available 3.5 kHz records are limited to localized core site surveys. In the vicinity of cores 006 and 007, the surficial geology is characterized by several prominent unconformities. Due to data gaps, the lateral extent and relationships of these unconformities to the core sites are inferred by reflector character.

Figure 3.18a illustrates the unconformity in the vicinity of core 006. On the basis of reflector character, one can trace it to the core site (Figure 3.18b) where it occurs at approximately 4 m sub-bottom.

Figure 3.18c depicts the near-surface unconformity seen in the core 007 area. It cannot be directly traced to the core site but the unconformity is most probably either the first sub-bottom reflector at 3.7 m or the second at 6.6 m (Figure 3.18d).

Figure 3.18. 3.5 kHz profiles in the vicinity of cores 006 and 007 from the slope off Tail of the Banks. A) Near-surface unconformity in the core 006 area; B) Core site 006; C) Near-surface unconformity in the vicinity of core 007; and, D) core site 007.



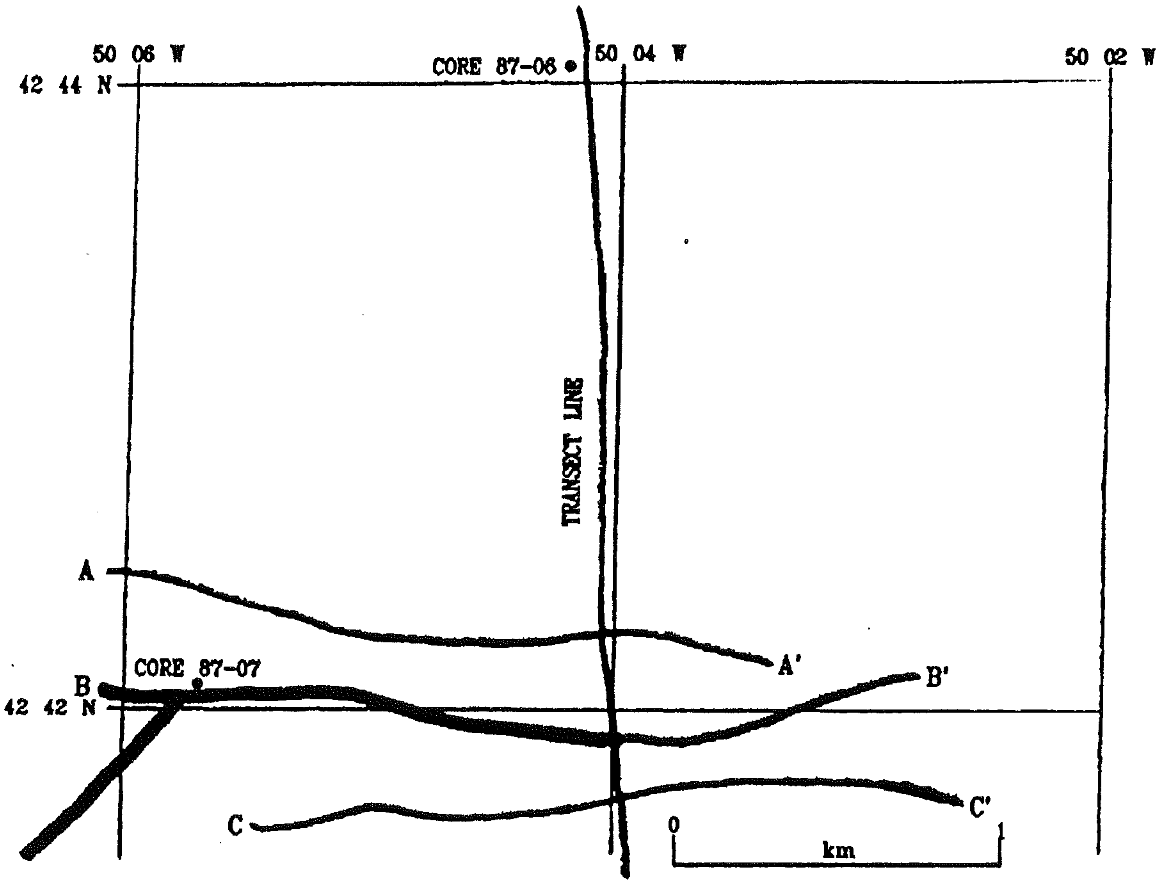
TWO-WAY TRAVEL TIME (SECONDS)
WATER DEPTH (METRES)
A
UNCONFORMITY
1.12
1.14
1.16
1.18
830
850
870
B
87-06
PROJECTED
1.1
1.12
1.14
1.16
810
830
850
C
UNCONFORMITY
1.72
1.74
1.76
1.78
1280
1300
1320
D
87-07
PROJECTED
1.7
1.72
1.74
1.76
1.78
1260
1280
1300
0
KM
1
SCALE

The surficial geology in the core 007 area was further investigated along three east-west profiles. Figure 3.19b illustrates the 12 kHz bathymetry along profiles annotated with observations from 3.5 kHz data. The distribution of near-surface acoustic facies, seen in the 3.5 kHz, is mapped with bold lines representing highly reflective ("hard-bottom") acoustic facies and dotted lines representing sub-bottom penetration and transparent facies. Figure 3.20b illustrates the results of a similar investigation in the vicinity of core 008.

The distribution of acoustic facies in the vicinity of cores 007 and 008 typically has transparent facies on locally high relief areas and hard-bottom facies along the channel banks. Transparent facies occur at the base of some channel banks as well.

On the lower slope, the transect line appears to run just off the crest of a major valley wall (Fig. 3.20b). Further upslope, the line has deviated from the crest and, unfortunately, runs well within this valley (Fig. 3.19b). The side echoes in the airgun seismic profile are most probably a result of this. Besides the major valley, whose extent is not revealed by the incomplete data, several minor channels exist running downslope. They vary independently in local relief downslope. For example, the channel seen furthest west in Figs. 3.19b and 3.20b tends to deepen downslope; whereas, the middle channel in Fig. 3.19b tends

Figure 3.19. 12 kHz strike profiles in the vicinity of core 007. A) Location of profiles and cores; B) Series of interpreted 3.5 kHz profiles showing surficial distribution of transparent and highly reflective ("hard-bottom") acoustic facies.



SCALE 1:25 000

BOLD LINES DENOTE LOCATION OF 3.5 kHz FIGURES

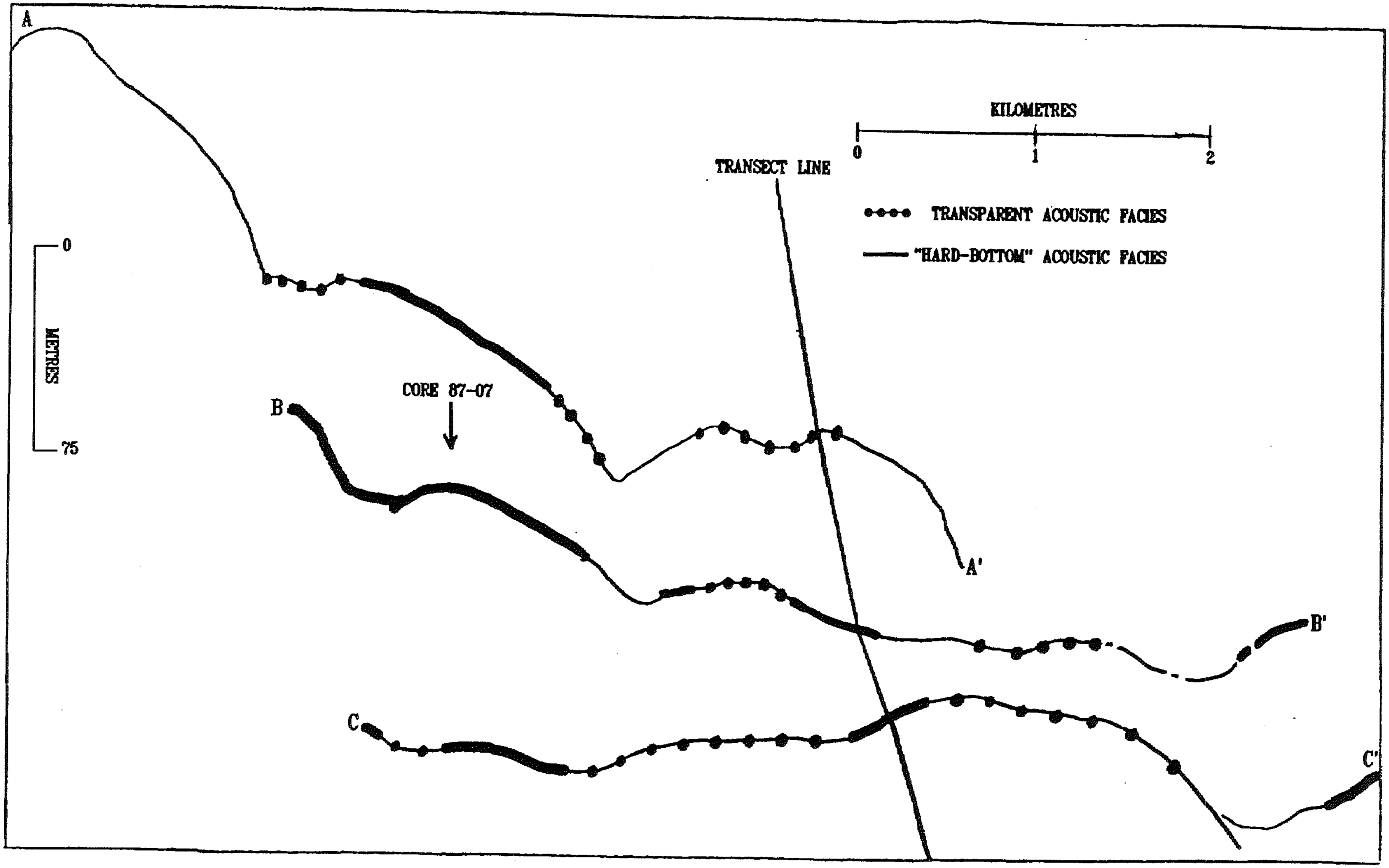
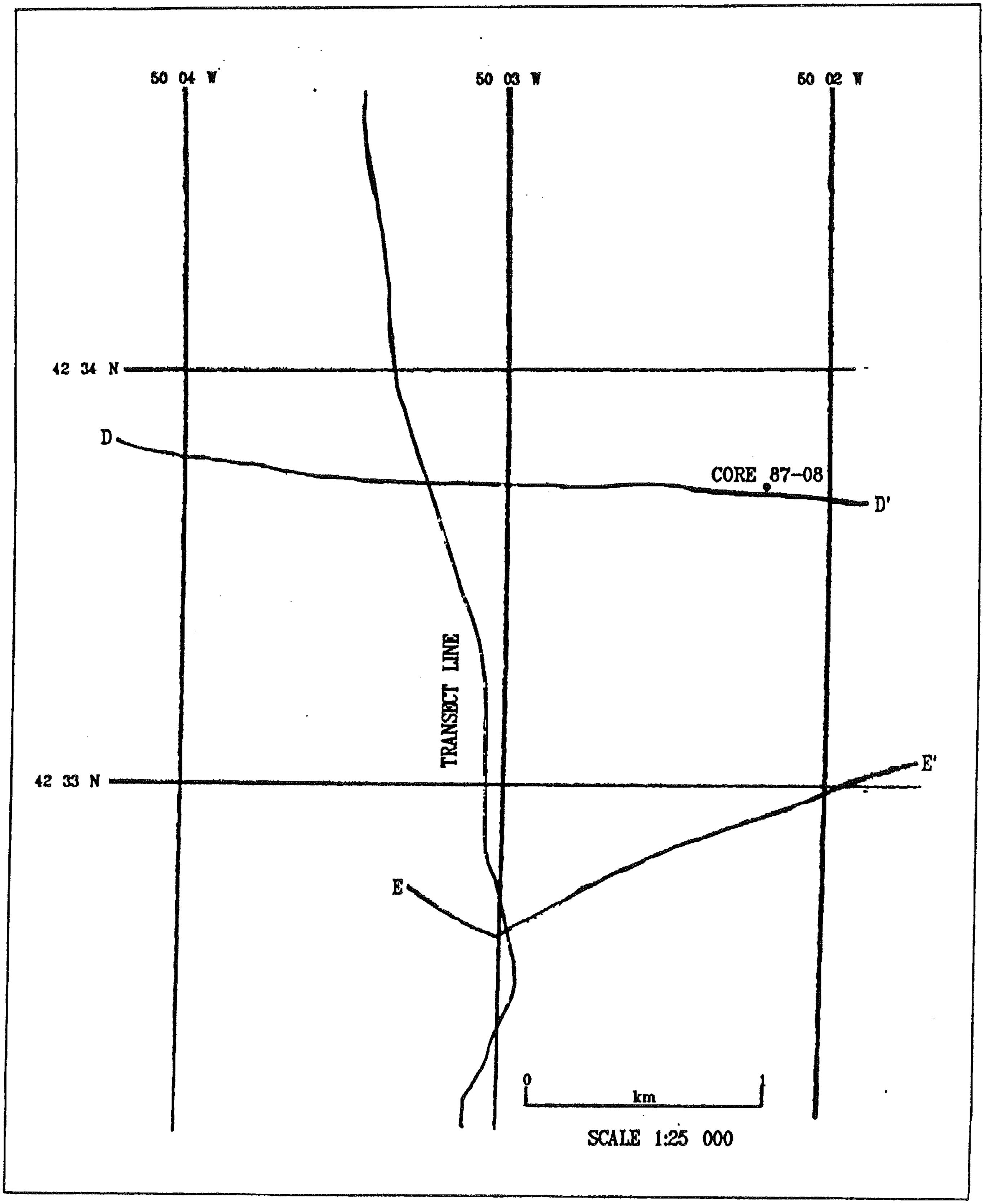
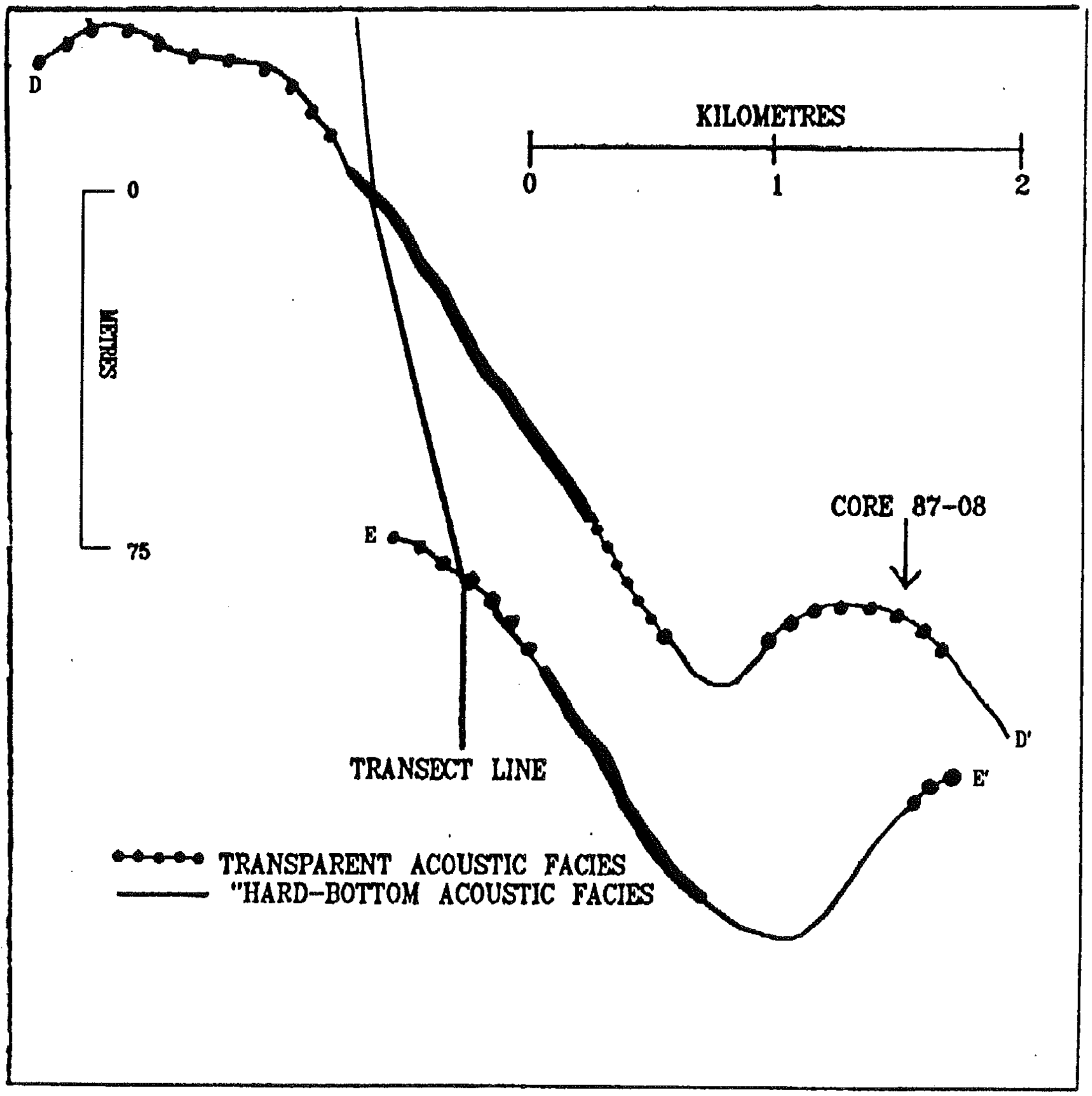

A
KILOMETRES
0
1
2
TRANSECT LINE
TRANSPARENT ACOUSTIC FACIES
"HARD-BOTTOM" ACOUSTIC FACIES
0
METRES
75
CORE 87-07
B
A'
B'
C
C'

Figure 3.20. 12 kHz strike profiles in the vicinity of core 008. A) Location of profile and core 008; B) Surficial distribution of transparent and highly reflective ("hard-bottom") acoustic facies.


50 04 W
50 03 W
50 02 W
42 34 N
42 33 N
D
D'
CORE 87-08
E
E'
TRANSECT LINE
0
1
km
SCALE 1:25 000


D
KILOMETRES
0
1
2
0
METRES
75
E
CORE 87-08
TRANSECT LINE
D'
E'
TRANSPARENT ACOUSTIC FACIES
"HARD-BOTTOM ACOUSTIC FACIES

to shallow downslope.

Core Presentation

Table 6 summarizes the collection data for the three cores available in the study area.

Table 6: Collection Data for Cores from the Tail of the Banks.

Core	Location	Water Depth(m)	Total Length (cm)
006	42 44.05N 50 04.20W	816	643
007	42 42.04N 50 05.70W	1262	1003
008	42 33.72N 50 02.19W	2420	1361

Figure 3.21 illustrates the downcore distribution of the lithofacies summarized in Table 7 and presents a tentative correlation between the cores.

Table 7: Description of Lithofacies: Tail of the Banks transect

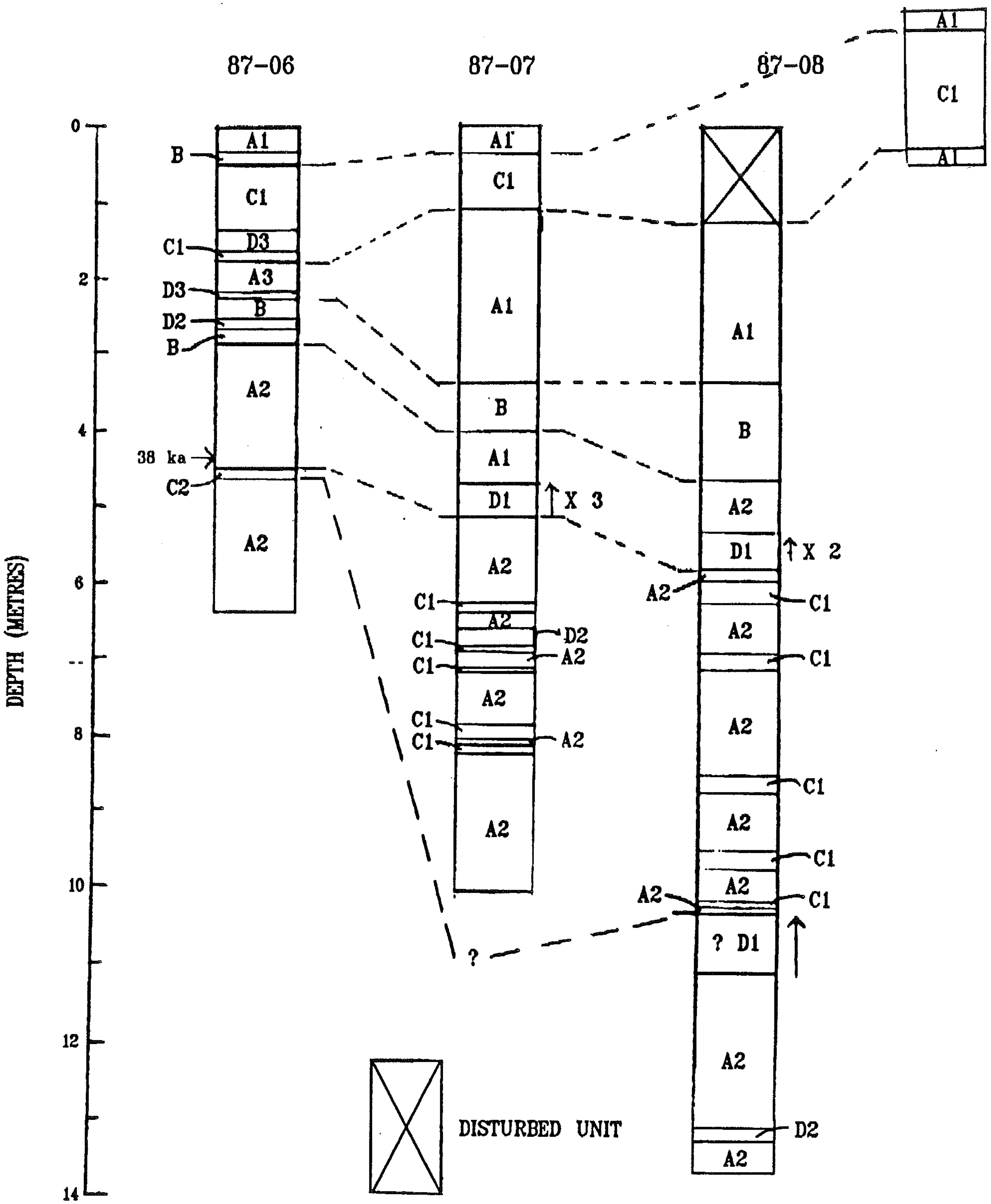
Facies A: olive to olive-grey bioturbated sediments --
  1) silty mud to mud with rare or no ice-rafted detritus
  2) silty mud to mud with abundant ice-rafted detritus
  3) sandy muds to muddy sands

Facies B: silty to sandy multicoloured muds, usually a mixture of light grey, olive, and brown

Facies C: thinly bedded marker mud beds --
  1) light grey silty mud to mud; generally having little sand
  2) dark grey to greyish black mud

Facies D: coarse grained facies, with varying amounts of interbedded mud, various colours --
  1) sand and sand-mud turbidites
  2) coarse-grained debris flows
  3) winnowed sands and gravels

Figure 3.21. Downcore distribution of lithofacies in cores from the slope off the Tail of the Banks and a tentative correlation between cores.


87-06
87-07
87-08
DEPTH (METRES)
0
2
4
6
8
10
12
14
A1
B
C1
C1
D3
A3
D3
B
D2
B
A2
38 ka
C2
A2
A1
C1
A1
B
A1
D1
X 3
A2
C1
A2
C1
D2
C1
A2
A2
C1
C1
A2
A2
A1
C1
A1
A1
B
A2
D1
X 2
A2
C1
A2
C1
A2
C1
A2
C1
A2
A2
C1
? D1
A2
D2
A2
?
DISTURBED UNIT

Group A facies correlate to those identified at La Have Slope. However, because the Tail of the Banks generally lacks glacial input from reddish sources, facies A represents the dominant form of hemipelagic sedimentation regardless of glacial conditions. The marker distinguishing glacial from interglacial deposits is the presence of abundant ice-rafted detritus.

In general Facies A muds represent the ambient sedimentation into the region. The varying amounts of sand and gravel were glacially supplied with the concentration of coarse-grained material being influenced by bottom current reworking.

The origin of facies B is difficult to ascertain. The association of grey, olive, and brown muds is seen at only one horizon but in all cores. A thin bed of reddish brown muds also occurs near the top of core 006.

Facies C incorporates marker mud beds which have been used to facilitate correlation of the cores. Facies C1 is a light grey unit lithologically similar to the carbonate-rich sediments in Baffin Bay (Aksu and Piper, 1987), Labrador Shelf (Josehans et al., 1986) and Flemish Pass (Piper et al, submitted). Clay-sized mineralogy determined for samples within this facies near the top of core 007 suggest elevated values for dolomite (Skene et al., 1991). This suggests that the Labrador Current may be active in delivering sediment the Tail of the Banks. It is unclear, however, whether the dolomite is indicative of a carbonate event or ice-rafting. At the top of the cores, facies C1 occurs as in situ deposition; whereas, the occurrence of C1 in the lower halves of cores 007 and 008 is possibly the result of turbidite deposition.

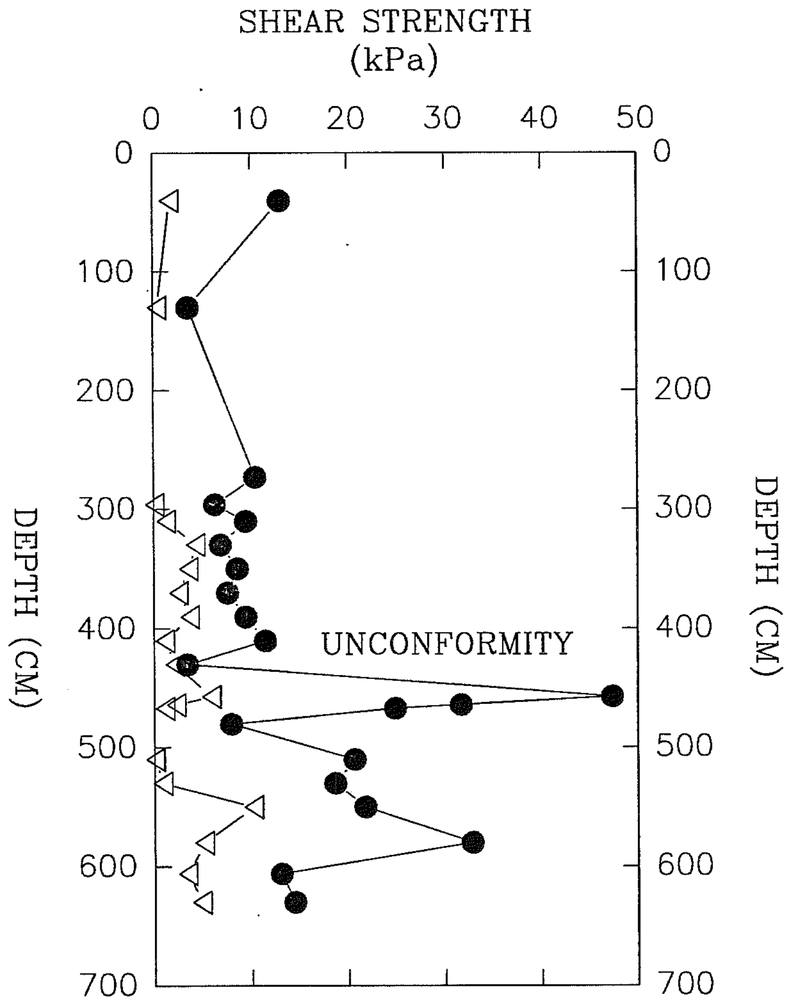
Facies C2 is a dark greyish black mud which is found in core 006 only. At this horizon (450 cm), there is a substantial increase in shear strength (Figure 3.22), suggesting that facies C2 marks the unconformity. The C-14 date (38 ka) immediately above facies C2 lends credence to this placement of the unconformity.

The coarse-grained facies at Tail of the Banks are included in facies D. Along with debris flows and coarse grained turbidites, winnowed sands and gravels are included. Winnowed horizons reflect activity of the Western Boundary Undercurrent. Thinly bedded debris flows are seen in all three cores. Due to their stratigraphic relationship, they appear unrelated.

Tentative correlation of the three cores uses facies B and facies C1 as marker horizons (Fig. 3.21). The correlation suggests that during the hiatus at core site 006 the alternating light grey and olive muds were being deposited downslope. A less certain correlation links the basal olive grey muds in core 006 to those in 008.

Figure 3.22. Downcore variation of shear strength in core 006 from the Tail of the Banks. Sudden increase at a depth of 450 cm is taken to represent the depth of the near-surface unconformity seen in Figure 3.18a.

CORE 87–008–006
TAIL OF THE BANKS
VANE SHEAR STRENGTH



4.0 MORPHOLOGIC CONTROL OF LATE QUATERNARY SEDIMENTATION

The three transects presented illustrate different modes of late Quaternary sedimentation. This variation can be part be related to slope morphology, namely i) depth of shelf break; ii) slope gradient; and, iii) pre-existing slope topography.

4.1 Depth of Shelf Break

Glacial-eustatic sea level changes and fluctuations in ice margins strongly influence sediment delivery to the continental slope (Piper et al., in prep). The depth of shelf break controls the effect which sea level changes have on this sediment delivery. Given a sea level lowering of approximately 100 to 120 m, characteristic of the late Wisconsinan on the outer shelf (Fader, 1989), shallow shelf breaks would be emergent and glacial-fluvial sediments could be delivered directly to the slope. As sea level rose, glacial-fluvial input would be restricted to the shelf. Deeper, non-emergent shelf breaks would have sediment delivery dependent upon glacial extent across the shelf. In ice-marginal situations, subglacial meltwater streams (closely akin to glacial-fluvial processes) would predominate. Under ice-distal conditions, meltwater plumes would be the dominate source of glacially derived sediment (Syvitski, 1991).

Figure 4.1. Schematic diagram of shelf break geometry relating how depth of shelf break and glacial conditions control point and line source sediment delivery. A) point source delivery; B) line source delivery (ice-distal); C) point source delivery within the same geometric constraints as B) (ice-proximal).

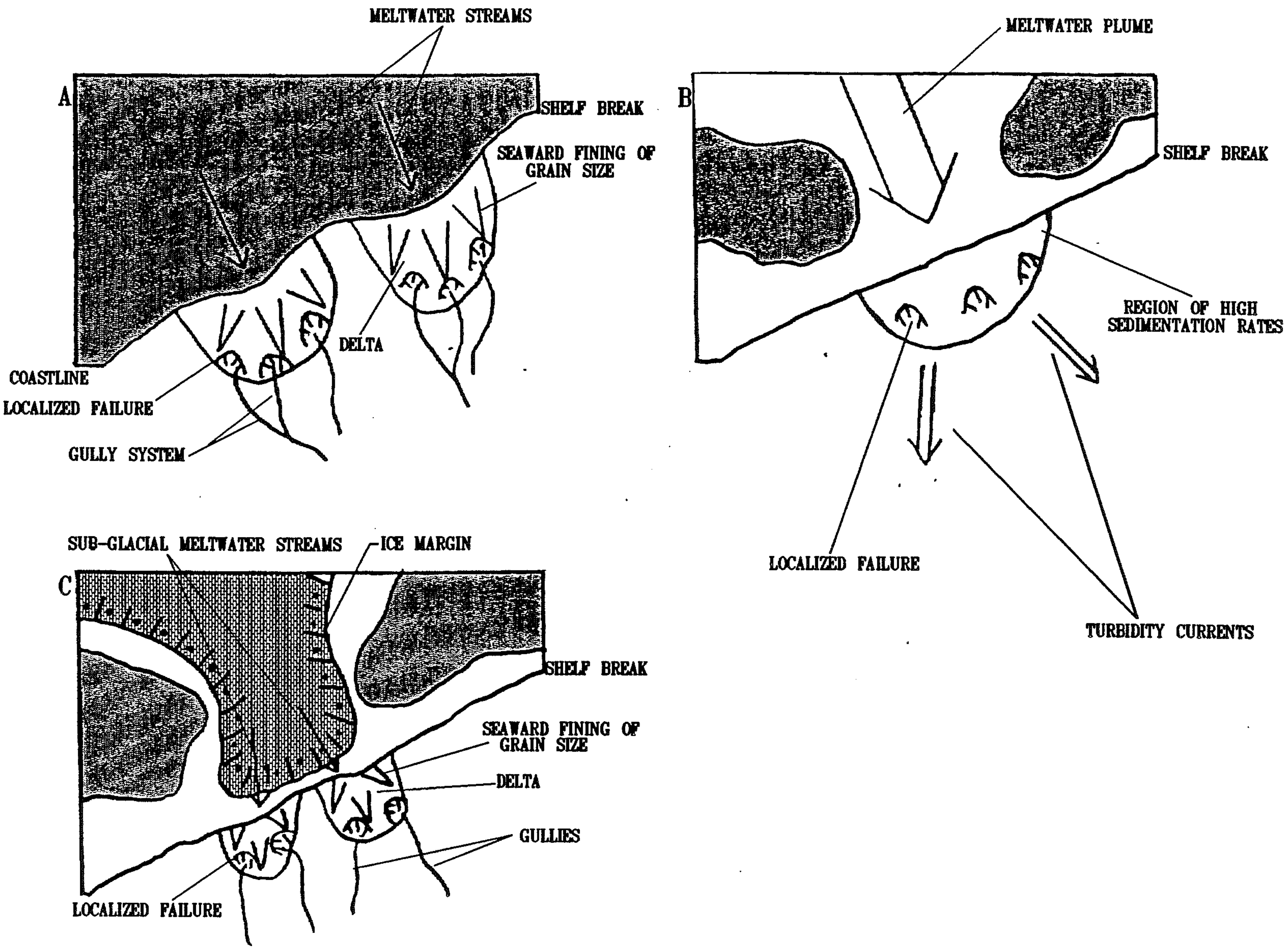

A
MELTWATER STREAMS
SHELF BREAK
SEAWARD FINING OF GRAIN SIZE
DELTA
COASTLINE
LOCALIZED FAILURE
GULLY SYSTEM
B
MELTWATER PLUME
SHELF BREAK
REGION OF HIGH SEDIMENTATION RATES
LOCALIZED FAILURE
TURBIDITY CURRENTS
C
SUB-GLACIAL MELTWATER STREAMS
ICE MARGIN
SHELF BREAK
SEAWARD FINING OF GRAIN SIZE
DELTA
GULLIES
LOCALIZED FAILURE

Figure 4.1a illustrates the sedimentation regime of an emergent shelf producing point source sediment delivery. Meltwater streams flowing directly to the shelf break would concentrate sediment at the stream mouth tending to form prograding delta extending to the upper slope. Sediments of glacial-fluvial origin are typically coarse grained and fairly well sorted. The classical delta depositional environment has a seaward fining of grain size (Syvitski et al., 1986). Progradation of these stream deltas would, therefore, load sands over muds.

Since sediments are delivered by glacial meltwater, the amount and rate of sediment supply would have a seasonal variation. Summer pulses of meltwater would tend to be the dominate source of the progradation, producing rapidly deposited sequences. Given that rapidity of deposition and the unstable loading of sediments by a prograding delta (with a high influx of coarse-grained material), eventual failure of the delta front sediments is probable. Failure is also possible because of the oversteepening caused by the rapid influx of sediments deposited close to the shelf break (paleo coastline; Syvitski et al., 1986).

Figure 4.1b depicts the setting of a deep shelf break remaining submerged during sea-level lowstands (line source sedimentation), in an ice-distal situation. Glacially derived sediments would tend to be delivered by meltwater plumes. These plumes, depending on distance from ice front, would tend to be fine grained. Flocculation of the suspended load upon mixing with substantial amount of saltwater seaward of the shelf break would produce a zone of high sedimentation on the upper slope. Coarser-grained sediments would be more likely to be delivered by major (episodic) meltwater plumes and, because of grain size, would also tend to be deposited in the high sedimentation zone. These episodic plumes would probably cause turbidity currents downslope.

The dominant factor controlling failure in Figure 4.1b is the oversteepening caused by high sedimentation rates and the instability of sediments deposited rapidly (i.e. high water content, ?pore pressure factor). Unstable sediment loading, derived from lithologic relationships, is probably less active because of the generally finer-grained nature of the supplied sediments. Failure in the line source scenario is probably localized as it is in the point source case. However, point source sedimentation would produce several independent areas of failure corresponding to the number of meltwater streams reaching the shelf break and forming deltas. On the other hand, line source sedimentation produces a more regional area of instability because glacial sediments are delivered by only one transport mechanism.

Figure 4.1c presents a situation where the line source setting of Figure 4.1b is converted to point source sedimentation in an ice marginal situation. Subglacial meltwater, rather than glacial-fluvial systems, are responsible for the delivery of coarse grained sediment directly to the slope. Figure 4.1c sediments differ from the situation 4.1a sediments in that ice marginal sediment delivery would be poorly sorted and have glacial till making up part of the sediment input. Other than sediment characteristics, the two settings would produce virtually the same result, though ice conditions between the two are different.

4.2 Slope Gradient

The gradient of the slope affects morphology by controlling the degree to which sediments are retained on the slope. Gradients seen on the Eastern Canadian continental slope typically range from 2 to 7 degrees. Through this range of gradients, one would expect the transition from sediment retention to sediment bypass.

Gradient tends to interact with line and point sources in a variety of relationships. The degree to which each effects the morphology seems to depend on gradient. High gradients causing sediment bypass tend to dominate morphology by simply not allowing significant thicknesses of Quaternary sediments to be deposited. Quantification of gradient effects leading to slumping is discussed by Normark and Piper (1991).

Lower gradients show more of an interaction in relation to upper slope failure. Gradient magnitude in point source settings would probably control the degree to which slumping would cause gully-cutting events and the amount of downcutting these events would produce. Gradient magnitude in line source settings is more likely to control the frequency of slumping (i.e. shallow gradients being less effected by the gravitational force, being more likely to retain unstable sediments in the absence of slumping triggered by seismic events).

4.3 Pre-existing Topography

Probably the most difficult factor to identify and assess is the pre-existing topography on the slope. First of all, the time scale over which one looks at the development of the continental slope is arbitrary. Though basal Quaternary (i.e. reflector C) is chosen for this model, the topography of the basal Quaternary surface is just as dependent on prior events as any marker since the formation of this continental slope in the Jurassic. The basal Quaternary is the pragmatic choice given the resolution limits of single channel airgun seismic (and its availability) and that the model is one of Quaternary sedimentation.

The relationship of pre-existing topography to slope morphology is that it represents the baseline upon which the Quaternary sediments rest. The morphology of the basal Quaternary surface allows for a comparison of sedimentation before and after the onset of Quaternary glaciations. Determination of processes (inferred from airgun seismic) which are independent of glacially induced sedimentation are important in constraining explanations produced by the first two geometric factors.

Principally, this factor considers the effect of pre-Quaternary processes on Quaternary sediments. For example, a basal Quaternary surface showing levee development and both lateral and upsection reflector continuity generally characterizes a slope under the influence of regular pelagic to hemipelagic sedimentation in the absence of instability features. If instability features can be seen in the Quaternary record, alone, then the genesis of instability is inferred to be a Quaternary phenomenon. Other the other hand, slopes which are highly deformed throughout their history cannot be as easily explained by glacially induced processes. The conclusion would be that a more fundamental process controls the morphologic expression of sedimentation.

5.0 DISCUSSION AND INTERPRETATION

Using the geometric parameters defined in the model, morphologic expression of Quaternary sedimentation at Logan Canyon, La Have Slope, and the Tail of the Banks can be, in part, explained.

Logan Canyon is analogous to the situation depicted by Figure 4.1a. Point source sedimentation coupled with a 4.5 to 5 degree gradient would have cut the observed gullies on the middle slope. The near-surface gully-cutting events (Figure 3.6b) show steep sided narrow gullies with amorphous fill, possibly suggesting that they were cut by a single event. Pre-existing topography was smooth to undulating denoting pre-Quaternary constructional processes which remained undisturbed by gully-cutting events. Debris flows are common in the lower section of core 87-003-007 from the area. Repeated slumping and other episodic deposition (debris flows and turbidites) would tend to be channelled through the gully system. This would then leave locally high relief areas as sites of continuous sedimentation. In part, this conclusion is supported by the lack of unconformities seen in the seismic profile.

La Have Slope is analogous to situation "b" and "c" in Figure 4.1. The glacial history of the La Have Slope area is generally thought to include various stages between ice-distal and ice-marginal situations (Piper et al., in prep). In an ice-distal scenario, the deep water shelf break and shallow gradient would have produced line source sedimentation, tending to be retained by the slope (Figure 4.1b). The pre-Quaternary topography is similar to that at Logan Canyon; however the pre-existing gradient would have been less. The lack of near-surface gully-cutting at La Have is partially explained by the lack of large quantities of glacially-derived coarse-grained material and the shallow gradient. Unchannelled episodic deposition is, in part, supported by the laterally extensive surficial debris flow seen. The downslope channels seen shallow with increasing water depth and were possibly cut by turbidity currents. They do not appear to form a complex gully system as seen at Logan Canyon. Core 004 supports the argument of high sedimentation rates on the upper middle to upper slope; whereas, the erosional cuts seen in the seismic suggest the presence of slumping. After the draping of these scarps by hemipelagic sediments, they appear as unconformities in the seismic record.

Deeper in the airgun seismic from La Have Slope (between the lavender and orange horizons) erosional cuts producing scarps continue to be common but so does broad gully cutting. This gully cutting is probably the result of an ice-marginal situation (Figure 4.1c). The existence of point source sedimentation caused by sub-glacial meltwater would not have produced a gully system similar to Logan Canyon because of the shallow gradient (higher degree of sediment retention).

Tail of the Banks with its shallow shelf break would have been emergent during sea-level lowstands. Geographically, however, the extent of ice on the Grand Banks does not support the input of glacial-fluvial meltwater to the area. In addition, the slope gradient at Tail of the Banks is 6.5 degrees and is the steepest seen in the transects studied by Piper et al. (in prep). Consequently, the dominance of sediment bypass would be more likely to characterize the transect. The pre-existing topography at Tail of the Banks is primarily typified by unconformities. These cannot be directly tied to any definite geologic horizon; but, it is inferred that the sediment bypass, along with influence of the Western Boundary Undercurrent, dominate the Quaternary sedimentation producing unconformities.

6.0 CONCLUSIONS

The model presented attempts to define a relationship between the constraints of slope geometry on the Quaternary sedimentation on the continental slope. The morphologic variables used tend to be interdependent and therefore the degree to which each one is active remains difficult to detect except in extreme cases (i.e. slope gradient at Tail of the Banks appears to be dominant geometric factor). In addition, geometric factors alone cannot fully explain Quaternary sedimentation. However, the role of geometry in constraining morphologic expression can be proposed.

The model does not attempt to cover all the aspects of slope stability. It intent is to describe the extent of geometrically induced sedimentation processes. At Logan Canyon, the existence of point source sedimentation and a relatively high gradient partially explains the presence of a complex middle slope gully system. A more complete discussion would involve the glacial history of the region, focusing on the composition of glacial-fluvial sediments delivered to the slope. La Have Slope with line source sedimentation and a shallow gradient can be in part expected to have a smooth topography and unconformities as predicted by the model. The triggering of slump event is less certain at La Have because such a lower gradient would tend to cause sediment retention. The degree of instability which the high sedimentation zone would have remains speculative as well.

Tail of the Banks as previously mentioned is dominated by the existence of a steep gradient causing sediment bypass. Inclusion of bottom current effects, long shore drift, etc. is necessary for a more complete understanding.

RECOMMENDATIONS FOR FUTURE WORK

The areas studied in this paper, generally suffer from a lack of available data. Realistically, one cannot expect an infinite amount of data and, consequently, only the most necessary data gaps are suggested to be filled. Several points of scientific interest have arisen which merit further work, also. The recommendations can therefore be divided into two groups: 1) data gaps and 2) further research of available data.

1) Data Gaps

i) Process existing multichannel (Line 29, 81-044) to see if it provides enough reflector continuity to correlate previously existing stratigraphy with the southeast side of the Logan Canyon study area.

ii) A general need exists to study strike seismic profiles for an understanding of the localized lateral variations in Cenozoic setting -- especially the development of levees, the migration of channels and gullies, and the extent of unconformities.

iii) Further core coverage of the Logan Canyon area.

iv) A more comprehensive study of the Tail of the Banks area -- need for seismic reconnaissance in the area.

2) Further Research

i) On the Scotian Slope, a rigorous determination of the importance of sediment colour in defining provenance and possibly depositional mechanism and provenance.

ii) Develop criteria for distinguishing debris flows from ice-rafted intervals in split core face description and X-radiography (the ice-rafting of sediment clasts).

iii) Effect of the Western Boundary Undercurrent on sediments from Tail of the Banks (well-sorted sands -- turbidite or winnowed?).

iv) Mapping depth to the hummocky reflector horizons (possible common basal Quaternary marker on the Scotian Slope).

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