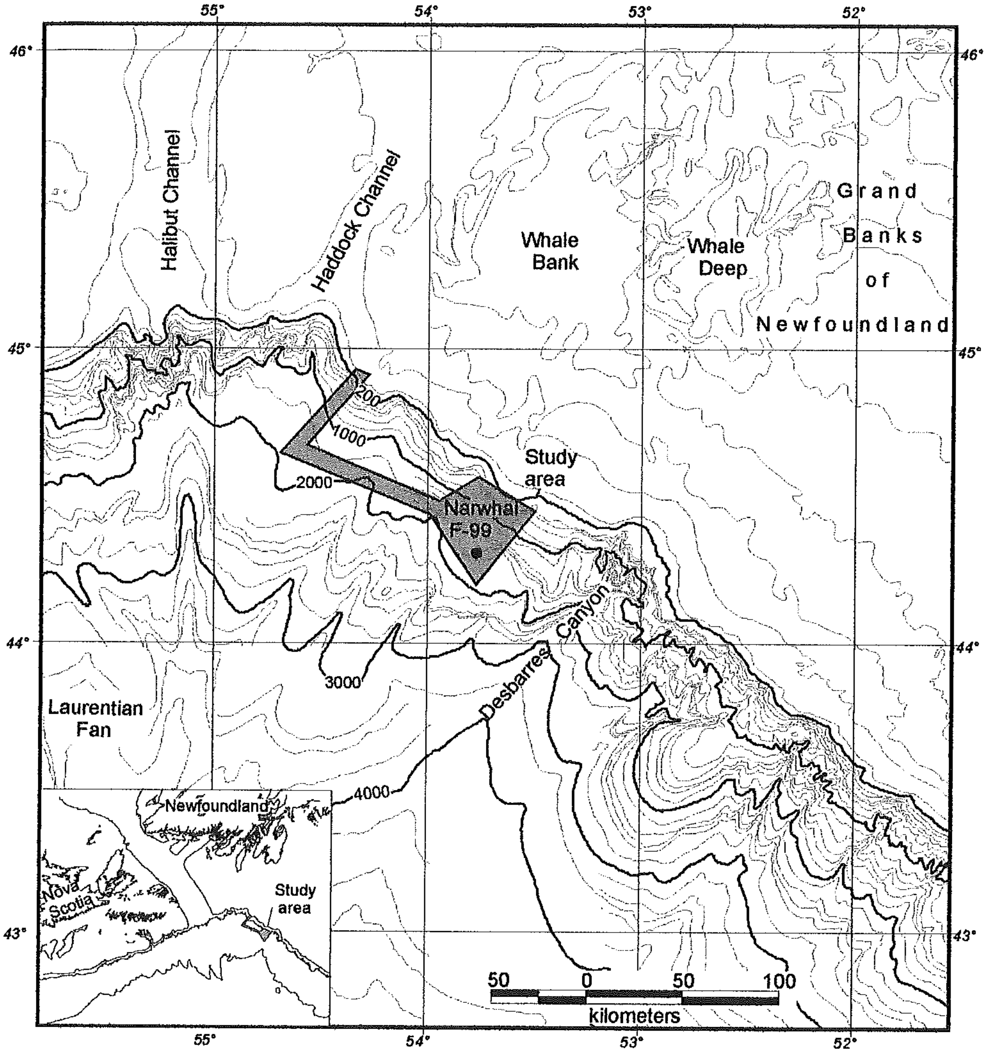
QUATERNARY GEOLOGY OF THE CONTINENTAL SLOPE IN THE VICINITY OF THE NARWHAL F-99 WELL SITE



D. Pass, D.J.W. Piper and D.C. Campbell

Geological Survey of Canada (Atlantic)

GEOLOGICAL SURVEY OF CANADA OPEN FILE #3894

This Open File is an edited version of a Co-op student work term report. It describes and interprets seismic reflection and 3.5 kHz profile data from the continental slope off Whale Bank. The work is part of the PERD project 6.3.2.6, Sediment instability on Continental Slopes (D.J.W. Piper).

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Introduction

The Narwhal area is located on the south western slope of the Grand Banks off Whale Bank, approximately 180 nautical miles south of St.John's (Fig. 1). The area was chosen for a detailed study of the continental slope because subsurface information was available from the Narwhal F-99 well site. This study of the Narwhal transect complements work on other transects across the southeast Canadian margin (Piper and Normark, 1989; Skene, 1991; Piper and Pereira, 1992; Piper et al., 2000).

Whale Bank is bounded to the northwest by Haddock Channel and to the southeast by a series of lows from Whale Deep to Desbarres Canyon. The shelf break in the eastern part of the study area is irregular and cut by several canyons. In the west, the shelf extends further seaward. The shelf break is at about 100 m water depth, at which point the gradient increases to about 0.3°. The gradient rapidly increases to about 2.0° near the 200 m contour.

The aim of the study is to determine what processes of erosion, transport, and deposition of slope sediments have occurred in the area during the Quaternary; and to compare these with other transects on the Scotian slope. Such studies provide a framework for understanding surficial and subsurface hazards for hydrocarbon exploration and development.

Data

Data were gathered on CSS Hudson cruise 91-020 to determine the subsurface geology and the nature of the seafloor (Fig. 2A). The following data types were collected on the 91-020 cruise:

-3.5 kHz profiler data were recorded on a half second sweep which covered 375 m of the water column. These records were used for classification of the seafloor bottom type. The penetration varied between 0-30 m.

- A 12 kHz hull mounted sounder was used for bathymetry and bottom profiling on a half second sweep. This rarely managed to penetrate the seafloor but provided excellent bathymetric detail, which were contoured and digitized to produce a new bathymetric map (Fig. 3).

-A 40 cubic inch sleeve gun was used for one strike and one oblique dip profile (Fig 2B). The gun was towed at a depth of 3-5 m. There were two streamers; an NSRF unit and a 100 ft SE. Both were towed at 3 m depth and the latter was digitally recorded.

-A Huntec deep-tow boomer system was used simultaneously with the sleeve gun. The fish was towed at 45-55 m below surface and there were two receiver hydrophone arrays; an internal and an external. A quarter second sweep rate was set on the recorders. Penetration reached depths of 60 m in some areas.

Pre-existing data included six piston cores from cruise 86-013, some 3.5 kHz records, and a seismic line from cruise 85-001. Six cores were obtained on cruise 86-013 from the continental slope near and above the Narwhal F-99 site (Fig. 2A). The cores located on the upper slope (4, 5, 6) recovered principally mud in their upper 11 m, and a radiocarbon date from core 5 yielded an age of 11.27 ka at a depth of about 10 m (Fig. 4). In contrast, cores 1, 2 and 3 from near the Narwhal F-99 well site have common sand beds and yielded dates of almost 14 ka at about 2.5 m in cores 1 and 2. Thus the thick Holocene sediment section on the upper slope is much thinner near the Narwhal well-site.

A series of industry seismic from the Narwhal well-site survey were used for correlation. The profiles included Nor 03, 13 and 24 (Fig 2A). A seismic line from cruise 85-001 was used as an additional dip line and provided information about the upslope geology around the start of the 91-020 strike profile (Fig. 2B).

Physiography

The continental slope south of Whale Bank is relatively smooth and lacks deeply incised canyons (Fig. 1). In this respect, it resembles parts of the central Scotian Slope. To the southeast, this slope segment is bounded by the deeply incised Desbarres Canyon. Several poorly mapped canyons are associated with the outlet of Haddock Channel, northwest of Whale Bank.

The continental slope upslope from the Narwhal well, however, is not completely featureless (Fig. 3). Strike profiles at about 1500 m water depth show a series of shallow valleys typically 50-100 m deep, which upslope near the 1000 m contour appear to be 150-200 m deep. The upper slope, above about 800 m water depth, appears relatively smooth. The nature of the transition between this smooth upper slope and the gullied lower slope is unknown.

A larger valley immediately southeast of the Narwhal site is 300-500 m deep and is flanked, at least on its northern side, by a prominent levee rising 150 m above the regional sea floor. We term this valley "Narwhal Valley".

Surficial reflection character

The top 20m of the sea bottom can be penetrated with a 3.5 kHz sounder. Piston cores taken in this area do not exceed this depth. A classification scheme was created using 3.5 kHz bottom signatures with typified subsurfaces verified by cores. This was used to make inferences about the subsurface where cores were lacking.

The 3.5 kHz reflection profiles were examined and classified by reflection type based on the top 20 m of penetration (Fig. 3). Irregularity of the bottom, strength of the reflections, and amount of penetration were factors in determining the reflection type. The records were not very informative in places because of rough seas: these areas were left blank on the track plot.

The upper slope (to water depths of 600 m) is characterized by hard bottom (black line in Fig. 3) and there is rarely any penetration. On the mid slope there was good acoustic penetration of 20-30 m, even on locally steep parts. The character of the upper few metres of seabed was assessed in areas of good penetration since this would be the interval sampled by coring. A transparent doublet symbolizes an acoustically transparent near surface package; stratified top units (e.g. Fig. 5) were marked in Grey stippled doublet. Locally, this distinction was vague.

The slope is cut by several channels and canyons. Almost all the valley bottoms produced hyperbolic diffractions and so appear as a different line type from the sides of the channel. Where hyperbolic diffractions were lacking, the bottom character is hard.

Cores

Sediments in < 450 m water depth on the upper slope are muddy sands, passing upslope into sands. On the middle slope, cores (core 5, Fig. 4) consist of about 10 m of bioturbated mud younger than about 11 ka. At the base of the cores, the sediment becomes a little sandier. Based on experience elsewhere on the eastern Canadian margin, much of the sedimentation probably took place in the early Holocene when sea level was much lower than present. Cores 1 and 2 near the Narwhal site have 12 m of bioturbated mud and rare sand younger than 14 ka and then alternating sands and muds below this depth. At about 4 mbsf is a mud rich in detrital carbonate correlated with the 14 ka Heinrich event H1 (Piper and Skene, 1998).

Seismic reflection profiles: Introduction

Two 40 cu. in. sleeve gun seismic profiles were run in the study area approximately following strike and dip. They intersect near the Narwhal F-99 well. The strike line crosses a dip line run on cruise 85-001 (Fig. 2B). The biostratigraphy of the upper part of the Narwhal well suggests that the upper 650 msec penetrated by the seismic profiles is likely to be of entirely Plio-Pleistocene age. Descriptions of individual features on the seismic lines are referenced by time.

The strike profile can be divided into three regions, based on the overall mode of sediment accumulation. (a) The northwest part of the profile (A to B in Fig. 6) has a smooth seafloor and continuous reflections, and has been designated as Region X (Fig. 2B). (b) The central portion (B to D in Fig. 6) exhibits shallow valleys and intervening levees, and has been designated Region Y(Fig. 2B). (c) The south east end of the profile (D to E in Fig. 6) consists of two levees separated by a low and is designated as Region Z (Fig. 2B). The Narwhal well site is on the higher southeastern levee, which is adjacent to the Narwhal Valley. The relatively complete section on this levee serves as the type section.

The strike profile provided the best data for geological interpretation. The dip profiles provide indications of up slope variations, but were difficult to use because of the lack of continuity of the reflections.

The well-site survey data provided information about the deeper structures in the area and were used to correlate reflections in the well-site area (Figs. 2A, 10).

Key horizons

Six reflections, each assigned a colour, were used to map key horizons in the subsurface. The Blue/Purple horizon is the deepest reflection easily traced throughout the profiles and best displays the regional attitude of the sediments. It typically occurs at 100 to 300 ms subbottom. It is unconformable in several places and marks the bases of most of the levees. The overlying five reflections illustrate the sedimentary events which controlled deposition and erosion of the sediments. They are, in order of ascension from Blue; Green, Grey, Brown, Pink, and Flesh. Green marks a period of erosion with subsequent draping over small levees built on the Blue horizon. The Grey reflection is simply a prominent reflector. The Brown and Pink reflections are two horizons at the bottom of a stratified sequence located near the tops of the levees. While the Pink is restricted to the levees, the Brown can be traced down some of the slopes. The Flesh reflection marks the bottom of a transparent unit at the levee crest and by character can be traced through almost the entire strike profile.

The descriptions of the reflections and their intervals are made from the reference section located on the levee at the Narwhal site (Figs. 6, 7).

<u>Blue reflection</u> - This reflection occurs at the base of all of the major levees and outcrops in several of the deep channels. The horizon lies uncomformably on older sediments with which it appears to have an erosional contact. Several angular unconformities lie below the reflection in the continuously stratified and non incised slope of profile A-B. Two others can be seen under the levee in the middle of section B-C. The reflection was difficult to trace in places such as through the bases of the levees. The horizon is very undulating and is locally covered by short discontinuous reflections. The Blue horizon is also the base for small, secondary mounds. In the central portion of the profile, between C and D, the Blue reflection appears to have been completely removed and we recognize an erosion surface, Purple, overlain by stratified sediments.

<u>Blue - Green interval</u> - This interval is present only on the levees as the Green horizon has been removed between the levees. The package varies in thickness from 80-100 ms. The unit is filled with continuous reflections but locally there are patches of short discontinuous reflections. These discontinuous reflections are most abundant in the middle of the levee where scattering of the acoustic signal is the most severe.

<u>Green reflection</u> - The Green reflection marks the horizon above which reflections begin to drape over the levees yet it is truncated at the margins of levees. The Green reflection is slightly irregular but continuous throughout the levees. It does not appear between levees due to later erosion.

<u>Green - Grey interval</u> - The lower half of this interval has continuous draping reflections which partially subdue the relief of the levee by covering the secondary levees. The package is fairly transparent and the

reflections are of higher amplitude near the bottom of the package, with amplitude decreasing upwards to the Grey horizon. There is also an upward trend to less continuity and local hyperbolic diffractions. The overall thickness of this interval is about 80 ms. The sharp reflections account for 30 ms with a gradual change to hyperbolics for 20 ms, while the low amplitude reflections comprise 30 ms.

<u>Grey reflection</u> - This reflection is a minor erosional marker in the levees. The reflection is a low amplitude doublet and is fairly undulating.

<u>Grey - Brown interval</u> - This interval is typically only present on the levees, having been eroded in the channels. Most of the package is transparent with some low amplitude reflections. The upper part of the sequence has two high amplitude reflections which can be traced down the side of the levee. The lower of the two appears to be an erosional horizon as it cuts down through several lower units almost to the Green level. The interval thickens from 40 to 60 ms from northwest to southeast.

<u>Brown reflection</u> - The Brown reflection marks a depositional horizon. It is a prominent doublet and is continuous and smooth across the levees. The reflection can be followed down the slopes of some of the levees with moderate success but the best correlation across erosional valleys is made based on its character. Depending on the location, the reflection underlies two different packages; a transparent package and a stratified package. Between ridges the overlying package is stratified.

<u>Brown - Pink interval</u> - This interval is largely limited to the levees, with a maximum thickness of 10 ms. The Brown Pink interval is variable, composed of transparent and stratified sediments which change laterally. The levee in the reference section has a transparent unit between the two reflections. In the topographic lows between levees and on the non-incised slope at the NW end of the profile, the package is stratified.

<u>Pink reflection</u> - The reflection is only easily identified on the levees. The Pink level marks the bottom of a package of stratified sediments and this character allows it to be correlated throughout the profile. It is an even drape on the levees.

<u>Pink - Flesh interval</u> - The two reflections are separated by a stratified package of sediments. The thickness varies from 40 to 60 ms on the levees but can be as thin as 20 ms in the channelized sections of the profile. The interval covers most of the Blue horizon except in places of intense erosion such as deep channels.

<u>Flesh reflection</u> - This reflection is present discontinuously throughout the region. The breaks are caused by deeply cut channels and steep slopes on the channel flanks. The reflection is located at the bottom of a transparent package which corresponds to the top of a stratified package in the reference section.

Flesh - surface - The transparent package which overlies the Flesh reflection is devoid of reflections in the type section, but off the levee, some stratification and hyperbolic diffractions were observed.

Geographic description of the seismic reflection profiles

REGION X The undissected northwest area

Strike Profile:

The northwest area shows an apparent dip to the southeast. The Blue horizon is an erosional surface which provided the basis for the rolling bathymetry. The basal Blue reflection was in turn influenced by a deeper more subtle reflection not everywhere visible on the profile. The sedimentary package on top of the Blue reflection thickens to the southeast (Fig. 6), with the erosional effects of region Y becoming progressively apparent and there is a thinning of the sedimentary package. At the NW end of the profile near the crossover with the 85-001 seismic line, there is a sharp drop in the seafloor probably due to a fault and/or steep channel wall.

Dip Profile:

Airgun profile 85001 (Fig. 8) crosses the continental slope seaward of Whale Bank. The profile appears to be strongly influenced by salt diapirism (MacLean and Wade, 1992) and faulting. The reflections characteristic of the section are very regular, but terminate abruptly at faults and diapiric structures. A few reflections are truncated at the edges of small channel fill sequences, but coarse sediments are thin or lacking on the channel floors. The upper slope (Fig. 8A) has the acoustic character of glacial till, with alternating acoustically amorphous and stratified intervals similar to that seen on the Scotian Slope by Mosher et al. (1989). The downslope pinchouts ("till tongues") may be till from grounded ice or diamict debris flows (King, 1993). A morainal mound is visible at about 450 mbsl and may represent a stable grounding line; the uppermost "till tongue" extends to 580 mbsl. A major fault extends to near the surface at this point and may be located on the seaward side of a salt diapir (MacLean and Wade 1992). Thick well-stratified proglacial sediments have accumulated downslope from this fault. The glacial till was probably derived from an ice stream in Haddock Channel. On the lower slope, in water depths of 800-1300 mbsl, the well-stratified Quaternary section is cut by numerous faults (Fig. 8B), some associated with salt diapirism. The base of the glacial section is tentatively identified on the basis of comparison of reflector character with the Scotian Slope (Mosher et al. 1989). Several failure scarps 10 40 m high are visible and there appear to be extensive areas of bedding plane slides, again similar to the Scotian Slope.

REGION Y The central channeled area

Strike Profile:

The central area of the profile consists of erosional lows between large levees (Fig. 6, B to D). These levees have a complete stratigraphy correlatable with the type section found in the southeast region. The relatively shallow depth of the basal Blue reflection gives a good indication of the degree of erosion that has taken place. It is fairly horizontal (it rises gently to the southeast) through this area, so it can be used as a datum for reference to these features. The ridges with relief greater than 300 ms separate channel systems. Some channels have been eroded to below the Blue reflection (e.g. just NW of D).

The stratigraphy of the channeled areas varies from site to site. Above the Blue reflection, generally no strata older than Brown are present. Minor levees with relief between 50-100 ms separate apparently active channels. These typically have hyperbolic diffractions and poor acoustic penetration. Preserved accumulations in the active channels rarely exceed 30 ms of sediment above the Blue datum.

A more detailed description of features from northwest to southeast is presented. Two major levees mark the base of the slope from the northwest region, separated by a channel which cuts down to the Blue reflection. Another deep channel incised to the Blue reflection bounds the second levee to the southeast. Southeast of this point, the Blue horizon appears horizontal. A third, more laterally extensive levee forms the other margin of the channel and has a complete stratigraphic sequence. On its southeastern face is a lower terrace which is the only place where the Grey-Brown interval is preserved outside of a levee. Its position gives an indication that the channel has gone through several erosional stages.

To the southeast is a channelized low section, where the Pink to Flesh interval is preserved on top of the Blue reflection. This interval is cut out by a small valley, just NW of C in Fig. 6. The channel almost cuts down to the Blue datum and the sediments in the depression give hyperbolic diffractions. A levee similar to the ones to the northwest of the channel to the southeast. Under this feature the Blue reflection starts to rise gently to the southeast, and continues to do so for the rest of the profile.

To the southwest the profile slowly climbs the regional slope, so that channels are present on the northwest side of the low sections instead of the southeast. The Blue horizon appears to have been eroded out and Purple marks a regional erosion surface commonly just 30 ms below the sea floor. There are several small levees in which the Flesh reflection was noted. The levees are not large and have no more than 80 ms of relief from the Purple datum. There are channels scattered throughout this low section, one of which cuts down to the Purple horizon between C and D in Fig. 6. This is likely an active channel as there are hyperbolic diffractions over the entire valley floor and no significant accumulations of stratified sediment. The remaining channels have mostly short discontinuous reflection, interpreted as sediment infill.

A small levee system just NW of D has the Flesh reflection and some of the Pink - Flesh interval. The levee has a mound on the south east end but the seismic records are not clear enough to determine the stratigraphy. The mound has a relief of 130 ms while the rest of the levee has but 80 ms of sediment above the Purple datum. The southeastern part of the central region is a channel, just NW of D the Purple reflection cannot be traced under the channel because of hyperbolic diffractions, which reach to depth of 50 ms.

REGION Z The complex levee of the southeast area

Strike Profile:

The southeast area extends from D to E (Fig. 6). It consists of a section of differential deposition bounded by levees to the northwest and southeast. The southeastern levee includes the reference section near the Narwhal well site.

The northwestern levee has a complete stratigraphic section above Blue, but only has a relief of about 230 ms. The reflections were correlated with the reference section based on character and relative thickness of the various intervals.

The Blue reflection is about 100 ms above the Purple erosion surface in region Y and is generally horizontal throughout the region.

There is a short section just SE of D where the reflections are of high amplitude, but short and largely discontinuous. This package fills a depression and is terminated to the northwest side by hyperbolic diffractions from the levee. At the surface a small channel is present at the edge of the levee which appears to be partially sediment filled. The concave feature appears to be a very large channel fill sequence.

To the southeast of this channel-fill sequence is an area of differential deposition and is separated from the previous section by a rise in deeper strata which results in mounding of Blue and influences strata to the surface, possibly an ancient levee. Reflections can be traced down off the type section and into the depression between the type section and this ancient levee. Here the Blue horizon is horizontal but shallower reflections, where present, have different character in this area. The Green reflection drops into the depression, entering the hollow about 40 ms above the Blue horizon, indicating erosion of about 80 ms of sediment . It becomes difficult to trace because of the discontinuity of the reflections. A reflection from the Grey-Brown interval cuts down in a similar fashion as the Green reflection and enters the depression about 70 ms above the datum. It also becomes discontinuous. Overall section thickness in the basin is only one third that of the levee. The Brown reflection is traceable from the levee throughout the section but it is closer to the surface because the Flesh reflection also marks an erosional event and removes about 50 ms of sediment. The sediments above the Flesh reflection appear to be similar in thickness as well as character and likely post date the major erosional period. There are a large number of hyperbolic diffractions which lie above the transparent package on top of the Flesh reflection. The 3.5 kHz and Huntec records show a near-surface feature with the acoustic characteristics of a debris flow. Thus it is likely that the Flesh to seabed interval was mainly depositional, but it did have significant downslope movement.

The reference section has been described in detail above. The Narwhal Valley cuts the type section on its southeast flank.

Dip Profile:

The zigzag line run approximately dip in the Narwhal area is of rather poor quality and seismic continuity is interrupted by slope valleys. The shallowest part of the profile is along strike (Fig. 9) at about 450 mbsl. Acoustic signature in both airgun and Huntec boomer suggest glacial till up to 70 ms thick overlying what appear to be prograded sandy deposits.

Description of the site-survey multichannel sparker data from the Narwhal well

Correlation of well-site survey sparker seismic with the Narwhal F-99 well is based on the summary by MacLean and Wade (1993, p. 144-145). Casing was set to 2310 m (about 2.9 sec), just below reflector II (Fig. 10). Sediments between 2310 and 2450 m (2.9 and 3.0 sec) are sandy shales with Miocene palynomorphs, that rest disconformably on 400 m of lower Oligocene shales.

In the well site survey seismic profiles (Fig. 10), the section above the Blue marker (reflector I in Fig. 10) at about 2.5 msec is better resolved in the single channel described above. A prominent planar packet of reflections at 3.0-3.1 sec at the well can be traced over the entire site survey, capped by reflector III (Fig. 10) which is correlated with the top of the Lower Oligocene sediments. Shallow channels are visible in the Oligocene section west of the well site ("a" in Fig. 10). At 0.1 to 0.2 sec above the planar Oligocene reflector is a significant erosion surface (reflection II in Fig. 10) with considerable relief, marked by abundant hyperbolic diffractions ("b" in Fig. 10). At the well site, the entire section between the planar packet at the top of the Lower Oligocene section (III) and the "Blue" reflection (I) is characterised by discontinuous reflections. On the basis of reflection character, this interval is interpreted as being relatively sandy. The middle part of the interval has the most continuous reflections. Westward, reflectors become more continuous, and in the upper part of the interval become mounded, interpreted as a low levee ("c" in Fig. 10). These data suggest that in the Miocene (?to Pliocene) a shallow channel with low levees was present near the site of the Quaternary Narwhal valley. A fundamental change in sedimentation took place above the "Blue" reflection. The well provides no information on the possible age of the "Blue" reflection, except that it is Miocene or younger.

Discussion

Origin of the seismic section: Pliocene - Quaternary sedimentation

Correlation by seismic character shows that only the top few reflections (above the Brown, or in some cases, the Flesh reflection) are preserved in some gully floors and appear to disconformably overlie the Blue or Purple reflection. Other gullies have a thicker sediment section, but the interval between the Flesh reflection and Blue commonly cannot be correlated with confidence from ridge to gully. The sequence above approximately the Brown horizon, on both the major ridges and in gullies, is relatively continuous over the whole area and does not show strong growth of mound-like geometry. On the major ridges, deposition was largely conformable, but from the Blue reflection upwards there is an overall development of a mounded seismic character that is most pronounced between Blue and Brown. The seismic character and thickness of the stratigraphic sequence above Blue is similar from one ridge to another. This suggests that much of the sediment section was deposited relatively uniformly in a sheet over the entire study area. They were then largely eroded within the gullies. The mounded character on the ridges, therefore, is probably the result of differential erosion on the ridge flanks, rather than differential deposition on the ridge crests. The amount of erosion within the gullies appears to have varied through time. The gullies showing most evidence for erosion are commonly adjacent to the most prominent ridges.

The similarity in seismic sequences between ridges implies not only sheet-like deposition but also that whatever geological changes produced these distinctive sequences, they were not restricted to a single valley system. Therefore, the factors most likely to have controlled the seismic stratigraphy are sea level change and changes in glacial supply of suspended sediment plumes. Coarse glacial sediment is more likely to have varied in rate of supply between different gully systems; variation in this supply may explain the variable erosion history of different gullies. The mound-like seismic character of the ridges can be explained by sheet-like deposition from proglacial sediment plumes with simultaneous flushing of gullies by turbidity currents (Piper and Sparkes, 1987).

Most ridges do not show the character of turbidite channel levees, in which sediment thickness increases towards a major channel. However, this character is observed on the ridge on which the Narwhal well is located; this ridge is interpreted as the northwestern levee of the 300-500 m. deep channel that appears to be of a larger scale than the gullies to the northwest. The backside of this levee shows the distinctive break in slope and thinning of strata recognised on the Laurentian Fan levees by Piper and Normark (1982, their Fig. 3). The gully northwest of this levee has a condensed section with a near-surface debris flow, presumably resulting from sediment failure on the back-side of the levee.

The general acoustic stratigraphy of the Narwhal area can be correlated on the basis of reflection character with the stratigraphy described by Piper and Normark (1989) to water depths of 1200 m on St Pierre Slope observations. The sequence above "Brown" in the Narwhal area corresponds to the sequence above "B" on St Pierre Slope. In both areas, the interval corresponds to a relatively uniform muddy drape that has been deposited over many previous sandy gullies and over some irregular topography in ridges dominated by mud deposition. The Blue reflection in the Narwhal area has a similar character to the "C" reflection on the St Pierre slope, where it occurs at 0.3 to 0.5 s bsf. In the Narwhal area, which lies in deeper water, Blue occurs at up to 0.4 s bsf. In both areas, this reflection marks an irregular erosional surface and a pronounced change in depositional style. Above this reflection, there is growth of levee- or mound-like features in both areas.

Piper and Normark correlated "B" (= Brown) with the base of outer shelf-upper slope diamicts. This horizon thus probably correlates with the onset of shelf-crossing glaciation, which Piper et al. (1994) show occurred in isotopic stage 12 at about 450 ka. The "C" horizon (=Blue) was correlated by Piper and Normark (1989), again on reflector character, with the sequence on the central Scotian Slope, where it corresponds to a horizon near the Pliocene-Quaternary boundary determined from the Acadia K-62 well (Piper et al. 1987).

Cores: Late Pleistocene - Holocene sedimentation

Cores and 3.5 kHz profiles show a distribution of surficial sediment similar to that seen on the Scotian Slope, with sands on the upper slope, thick early Holocene muds on the middle slope, passing downslope into thinner Holocene muds. Large turbidity currents passed down Narwhal Valley in the late Pleistocene, when much of the Grand Banks was emergent, spilling fine sand onto the 400 m high levee.

Synthesis: comparison with the Scotian Slope and implications for sediment stability

The Pliocene-Quaternary stratigraphic evolution of the S.W. Grand Banks Slope in the Narwhal area is similar to that of the central Scotian Slope as determined by Piper et al. (1987). In the Pliocene, a few wide, shallow slope valleys built low levees and funneled sand to deep water. One such valley approximately followed the modern Narwhal Valley. At the beginning of the Pleistocene, numerous smaller slope gullies were formed and mound-like muddy deposits accumulated between the gullies. Sometime in the mid-Pleistocene, a more widespread mud drape was deposited over much of the slope, although the main valleys continued to be flushed clean. Surficial sediments in the Narwhal area are much sandier than those on much of the Scotian Slope, probably as a result of the shallower shelf break.

Bedding plane slides appear widespread in areas of thick proglacial sediment (failure scarps, Fig. 8B), creating small debris flow deposits in places. Headscarps appear to coincide with faults in the Cenozoic section. This suggests that experience on the Scotian Slope regarding sediment instability can probably be applied to the area off Whale Bank.

Acknowledgments

We thank GSC (A) and DFO personnel working on the C.S.S. Hudson for their assistance in acquiring the data. We thank Manadrill for provision of site survey seismic profiles for the Narwhal well site.

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FIGURE CAPTIONS

Fig. 1. Location of the Narwhal F-99 well and study area on the S.W. Grand Banks Slope. Box shows area in Fig. 2A.

Fig. 2. A Track plots showing available underway data types and cores.
B Track plot of 91-020 and 85-001 showing location of line drawings in Figure 6.

Fig. 3. New bathymetric compilation (in metres) for the study area based on GSC(A) echosounder profiles and sparse Canadian Hydrographic Service data. Map also shows distribution of reflector types interpreted from 3.5 kHz sounder profiles.

Fig. 4. Summary stratigraphy of cores 86-013-01, 02 and 05 from the Narwhal area. Radiocarbon dates are summarised in Table 1.

Fig. 5. 3.5 kHz profile showing location of cores 86-013-01 and 02.

Fig. 6. Photographs and line drawings of GSC(A) seismic from cruise 91-020. (Location of sections A-B, B-C, C-D, and D-E are shown in Fig. 2(b))

Fig. 7. Detail of the type section of the airgun line at the Narwhal well site

Fig. 8. A Dip line on upper continental slope NW of Narwhal area. Airgun data from 85-001.
B Dip line on middle continental slope NW of Narwhal area. Airgun data from 85-001.

Fig. 9. Shallow strike profile of the zigzag dip line upslope from the Narwhal F-99 well site. Airgun data from 91-020.

Fig. 10. Three industry site-survey multichannel sparker seismic profiles, showing seismic stratigraphy and acoustic features described in text.

Fig. 11. Seismic correlation of the Narwhal area with the St Pierre Slope seismic stratigraphy of Piper and Normark (1991).

Table 1. New radiocarbon dates from the Narwhal area

Core	**Depth (cm)**	**Material**	**Age***	**Lab No**
86013-001	240	Colus pubescens (?reworked)	13860 ± 90	Beta 20732 ETH 2294
86013-002	248	Nuculana tenuisulcata (paired valves)	13980 ± 250	Beta 20739 ETH 3001
86013-005	433	Nuculana pernula (paired valves)	9710 ± 85	Beta 34306 ETH 6058
86013-005	657	Nuculana pernula (paired valves)	10280 ± 75	Beta 34304 ETH 6056
86013-005	855	unidentified mollusc fragment	10805 ± 75	Beta 34302 ETH 6054
86013-005	1006	unidentified mollusc fragment	11270 ± 90	Beta 34303 ETH 6055

* ages reported in uncalibrated conventional C-14 years B.P. corrected for fractionation to a base of $\delta^{13}C$ = -25‰. Errors represent 68.3% confidence limits.

Appendix 1: Figures 1-11

Fig. 1

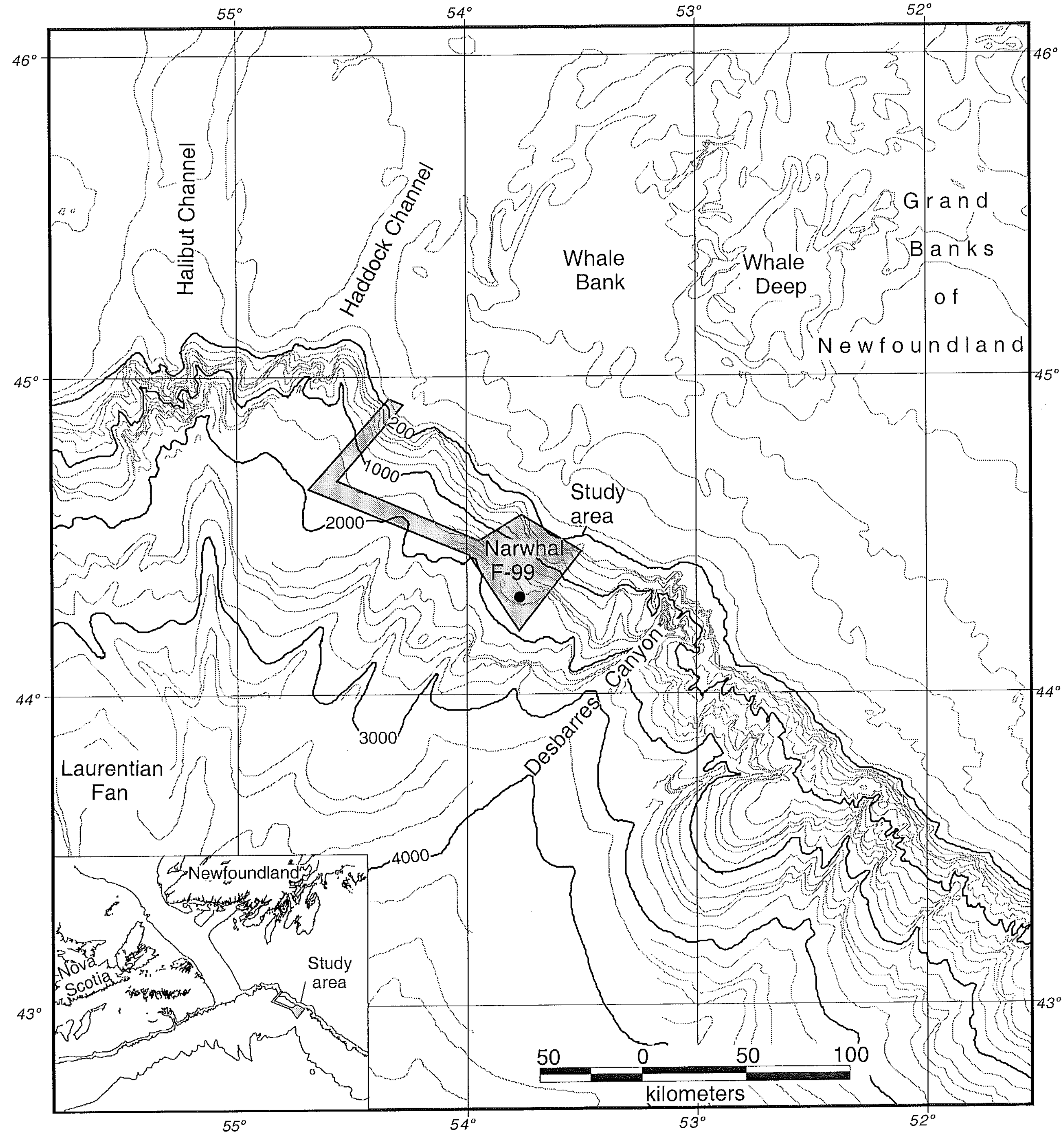

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Figure 1 (feb 2, 00)

Fig. 2

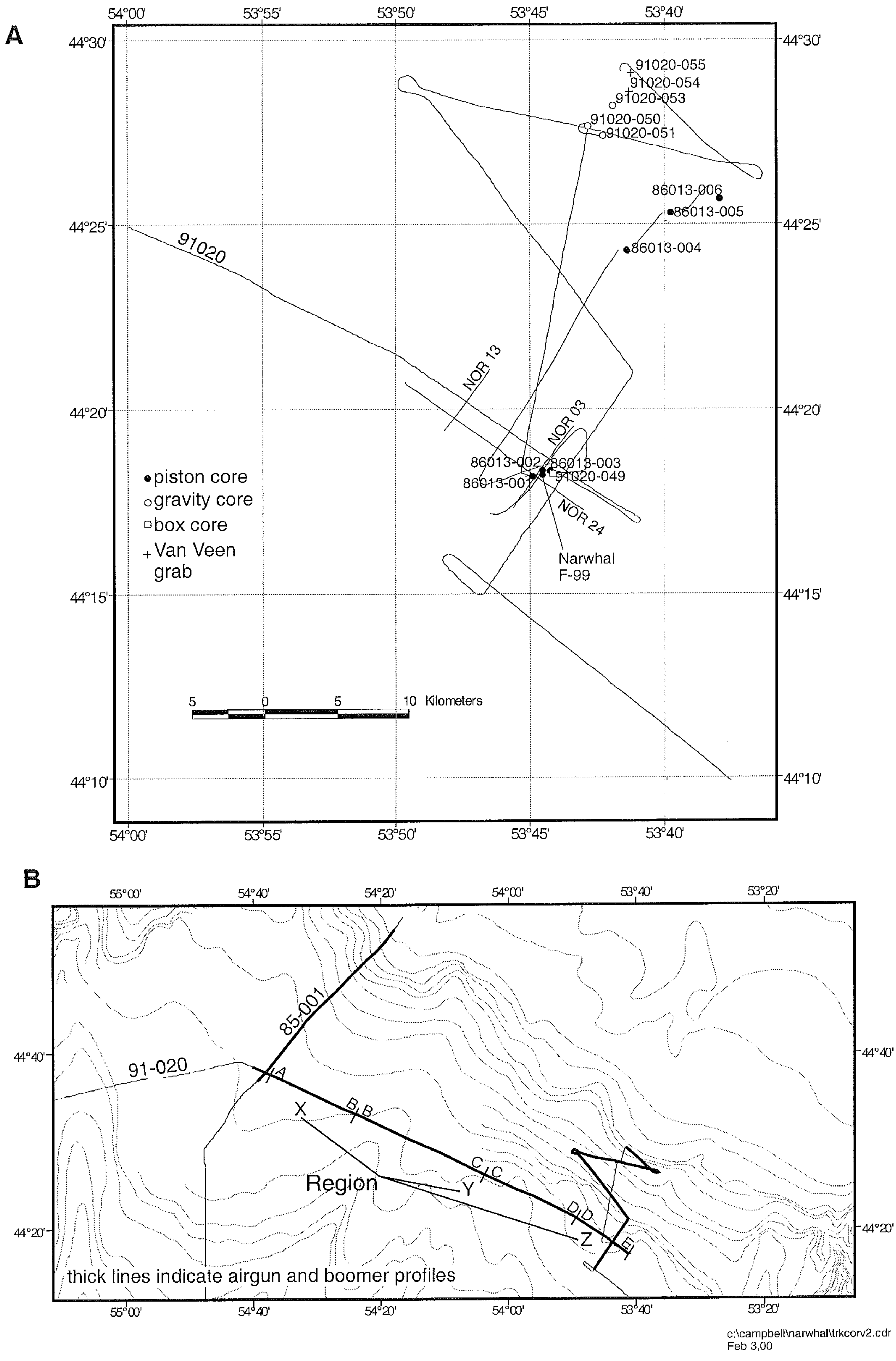

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Fig. 3

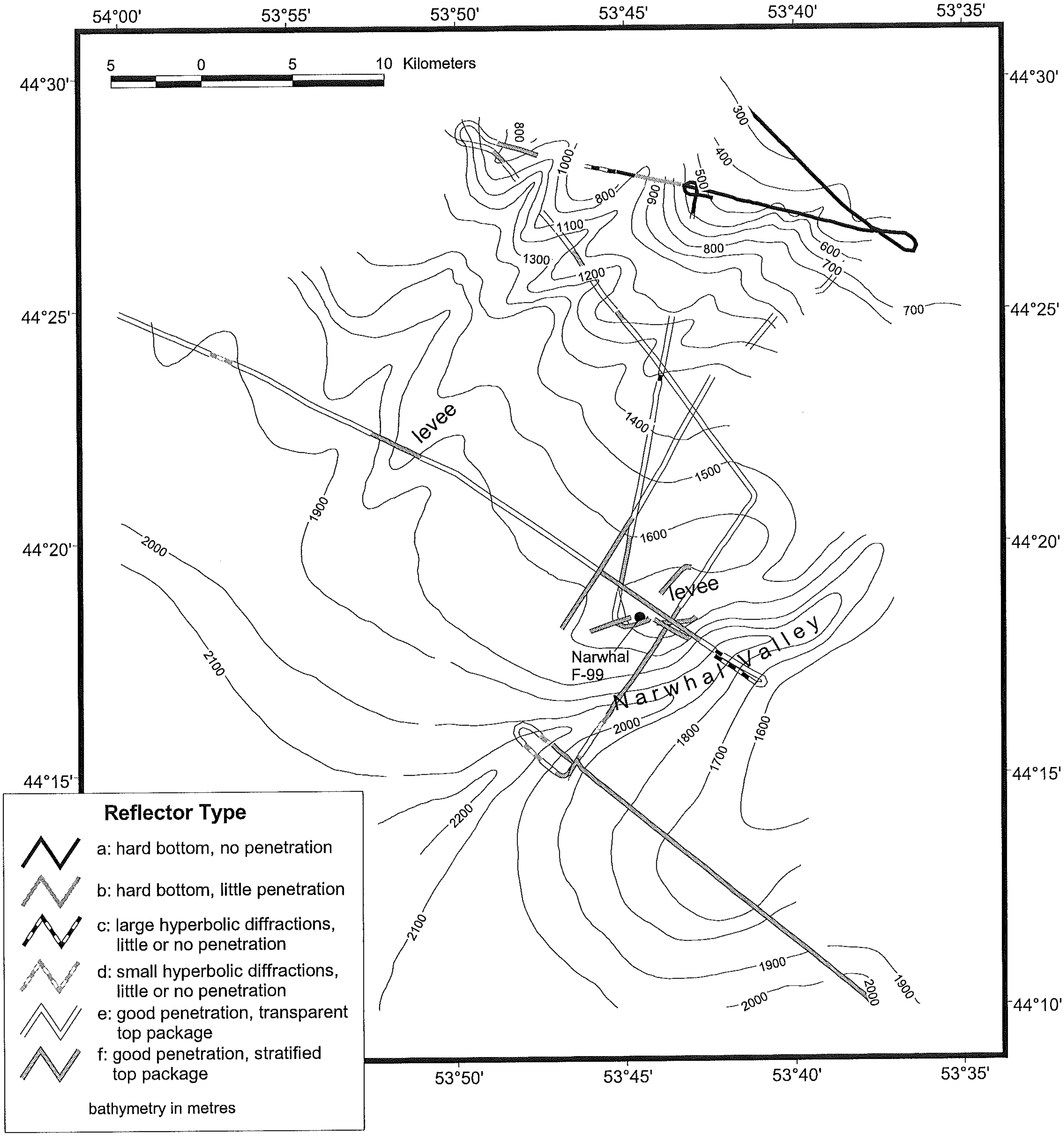

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Figure 3 (Jan 20, 00)

Fig.4

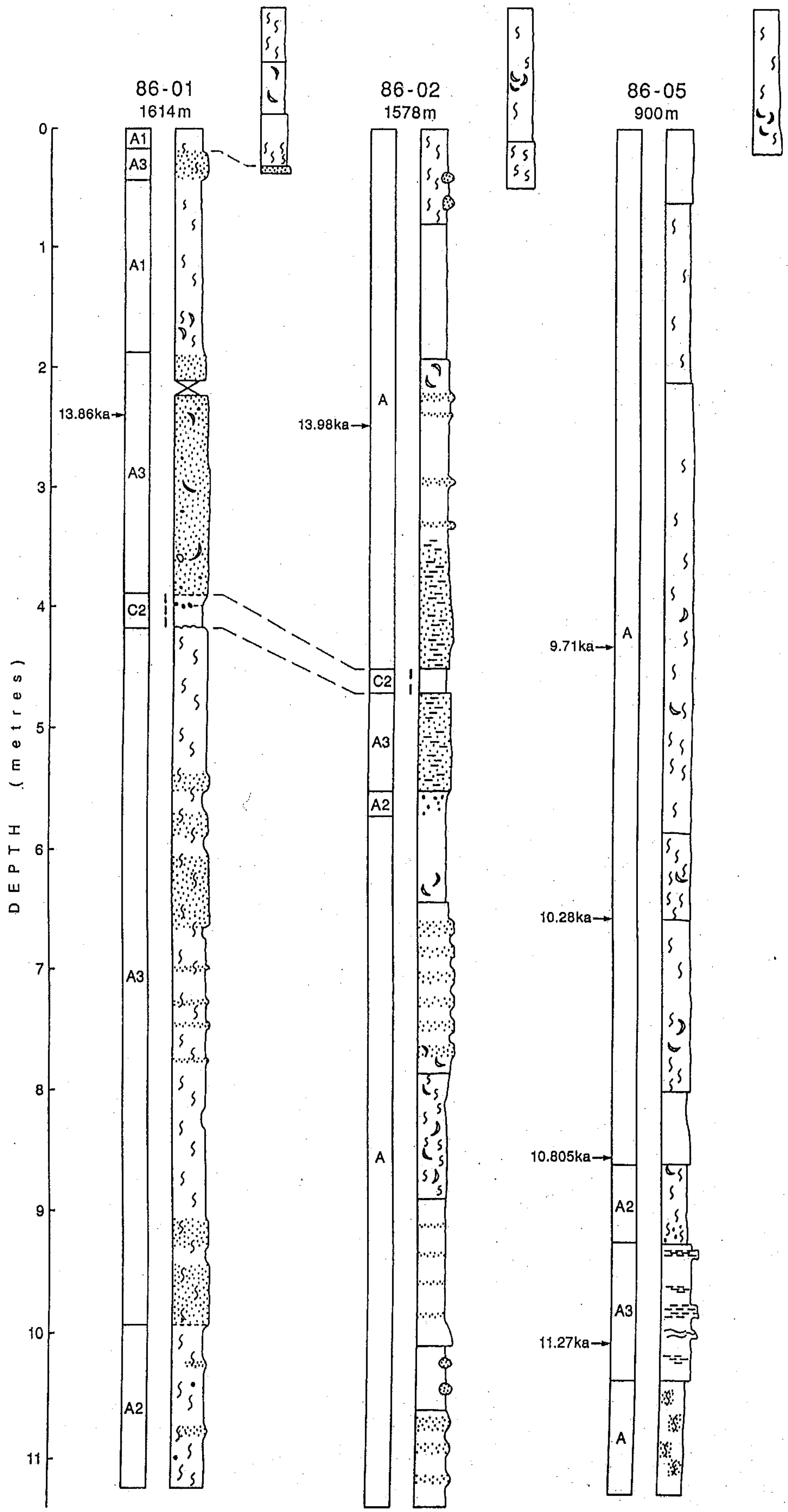

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Figure 4
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narwhal
01/18/00

Fig. 5

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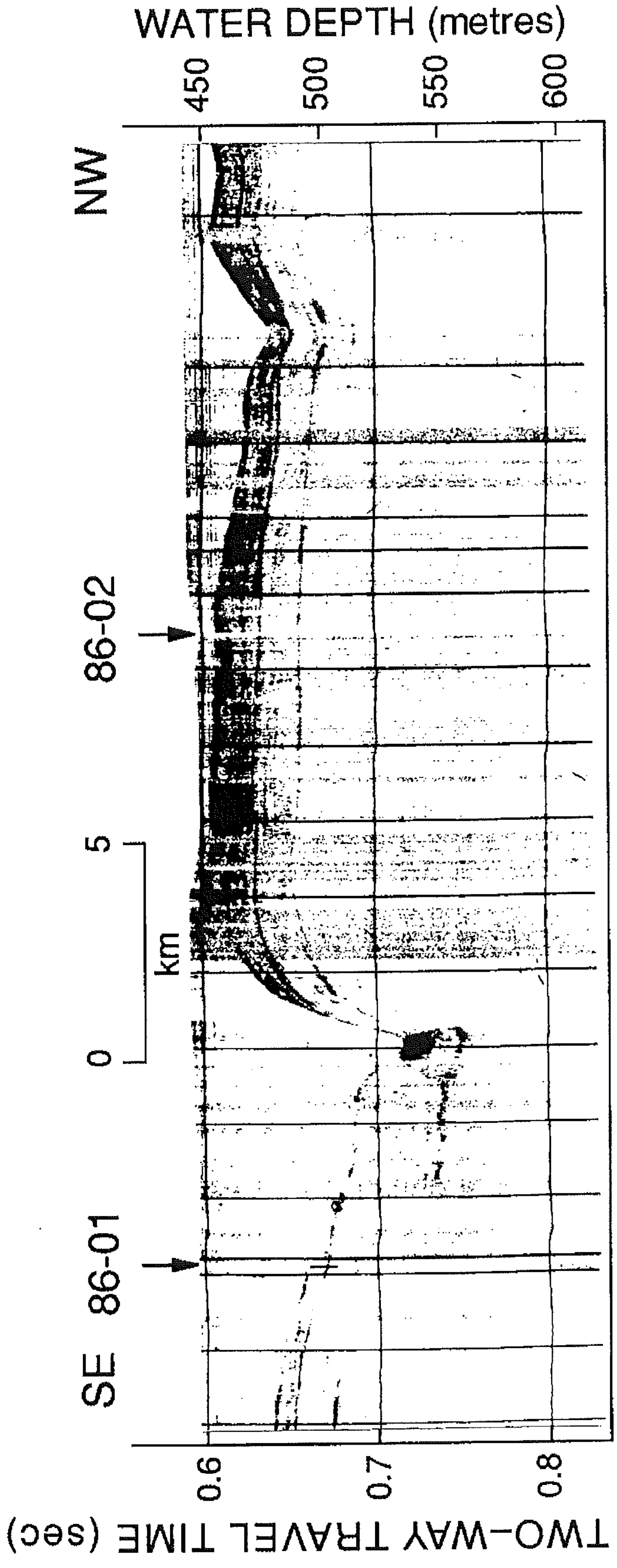

Fig. 6

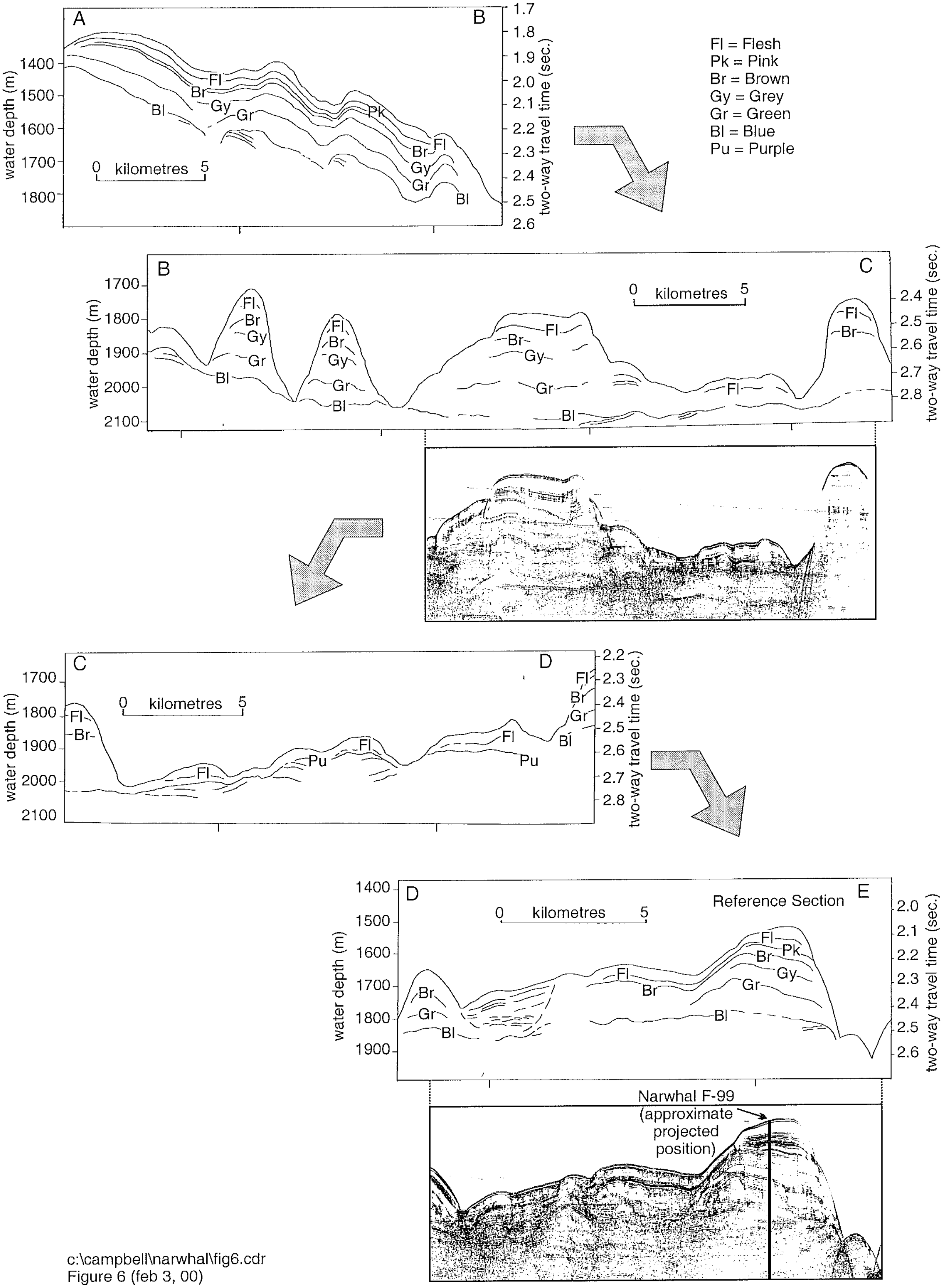

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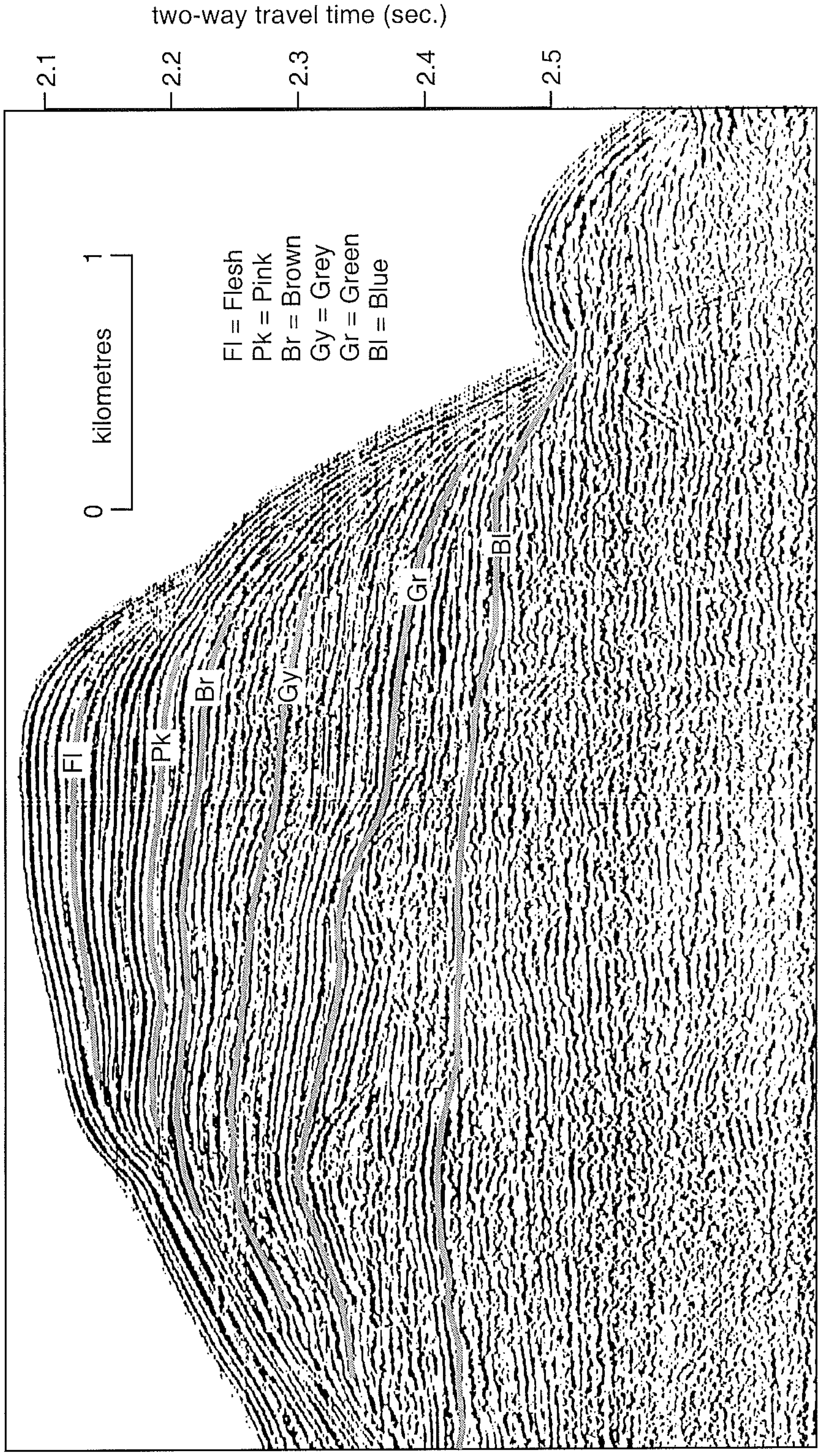
Figure 6 (feb 3, 00)

Fig. 7



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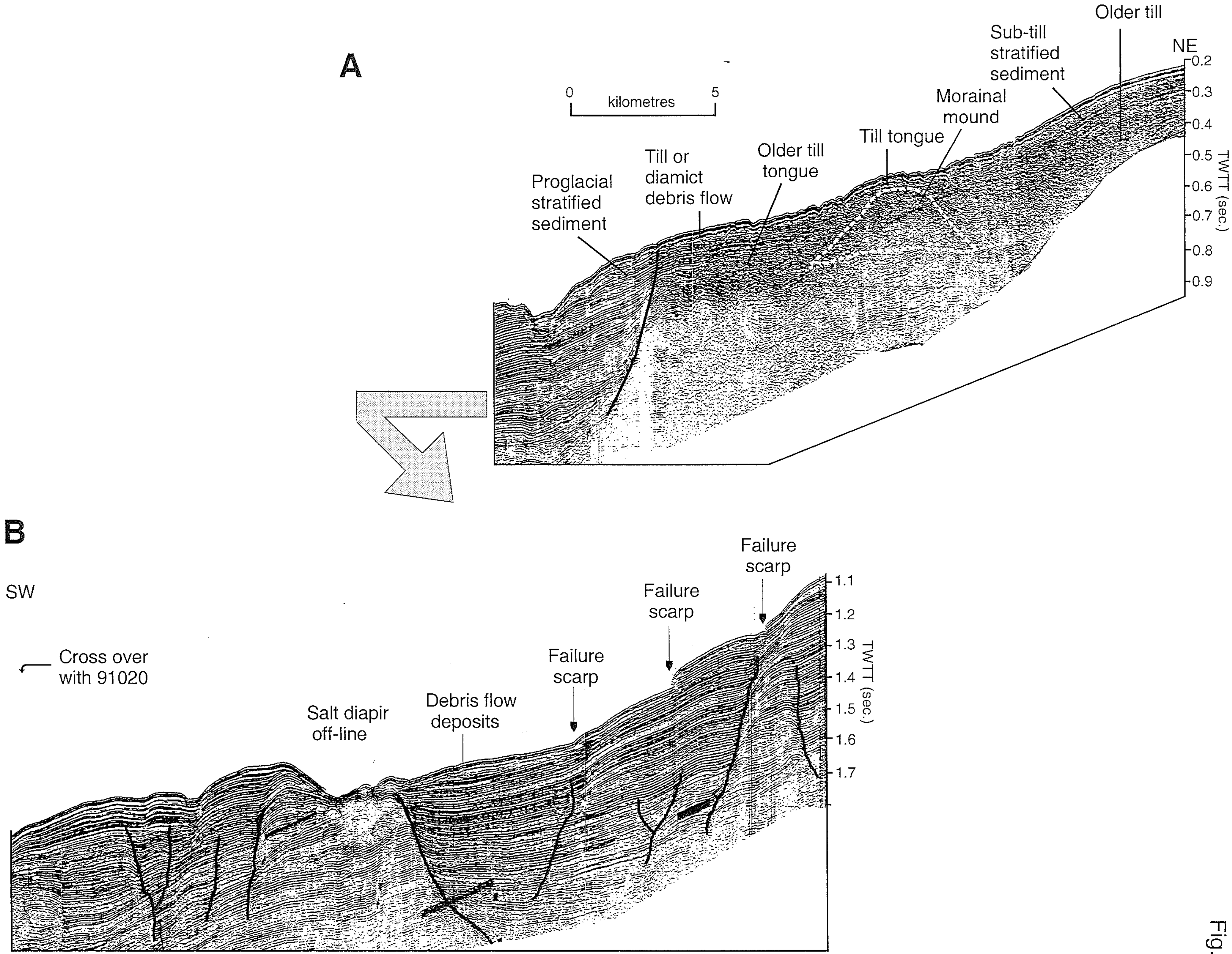

Fig. 8

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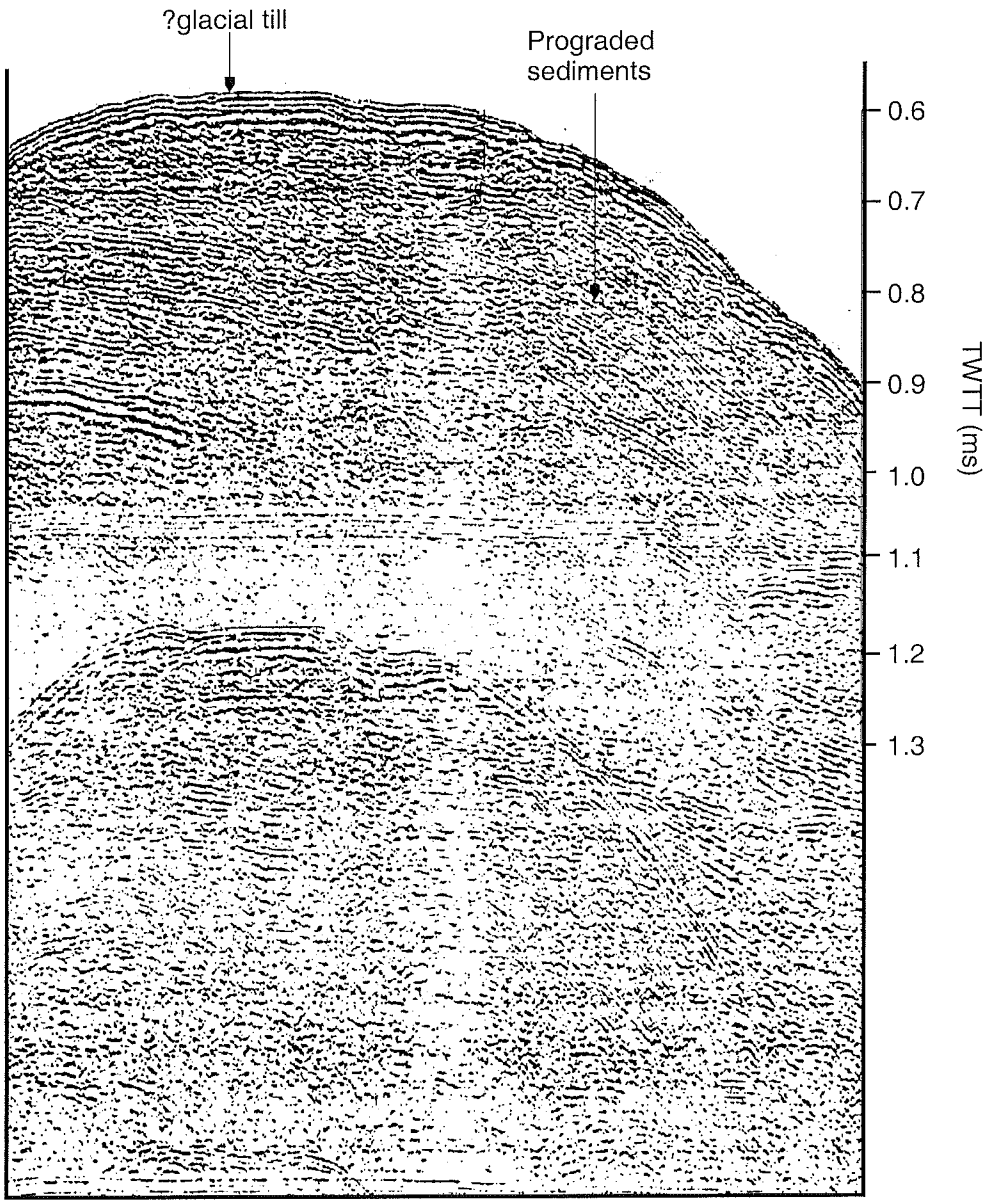
feb 3, 00

Fig. 9



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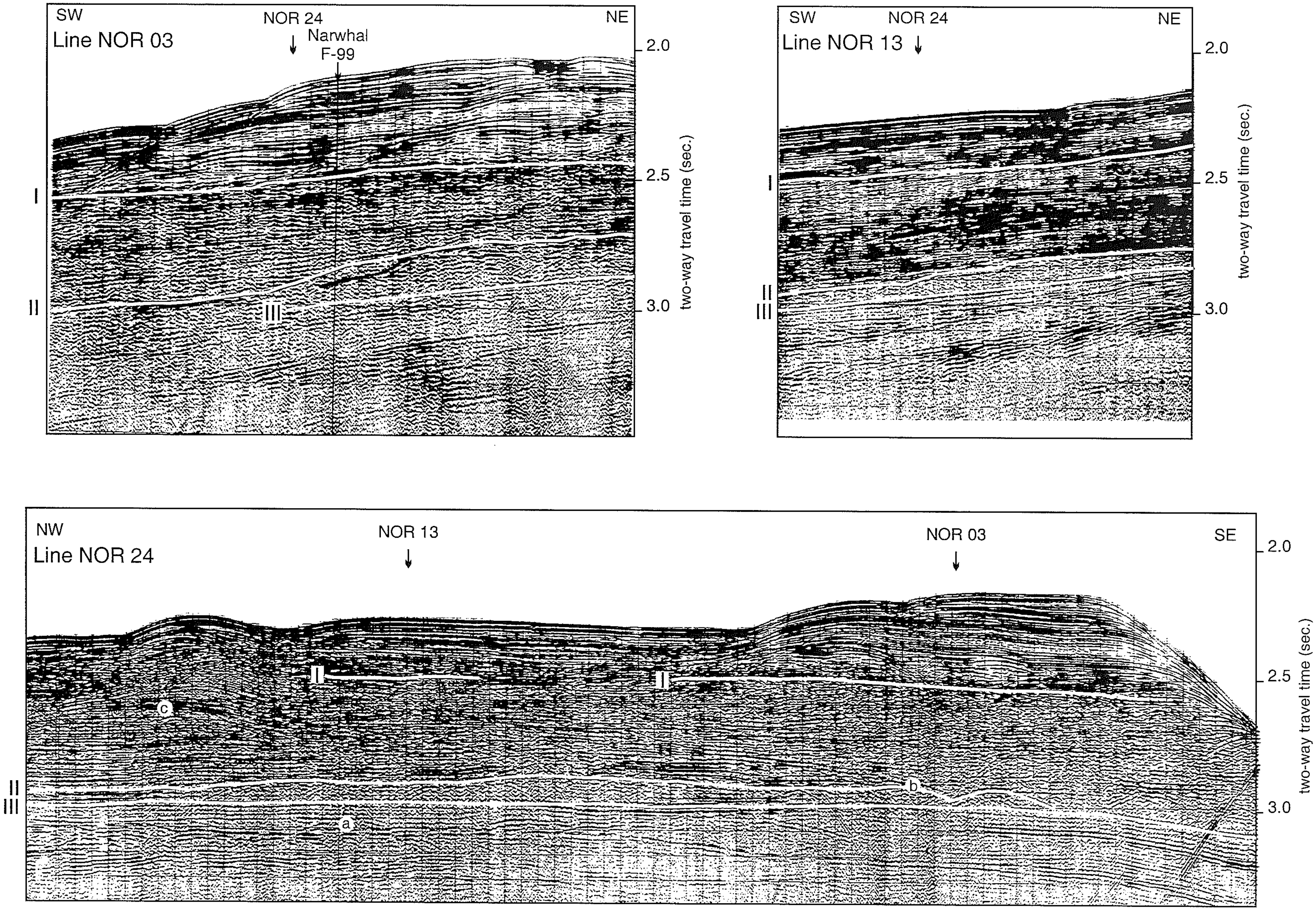

Fig. 10

c:\campbell\narwhal\ind_lin.cdr
Figure 8 feb 3,00

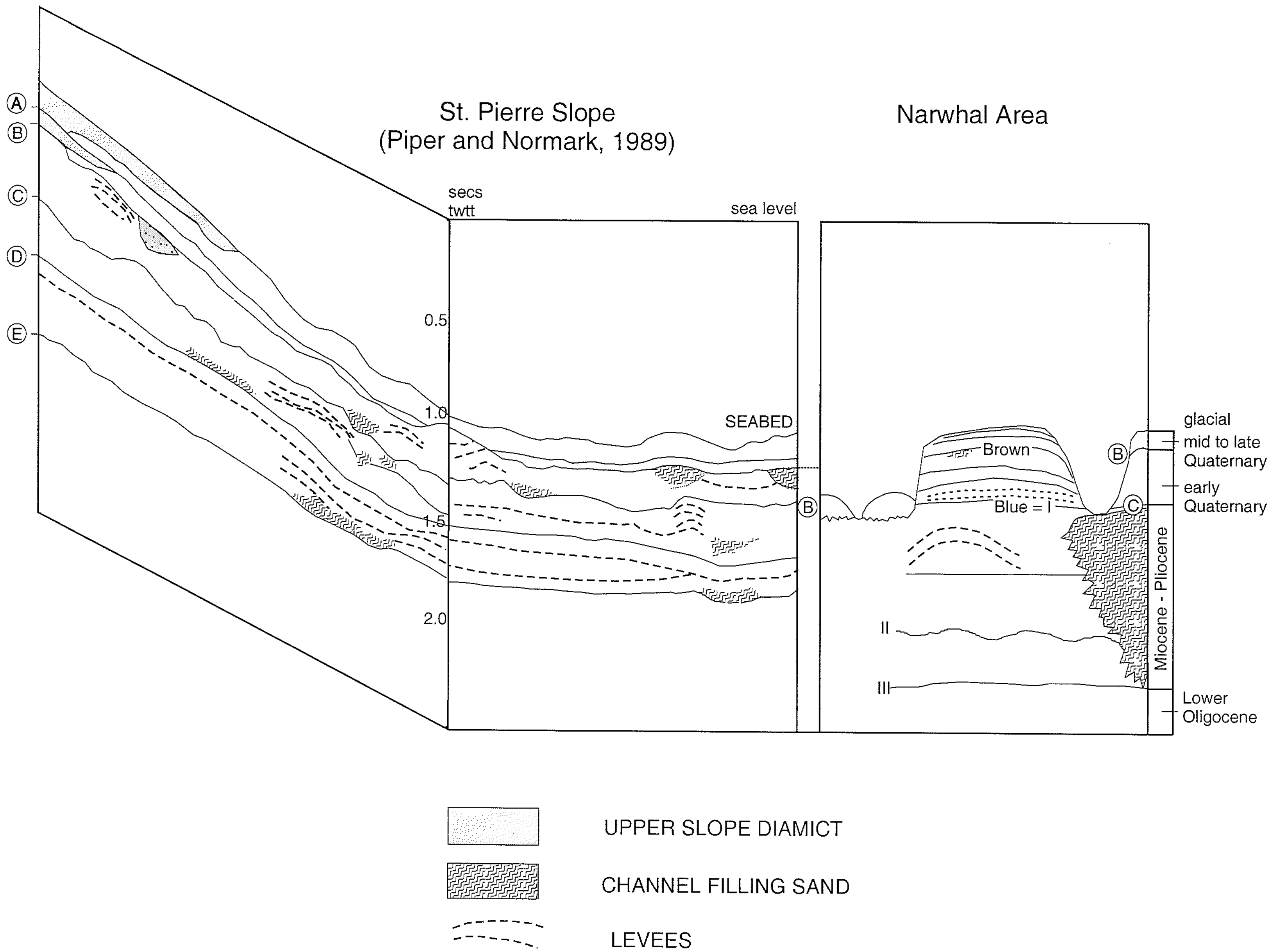

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Figure 9 (feb 3, 00)

Fig. 11