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RECENT NEARSHORE GEOPHYSICAL AND GEOTECHNICAL STUDY IMPLICATIONS TO THE INTERPRETATION OF THE SHALLOW QUATERNARY SECTION OF THE SOUTH CENTRAL BEAUFORT SEA

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Abstract

An evaluation of recently acquired geophysical and geotechnical borehole data from the inshore areas of the Mackenzie Delta have indicated the presence of a 15 to 18 km broad Inshore Basin feature that has been created by significant thermokarst subsidence. The subsidence is the result of the thermokarst thaw of the upper 80-90 m of the frozen sediment column which has reduced its volume by 15 to 20% resulting in subsidence of from 12 to 18 m throughout the basin. In the study area of the Akpak Plateau region the offshore boundary of the Inshore Thermokarst Basin lies approximately at the 6-8 m water depth contour which is roughly 16 to 18 km from the shoreline of North Point on Richards Island. The inshore boundary of the basin lies in the region of 0.5 to 1 km from the shoreline in 1.5 to 2 m of water. The inshore boundary is believed to coincide with the depth of freezing of the winter shorefast ice along the coastline at which point the moderating temperatures in the water column result in mean annual seabed temperatures of +1 to +1.5°C and thus the continued downward degradation of the permafrost toward the offshore. The thaw front associated with this premafrost degradation is observed to dip to seaward at an angle of from 13 to 15° with a distinct and well defined subsidence collapse basin edge directly above this steep thaw front.

This Inshore Thermokarst Basin feature provides significant sedimentary accommodation space which is believed to trap the coarser faction of the sediments derived from shoreline erosion in the initial collapse edge of the basin adjacent to the thaw front. The finer silt and clay factions are moved offshore and deposited either within the central portions of the basin itself, or are moved further offshore to be deposited as the offshore Unit A marine clays. Onlapped bedding horizons are noted within the basin which indicate some of these fines are deposited within the basin though these are most likely the siltier and fine sand components which can withstand the higher energy environments of the 3 to 8 m water depths without being swept away during summer storm events.

Throughout this inshore basin shallow gas is virtually ubiquitous which totally mask acoustic penetration and seismostratigraphic interpretations throughout most of this region. Local acoustic windows are observed near the offshore boundary and again near the inshore boundary of the basin with very random occurrences within the central portions of the basin. It is believed that the majority of these gases are simply "air" that has been released during thaw of the permafrost though some contribution of methane is likely from decaying organics trapped within the basin fill sediments.

Because of the shallow gas masking throughout the basin a continuous seismic profile could not be obtained from the offshore to onshore regions. Seismoacoustic characteristics within the acoustic windows combined with a virtually continuous borehole profile show no indication of a lateral discontinuity between the onshore and offshore geological sections however. Thus it is concluded that the geological sections are continuous and the Unit C sediments in the offshore correlate with the Kittigazuit/Kidluit Formation onshore, the Unit D marine clays offshore correlate with the Hooper Clays onshore and the Unit E sands offshore correlate with the Kendall Sands onshore. Because of the gentle westward dipping offshore stratigraphic relationships (Lewis 1991) a question is raised as to whether the Hooper and Kendall units defined beneath Richards Island (Dallimore et.al., 1991) are in fact correlative with the type section units defined by Rampton, 1988 on Hooper and Kendall Islands to the west.

Introduction

Significant effort has been expended on the understanding of the Quaternary geology of the Central Beaufort Shelf and the regions of the onshore Mackenzie Delta over the past 15 to 20 years. These studies have resulted in two separate interpretations of the regions that are somewhat at odds to each other and physically separated by a distinct band of approximately 10 km width. This separation is a result of the broad very shallow water, virtually flat, area that bands the Mackenzie Delta coastline and has been all but inaccessible to marine geophysical techniques and direct geological investigation in the past. This study has attempts to breech this region by utilizing recent geophysical study programs and geological borehole studies to catagorize the potential correlations and to outline the implications to the offshore geological model for the Central Beaufort Sea currently in use by the Geological Survey of Canada. Figure 1 outlines the primary area of study related to this program and locates the regions within the Beaufort Sea Coastal Region.

The present study is concentrated in the region of Richards Island on the Mackenzie Delta and extends offshore onto the Akpak Plateau and Kugmallit Channel regions of the Beaufort Shelf. Since the discovery of the 300 to 400 million barrel Amauligak offshore oil structure in the 1980's there has been a high level of interest in the physical characteristics of the shallow geologic section of the inshore region of the Beaufort Sea. An understanding of the entire Beaufort Shelf remains the ultimate goal of the GSC and the Oil Industry Operators, however the zone between the Amauligak oil bearing structure and the shoreline of North Point in the NWT is the focus of this and other recent studies. Direct and immediate interests pertain primarily to the geotechnical and geodynamic parameters of these sediments in relation to the cost effective installation of an offshore pipeline between these two points.

The driving forces and primary concerns are strength of the sediments with relation to pipeline trenching requirements and sidewall stabilities and how these are impacted by factors such as ice scouring to determine minimum safe pipeline burial depths. Also of concern are potential hazards such as thermal thaw subsidence related to degradation of permafrost beneath the structures (both pipeline and offshore and onshore facilities) and any shallow gas within the sediments which might be of sufficient volume and pressures to affect the strength of the sedimentary materials. Ultimately a comprehensive understanding of these characteristics are necessary to allow an environmentally sound, minimal cost pipeline design and installation that will survive the anticipated production lifetime of the offshore field. Without this pre-design information the presently speculated "over designed" safety margin, projected costs of Amauligak development is un-economic at current and near term (next 10-20 years) projected world oil prices. With an accurate physical parameters and seabed dynamics knowledge base it may, however, be possible to safely reduce these design margins and therefore total project costs such that the Beaufort offshore fields can be produced economically in a nearer term.

In order to properly understand the physical parameters of these materials and particularly their spatial distribution over the 36 km of this potential pipeline route, it has become evident that a more fully detailed understanding of their depositional history, thermal environment and current thermal status is required. This is particularly true within the inshore 10 to 15 km of the presently proposed pipeline route as the shallow waters of these regions have not generally been conducive to the study techniques used in the offshore and within other regions of the world.

This study looks at some initial nearshore data sets that have recently been collected with the aim of extending the understanding of the geological conditions in this nearshore zone and thus the associated geotechnical conditions along with the overall geological developments of the Beaufort Shelf.

Scope of Work

The present study is designed to look at the inshore portions of the Akpak Plateau and particularly the megatransect line within the region of the south central Beaufort Sea study area. The primary task has been to correlate recently acquired seismic/subbottom reflection profile data with borehole data to refine the surficial sediment stratigraphy, stratigraphic models and permafrost distributions of these sites. This study is ultimately to provide a detailed spatial and geotechnical evaluation of the Amauligak to North Point pipeline route zone that might be used as a guide to the design engineering of the pipeline for a more detailed cost estimate. This entails collecting and summarizing the geotechnical borehole information in the local area as well as the inshore geophysical data and attempting to catagorize the region into zones that will relate to different geotechnical and seabed dynamic regions for the purpose of specification of pipeline design.

Authorization

This report has been authorized under Task 4 of D.S.S. contract 23420-2-M194/01-ORC issued to Lewis Geophysical Consulting. The program has been completed under the direction of Mr Steve Blasco of the Atlantic Geoscience Centre, of the Geological Survey of Canada at Bedford Institute of Oceanography in Dartmouth, Nova Scotia. Funding has been provided under Task 6 of the Panel of Energy Research and Development (PEED).

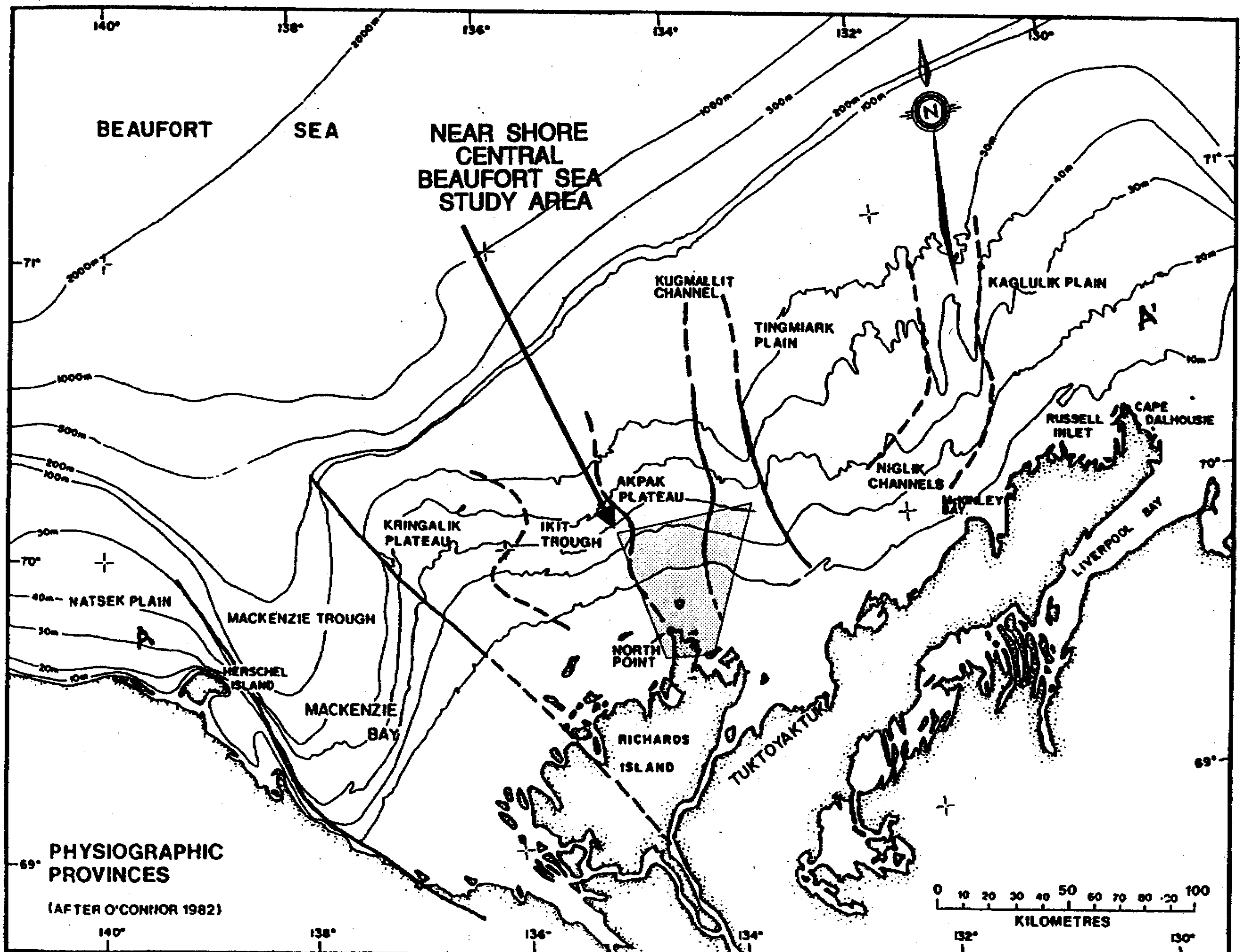


FIGURE 1 Near Shore Zone Central Beaufort Sea Study Area Location Map

Akpak/Kugmallit and Richards Island Geological Background

The presently accepted geologic backgrounds of the onshore and offshore sections of the Beaufort Shelf / Tuktoyaktuk Coastland study areas are complex in nature and at present are conflicting. The conflicts are not so much in sedimentary environment and source derivation of these materials but in their interpreted age relationships. The following subsections summarize both areas and attempt to define the primary discrepancies in the geological models for the two regimes.

Onshore Areas

Rampton (1988) has presented an extensive summary of the Quaternary Geology of the Tuktoyaktuk Coastlands of the Northwest Territories. His study area covers the region from Cape Bathurst to the Yukon and Figure 2 reproduced from Rampton (1988) shows Rampton's study area and his physiographic subdivisions of the Tuktoyaktuk Coastlands and adjacent areas. Figure 3 is a tentative chronology and correlation of lithostratigraphic units and geological events derived from his study of these areas. Dallimore and Vincent, 1991, have summarized and provided additional more specific descriptions of the surficial geological conditions in the North Head region of Richards Island related to the specific borehole study associated with the onshore offshore transect study program. Figure 4 is a simplified surficial geology map of Richards Island reproduced from Dallimore and Vincent, 1991.

Within this extensive documentation the geologic section of the North Point region of Richards Island (area adjacent to the offshore study area) is described to consist of the following Formations and Members of Formations with age determinations based on Rampton's 1988 interpretations. The following summaries are from youngest to oldest:

Parson Lake Formation sediments: (Recent Holocene lacustrine deposits):

> The Parsons Lake Formation consists of recent sedimentary infill within the relict and presently extensive thermokarst lakes developed within the regions. The thermokarst lacustrine deposits were formed through wave and current reworking of debris introduced into the lakes by retrogressive-thaw flow slides. The materials

are similar in texture to the materials constituting the surrounding terrain. The lacustrine deposits are generally thinly bedded clay, silt and fine sand and commonly are high in organic content. In many places their bases grade into colluvium and contain a large number of stones and fragments of wood and peat. Shore zones generally have a concentration of stones though well sorted gravelly beaches are the exception unless the surrounding sedimentary materials have high concentrations of sands and gravels. These sediments are generally observed to be between 1.5 and 8 m in thickness and correspondingly localized in areai extent. The refreezing of these materials after a lake has been drained commonly results in pingo formation as observed throughout the study area. These sediments rest unconformably and with local extent on top of either Toker Point materials or Kittigazuit sand materials depending on the local conditions and area.

Toker Point Member of the Tuktoyaktuk Formation (early Wisconsin till? diamict):

On Richards Island these sediments are characterised as till and associated gravel and sand deposited directly or with minor reworking by glacier ice and generally modified by cryoturbation. These till diamict materials have been noted to contain up to 30% massive ice. In the region of Richards Island Rampton has mapped these materials to be veneer sediments generally less than 1 m thick. Dallimore and Vincent (1991) describe the surficial veneer to be composed of a diamicton which is either Toker Point till or till reworked by solifluction and other processes. The diamicton is absent in some locations, but in other areas it may be up to 10 m thick (Note: borehole BH01 recorded 27.7 m of sand diamict ????). Dallimore and Vincent (1991) report that the glacial episode which deposited these sediments also cause substantial glaciotectonic deformation (????) to the underlying sediments with some localized thrusting and folding of thick packages of sediment. On northern Richards Island the Toker Point sediments are commonly re-worked to form a typically thin lag gravel deposit. Throughout the region these till materials rest unconformably on top of the Kittigazuit Sand Formation

Kittigazuit Sand Formation (Pre Early Wisconsinan Possibly Mid Pleistocene fluvial or aeolian sands):

These sands are typically light brown in colour and of fine and relatively uniform grain size with a general lack of organics or fossils. The sands are typically thinly bedded with individual beds commonly 0.5 - 8 cm thick and rarely up to 20 cm thick. Individual beds may grade from silty fine sand to clean fine sand or from a clean fine sand to a medium-fine sand. Their most characteristic feature is the presence of large scale planar cross beds. In the Richards Island region Dallimore and Vincent report individual co-planar bedding sets are observed to be greater than 10 m high, dipping 5 to 35 degrees mainly to the east but with intersecting sets dipping in other directions. The sands rarely show thin silty sand interbeds and very occasional thin detrital organic bands. Rampton interprets the foreset beds to be indicative of a deltaic deposition by rapid influx of sediment during a period of cold dry climate. Paleoecological analysis of an organic-rich bed in an exposure in the vicinity of Mason Bay has revealed a relatively diverse plant and insect macrofossil assemblage thought to reflect terrestrial depositional conditions (Matthews, 1988) most likely in the form of large aeolian sand dunes. Borehole BH-01a on Richards Island reports these sands to be at least 26.5 m thick with the base of the unit at an elevation of -22.5 m relative to sea level (Jenner and Blasco in Dallimore, 1991). The basal contact of the Kittigazuit sands indicates no channelling or weathering conditions as it overlies the sands of the Kidluit Formation (Rampton, 1988).

Kidluit Sand Formation (Pre Early Wisconsinan Possibly Mid Pleistocene fluvial sands):

The Kidluit Formation consistently is a grey, well sorted ("clean"), medium to medium-fine grained sand. Commonly bedding is planar and horizontal to gently dipping with coal and wood detritus and pebbly lenses or pebbles, some with granitic composition, may be present within the unit. Some locations indicate cross bedded sequences up to 20 cm thick with many lenses of wood detritus and coal fragments. Fossil remains of both fresh water and marine mollusks have been found within these sediments though the fragile fresh water species were more complete suggesting little transportation while the marine specimens tended to be broken and worn suggesting possible reworking from the underlying marine clay sediments. Rampton, 1988 interprets these sediments to probably have been deposited on a broad alluvial plain characterized by streams with braided channels. Macrofossils assemblages indicate that the area was characterized by climate typical of the northern boreal forest during deposition of these sediments. These sands are noted to be 7.9 m thick at an elevation of -22.5 m to -30.4 m below sea level on Richards Island based on BH-01a. These sands lie (unconformably ?) on a clay horizon informally defined as the Hooper Clay.

Hooper Clay (pre-Early Wisconsinan possibly Illinoian? marine clays);

The Hooper clay unit is a silty clay sequence containing abundant marine shell fragments and shells. Some exposures on Hooper Island show the clays up to 10 m thick and containing thin laminae of silt and sand. Beneath Richards Island the BH-01a borehole indicates that the clays are 6.28 m thick at an elevation of -30.4 m to -36.68 m relative to sea level (Jenner and Blasco, 1991). Geographically the Rampton's type section Hooper clays are noted to the west of Richards Island at exposures on the Mackenzie Bay Islands though are not noted within the sediment below the Tuktoyaktuk Peninsula or for that matter 40 km to the south in the vicinity of Dennis Lagoon on Richards Island (Rampton, 1988). Type section exposure of these clays on Summer, Hooper, Pelly and Kendall Islands have been described as glacially deformed by Rampton, 1988. (Note: at this time there is no direct correlation of the clays beneath Richards Island with the type section clays of the western islands and these may not actually correlate with the Hooper clays) The Hooper clays rest on Kendall Sand (informally named unit) sediments on an undefined contact.

Kendall Sands (pre Early Wisconsinan Possibly Illinoian? marine(?) sands):

The Kendall Sand unit is the lowermost unit described by Rampton in the study area and is primarily a sand unit with interbeds of silty clay. The sands contain an abundance of marine shell fragments and shells and are commonly mottled orange in colour (on weathered exposures - mottled black and fetid smelling on fresh exposure). The shells and interbeds of clays have been interpreted to mean that these sediments have a marine origin though exposures show tilted and deformed character of exposures on Hooper Island. It is assumed that Rampton only had access to the upper contact of the Kendall sediments and therefore they may represent nearshore transitional sediments grading to onshore fluvial or aeolian sediments with depth. The base and deeper sections of the Kendall sands have not been noted in the study area. Borehole BH-01a on Richards Island only samples the top of the Kendall sands which are described as fine, olive grey sands at an elevation of 36.68 m below sea level. Geographically Rampton only reports these materials toward the west of Richards Island and has not correlated the unit to any boreholes toward the east.

Age correlations of the described units is based on the observed stratigraphic relationships with respect to the interpreted glaciations in the region. Primarily the relative ages of the sediments are limited by the Toker Point diamict which is interpreted to be a till that is correlated to the Toker Point Stade glaciation on Tuk Peninsula and correlates with the Buckland Glaciation (Yukon Territories) and the Franklin Bay Glaciation (Amundsen Gulf). These glaciations are assumed to be Early Wisconsinan in age or approximately 60 to 100 thousand years before present. If this interpretation is correct then all deeper sediments described above are assumed to be Middle to Early Pleistocene in age.

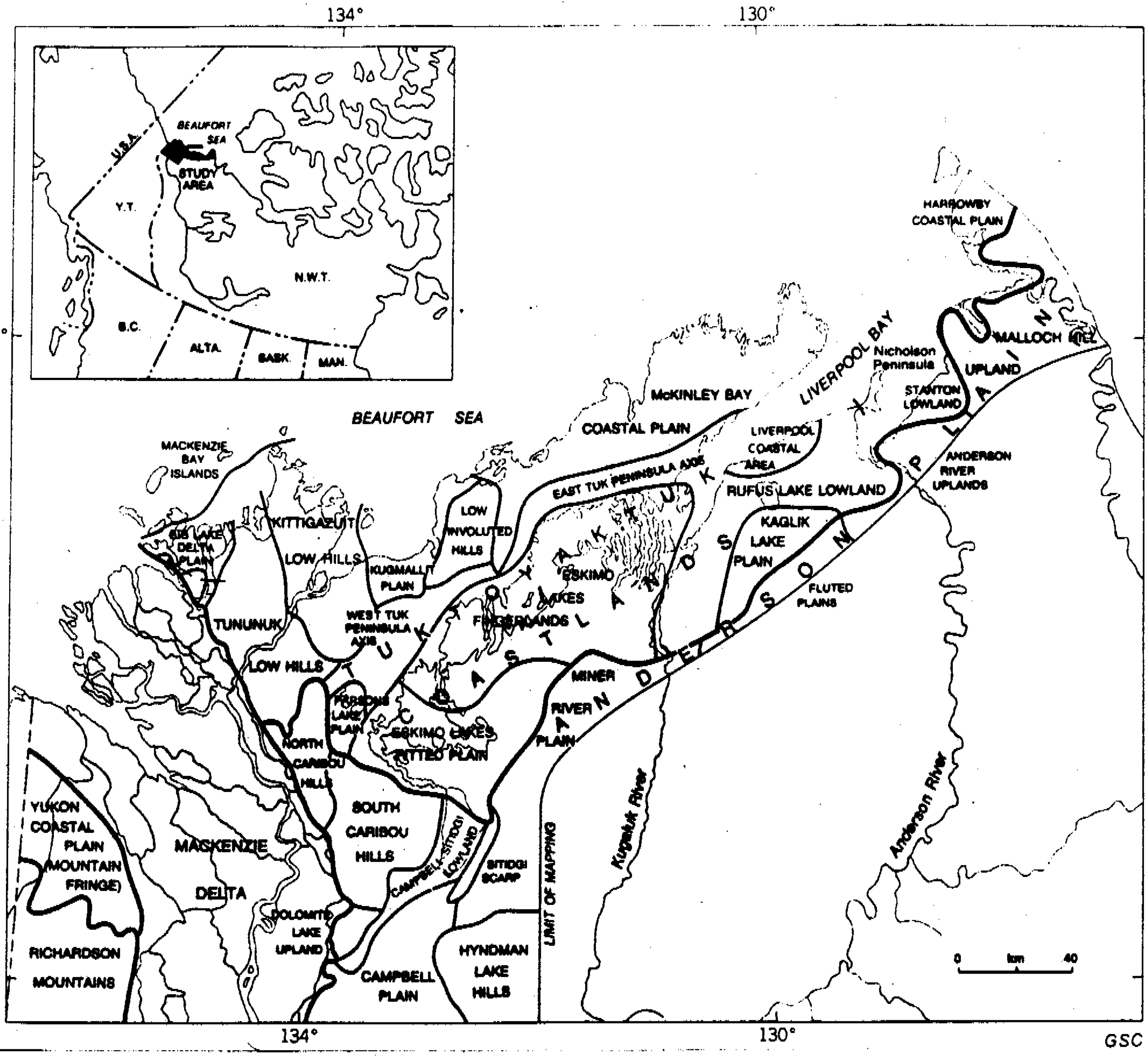


Figure 2 Location areas of Rampton's study area and his physiographic subdivisions of the Tuktoyaktuk Coastlands and adjacent areas. (reproduced from Rampton 1988)

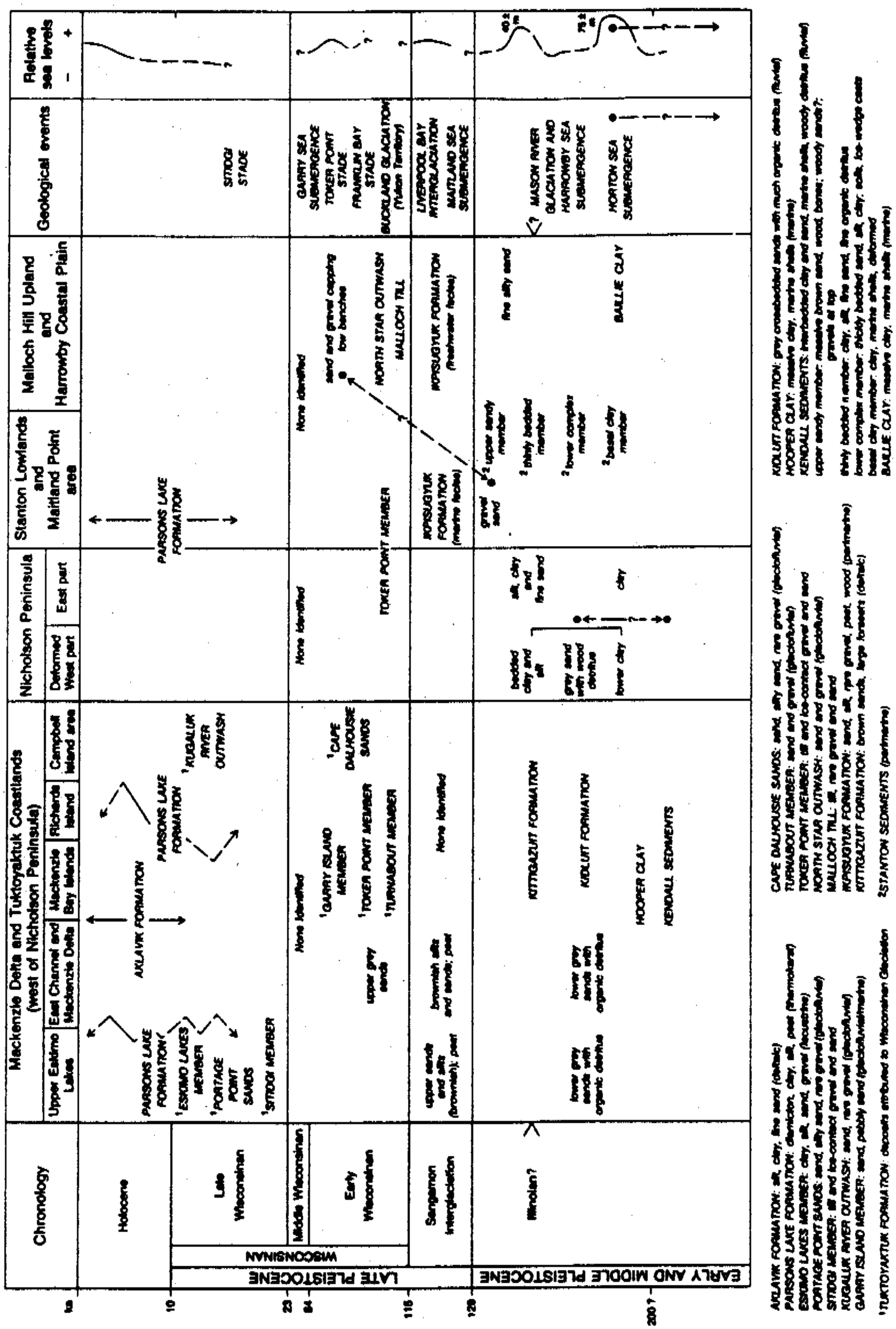
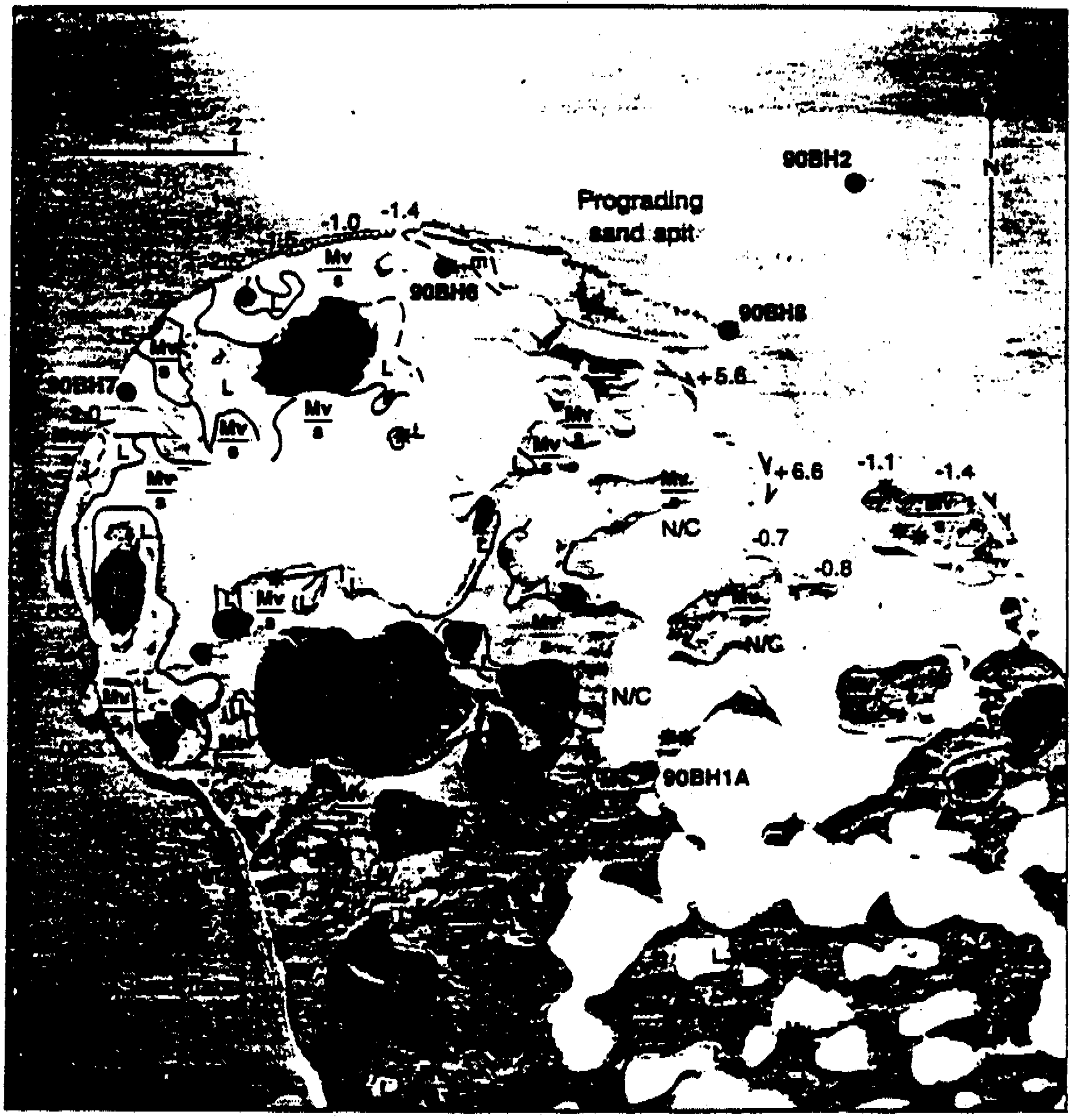


Figure 3 Tentative chronology and correlation of lithostratigraphic units and geological events derived from Rampton 1988 study of the Tuktoyaktuk Coastlands (Reproduced from Rampton 1988).



Marine sands and silts	m	*Stable coastline*	N/C
Lacustrine sediments	L	*Average coastal retreat (m/yr)*	-1.4
Discontinuous veneer of glacial till over pre-Wisconsinan sands	Mv/s	*Recent eolian activity*	●
Glacial till over pre-Wisconsinan sands	Mv/s	*Borehole*	● 90BH2
		Retrogressive-thaw flow slides	
		Sedimentation	

Figure 4 Simplified surficial geology map of Richards Island (reproduced from Dallimore and Vincent, 1991.)

Offshore Areas

The geological model for the offshore areas of the Beaufort Shelf has been originally defined and documented by O'Connor, 1980 and 1982. This model was defined using offshore seismic stratigraphy combined with borehole descriptions of the sediments and has been accepted by the GSC and the offshore operators in the Beaufort to be representative of the offshore areas. This model has been somewhat extended and refined by Lewis, 1991 for the Central Beaufort Shelf area and many authors have contributed towards these refinements over the past 10 years.

Table 1 summarizes the seismostratigraphic descriptions and stratigraphic relationships of the offshore geological model for the Central Beaufort area. This table is based on the descriptions presented in O'Connor, 1980 and 1982 and has been expanded and detailed within Lewis, 1991.

As an adjunct to the offshore model for the Beaufort Hill et.al., 1991 has introduced a series of informal formation names which he used to help explain the lateral variability of these surficial units as one moves from west to east across the shelf. Figure 5 shows a schematic diagram of these formations with the O'Connor designations along the right hand side of the diagram.

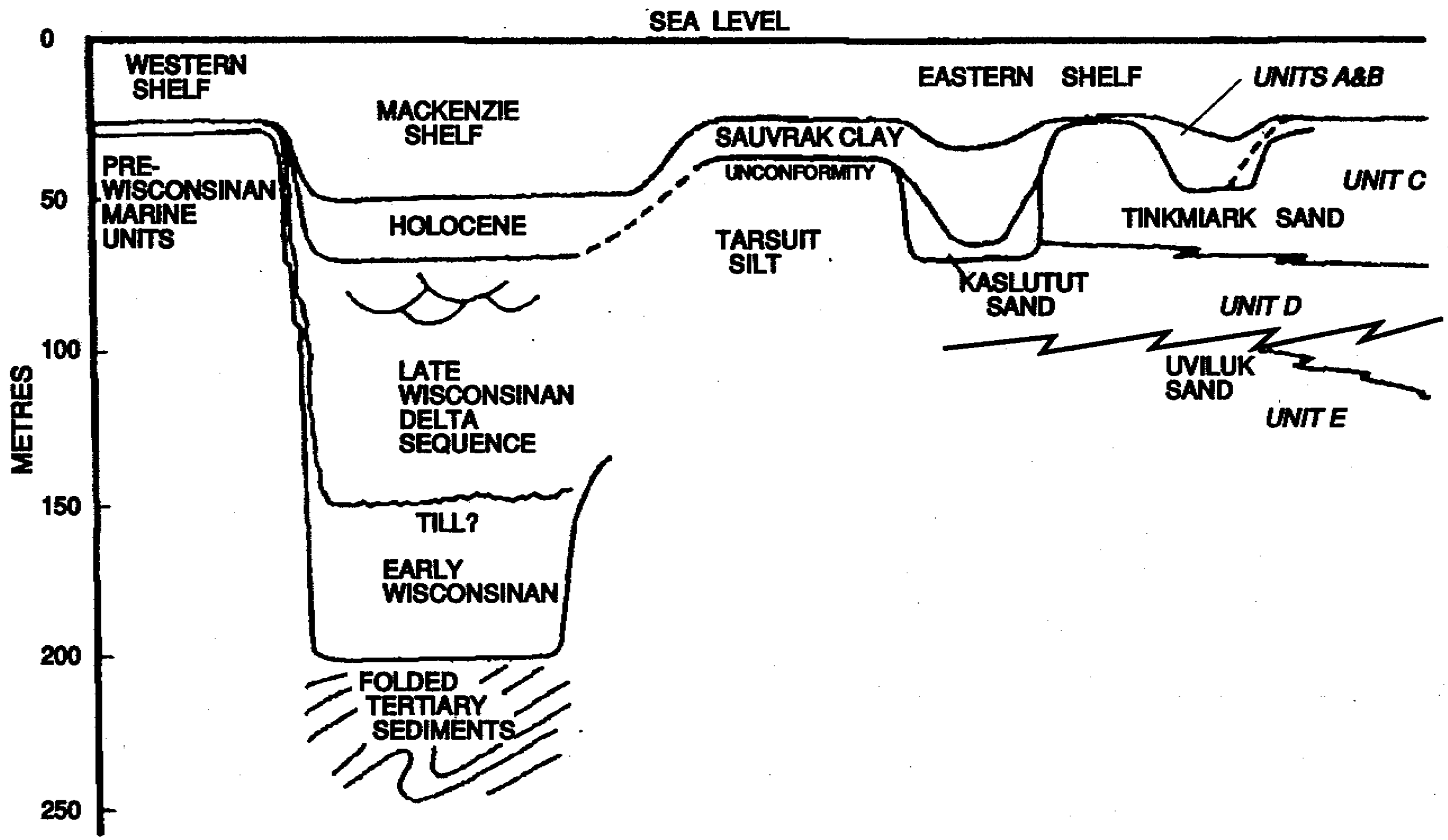


Figure 5: Schematic cross-section of the Beaufort Shelf showing the main stratigraphic units (defined by and modified from Hill et. al., 1991).

TABLE 1 CENTRAL BEAUFORT SEA: SURFICIAL SEISMO-STRATIGRAPHIC GEOLOGIC MODEL SUMMARY

UNIT DESIGNATIONS Unit	Bounding Acoustic Reflectors	UNIT DESCRIPTIONS
A	seabed - B(gradational)	**Holocene - Marine Clays - no Onshore equivalent** Horizontal sequence of recent marine sediments deposited on the shelf following the last sea level rise. Generally restricted to water depths greater than 10 to 15 m. where it drapes the topographic features of the underlying sediments and is usually thickened within topographic lows. Seismo-acoustically transparent character with few to virtually no preserved internal reflecting horizons. Unit is most often heavily ice scoured to it's base. Ice scouring has destroyed any internal reflectors that may have been generated during deposition. The unit consists of grey to black, soft to firm clays or silty clays, usually containing traces of fine sand and organics, often in the form of fine laminations. Unit A is geotechnically defined by high water contents (usually > 50%) and low to very low shear strengths (1 to 30 kPa). Commonly due to the disrupted nature of these sediments a contact with the underlying Unit B materials cannot be detected with seismic methods and may only be described by a vague increase in internal reflectivity on high frequency seismic data. The base of Unit A grades into:
B	B - U/C or seabed - U/C	**Holocene - Transgressive Silts/Clays and Sands - no onshore equivalent (?Parsons Lake Fm?)** A transgressive sequence which includes deltaic, lagoonal and littoral sediments deposited in a complex high energy transitional environment related to rising sea level. Deposition of this unit presently continues in water depths of less than approximately 10 m near the coastline. Seismo-acoustically, Unit B is relatively transparent with flat lying to complex internal bedding structures which have in some areas been disrupted by ice scour resulting in an acoustic unit similar to A, though with a slightly increased internal reflectivity represented as a grey tone on the acoustic records. The A/B contact is very poorly defined on most acoustic records and normally consists of a 1 to 3 m thick gradational transition zone to slightly higher internal reflectivity when it can be identified at all acoustically. The unit is composed of a spatially discontinuous and highly variable sequence of thin, interbedded sands, silts and stiff clays. Geotechnically the unit is lower in water content (<50%) and typically though not always is stiffer with shear strengths in the range of 30 - 100 kPa. Unit B rests unconformably on:
C	U/C - Unit D or seabed - Unit D	**Early Holocene and Late Pleistocene - Fluvial & Paralic/deltaic and Outwash Sheet sands** **Onshore Correlation - Toker Point, Kittigazuit and Kidluit Formations ??** An underlying, older sequence which comprises coastal plain sand sediments. The B/C contact represents a subaerial erosional contact in some locations and a transgressional unconformity contact in others. In most areas of the Beaufort the contact acoustic reflector is commonly of high amplitude and generally smooth in nature. Within some regions (notably inshore areas and areas with coarser materials at seabed) the contact is highly variable in character and often becomes un-mappable. When visible on the acoustics it most often is interpreted as a subaerial erosional contact. Seismo-acoustically the unit is highly irregular in character with moderate to high internal acoustic backscatter. Internal acoustic structure, when observed, is primarily composed of numerous, varied amplitude, discontinuous and complex reflectors that are representative of complex cut and fill channelling in a virtually un-mappable spatial pattern. Occasionally bottomset and/or topset reflections of foreset bedding sequences are noted. The occurrence of ice bearing sediments in the form of Hummocky Acoustic Permafrost (HAPF) within this unit is widespread. In offshore regions (water depths greater than approx 25 m) HAPF reflections are predominantly at depths of 10 to 20 below the top of Unit C while in nearshore (8 - 15 m water depths) regions HAPF reflectors are noted throughout the unit C materials and are occasionally seen within 2 to 4 m of the top of Unit C. Unit C consists predominantly of fine to medium grained, grey or brown sand that is firm to very firm and relatively barren of fossils. The base of the unit is poorly defined on most high resolution acoustic records throughout the Central Beaufort Shelf and is usually inferred from the base of the complex bedding channel structures observed on the seismic records. Unit C overlies:

TABLE 1 (cont'd) CENTRAL BEAUFORT SEA: SURFICIAL SEISMO-STRATIGRAPHIC GEOLOGIC MODEL SUMMARY

(cont'd)

UNIT DESIGNATIONS Unit	Bounding Acoustic Reflectors	UNIT DESCRIPTIONS
D	Unit D - E	**Pleistocene - Marine Clay/Silts** **Onshore Correlation - Hooper Clay Formation ??** A sequence of fine grained silts and clays of predominantly marine origin. Acoustically the unit is transparent with only occasional faint, conformable bedding planes noted on the records. The top of the unit normally shows no distinct mappable acoustic reflecting horizon and is inferred from the bases of the lowest channel structures observed within the overlying Unit C. Radio Carbon age dating from an offshore sample at the Uviluk drill site on the eastern Tingmiark Plane from just above Unit E indicated an age of 21,000 years (Note: possibly for sediments of E_{ab} acoustic correlation uncertain at this time). These materials lie paraconformably on:
E_{ab}	E - E'	**Pleistocene - Marine Clay/Silts and Transitional Silts/Sands** **Onshore Correlation - ??? possibly lower Hooper Fm. ???** Horizon E representing a thin (2 m) frozen sand horizon which caps a continued sequence of marine silts and clays. Unit E_{ab} consists of the capping sand and the underlying marine sediments which infill the channel or basin structures observed on the E' reflecting horizon. Acoustically these sediments are only represented on the lower frequency airgun records at a low resolution. They show a moderate to strong reflecting character to horizon E with low amplitude vaguely defined reflections within the marine silty clays. Through the western half of the Central Beaufort study region E_{ab} is represented by local small channel fill structures on top of Horizon E'. Below Kugmallit Channel horizons E and E' diverge with Unit E_{ab} thickening toward the east and the overlying Unit D thinning to an onlapping pinchout below the Tingmiark Plain area in a line paralleling the Tuktoyaktuk Peninsula. Unit E_{ab} rest unconformably on:
E	E' to limit of seismics	**Pleistocene - Fluvial and Paralic/ Deltaic Outwash Sheet Sands** **Onshore Correlation - Kendall Sand Formation ???** A much older sequence of coarser grained sands that are commonly massively ice bonded forming the top of the main body of Acoustic Permafrost in the Beaufort region. Acoustically Horizon E' presents a high amplitude irregular and often discontinuous reflection (masked by overlying gas or HAPF) with a low relief (5 to 10 m) channelled topographic expression. In many areas (including regions of the Transect) horizons E' and E are observed to merge into a single acoustic reflection. Throughout most regions below Akpak Plateau and toward the east the E reflecting horizon represents the top of Stratigraphically controlled Acoustic Permafrost (SCAFP) in the region and mask all deeper reflection on high resolution seismics. Below this horizon the sediments are generally massive in character, though localized acoustic windows indicate repeated similar seismo-acoustic sedimentary sequences. The lateral equivalent unit at the Tarsuit well site suggests these sands are $\geq$ 27,000 years old, or older.

Correlation Problems

After a comparison of the above descriptions of the onshore and offshore geological models for the Beaufort Shelf and the Tuktoyaktuk Coastlands the immediate tendency is to draw equivalence of onshore Kittigazuit and Kidluit sands with Unit C, Hooper clay with Unit D and Kendall Sand with Unit E based on structure and lithology similarities. This correlation is further enhanced by the structural and lithological similarities to these two sections detailed by Jenner and Blasco, 1991 when describing the core sections of the onshore - offshore transect program conducted in 1990 (Dallimore, 1991).

The primary drawback to this correlation falls on sedimentary age discrepancies between the two sections. According to careful age dating sample selections in offshore Units C and D these materials are interpreted to be less than 21,000 years old while Kittigazuit to Hooper materials onshore are correlated to the Early to Mid Pleistocene >60,000 to 120,000 years. This discrepancy has remained a major question because of the structural lack of continuity of the seismostratigraphic and direct geological mapping of these units over the inshore shallow water zone which is 10 to 15 km wide over much of the Mackenzie Delta region.

This problem has been partially addressed from a geotechnical point of view with the Megatransect borehole program which indicates that structural and lithologic similarities correlate but still allows possibilities of discontinuities within the sections not as yet sampled.

If the offshore model and ages are correct this leaves the question of exactly what is the Toker Point till/diamict. If it is young it would have to correlate with the Sitidgi Stade most recent glaciation which supposedly did not reach the Beaufort coastline. Therefore some alternate mode of deposition would be necessary to account for these materials over Richards Island and other regions of the coastal Beaufort areas. Along with this problem, there is also the question of what has caused the "glaciotectonic" deformations within the underlying sediments if the area has not been overridden by ice of the Late Wisconsinan period and these sediments are young as described in the offshore model.

New Data Sets

Since the most recent geological summary interpretation of the Central Beaufort study area completed in 1990-91 by Lewis (1991) a significant amount of data has either been collected after this study or was under analysis at the time of this study and not available to that synthesis. These studies included both offshore and nearshore geophysical studies as well as additional geotechnical borehole programs that were conducted by both government and industry since 1988. The previous compilations by Lewis (1991) and O'Connor (1980, 1982) utilized both industry and government data sets up to and including the 1988 CCGS Nahidik survey program (for extensive track location maps refer to Lewis, 1991) This program includes and adds the following three data sets.

ARKTOS BETA / CCGS NAHIDIK

During the summer survey season of 1991 an unique geophysical survey program was conducted within the shallow water regions (0 to 7 m) off the northeastern shoreline of North Point and within the intertidal breached lakes of the North Head Peninsula. This study was conducted by Mr Steve Solomon of the GSC using the Arktos Beta amphibious vehicle developed by Watercraft Offshore Canada Ltd and owned and operated by the Canadian Coast Guard. During the summer of 1990 an experimental trial of this vehicle and geophysical instrumentation configuration was completed in the Tuktoyaktuk area and described by Lewis (1991). Additional instrumentation and modifications were incorporated for the 1991 season and are described in detail in Solomon (in press ???). In total some 293 km of high resolution boomer seismic and sidescan sonar data were collected along with some amount of marine EM data and numerous grab samples. Full analysis of the coastal zone implications of this and other more recent studies are being compiled and analyzed by Steve Solomon at AGC (personal comm.)

The unique feature of this survey program was that by using this amphibious vehicle, water depths and restricting sand bars were not an access limiting factor other than the limitation of having sufficient water available to submerge the marine geophysical systems for their operation. Also the vehicle was sufficiently self contained that it could reliably operate in the remote region of North Point in a safe manner without the fear of becoming grounded on sand bars or bogged down within the swampy terrain. Figure 6 shows the survey track lines of this program though note that because of the restricted waterways of the area much of the track plot could not be reproduced without significant overwriting of the line and fix labels. To utilize these data it was necessary to access lines on a day by day or line by line basis using layered systems on a video screen.

In addition to the Arktos survey lines additional offshore extension of these survey lines were completed during a short offshore geophysical survey and sampling program conducted from the C.C.G.S NAHIDIK immediately following the inshore program in 1991. These survey track lines are also shown on the figure and extend into the offshore regions continuing some of the lines collected with the Arktos vehicle.

Gulf Pipeline Studies

Gulf Canada Resources Limited, as the operating partner in the Amauligak Development Studies Program has conducted both geophysical and geotechnical borehole programs along a corridor extending from the Amauligak discovery during 1988-89. These data were previously held proprietary and are used within this study to extend the nearshore regions into the offshore and for detailed correlations with the borehole and cone penetrometer information. Figure 7 is a track plot of the grid survey conducted over the proposed route. Sidescan, bathymetry and Boomer seismic data were collected along these track lines during the summer season of 1988 and a detailed report was produced by McGregor Geosciences Ltd in 1989. A summary report by Lewis (1988) was compiled on the basis of the central line of this grid collected during the Nahidik 1987 survey program and integrated these data with the GSC offshore geologic model.

Onshore - Offshore Borehole Transect

During the spring and early summer of 1990 an onshore and on ice geotechnical drilling program was conducted by the GSC to investigate the geology and geotechnical conditions of the Beaufort Sea Shelf and coastal areas in the vicinity of Northern Richards Island. This study was designed to extend and supplement the detailed geotechnical programs of the Gulf Pipeline study programs (EBA, 1988a and 1988b) in order to utilize the combined data sets for a more comprehensive understanding of the geological implications along a single onshore offshore transect.

Four deep and one shallow boreholes were completed along the shallow water extension of the pipeline corridor and 13 Cone penetrometer tests were completed as well. In addition 4 boreholes were completed in the onshore areas of Richards Island (Dallimore ed., 1991). Figure 8 shows the locations of these boreholes along with the locations of the boreholes and cone penetrometer test conducted during winter and summer Gulf drilling program in 1988 (EBA, 1988a and 1988b).

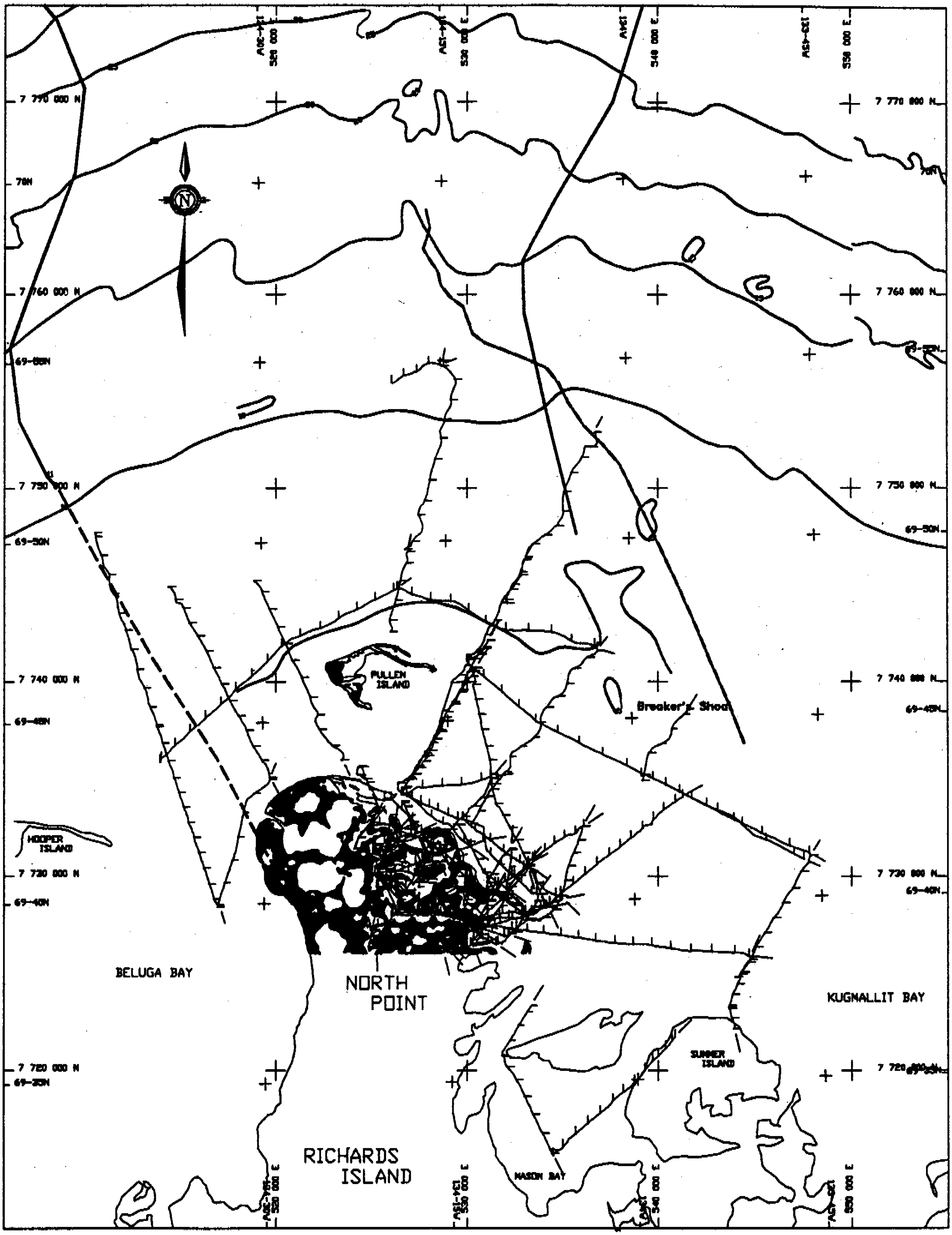


FIGURE 6: ARKTOS BETA and CCGS NAHIDIK 1991 survey tracks in the nearshore regions of North Point and Richards Island.

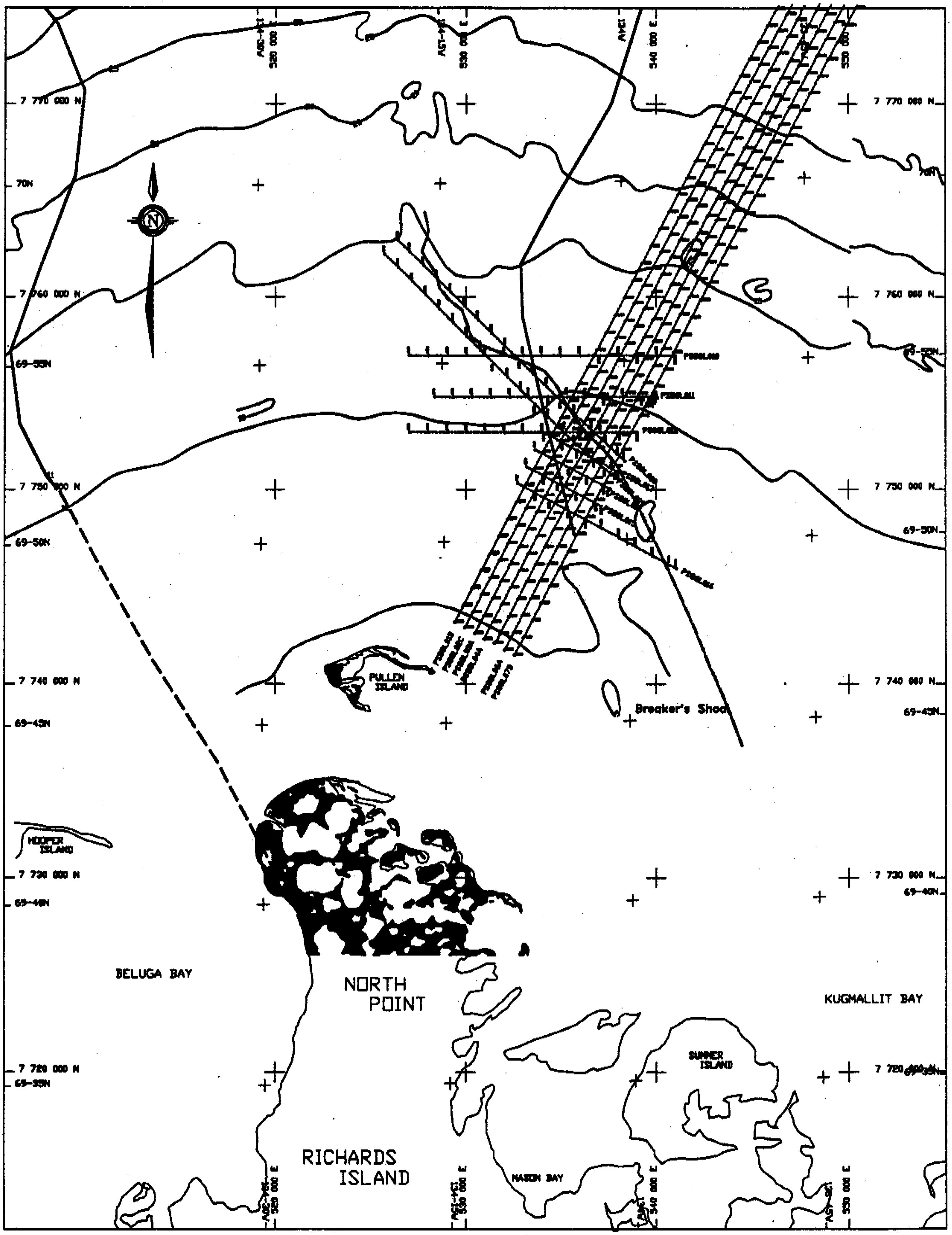


FIGURE 7: Gulf 1988 survey lines along the proposed Amauligak to North Head pipeline corridor. Note: Lines terminated 1 km north of plot grid.

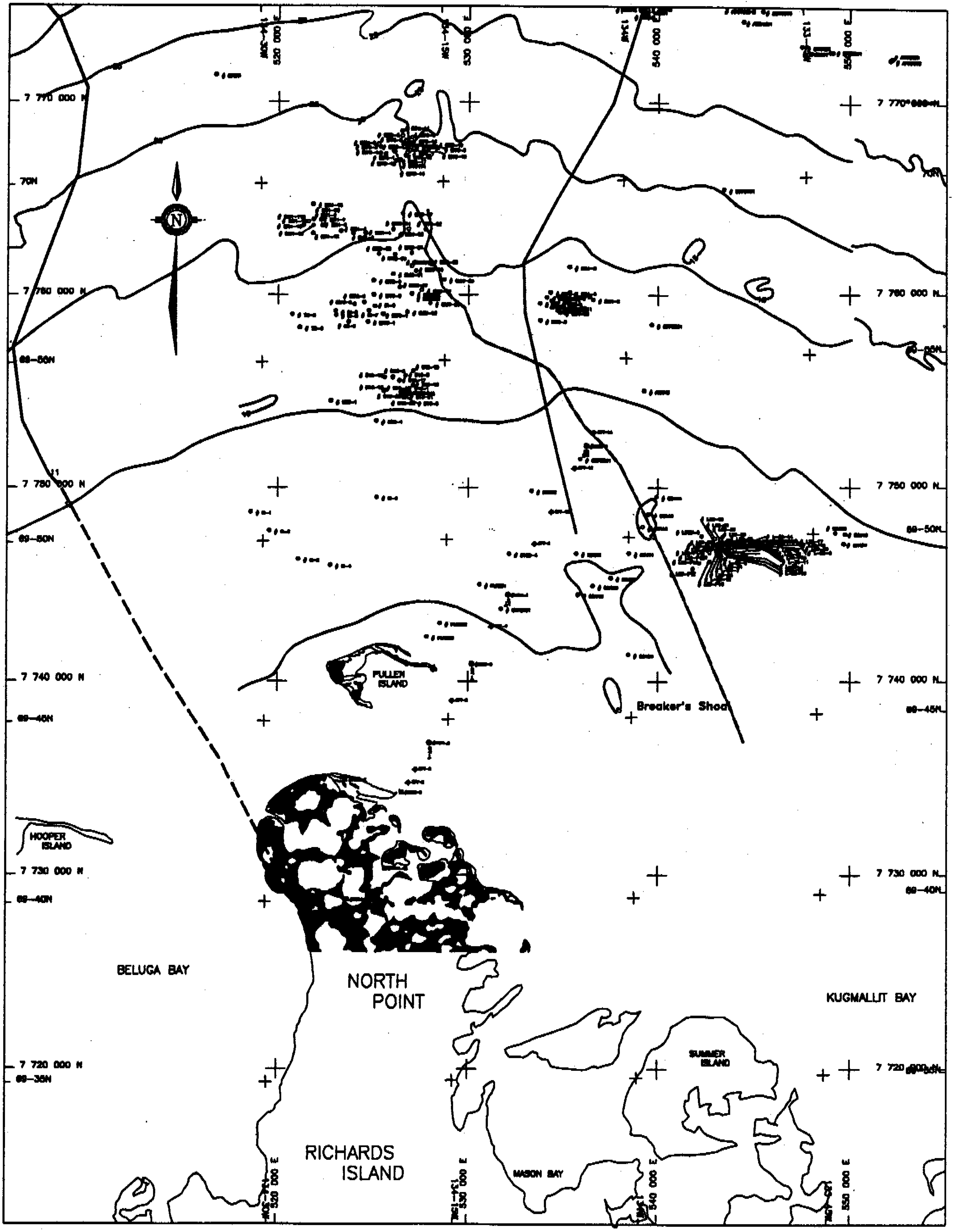


FIGURE 8: GSC and Industry Borehole and CPT locations in the nearshore Akpak Plateau and Kugmallit Channel areas of the Southern Beaufort Sea.

Geophysical Observations

The following subsections outline the seismostratigraphy of the offshore, nearshore and transition zone areas of the Richards Island - Akpak Plateau and Kugmallit Channel physiographic regions of the Beaufort Shelf. In this study the offshore seismostratigraphy is provided as a comparison base for the data from the nearshore and transition zones which are the focus of this study.

Offshore Seismostratigraphy

The offshore seismostratigraphy of the Akpak Plateau and Kugmallit Channel regions have been presented in significant detail within Lewis 1991 and O'Connor 1980 and 1982 and numerous proprietary reports of the industry operators. The following sections are presented primarily as a basis of comparison for the later near shore sections and discussions.

Kugmallit Channel Region

The seismic data within the Kugmallit channel is described in considerable detail here as it represents a relatively distortion free seismostratigraphic type section for the offshore Central Beaufort Shelf area. This area is notable in the sense that Acoustic Permafrost Reflectors (APF's) and shallow gas are relatively rare in this region and therefore good quality seismostratigraphic records can be obtained. This area is also primarily in water depths greater than 10 m which represents the offshore Beaufort shelf areas that were transgressed quickly during a period of relatively fast sea level rise throughout the Early and Middle portions of the Holocene.

The Kugmallit channel contains from 0 to about 20 m of Holocene Unit A and B sediments overlying from 15 to 40 m of Unit C sands. Boreholes indicate a Unit D clay layer below the sands which are usually not identifiable on the seismic records that are of variable thickness from 10 to about 15 m. These clays overlie deeper sands of Unit E which are typically ice bonded and present a high amplitude acoustic return on the seismics.

Most seismic records do not show a distinct differentiation between units A and B within the Kugmallit Channel, however, on occasion 3.5 and/or 7 kHz profiler records and occasionally some boomer records will indicate a hazy gradational increase in internal reflectivity in the depth zone of 2 to 5 m below the seabed. Figure 9 shows an example profiler and boomer record from the pipeline corridor region that indicates this character. This vague transition has been interpreted by this author (Lewis 1991) and some others to represent the transition between units A and B. The primary distinction between the marine clays of Unit A and the mixed silts, clays and sands of Unit B is defined by geotechnical shear strengths and water contents. Unit A marine clays and silts are typically very lose materials with water contents of from 50% to 70% that exhibit shear strengths of typically less than 30 kPa. The Unit B materials tend to be noticeably stiffer with shear strengths between 30 and 100 kPa and water contents in the range of 40% and tend to be siltier with occasional sand and/or gravel intervals.

Unit A is generally not observed in water depths of less than about 15 m and in these areas Unit B is typically observed to be exposed at the seabed. It should be noted that even in deeper waters this vague boundary can only be interpreted from very good quality acoustic records that were collected under very good weather conditions (virtually flat calm seas).

Figure 10 shows two portions of a seismic line within the Kugmallit channel portion of the Amauligak pipeline corridor which show the typical character of the Unit A and B materials. Record A indicates approximately a 12 m thickness of undifferentiated units A and B sediments just below the seabed. Figure B indicates approximately 8 m of these sediments. These materials typically are unstratified on the seismic records consisting of silts and clays. The reason that they are unstratified is attributed to the dynamic and disrupting effects of ice scouring rather than that they were originally laid down in a massive character. Occasionally high quality boomer and 3.5 kHz profiler records will show local regions of discontinuous stratification that is disrupted and truncated by scours at random depths within these sediments.

Generally the amount of stratification seen within these undifferentiated Unit A & B materials (usually within Unit B) increases toward the base of the unit which lies primarily on top of a peneplaned transgression unconformity designated U/C1 by Lewis (1991) and O'Connor (1982) and by McGregor (1989). At the base of this sequence these materials commonly rest unconformably on top of the older Unit C materials. It is noted that in many local areas the materials lie over further finely banded and sometimes complex stratified ponded basin or channel infill sedimentary materials that are of similar if not identical composition. These basin fill materials are interpreted to be lacustrine, riverine and or nearshore marine materials that fall within an ambiguous unit designation. Some basins may have been only partially infilled at the time of transgression and therefore are all or partially filled with Unit B materials (Figure 10A) while other basins may have been completely filled and were essentially truncated and eroded down during transgression (Figure 10 B) which technically allocates these materials to the non marine Unit C sequence. The unconformable base of these channel/lake basin sediments is designated U/CL by Lewis (1991) (to differentiate it from a deeper U/C2 defined by O'Connor to the west on the Kringalik Plateau) and was considered to be U/C by O'Connor (1982) while McGregor (1989) referred to this horizon as U/C2.

McGregor (1989) has allocated the undifferentiated sediments of Units A and B above the U/C1 transgression unconformity to a Seismic Sequence 1 and we believe incorrectly indicated these materials to be ascribed to Unit A alone. The lower stratified materials (sometimes above U/C) and the ponded basin fill materials found between U/C1 and U/CL were ascribed to Unit B and Seismic Sequence 2 by McGregor (1989). This present study and that of Lewis (1991) suggest that the ponded materials are ambiguous in nature and depositional history and therefore should best be ascribed to some new unit possibly designated Unit BC as some if not all of these materials have likely been deposited prior to transgression. A parallel to the onshore Parsons Lake lacustrine Holocene sediments might be made with these materials.

The unconformity horizons U/C1 and U/CL define the top of the sand materials which constitute Unit C within the region. In approximately 60% to 70% of the region beneath Kugmallit channel these unconformity surfaces coincide as a result of planation of the U/C1 transgression unconformity and removal and redistribution of the Unit C materials during transgression. The seismic character of the Unit C materials is characterized initially by the high amplitude return of the unconformity reflector and then by a thick sequence of weak (low amplitude) and complex reflection patterns within the unit. Figures 9 and 10 indicate the typical response of Unit C materials on surface towed boomer data. The faint and discontinuous reflections characterize materials that are highly complex in depositional character with numerous clinoforms, channels structures and discontinuous or truncated reflecting patterns. These seismic structures are similar to what may have formed under a braided stream environment with channels cross-cutting channels on numerous occasions and possibly interspersed with eolian sand dune formation creating some of the clinoform structures observed.

Figure 11 is an airgun seismic record from within Kugmallit Channel (just east of the study area) which indicates some of the deeper characteristics of Units C, D and E that are not well defined on the Boomer record of Figure 9 and 10. This data indicates the complex nature of Unit C though the definition of the cross cutting and complex reflection patterns are less definitive as a result of the lower frequency and resolution of this system. The record show one occurrence of a shallow APF horizon on the southern end of the line which clearly masks all deeper penetration directly below it and presents a uniquely high amplitude return on the record. This record also indicates a more well defined relationship of the Units D and E than are commonly encountered in most records. On this record Unit D does produce an acoustic reflection that can be mapped which is unusual on most records. Also Unit E shows a dual reflection at depth which was correlated to a shallow sand horizon overlying a second silty clay (Unit E_{ab}) that actually overlies the massive sands of Unit E. The E and E' reflecting horizons show a high amplitude reflecting character which implies that the corresponding sediments are frozen sands. Toward the west the E and E' reflections commonly merge to a single horizon with numerous local basin structures noted that are likely filled with Unit E_{ab} sediments.

Borehole samples of Unit C indicate primarily a fine grained massive sand with occasional thin interbeds of silt and clay (probably the base of fluvial channels) and occasional thin gravel lenses (possibly the result of erosional winnowing and residual coarser lag materials). Beneath the Kugmallit channel Unit C is predominantly unfrozen though local areas of Acoustic Permafrost (APF) are observed as island like lenses that tend to be deeper within the unit but at random depths within the unit. Borings have indicated these APF reflections to be associated with coarser grained well bonded (frozen) sands containing both V type visible and N type non-visible ice (Unified soil classification and ground ice table in Appendix A).

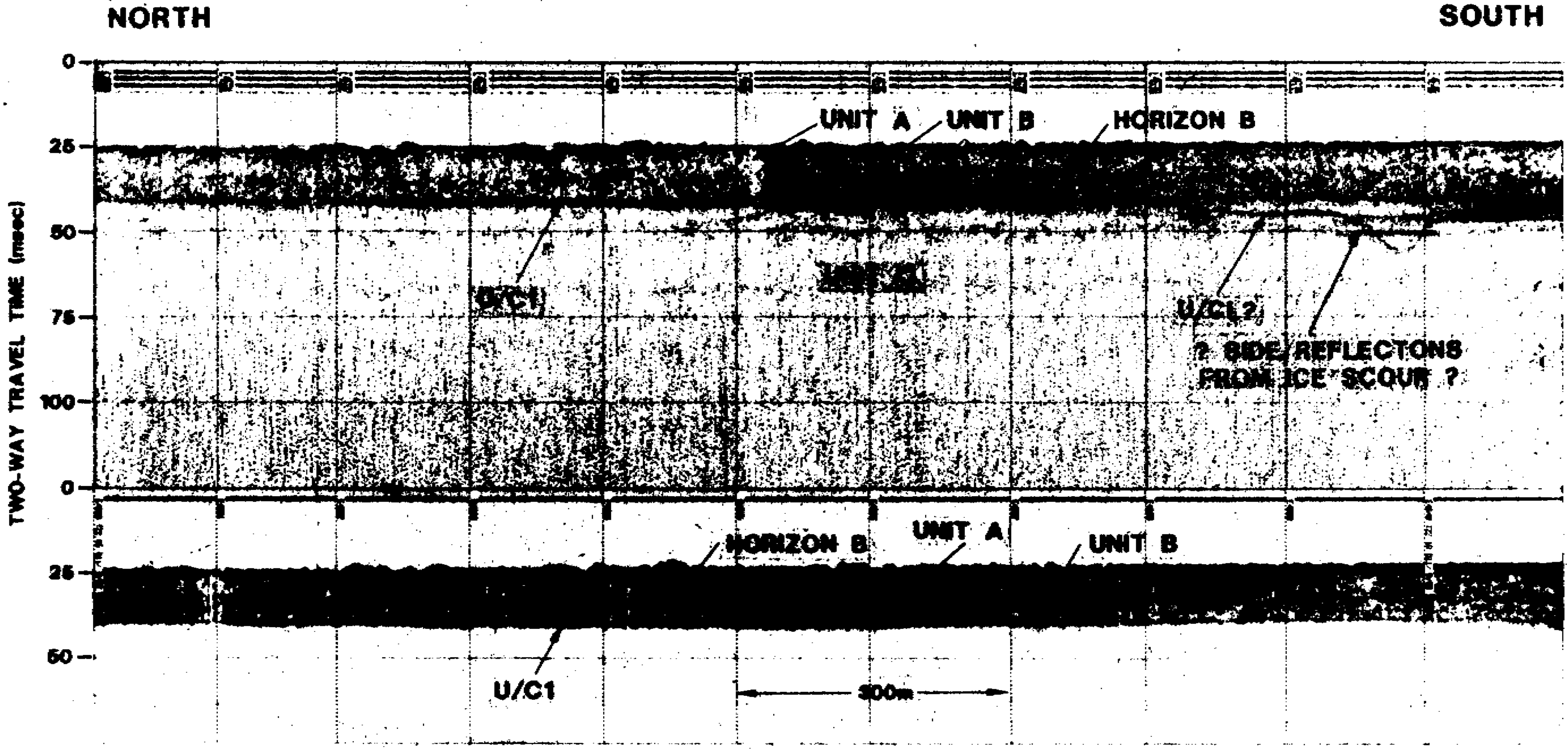
Few offshore records indicate an identifiable reflection from the top of Unit D in the area which is a fine grained marine clay/silt composition (Figure 11 is a notable exception to this). These materials are normally characterized on the seismics by simply a lack of acoustic reflections or a massive appearance in most instances. This unit is normally only truly identified with borehole confirmation, though where these data are available it is apparent that the base of (or deepest) channelling of the Unit C cross cut bedding essentially identifies the top of Unit

D on the acoustic records. On most records the base of channelling is highly variable in depth within a 10 to 15 m range which suggests that the clays have been incised by these channels and therefore the contact between C and D is erosional in nature. This implies that there may have been some unknown period of exposure of Unit D to sub aerial conditions subsequent to the regression of the seas and prior to deposition of the overlying sands of Unit C. This implication is reinforced by the observation of desiccation cracks within the clays of Unit D observed in a number of boreholes. The boreholes also commonly refer to microfolds within the bedding planes of Unit D which may imply that these sediments were subjected to deformations similar to those taking place within Units A and B at present associated with seabed ice scouring. Alternately some deformation mechanism associated with the loading of the overlying materials and/or freezing of these materials associated with ice aggradation and possibly degradation may have caused the microfolding. These observed microfolds if associated with ice scour disruption of the sediment could be the reason that these materials seldom provide any recognizable pattern to the seismic technique.

Units C and D together are designated as Seismic Sequence 3 by McGregor, 1989 to represent a transgression/regression depositional cycle on the Beaufort Shelf.

Figure 11 indicates a high amplitude reflecting surface (reflector U/CE) at a depth of approximately 50 ms (42 to 47 m below seabed). This reflector has been identified on a regional basis to represent the top of acoustic Unit E within the region. Unit D rests paraconformably on the top of this reflecting horizon and the horizon is highly planar in character. This horizon is noted to be a near planar surface which uniformly dips (approx. 0.08°) toward the north-northwest (approximately 339° True) within the site area. A related, slightly deeper, reflection (U/CE' reflecting horizon), which is sometimes coincident with horizon U/CE, is incised by numerous shallow channel or basin like features beneath the Akpak Plateau and below the Kugmallit Channel these reflectors diverge toward the east (Lewis, 1991). The acoustic character of the included materials is reminiscent of the basin infill materials observed between U/C1 and U/CL separating the sediments of Unit B from Unit C in local areas. Acoustically these Unit E_{ab} sediments are often acoustically banded in character, though the resolutions of the seismics at these subsurface depths does not provide detailed acoustic definition of the bedding structures as it does between the shallower (UC1-U/CL) unconformities.

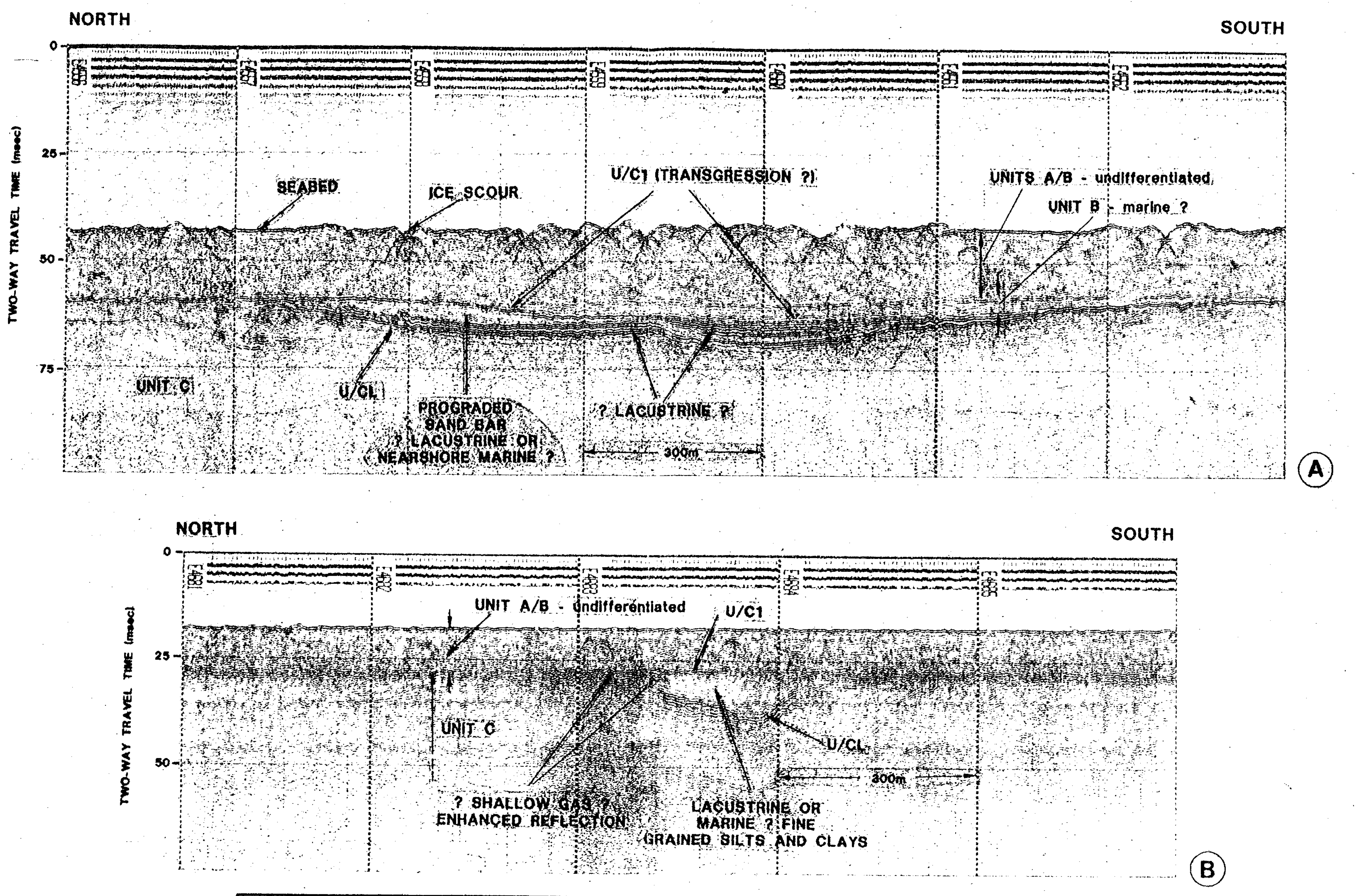
LINE NAH-88-PIP1



IKB Boomer and 7 kHz Profiler record from line NAH-88-PIP1 within the Kugmallit Channel area which displays an amorphous poorly delineated reflecting horizon within the surficial Holocene sediments that is tentatively identified as the top of Unit B.

SOUTH CENTRAL BEAUFORT SHELF SURFICIAL GEOLOGY LEWIS GEOPHYSICAL CONSULTING PROJ. L90-01

FIGURE 4-15
FIGURE 9 L92-



IKB Boomer data of Line NAH-88-PIP1 from two locations within Kugmallit Channel showing unconformities U/C1 and U/CL and the possible lacustrine or marine transgressive infill sediments with their varied and complex acoustic patterns.

SOUTH CENTRAL BEAUFORT SHELF
SURFICIAL GEOLOGY

LEWIS GEOPHYSICAL CONSULTING PROJ. L90-01

FIGURE 4-13
FIGURE 10

Akpak Plateau Region

The physiographic region of the Akpak Plateau represents a bathymetrically high area where the unconformity surfaces U/C1 and U/CL are either at or near the seabed. This region contains a significantly high proportion of shallow "Hummocky Type Acoustic Permafrost" (HAPF) and occasionally shallow gas within the sediment column which significantly degrades the quality and interpretability of the high resolution seismic data that can be obtained within the region. Figure 12 is a typical airgun and boomer record from the offshore portion of the Akpak Plateau in water depths ranging from 23 to 28 m. This regions indicates 4 to 5 m of recent Holocene Unit A/B sediments overlying a smoothly planed gently dipping U/C1 transgression unconformity horizon. In the central portion of the figure a broad shallow local basin structure is noted that coincides with a broad talik zone on the airgun record where good definition of the Unit C acoustic character is noted along with a well defined return of the U/CE reflecting horizon at a depth of approximately 95 ms (80 to 85 m) below sea level. The reflecting horizons within Unit C indicate highly complex reflection characters with many discontinuous dipping beds in what appears to be almost random orientations. This character has been referred to as the "normal character" of the Unit C acoustic response. Other regions of this record are partially of totally masked by gas or ice characteristics. This record also indicates one of the typical responses associated with the HAPF's seen in the area. In some cases the HAPF's show distinct top and bottom reflections that are taken to indicate either two separate thin well bonded sands horizons of possibly an single thick well bonded sand lens.

In the shoaler 8 to 15 m water depth regions of the Akpak Plateau region the records commonly indicate a complex mixture of both HAPF's and shallow gas within the section. These regions make the reflection acoustics virtually un-interpretable over considerable lengths of any transect line. Figure 13 shows a section of line NAH-88-P8A in which a mixture of both gas and APF is present indicating the significant masking that occurs in this situation. On examination of the boomer and airgun record it is apparent that shallow gas is prevalent at the U/CL horizon and some has collected above within the Unit B? sediments. The airgun record also shows a lower frequency high amplitude reflection deeper in the section that is tentatively correlated with APF materials. Figure 14 from line PS88-011 shows similar though slightly different response which is attributed to lower concentrations of shallow gas which allows the acoustic permafrost high in the area to be seen somewhat more clearly. These records both show acoustic windows that occasionally allow mapping of the deeper Unit E horizons.

LINE NAH-88-P5

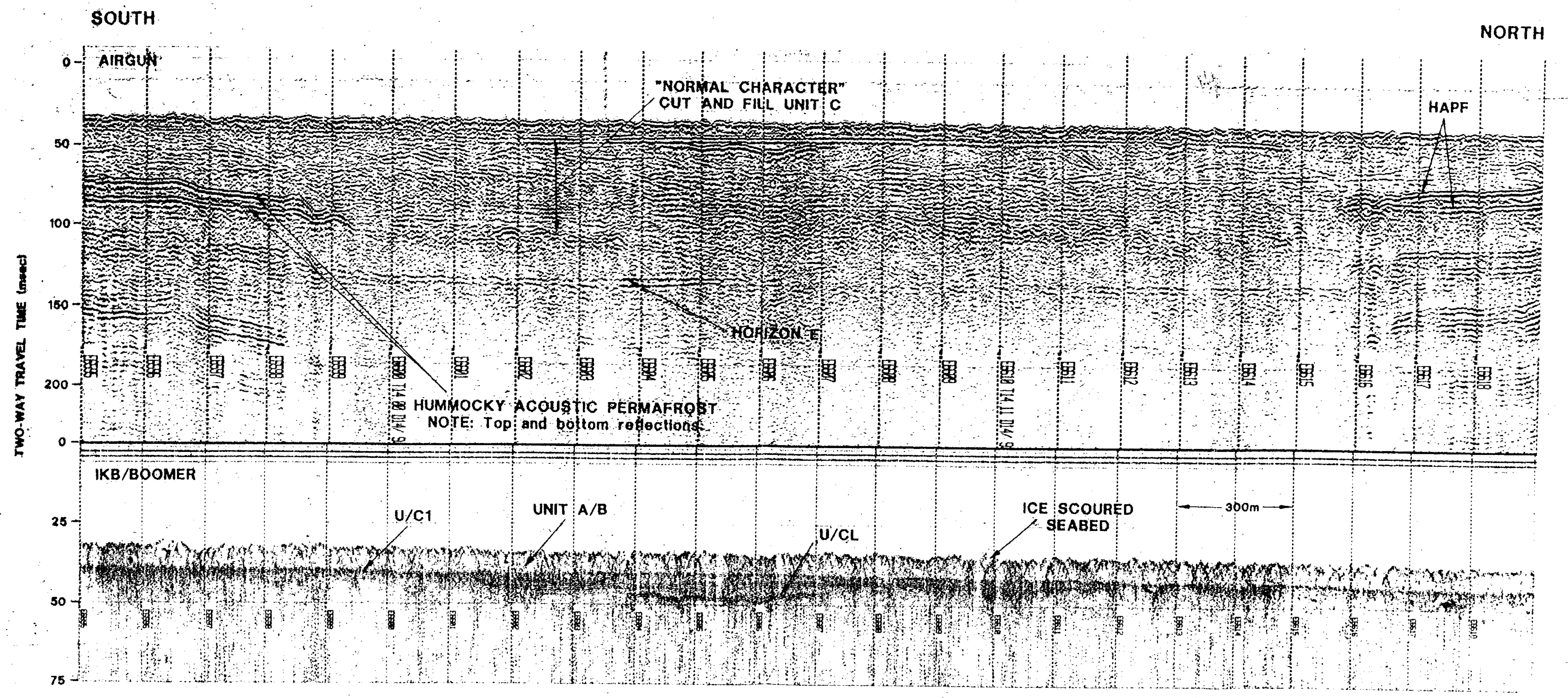
Airgun record from Line NAH-88-P5 within Kugmallit Channel indicating a possible reflecting horizon associated with the presumed top of Unit D, and the possible onlapping pinchout of Unit D onto Horizon E.

SOUTH CENTRAL BEAUFORT SHELF SURFICIAL GEOLOGY

LEWIS GEOPHYSICAL CONSULTING PROJ. L90-01

FIGURE 4-6
FIGURE 11

LINE NAH-88-P3

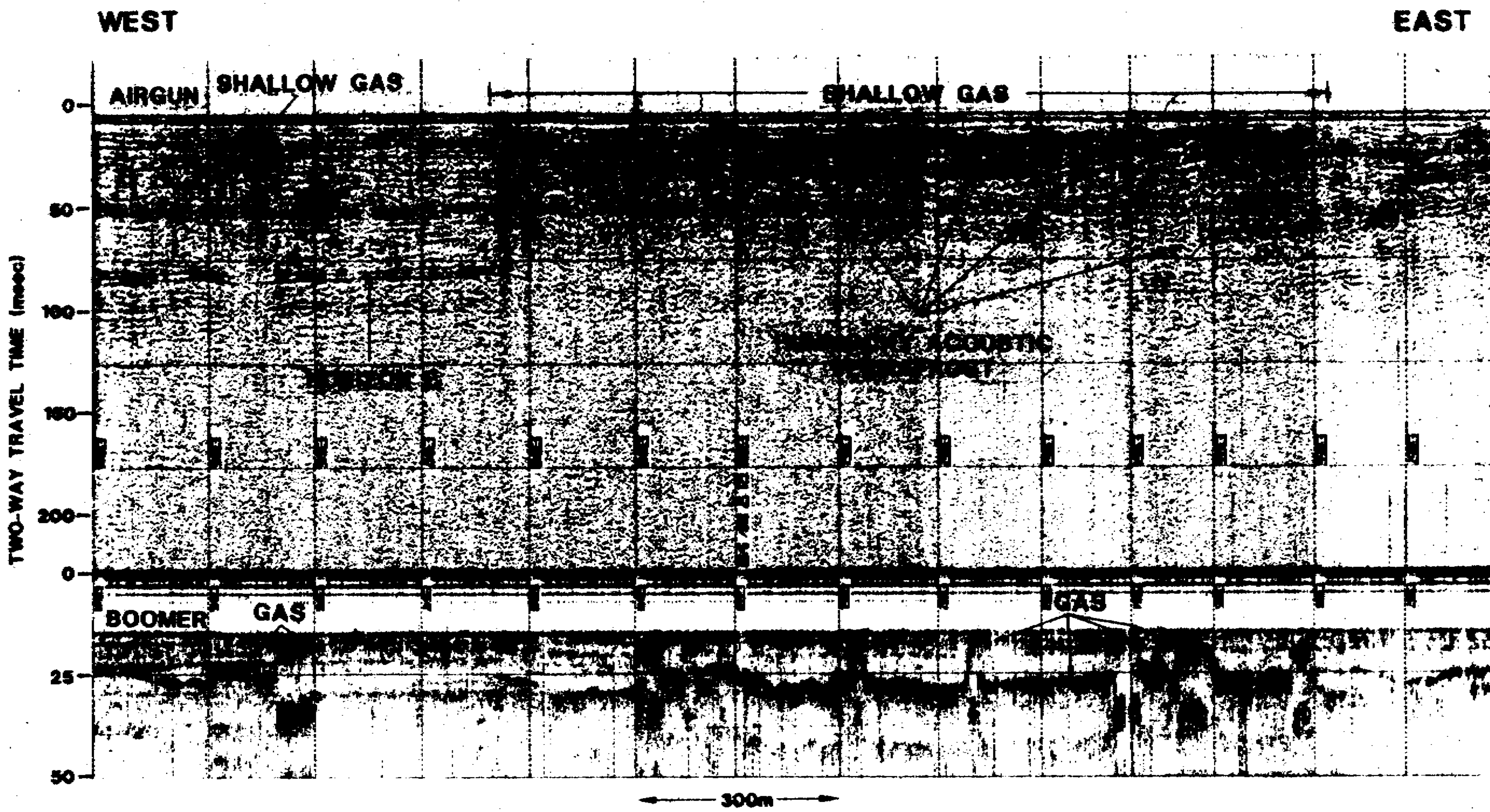


Airgun and Boomer profiles of Line NAH-88-P3 from the offshore region of Akpak Plateau displaying the complex cut and fill channelling patterns of acoustic reflectors within Unit C which defines its "normal character", along with double HAPF reflections and the dual unconformities on the top of Unit C.

SOUTH CENTRAL BEAUFORT SHELF SURFICIAL GEOLOGY LEWIS GEOPHYSICAL CONSULTING PROJ. L90-01

FIGURE 4-7
FIGURE 12 L92-04

LINE NAH-88-P8A



Airgun and Boomer data from line NAH-88-P8 showing the complex mixed HAPF (short high amplitude, low frequency reflectors) and shallow gas reflection (high amplitude, higher frequency capping reflectors with high backscatter and masking) acoustic characteristics of the inshore Akpak Plateau region illustrating the difficulty of distinguishing the two.

SOUTH CENTRAL BEAUFORT SHELF SURFICIAL GEOLOGY

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FIGURE 4-12
FIGURE 13 L92-04

Outer Sub-Seabed Ridge

The Outer Sub-Seabed Ridge feature is apparent only within the Unit C materials and shows little or no expression on the bathymetic record for the area as evidenced by the profile of Figure 15, or the bathymetric contours in the region and other crossing lines not displayed here. The feature is characterized on the seismic records by a highly reflective seabed which is indicated by a relatively strong second multiple reflection return on the records. This character is usually indicative of harder sandy materials on the seabed as opposed to the areas where silts and clays are present and little or no multiple reflection is observed. The acoustic and interpretation profiles of this ridge show thin Recent surficial cover which is commonly in local basin features.

Figure 16 shows a sample record from the seaward portion of the ridge where there is virtually no recent sediment cover. Possibly because of this lack of surficial cover and the expanded horizontal display of this record the internal reflections of the Unit C materials are seen to be very thin beds that are highly complex in structural character. This record is a particulary clear example of the typical Unit C cut and fill type relationships that often are too congested to be visible and interpreted on more standard (typically more horizontally compressed) type displays. At depths of 12 to 14 m below the seabed a number of discontinuous and higher amplitude (APF) reflections are observed which have been correlated by seismic refraction and borehole samples to be related to shallow frozen soils. These reflections are masked within the multiple of this boomer record, however they stand out more prominently on the correlating airgun profiles. Also this record indicates local small hyperbolic reflection zones which may be associated with local cobble or boulder lag materials near the seabed.

The seaward high is separated by a gassy clay/silt filled basin from a second high region that is shown in Figure 17 (km 20.6 to km19). This record indicates a series of hummocks that are highly reflective and appear to be composed of numerous hyperbolic reflections. There are essentially four hummocky ridges or mounds noted that are separated by local basin features containing acoustically transparent materials with little or no internal bedding structures seen on the acoustic records. From the reflection seismics the highly reflective character of these hummocks would most likely be interpreted to represent a gravel veneer or lag overlying the top of Unit C materials. Boreholes indicated no detectable thickness of gravel lag (PS88S12 and S13) but simply silty materials overlying grey brown sand with traces of silt and shell

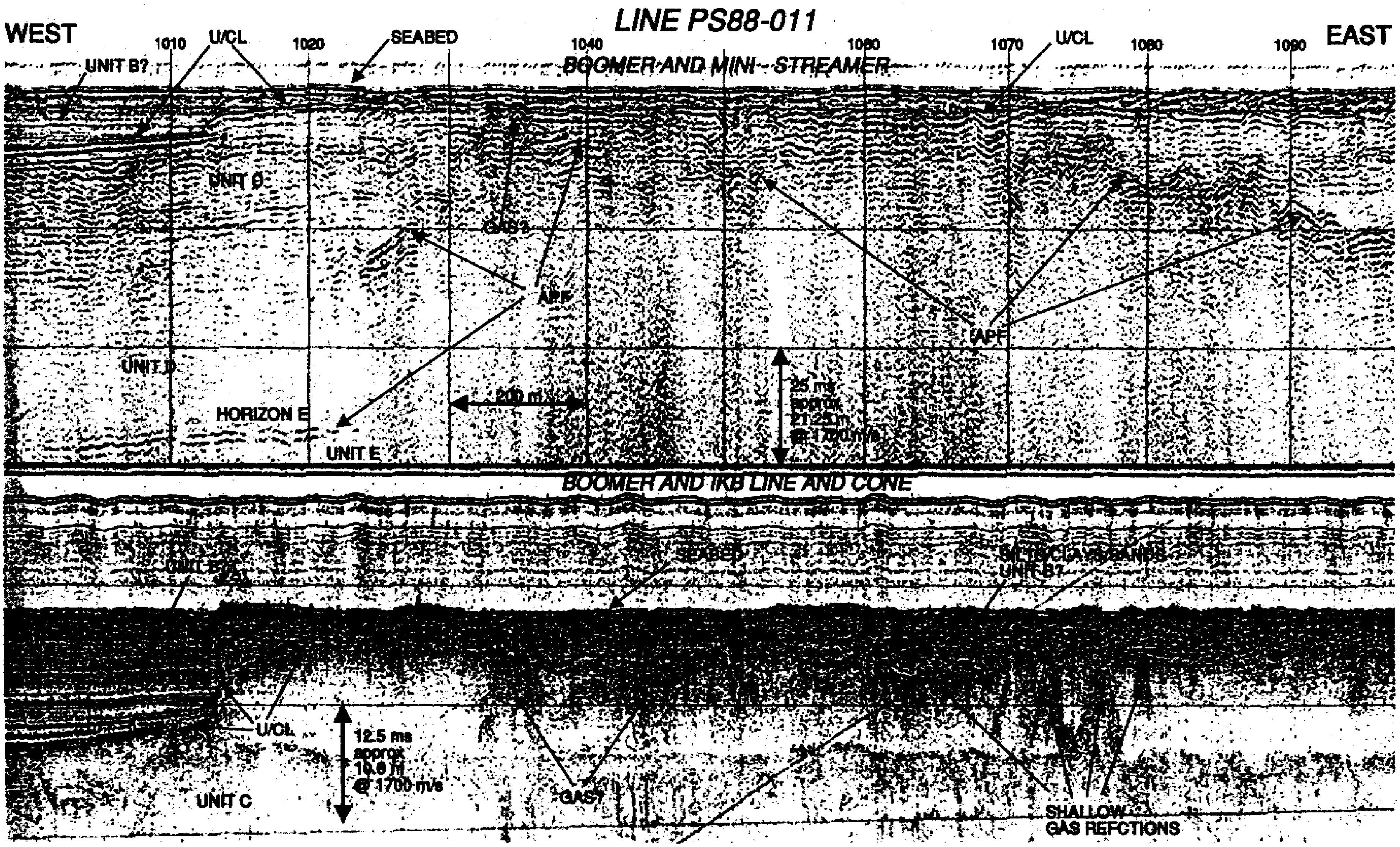
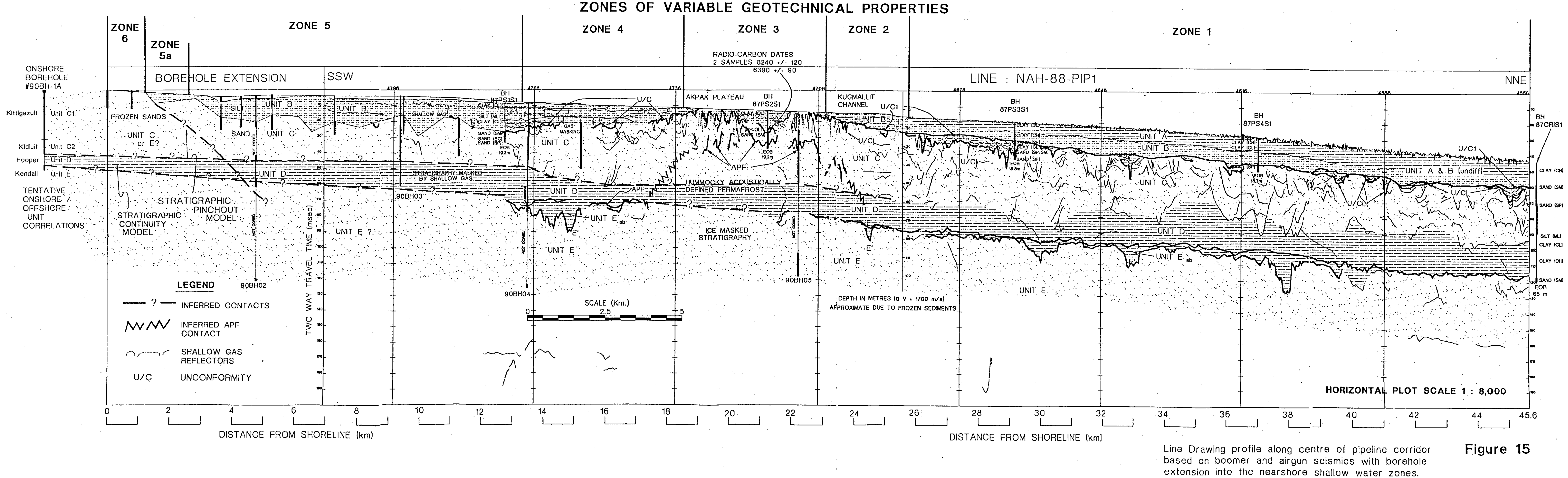


Figure 14: Typical high resolution seismic response over the central Akpak Plateau region indicating highly variable permafrost and gas masking of deeper horizons. Commonly 2 to 12 m of clay/silt/sands overlie U/CL which could be either Unit B transgressive materials or residual pre-transgression basin fill lacustrine sediments. (Record compliments of Gulf Canada Resources Ltd.)



Line Drawing profile along centre of pipeline corridor based on boomer and airgun seismics with borehole extension into the nearshore shallow water zones.

Figure 15

Often it is difficult or impossible to distinguish between permafrost and shallow gas from seismic reflection data alone throughout these areas. Either deep towed refraction seismics, to identify acoustic velocities of the sediments and the ice features or direct sampling with boreholes is necessary to accurately discriminate these features. A number of highly localized and generally small sized acoustic windows are noted within the area which allow interpretation of continuity of the geologic section from the Kugmallit Channel region toward the west, at least to within the Ikit Trough. To the west of the Ikit Trough and beneath the Kringalik Plateau a fining trend in the composition of the Unit C materials has inhibited the formation of Acoustic Permafrost and the resulting masking of the seismic data that is associated with it.

These records are typical of the Akpak Plateau region of the offshore section in water depths of greater than about 8 m. In localized areas the U/CL unconformity is seen to be directly at the seabed though this is not common throughout the area. The following section describes and illustrates one of these ridge features.

Nearshore Seismostratigraphy

The above sections describe the offshore regions that are characteristic of the Central Beaufort Shelf Region and represent typical sections that have been used in the definitions of the offshore geological model for the Beaufort Shelf by previous authors (O'Connor, 1982, Blasco et.al., 1990, and Lewis, 1991). The following sub-sections detail the seismo-stratigraphy of the shallower water regions (<10 m) and draws attention to the similarities and differences to both the offshore and onshore geologic models and formations. The principal study area that contains extensive data, at present, consists of the inshore regions of the Akpak Plateau in the vicinity of Pullen Island and North Point of Richards Island. Other regions do not, as yet, have sufficient geophysical and geotechnical data available to attempt a comparison and contrast at this time.

The region that presently has the most comprehensive data concentrates within the Amauligak to North Head Pipeline corridor and therefore this has been used as a type section for this study. Figure 15 is an interpreted seismo-acoustic line drawing profile along the centre of the pipeline corridor with an extension into the inshore regions via borehole and cone penetrometer testing. This section indicates a gentle bathymetric rise out of the Kugmallit Channel onto a region of the Akpak Plateau at 23 km from the shore terminal point in approximately 10 m of water. From here, the seabed rises at a very gentle slope to the shoreline. In the subsurface the U/C1-U/CL unconformity rises to the seabed just inshore of the Kugmallit Channel boundary and this region has been termed the Outer Sub-Seabed Ridge section of the pipeline corridor profile. This region of exposed or nearly exposed Unit C materials extends for approximately 4.5 km along the transect before dropping into an Inner Basin region that contains significant thicknesses (14 to 18 m) of Recent transgressional silts and clays overlying an unconformity horizon. Shallow reflections within these sediments are commonly observed to outcrop at the seabed which could imply that the seabed is erosional in nature and the transgression unconformity (U/C1) has not as yet completed its down-cutting of these sediments. Alternately this may imply continued basin subsidence within this zone and corresponding onlapping sedimentation.

fragments and organic pockets. Seismic refraction over these features indicated acoustic velocities in the range of 1700 to 1900 m/s which was originally interpreted to represent gravels or possible ice. APF reflections are noted very shallow in the section below this region and boreholes have confirmed frozen materials as shallow as 8 m below the seabed (PS88-S13). The highly reflective nature of this unconformity surface therefore most likely relates to the shell and organic veneer that may generate a thin shallow gas zone which results in the highly reflective character.

The deeper zones below this sub-surface ridge feature are generally masked by high amplitude APF reflectors which have been correlated to frozen sediments on numerous of the boreholes along the transect. The sub-surface ridge feature has been mapped on adjacent and crossing lines and runs generally in a NW to SE direction which is roughly parallel to the boundary of the Kugmallit Channel in this vicinity (McGregor, 1989). Throughout this region little interpretable continuity of the deeper Unit D and E reflecting horizons can be maintained though occasionally acoustic windows are encountered that allow glimpses of the deeper structures which strongly suggest continuity of the stratigraphic section through the region. The HAPF reflecting frozen sediments are correlated to the areas under the ridge features and are not observed on the records inshore of this ridge and are only occasionally seen offshore beneath the Kugmallit Channel. Throughout this area and also toward the inshore areas shallow gas becomes increasingly common in the section which compounds the seismic masking that is observed.

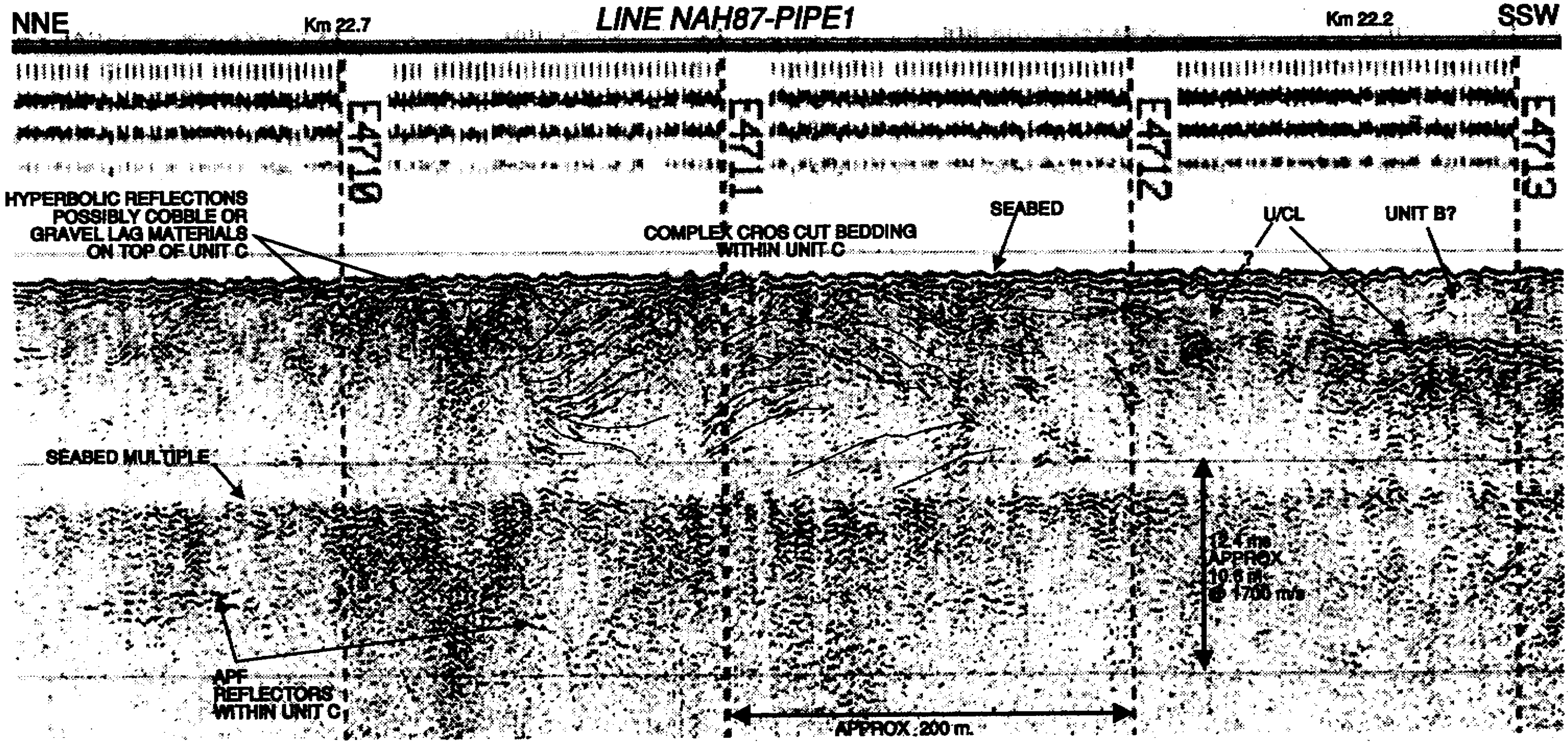


Figure 16: Example Boomer - IKB Seistec record over the outer ridge along the pipeline corridor indicating the region where Unit C is at or near the seabed. Thin highly complex cross-cut bedding structures are noted within Unit C in the central portion of the record.

IKB Seistek record showing the hummocky highly reflective horizons interpreted as possible gravels between km 19.1 and 20.3

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DATE: 02/05/88
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FIGURE 17 L92-04

Hooper Clays onshore). Deeper reflections tend to be variable in amplitude and disjointed stratigraphically which likely reflects gas or ice enhanced local reflectivity variations. One possible explanation of this could be a thaw front passing though the depth ranges of 32 m on the inshore end of the record to approximately 45 m just beyond the centre of the figure. In this area the top of Unit E is at a depth of approximately 50 m below sea level on this display.

Based on the seismic profiles within the acoustic windows from both the outer and inner areas of the inshore basin region there are no distinguishing features that might indicate differing stratigraphic sequences from offshore to very nearshore and thus, probably the onshore section.

Inner Basin

To the south of the outer sub-seabed ridge feature an unusually extensive region of thick Unit B materials are observed within a broad inshore basin like feature which extends virtually from km 19 of the centre profile to the shoreline of North Head. This region is poorly mapped acoustically owing to two factors. First the general water depths are 7 m or less and many survey vessels are unable to work in this region because of draft restrictions and secondly because the region exhibits extensive acoustic masking as a result of broad areas of shallow gas within the section. As a result the definition of the seismostratigraphic character in the region is restricted to a limited number of localized zones of acoustic windows through the gas masking and has been highly supplemented by interpretations based on the borehole and CPT transects carried out by Gulf and the GSC during 1988 and 1990 respectively.

Figure 18 is a map of the regions that are seismically masked by shallow gas based on recent survey data in inshore areas and has been extended into the offshore by integration of an ice (APF) and gas mapping of the offshore region by O'Connor published in 1985. The single diagonal hatched region in the inshore region is representative of masked areas that are attributed to solely shallow gas trapped within the sediments. In most cases the gas is prevalent within the shallow silts and clays infilling the broad inshore basin noted above and occasionally is noted at the unconformity surface at the base of these Unit B(?) sediments. The cross-hatched region in the offshore represents areas where a mixture of shallow gas and Acoustic Permafrost reflections mask the deeper penetration of the records (from O'Connor, 1985 based on ESSO data set). In this offshore region the masking is typical of that shown in Figures 12, 13 and 14 as discussed for the Akpak Plateau and is normally within the Unit C sediments (ice and gas) and occasionally within the overlying Unit B materials (gas). The offshore masking regions tend to be more localized in nature and are likely associated with old drainage patterns and the topographic highs that preserved permafrost while the lower areas represented lake or river basin talik features. The hatching boundary displayed here represents the approximate offshore limit of the inshore basin structure.

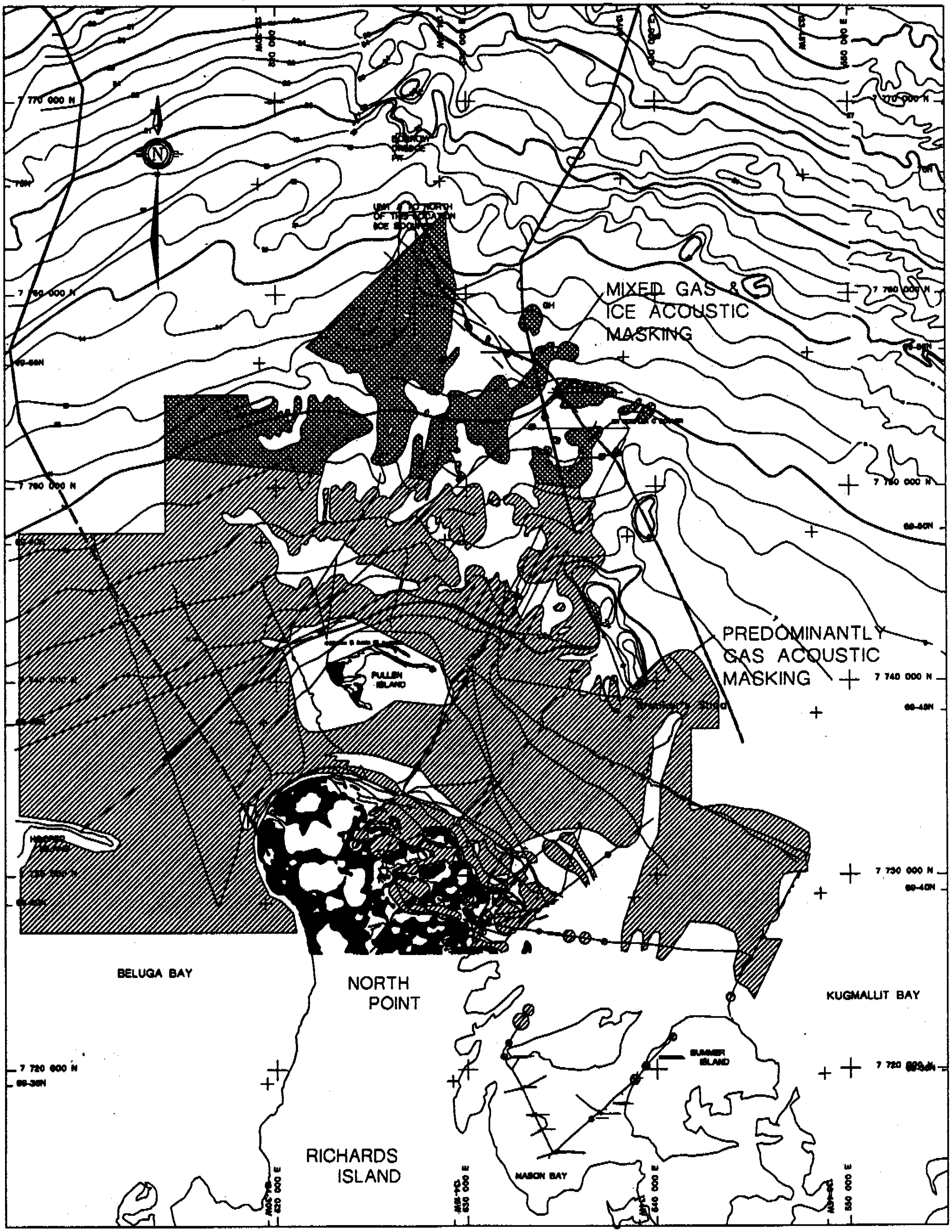


FIGURE 18: Akpak Plateau and inshore regions that are acoustically masked by shallow gas (inshore) and or mixed Acoustic Permafrost and gas (offshore). (region north of 7745000 N based on O'Connor, 1985)

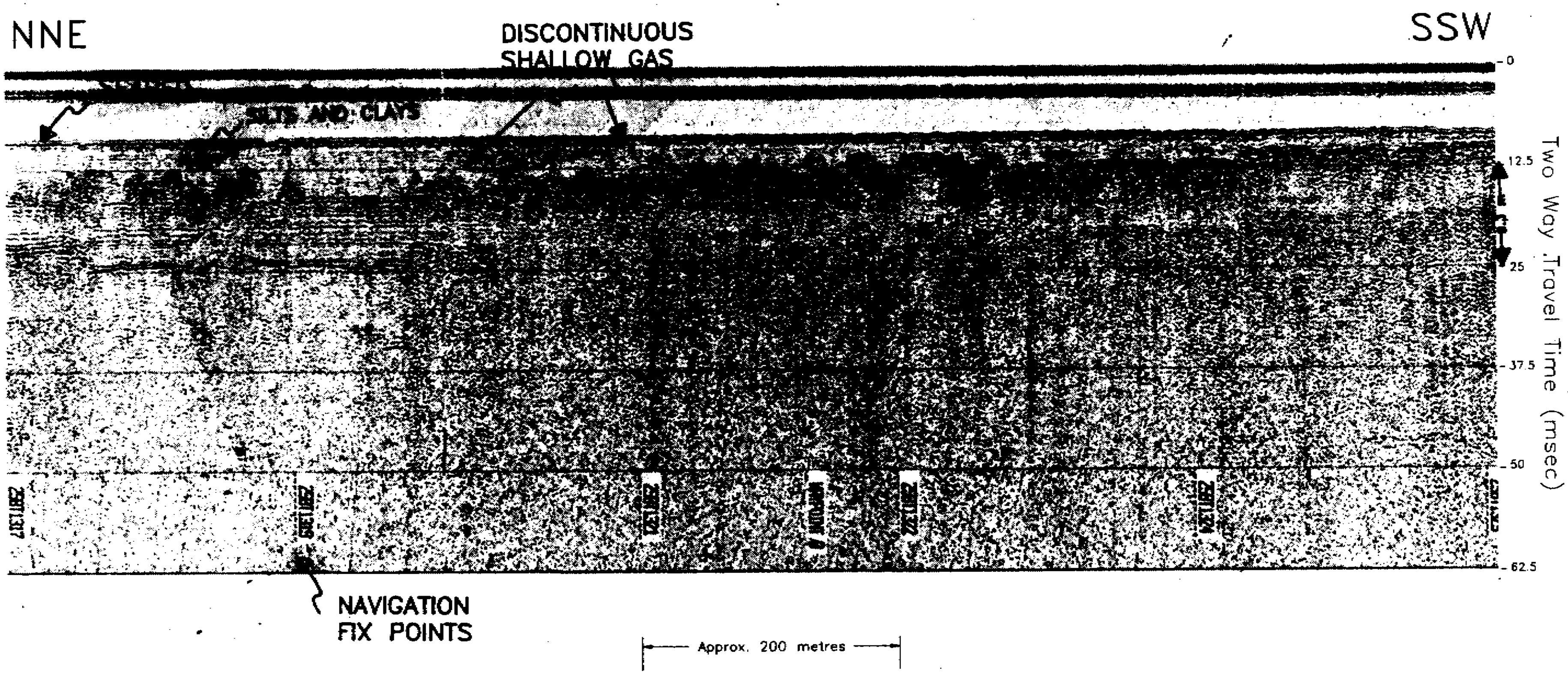
It is noted that most of the inshore region is acoustically masked by gassy sediments though there are relatively extensive acoustic windows near the offshore boundary of the basin feature. Also in the region just adjacent to the shoreline of North Head acoustic windows are noted that appear to follow the coastline and may be related to recent inundation of these regions (discussed below).

The following sections outline the acoustic characteristics of the gassy and acoustic window portions of this inshore basin.

Gas Masking Zones

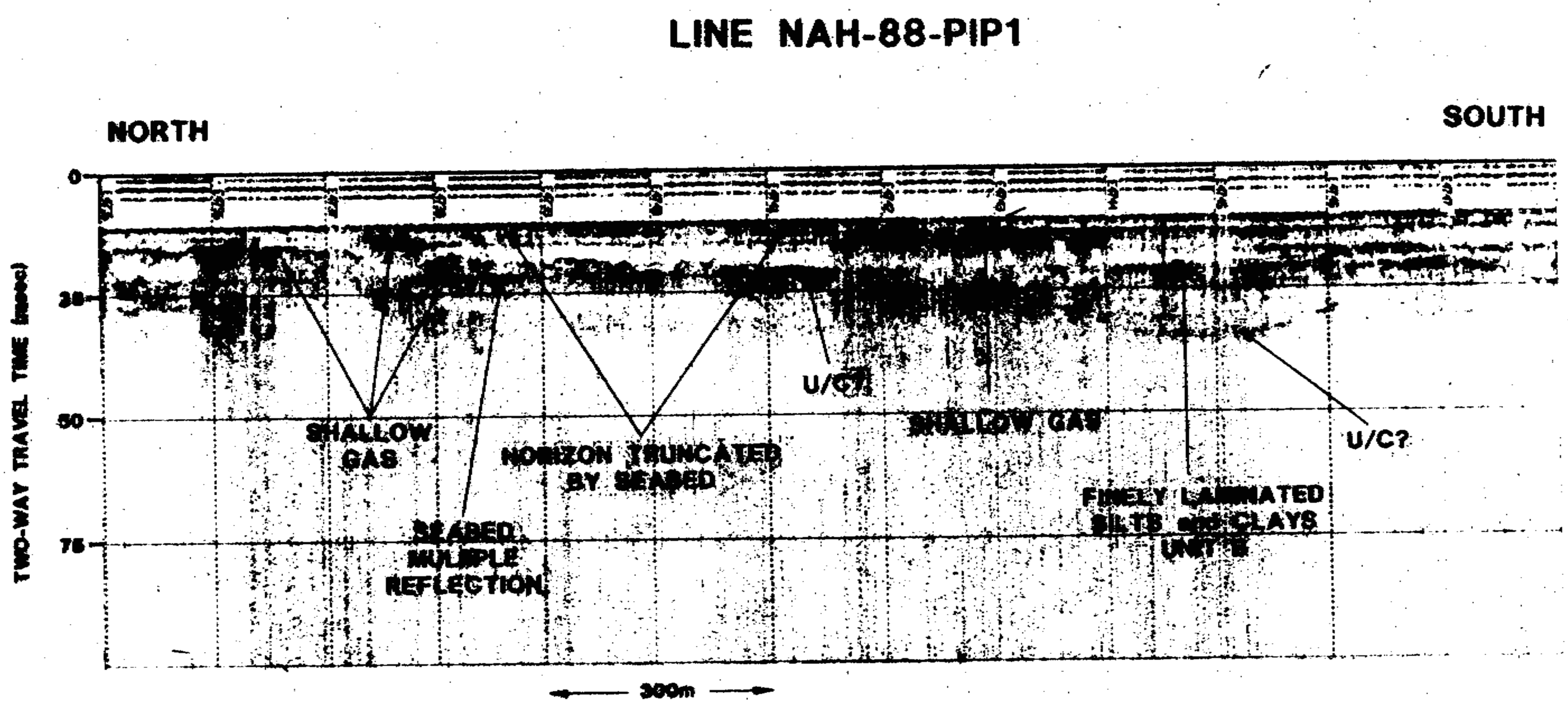
Figure 18 indicates the presently mapped extent of the shallow gas distribution in the inshore basin zone. As is evident from this map the seismic coverage in this area is extremely sparse, particularly inside the 5 m water depth zone. In the region surrounding Pullen Island and particularly to the southwest of Pullen Island on the few lines into Beluga Bay the gassy zones are virtually ubiquitous. There are no data in the immediate vicinity of the southern portion of Pullen Island and the boundary is speculated through this region.

This shallow gas masking effectively eliminates seismostratigraphic interpretation of high resolution profiler, boomer and most airgun seismic records below the depths were it occurs in the sediments. Within extensive regions of this inshore region the gassy zones tend to be trapped approximately 1 to 2 m below the seabed effectively restricting or masking any deeper penetration and interpretation. Figure 19 shows an example of this type of masking on the inshore end of the pipeline corridor (Line NAH-87-PIPE at approximately km 12-13) and it is noted that the gases tend to be trapped below low reflectivity and presumably relatively impervious stratigraphic horizons over some areas of the section. These stratigraphic horizons are breached in many locations and the characteristic gassy acoustic backscatter is observed to migrate to a slightly higher trapping layer. This breaching and jumping up and down of the gassy zones is common and indicative of the gaseous nature of this masking obstruction throughout the area.



IKB Seistek record indicating the heavy masking of subbottom reflectors by shallow gas in the inshore regions	JOB No.: 88-06	
	DRAWN BY: JFL	
	DATE: 02/05/88	DWG No.: 3-8

FIGURE 19 L92-04



Boomer record from Line NAH-88-PIP1 in the inshore region near North Point showing reflecting horizons within unit B that are truncated at the seabed which implies recent seabed erosion and/or reworking of Unit B(?) materials in the shallow water regions.

SOUTH CENTRAL BEAUFORT SHELF SURFICIAL GEOLOGY

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FIGURE 4-16

FIGURE 20 L92-04

Figure 20 is a record further to the north from the transition area within the offshore acoustic window. This record shows local isolated concentrations of shallow gas backscatter that mask lower reflections. This record also shows the surficial sediments that infill the inshore basin to be onlapping the offshore ridge structure toward the north.

Gas testing of borehole samples thorough this area has generally not shown significant gas contents though the acoustic masking horizons are sometimes associated with a sandy layer underlying finer clay or silt layer. In these cases it is assumed that the overlying clay/silts are acting as a capping layer and the sands provide sufficient void space for bubble formation which in even very low concentration significantly alters the acoustic properties of the sediments (Strachan, 1985, Whelan et.al., 1977).

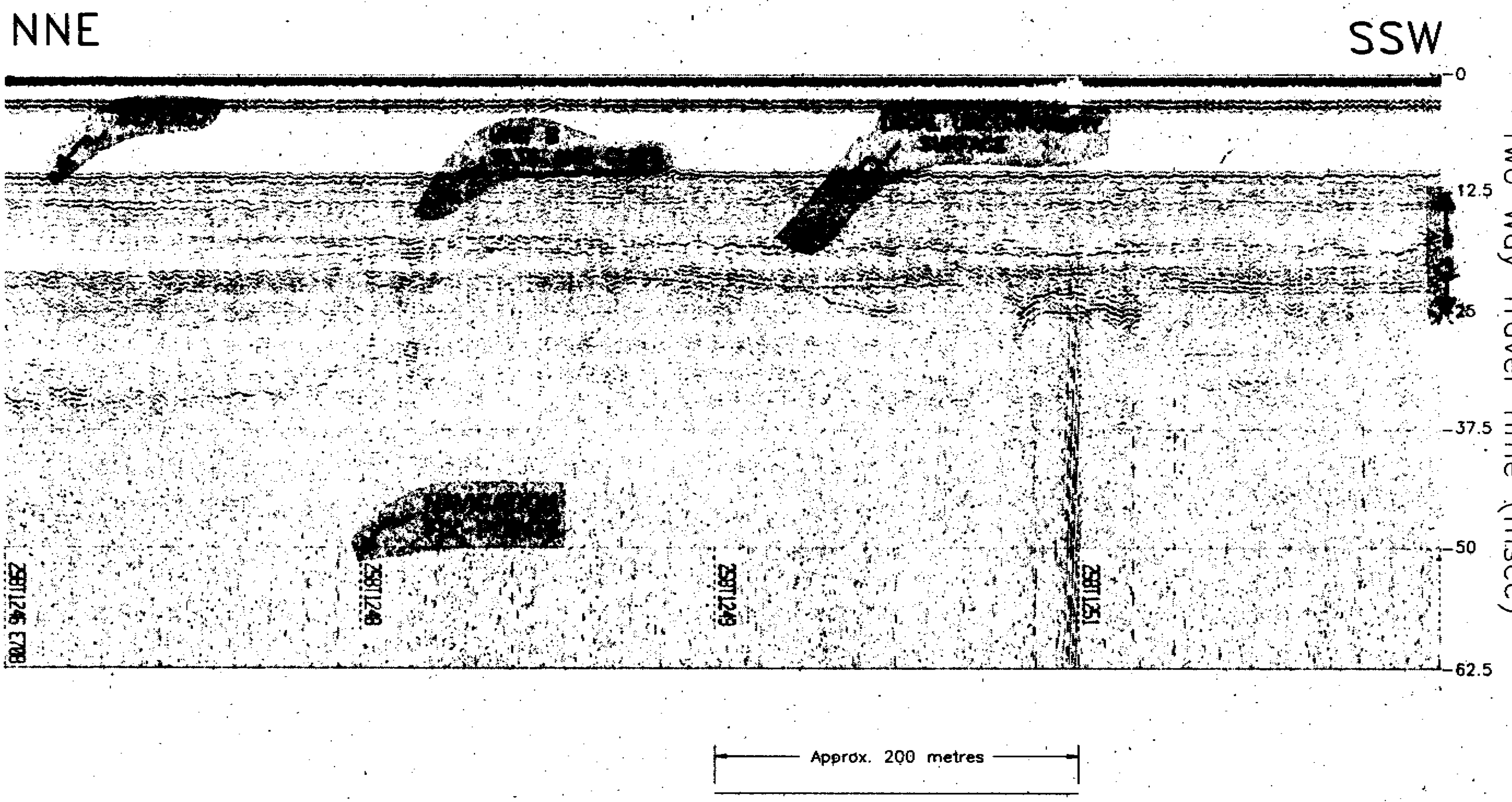
Acoustic Windows

The local acoustic windows within the inshore basin region provide us with the only areas where the seismostratigraphy of the region can be effectively viewed and interpreted. This basin area is seen to extend from approximately km 19 along the pipeline corridor to within 200 to 500 m from the shoreline of North Head, with the exclusion of Pullen Island. Most of the gas masking zone in the region is concentrated within the middle to upper regions of the Unit B silt and clay infill materials and as a result, even the depositional interpretation of these materials is restricted to the acoustic window zones. The overall effect of these characteristics are that the seismostratigraphy throughout the basin is localized and thus can only be inferred from the acoustic windows and must be supplemented and extended by borehole data through much of the region.

There are two basic zones of acoustic windowing in this inshore basin region, along the offshore boundaries of the basin (northern) and in the inshore region predominantly just adjacent to the coast (southern). In the northern window zone the stratigraphy follows the normal pattern of the Beaufort Sea geological model with the exception that there is virtually no occurrence of the soft Unit A material and presumably because of the shallow water (limited ice scour) the stratigraphy within Unit B is preserved.

shallow gas masking with good penetration and definition on the boomer record. The area is in approximately 3 m of water and the seabed is virtually flat and smooth with a very slight offshore slope. A well defined unconformity horizon is seen between 8 and about 12 m below sea level which also dips somewhat irregularly toward the offshore. The sediments overlying this unconformity exhibit a distinct reflecting horizon that merges with the seabed at the SW end of the record and is approximately 1.5 to 2 m below the seabed on the NE end of the record. This horizon suggest an onlapping depositional environment for the materials above this reflector, alternately it could be representative of continued erosion by wave base in the region. The sediment below the onlap reflector exhibit a slightly higher internal reflectivity and the correlating higher resolution IKB Line and Cone records indicate a complex basin fill and cross bedded depositional environment similar to that of Figure 22. This stratigraphic relationship may be the nearshore equivalent of the buried local unconformity surface noted in Figure 21 and the truncated or onlapping reflecting surface noted in Figure 20 in the offshore acoustic windows and shallow gas sections. Below the U/CL unconformity surface the records indicate approximately a 20-24 m thickness of massive sediments with complex moderate to highly reflective acoustic character that is similar and probably equivalent to the complex cross cut bedding structure of the offshore Unit C sediments (Kittigazuit/Kidluit sands onshore). Within this sequence local high to very high acoustic reflectors are observed which could be either shallow gas enhanced stratigraphic reflectors or thin frozen sediment layers that enhance the acoustic returns. From a depth of approximately 32 to 39 m a thin horizontal sequence of reflectors are noted that approximately correlate with the Hooper Clay sequence in the onshore section and are associated with Unit D in the offshore. This (clay?) sequence may be more visible on these inshore boomer data than is common in the offshore due to the shallow water coupling of the source to the seabed in this region, or possibly they have been enhanced due to the digital processing that these records were run through to produce this display.

Figure 24 is a second boomer / mini-streamer record from the very inshore end of the Pipeline Corridor within the nearshore acoustic window that is noted adjacent to the shoreline (approx km 2.4 to 3.6). This example is also in 2 to 3 m of water and shows thick (8 to 13 m) accumulation of silts, clays and possibly sandy recent sediments overlying a distinct unconformity horizon. In this case no onlapping horizon is noted however. Below the unconformity a 20 to 27 m thickness of massive to cross-cut bedded sediments are observed to overlie a horizontal reflecting horizon believed to represent the top of Unit D (possibly



IKB Seistek record showing the local unconformity surface within Unit B **near km 16.5**	**JOB No.:** 88-06	
	DRAWN BY: JFL	
	DATE: 02/05/88	**DWG No.:** 3-7

FIGURE 21

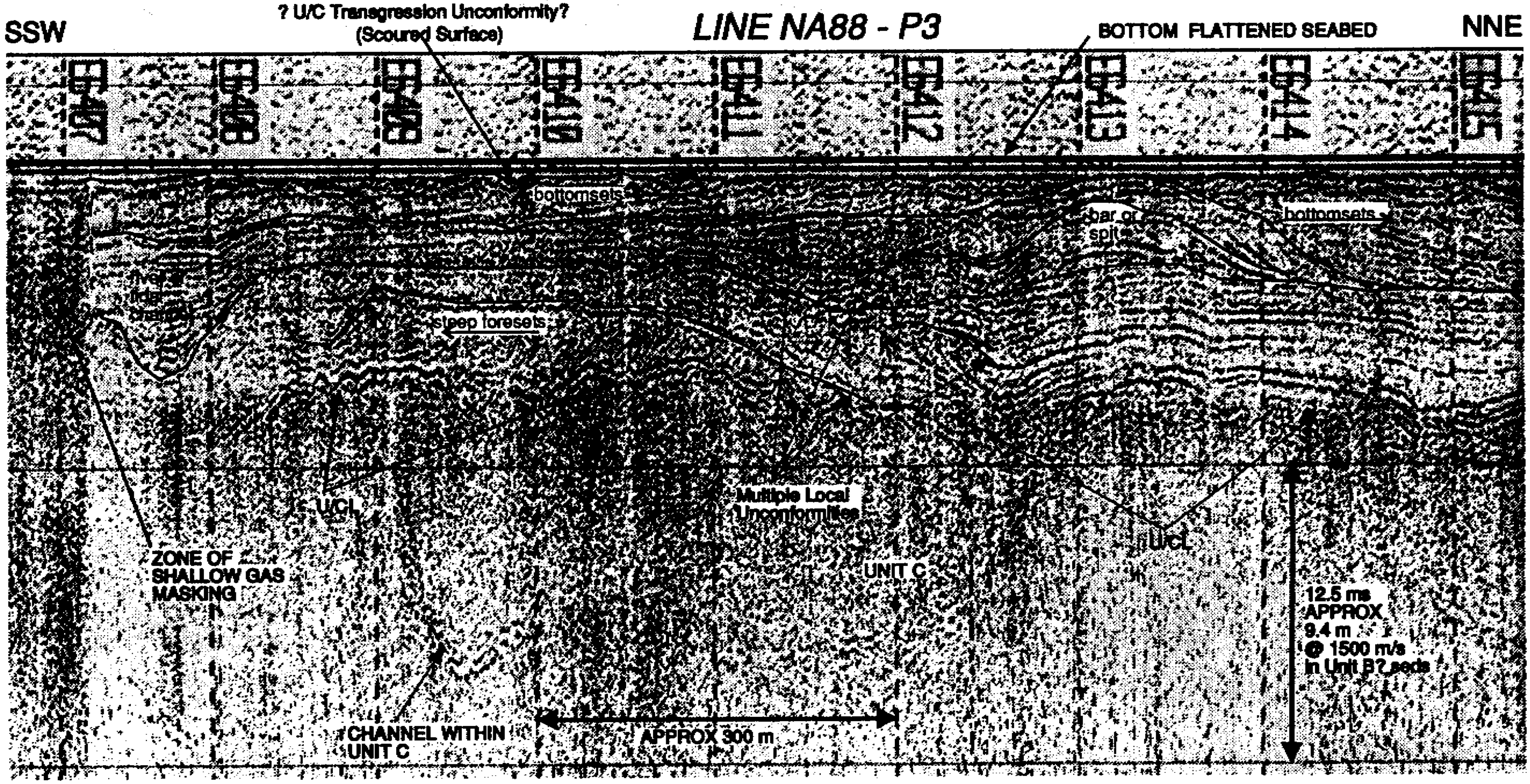


Figure 22: Boomer and IKB Seistec record from the inshore basin area just north of Pullen Island showing the highly complex stratigraphy within the inshore Unit B silts and clays. Stratigraphy suggests complex bars and spits were formed during deposition however the seabed is currently erosional with an irregular, possibly scoured, surface beneath a smooth but thin (<1.5 m.) active layer just at the seabed.

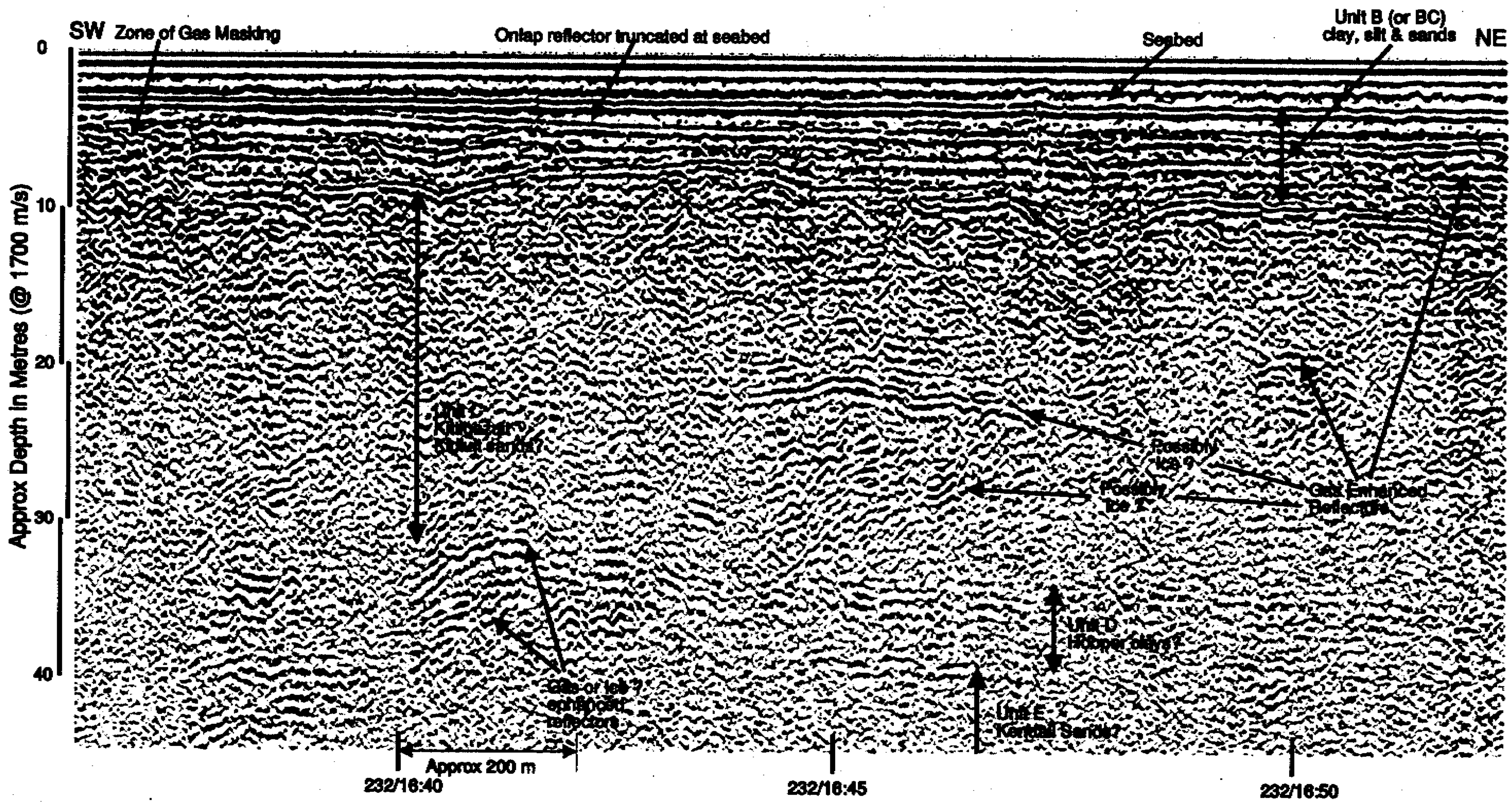


Figure 23: Example Boomer / mini-streamer record from an Acoustic Window SE of Reindeer Island indicating structures within Units C, D and E. Note regions of gas and or ice enhanced reflector amplitudes and thick Unit B(?) materials with onlap truncated horizon at the seabed.

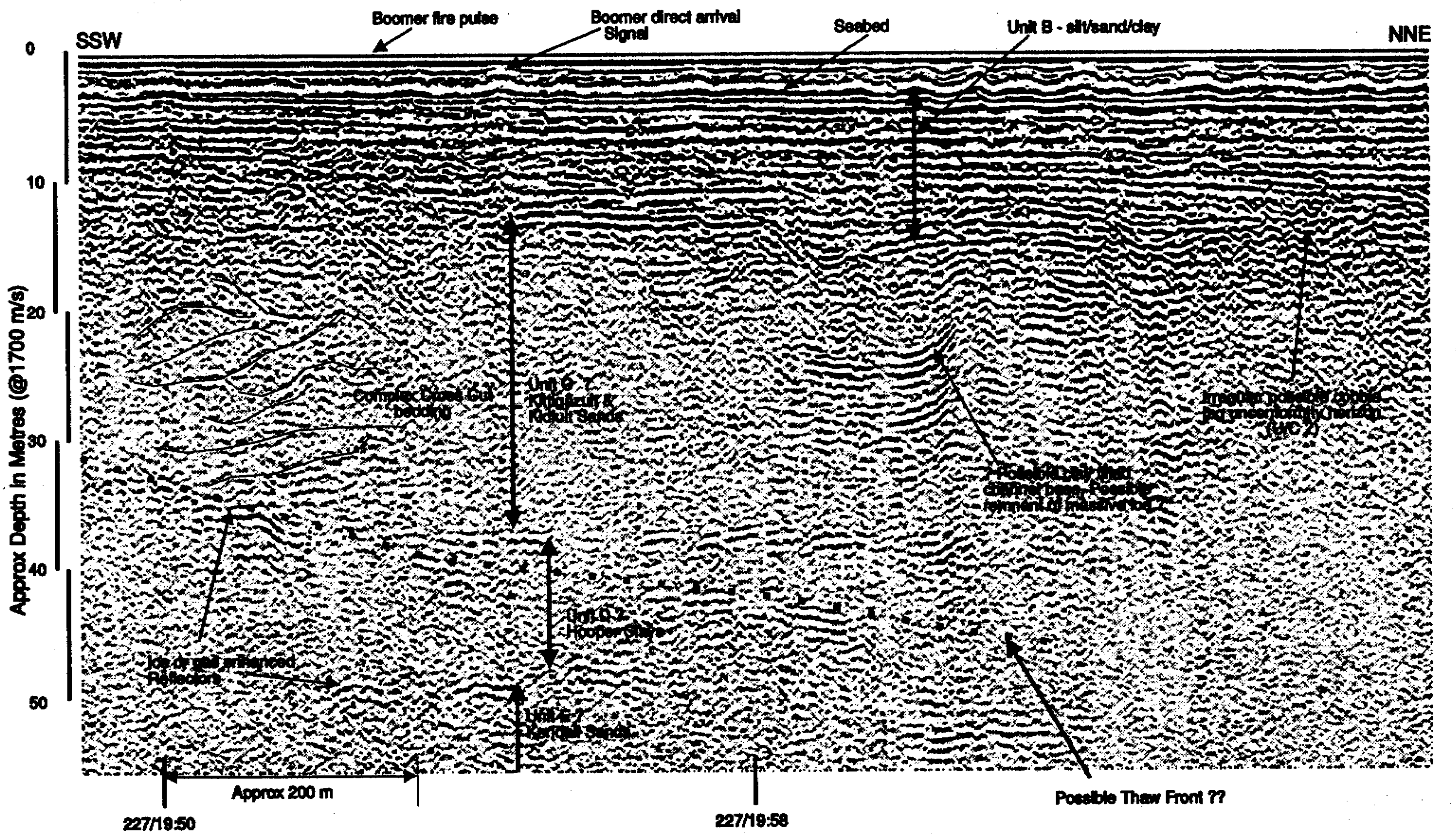


Figure 24: Boomer record from the inshore end of the Pipeline Corridor indicating the thick sequence of Recent materials infilling the collapse basin and the deeper seismostratigraphic sequences. Region offshore from this record is masked by shallow gas above, or cobble lag sediments at, the unconformity surface.

Onshore Offshore Permafrost Transition

The primary reasons that the very shallow water survey concept and the ARKTOS BETA program was initiated has been related to the need to study and possibly map the onshore to offshore geological and permafrost transition and the nearshore shallow regions of the Beaufort Sea. Attempts to map the offshore stratigraphy to the onshore had previously been restricted because of the inability to obtain a continuous seismic profile from the offshore areas right into the beach, and thus correlate it with the onshore geologic section. Along most of the Mackenzie Delta coastline the very shallow waters have resulted in approximately a 10 km data gap between the onshore / offshore geologic sections. The 1991 ARKTOS BETA survey program provided a number of transects that terminated at the shoreline and these have effectively shown that the permafrost boundary is very steep, with degradation of the permafrost occurring over a very narrow band just beyond the areas of winter bottom fast ice (>1.5 to 2.0 m of water). In many cases the acoustic permafrost could not be clearly delineated on the approach lines and initially this was puzzling. In was subsequently noticed that on oblique approaches to the shore a reflection that appeared to cross the geologic stratigraphy was observed. This reflector is interpreted to be the thaw front of the degrading permafrost and is observed to be so steep (in terms of seismic profiling display formats) that on a perpendicular approach to the shore in would effectively be near vertical on the normal seismic display even at the slow 2 knot survey speed of ARKTOS BETA. As a result of this characteristic the permafrost boundary would be virtually un-interpretable as a thaw front on a perpendicular or steep angle approach to the shoreline.

Figure 25 is a boomer record from an oblique approach to the northeastern shore of Reindeer Island just to the north of Hanson Harbour. Just seaward of the nearshore sandbar at the ESE end of the line a very high amplitude APF reflector is seen to dip in a seaward direction with an apparent slope of 20 m over approximately 250 m of the line length (approx 4.5 deg). On the assumption of a straight shoreline and permafrost break in relation to the survey line this apparent dip translates into a true dip on this horizon of approximately 12°. The thaw boundary becomes ambiguous at a sub-sea depth of approximately 20 m and might continue at roughly the same angle to a depth of 40 m on the WNW end of this display or it may shallow out and run nearly horizontal along the slightly enhanced reflections at the 20 m depth level. The character of the Unit C (or Kittigazuit) sediments above the APF thaw front is highly reflective with numerous small hyperbolic reflections. This character could be caused by one or more of the following three possible factors:

1. Hyperbolics could represent boulders and cobbles within the sediments (not apparent from boreholes and CPT's)

2. It might indicate that the stratigraphy has been completely jumbled through the cycle of first aggradation (expansion) and subsequent degradation (collapse) of the permafrost. This might form many small blocks of semi-competent sediments that would cause the hyperbolic reflection patterns.

3. They might be the result of the thawing of these sediments (and possibly massive ice) that would likely release air bubbles trapped within the ice and sediments and that these are presently migrating up through the sediment column and escaping at the seabed. These migrating gas pockets could produce the highly reflective hyperbolics that are seen throughout the first 18-20 m of the sediment column and extending virtually to the seabed.

The third possibility would explain the fact that further offshore the surficial clay-silt infill sediments are clear of gasses and then show gas trapping as the clay layers start to consolidate and form an impermeable trapping horizon.

Below the hyperbolic zone a zone of complex stratigraphy is noted from a depth of approximately 16 to 22 m. that is represented as the alternate thaw boundary on the figure. This region might be associated with the fact that the underlying Unit D clays (Hooper Clays) either were never frozen and thus did not collapse and disrupt the overlying stratigraphy, or that these sediments have not as yet completely thawed and still retain some of their original depositional stratigraphic character.

Figure 26 is a section of record from an acoustic window along the western shoreline of the inner part of Hanson Harbour, to the south of Reindeer Island. This portion of the survey line arcs slightly away from and then back towards a slightly concave shoreline and appears to run along the edge of the permafrost thaw front in this region. The record indicates approximately 10-12 m of recent basin fill materials and a U shaped moderate to high amplitude APF type reflector that extends to a depth of approximately 25-28 m at the furthest extent into the harbour basin. In the upper portions there are again a number of hyperbolic reflections within both the Unit C (Kittigazuit) sands and within the infilled Holocene sediments of Unit B (and/or Parsons Lake Fm). In the central portions of this record some deeper, high amplitude, stratigraphically controlled APF reflections are seen which most likely represent the still frozen sands of Unit E (or the Kendall Sands). Acoustic penetration to these depths is apparently possible because of the lessor attenuating and backscattering characteristics of the Unit D (or Hooper) clays that would be expected at approximately the base of the thaw front in this location (possibly unfrozen or partially unfrozen due to interstertial salts in the clays).

Hanson Harbour is roughly circular in shape and probably represents the remains of a transgressed thermokarst lake that has been breached and inundated by the sea. It is estimated that the slope of the permafrost thaw front in this region is approximately 14-15° or steeper from these records and may be slightly steeper than would be expected along the open shoreline. This would be due to the potentially longer warming period associated with the thermokarst lakes existence prior to marine inundation.

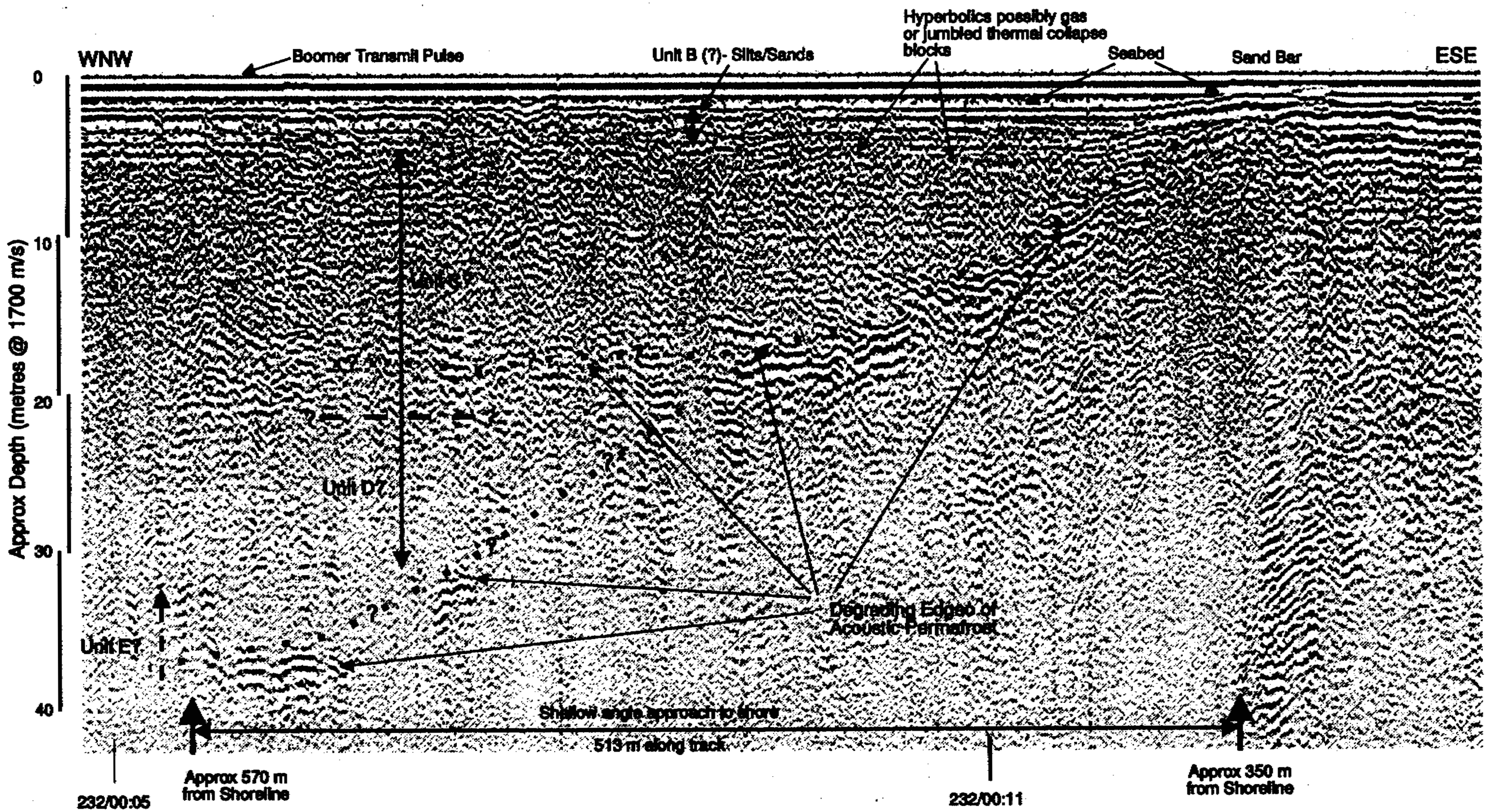


Figure 25: Boomer record of an oblique approach to the northeastern shoreline of Reindeer Island with a shoal at the ESE end of the line. Record shows high amplitude APF reflectors rapidly dipping offshore with slight increase in water depth.

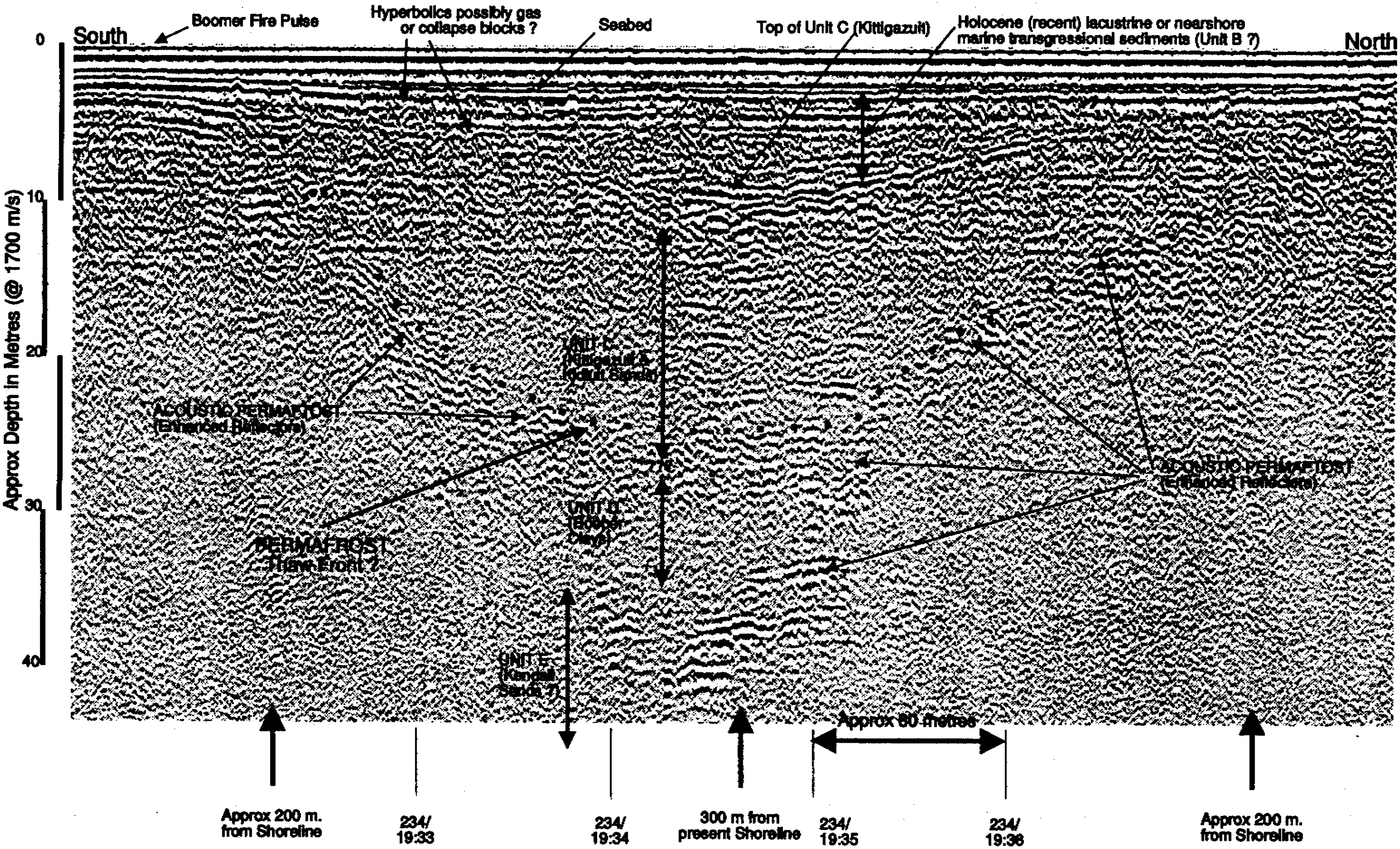


Figure 26: Boomer record paralleling the western shoreline of Hanson Harbour to the south of Reindeer Island. Line arcs slightly away from shore and shows APF reflectors rapidly dipping away from shore correlating with slight increase in the water depth.

Discussion

Observations of the seismic characteristics associated with the offshore, shallow basin and very nearshore regions of the area around North Head lead to a number of speculative conclusions regarding the geologic section and sediment dynamics of the region. These seismic observations are incorporated with data from an overview of the geotechnical borehole data in the area to suggest some levels of modification to the onshore / offshore geologic transition zone. The following observations and speculations are made with the implicit understanding that continuous seismic observations from the offshore areas to the near and onshore areas were not possible due to the shallow gas masking in the nearshore basin region. Throughout the following discussions questions and points that are felt to require further confirmation or data collection are included when relevant.

Geological Onshore - Offshore Correlations

Both the seismic and the borehole data that is available provide no evidence for a significant angular unconformity or break in the continuity of geological formations from onshore to offshore. The marine seismics indicate that the Unit C materials show essentially identical seismostratigraphic character (cut and fill / cross-bedded) in the offshore areas as they do within the local acoustic windows in the nearshore regions. The stratigraphic relationship of sand over clay over sand (Unit C over Unit D over Unit E or Kittigazuit/Kidluit Sand over Hooper Clay over Kendall Sand) is identical in both the offshore, nearshore and onshore sections both from seismic and borehole observations. In addition to this the detailed sedimentological analysis of the boreholes of the onshore / offshore transect section identified virtually identical depositional, colour and grain size relationships from the onshore, nearshore and offshore boreholes (Jenner and Blasco, 1991). Based on these observation we conclude that the geologic sections and therefore formations are continuous between the offshore Akpak Plateau and the onshore North Point / Richards Island sections.

With this conclusion we are left with a major difficulty associated with the relative ages of the onshore (old) and offshore (young) geological interpretations for the two areas. This discrepancy might be resolved by:

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CANADA 1842 GEOLOGICAL SURVEY - COMMISSION GÉOLOGIQUE

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1 Reviewing and substantiating the ages of the offshore section which at this point in time are bounded by young ages at the base of Unit D (21 k.a.) at the Uviluk site and an age of 27 k.a. at a depth of 140 m at the Tarsuit site (to the west) (Hill et.al., 1985). At this point in time we would like to see more data to substantiate these ages and to be absolutely certain that these are not anomalous ages due to contamination or some other factor. This could result in the offshore section being older and therefore correlating with the onshore section.

2 Reviewing the age relationships of the onshore section. If the Toker Point diamict (till?) is not actually an ice contact till, but could possibly be related to a glacial outwash or heavily ice scoured, with glacial ice rafted debris, glacio-marine or glacio-lacustrine deposit, it might then be associated with the Sitidgi Stade Late Wisconsinan glaciation. Therefore the premise of the onshore age dates might be shifted to a much younger overall age which would thus correlate with the offshore section. It is felt that close and detailed evaluations of these relations should be carried out.

One other point should be mentioned here. This relates to the question of why do the Hooper Clays and Kendall sands outcrop at sea level on the type section areas of Hooper and Kendall Islands some 22 and 37 km to the west respectively, while the marine seismics suggest that the Richards Island (borehole defined) Hooper and Kendall formations are 30 to 40 m below sea-level. Also these eastern defined formations dip toward the northwest when correlated to the offshore section. Thus it would be expected that the correlating Hooper and Kendall formation at the type area should be far below sea level. From this relationship the implication is that the deeper clays and sands observed below Richards Island are not correlative to Rampton's (1988) Hooper and Kendall Formations further to the west. Thus the Hooper and Kendall type section formations may be related to the westward finning trend seen within the offshore sediments of Unit C (Tingmiark Sand -> Kaslutut Sand -> Tarsuit Silt after Hill et.al., 1991) and the deeper clay and sand formations below Richards Island possibly represent a different formation entirely. Thus the deeper clay and sand formation at the Richards Island site are possibly mis-named in relation to the present onshore geological section as defined by Rampton (1988).

Figure 21 is a section of Boomer record from km 16.5 of the pipeline corridor that shows some characteristics of the stratigraphy within the Unit B basin fill silts and clays. This section shows a local unconformity within the sequence which might be interpreted as U/C1and the stratigraphy below this unconformity suggest more complex and dynamic structures that possibly were deposited in the nearshore wave and tidal current zone. Figure 22 is a record closer to Pullen Island within the relatively large acoustic window that is oriented in an east-west direction. This record has been displayed in a bottom flattened format because heave motion completely disrupted the original continuity of the sub-seabed stratigraphy. With this display format very detailed and complex stratigraphy is apparent within the Unit B materials. In this short section at least four local unconformity surfaces are seen within the Unit B section that indicate foresets in varied (opposing) orientations along with local channelling and bar or spit formations. Also there is an erosional unconformity noted within 1.5 m of the seabed which suggests a scoured surface that is likely infilled by a surficial mobile layer (sandy?) that has been swept to a smooth flat surface by wave and current action. Note: if the seabed surface was not virtually flat and planar the bottom flattening display technique would mirror the seabed irregularities in the subsurface reflectors. Most regions show stratigraphy within Unit B that is similar to the first of these figures though some local areas suggest the more complex stratigraphy apparent in Figure 22 though record quality and particularly weather condition during collection are very important in order to display and interpret this complexity on the acoustic records. The characteristics of the Unit C, D and E acoustic reflectors through this region tends to be equivalent to those seen in the offshore examples discussed previously.

Figures 23 and 24 show example boomer with mini-streamer records from two localized acoustic windows along the northeastern shore of North Point. Since low frequency airgun or sparker records were not available during the Arktos Beta survey program these records were reproduced for optimization of the deeper penetration in order to delineate the acoustic permafrost and deeper subsurface stratigraphy

Figure 23 is located to the southeast of the Hansen Harbour embayment south of Reindeer Island on the offshore side of the submerged sandbar that crosses the mouth of the bay. The record indicates a small region of gas masking on it's southwestern end and the beginnings of a large and extensive masking zone on the northeastern end of the line. Between these gaseous regions there is approximately a 1.2 km long section of record that has little or no

Permafrost Distribution and Degradation

Inshore of the Outer sub-seabed Ridge feature along the pipeline corridor, Acoustic Permafrost is conspicuous by its absence within virtually all seismic data within the inshore basin feature (from approximately 17-18 km offshore to 0.5-2 km offshore). No indication of shallow APF features are noted within the Unit C materials until the permafrost transition zone is encountered, generally within a kilometre of the shore and where water depths of less than 1.5-2 m are encountered. The boundary between the all gas acoustic masking and the offshore mixed gas and ice masking regions shown on Figure 18 approximates the offshore boundary of the inshore basin feature where permafrost is no longer observed on the seismic data.

Taylor and Allen, 1991 described the permafrost encountered in the onshore-offshore borehole transect and noted that the three inshore boreholes showed unbonded conditions to considerable depth. In fact BH02 did not encounter ice bonded sediments until a depth of approximately 90 m below sea level. Figure 27 is a plot of the temperature measurements from the four offshore boreholes which clearly indicates that the temperatures for BH2, 3 and 4 are well above the freezing point for considerable depths below the seabed while the most offshore borehole (BH05) is well below the freezing point both at the seabed and at depth. Figure 28 from their study shows the extrapolated mean annual bottom water (sediment) temperatures related to the water depths at the drilling location. Both figures also give temperatures for the Isserk wellsite which is even further offshore on the Akpak Plateau. This temperature regime implies that in the offshore area with water depths of greater than approximately 7 to 10 m are therefore in a sub-freezing environment and thus permafrost within the sediments would not be degrading at present. These offshore temperatures are associated with the influence of Arctic Ocean waters while the inshore region is influenced by the warm water outflow of the Mackenzie. Thus regions inshore of this depth are within a zone of net permafrost degradation.

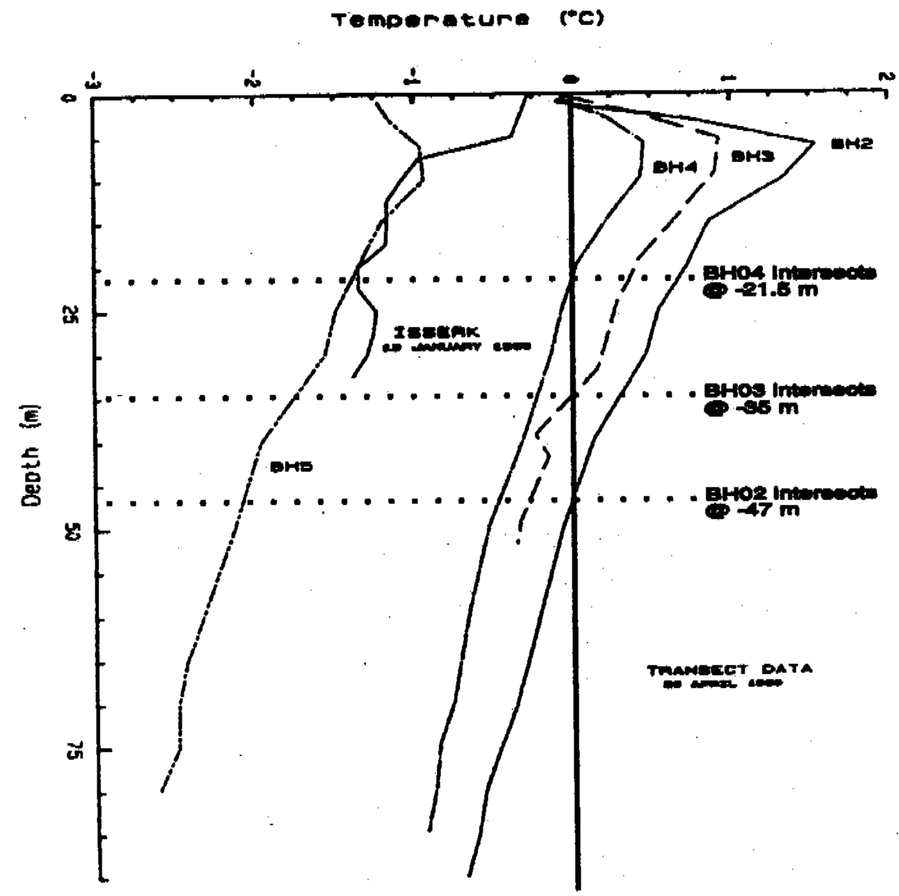

Figure 27: Temperature - depth plot for boreholes BH02 - BH05 and the Isserk drill site further offshore. (reproduced from Taylor and Allen, 1991)

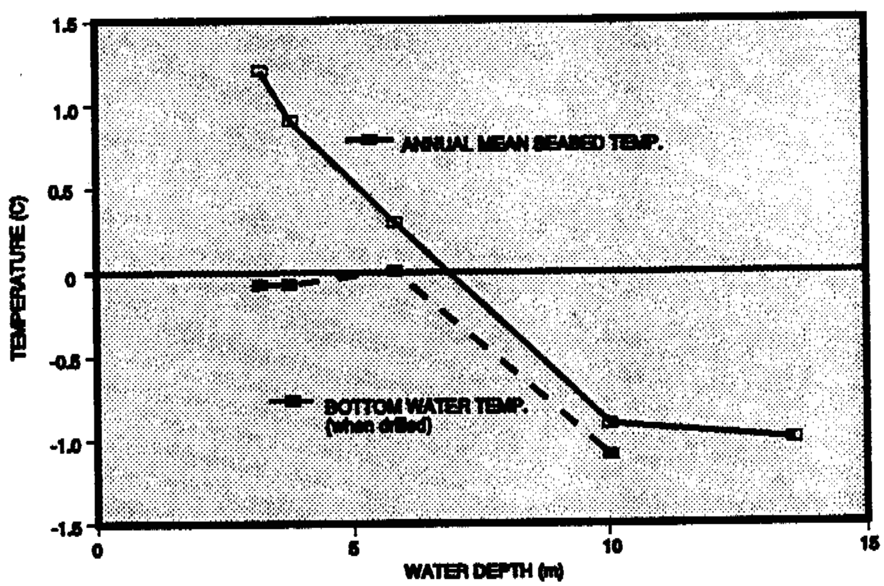

Figure 28: Plot of mean annual seabed (sediment) temperature verses water depth along with water bottom temperatures at time of drilling for

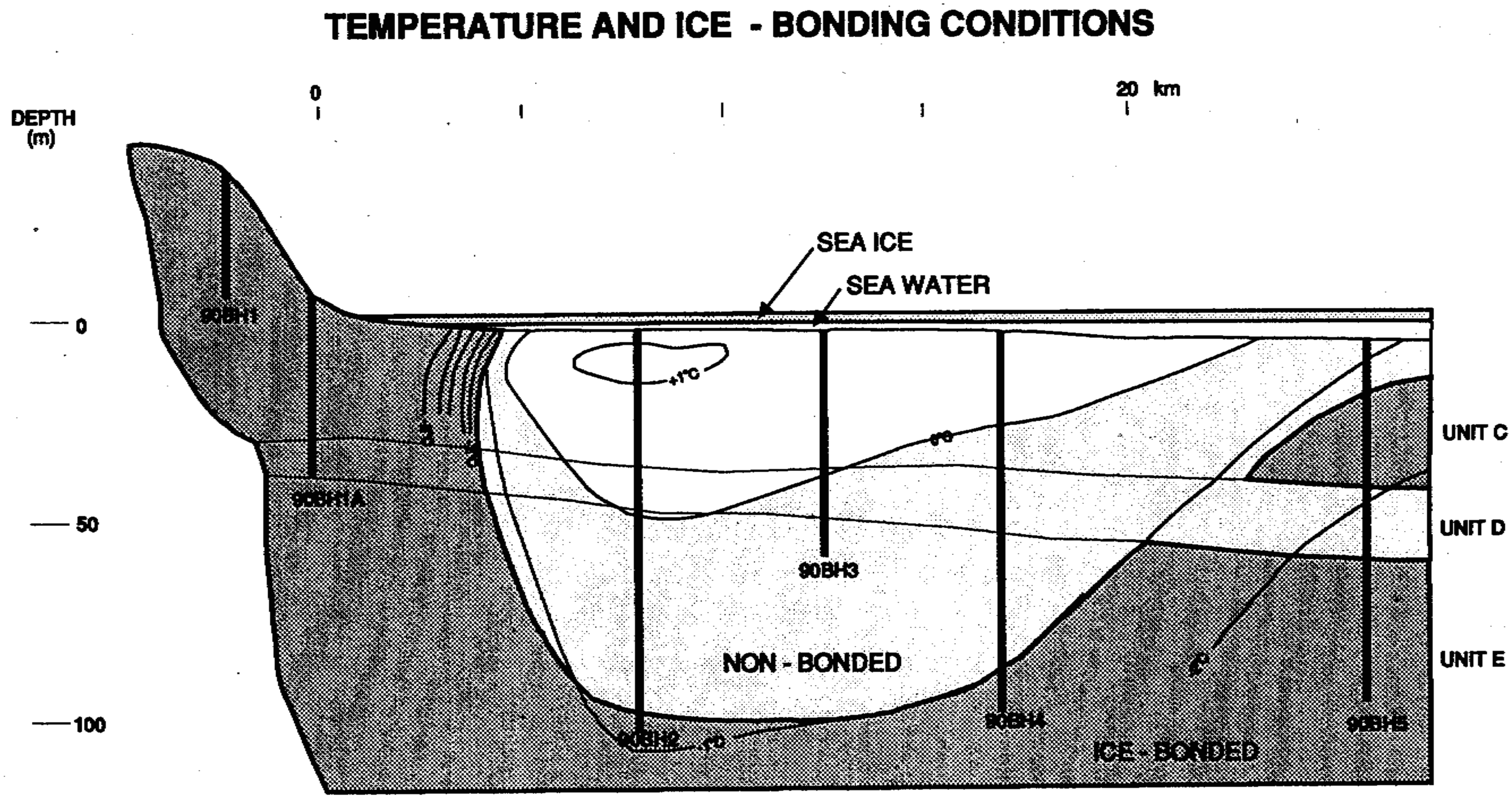

Figure 29: Sub seabed temperature contours and ice bonded sediment conditions over the inshore 25 km of the pipeline corridor to the northeast of North Head on Richards Island. (Reproduced from Taylor and Allen, 1991)

These temperature and ice bonding conditions led Dallimore (1991) and Dallimore and Taylor (1992) to produce the drawing of temperature isotherms and ice bonding conditions for the inshore area of the pipeline corridor shown in Figure 29. This drawing indicates an extensive talik region along the inshore portion of the pipeline corridor. The implications of this extensive talik region are that considerable thermokarst subsidence will be associated with the thawing of the ice within these sediments as there is 10% to 40% by volume of excess ice within the sediments of the Kittigazuit formation (Dallimore and Taylor, 1992). It is this process which is believed to be the cause of formation of the Inshore Basin feature described earlier.

Inshore Basin Formation and Depositional Environment

The major inshore basin feature noted throughout the previous sections extends from approximately 17 to 18 km from shore in water depths of 6-8 m toward the shoreline to water depths of approximately 2 m. In the region north of North Point, Pullen Island is a local high in the overall basin feature which is continuous on the east and west sides of the island. The offshore margin of the basin is only vaguely defined at present due to the limited number of survey lines that extend into the basin outside of the pipeline corridor area. Observations over the Akpak Plateau indicate that in many areas there are channel like depressions in the offshore highs that are suggestive of drainage patterns and/or older thermokarst lakes with associated talik zones (Fortin, 1986 and 1989). These depressions present the same acoustic and general physiographic characteristics locally distributed through the plateau that are observed the inshore basin and effectively complicate the definition and mapping of the offshore boundary of the basin itself, and imply that the boundary is highly irregular in nature.

The seismic and borehole observations suggest that formation of the inshore basin feature is primarily the result of thermokarst subsidence of the area. Observations of the onshore sediments of the Toker Point and Kittigazuit/Kidluit sediments indicate that they contain from 10 - 40% excess volume of ice with higher concentrations near the surface (ie. just below the active layer). Dallimore and Taylor, 1992 suggest that settlement in the order of 1 m for every 10 m thawed are realistic from liberation of excess pore waters based on the bulk densities and water contents found in the onshore and offshore boreholes along the transect. They also note that settlement could exceed 10 m for a 30 m frozen thickness if massive ice layers are encountered as are observed in some regions of the North Head onshore section. Simple thaw of interstitial waters will result in a 10% volume reduction of the water contents which would account for up to 5% of the subsidence (assuming 50% water contents). Additionally thaw of the visible ice component which would result in expulsion of the interstitial waters could account for a further 0% to 30% reduction in volume of the sediments. Thus simple thawing to 90 m depth would likely result in approximately a 15% reduction in volume of the sediment column or approximately 13.5 m of subsidence which is consistent with the observed thickness of the inshore basin feature (12 - 18 m).

The offshore boundary of the basin is complex and, though represented on the profile of Figures 15 and 29, at this point in time we feel that these representations may not adequately describe areas outside the pipeline corridor zone. Because of the cooler sea bottom temperature regime in the offshore it is unknown if the offshore boundary of the basin feature is actively migrating to seaward (or shoreward) or if it represents a currently stable state condition. The inshore boundary of the basin is known to be currently active based on the measurable shoreline retreat rates along the coast (Hill, 1991, Solomon, pers. comm.). Figure 30 is a schematic representation of what we believe the inshore, currently active, boundary of the basin entails. This figure indicates a complex and active shoreline area with wave action erosion and bottom fast ice erosion currently playing an active roll in cutting back the coastline. Thermokarst collapse of the seashore cliffs along with wind and rain erosion cut back the high ground and move sediments to the beach where wave and ice erosion combine to transport these material toward the offshore. This nearshore action plains the land surface first to sea level and then erodes the beach areas to depths of at least 1.5 to 2 m below sea level.

In water depths of less than 1.5 to 2 m the winter sea ice freezes down to the seabed and thus allows thermal transfer of the very cold winter temperatures into the seabed sediments. Thus the region is maintained at an annual surficial sediment temperature below the freezing point and as a result the nearshore zone maintains a net permafrost stable condition. Because of the higher heating capacity of the nearshore waters it is likely that the active thaw layer at the seabed is deeper in this region than would be the case on shore where air is the primary thermal medium. Once the erosion (predominant) and/or relative sea level rise (secondary at present) has lowered the depth to the point that the winter ice no longer freezes solid to the seabed the thermal conditions dramatically alter to the point that the mean annual seabed temperatures are in the order of +1to +1.5°C. At this point the active layer degradation of the permafrost level becomes continuous and the permafrost thaw front will continue downward on an annual basis. The rate of progression of the thaw front will be a function of the thermal conductivities of the sediments and the annualized seawater temperatures but will be slowed by the latent heat of thawing of the ice within the sediments. Presently limited observations indicate that the thaw front dips to seaward at an angle of approximately 13 to 15° though this might not be representative of all regions. This angle would also likely vary as a function of the wave and current actions along the shoreline and subsequent retreat rates of the shorelines. Thus a protected cove (or thermokarst lake) where wave and current actions are reduced might produce a steeper angled thaw front than a highly active open shore where erosion is higher and the shoreline is retreating faster. At this time there are insufficient seismic or borehole profiles across the thaw front to confirm these suppositions.

With a continuous thaw front dip angle of 13 to 15° the sediments would be thawed to a depth of 90 m (depth of ice bonding noted in BH02) over a distance or 330 - 390 m from the thaw break at the 1.5 to 2 m water depth. Thus there could potentially be thaw subsidence of up to 10-15 m over this short distance. It is more likely that the thaw front boundary shallows at depth (not apparent on the presently available seismic sections due to limited penetration) as stable state thermal conditions are reached with the large mass of deep permafrost (to depths of 400 to 600 m). This sort of boundary edge is generally consistent with the inshore edge of the basin feature observed on the seismic sections that are available at present. These records indicate a rapid drop into the basin to depths of 6-10 m near the edge (melting of the Unit C / Kittigazuit/Kidluit sediments) followed by a more gradual thickening of the basin toward the offshore over the next 1 to 2 km where the basin unconformity (U/CL) is typically at depths of 13 to 18 m below the seabed.

The rapid subsidence (6-10 m) over the first 100 to 200 m of the basin structure provides a significant sediment accommodation space which acts as a sediment trap for the materials being eroded from the retreating shoreline. This accommodation space would likely trap a significant portion of the coarser sediments that are moved by traction load off the beach area by wave and current actions along with some of the fine sediments. The finer silt and clay faction would be suspended in this process and predominantly transported further offshore, depending on the wave and current action. This hypothesis is generally consistent with the seismic and borehole observations in the region. This process would account for the onlapping acoustic horizons noted in Figure 24 in the nearshore area of the basin and Figure 20 in the offshore region.

The other characteristic of the inshore basin sediments are that throughout the region the presence of shallow gas trapped within these materials is almost ubiquitous. The shallow gas trapped within these sediments masks acoustic penetration over virtually the entire basin and thus inhibits the seismostratigraphic interpretation of the area. Initially these gases were thought likely to be methane or ethane in composition generated from decay of organics and/or migration from deeper in the section. This interpretation was generally not confirmed by gas testing of borehole samples however. The recent nearshore records such as example Figures 24 and 25 suggest an alternate possibility. Within the 200 to 500 m region offshore from the edge of the basin margin the seismics commonly show an acoustic window and the upper 15 to 20 m of this section is commonly virtually incoherent in acoustic character with many hyperbolic reflections throughout this zone. These hyperbolics tend to be randomly distributed within the Unit C and up into the recently deposited Unit B materials. Also, proceeding offshore the hyperbolic reflections tend to rise in the section culminating in a gas masking horizon in the offshore area where the onlapped finer silt and clay sequence is seen just below the seabed. Where, initially it was thought the gas resulted from decay of organics trapped within the Unit B materials infilling the basin, these records suggest that a significant portion of these gases may be from a source within the Unit C materials which are typically devoid of organic materials. It is postulated that the gases are actually primarily "air" that has been trapped within the massive ice and generally frozen Unit C sediments that is released as these materials thaw and migrate upward through the section. Initially these gases escape into the seawater in the very nearshore newly formed basin where the coarser faction Unit B materials would accumulate. Once the finer materials begin to form silt and clay layering beyond the onlap horizons these gases would become trapped beneath the more impervious (particularly clay layers) horizons and form the masking acoustic reflection zones seen on the seismic sections in the area. This explanation would account for the low methane concentrations observed within the inshore basin that are derived from the borehole tests. To the authors knowledge gas testing procedures have not commonly reported air (O_2 or CO_2) free gas contents within the cores which would still produce the shallow gas reflection characteristics observed in this region. Tests of this nature would be required to verify this postulation on new cores or properly stored gas samples from previous cores in the region.

The above paragraphs outline the thermodynamic reason and the presently interpreted depositional environment for the nearshore basin feature along the Mackenzie Delta coastline. Although this discussion describes the current depositional and thermal environment it does not explain how these conditions came to exist and particularly why the offshore region beyond 6-8 m water depth has permafrost still existing very near to the top of the Unit C sedimentary materials. The following discussion sub-section will attempt to bring this into perspective.

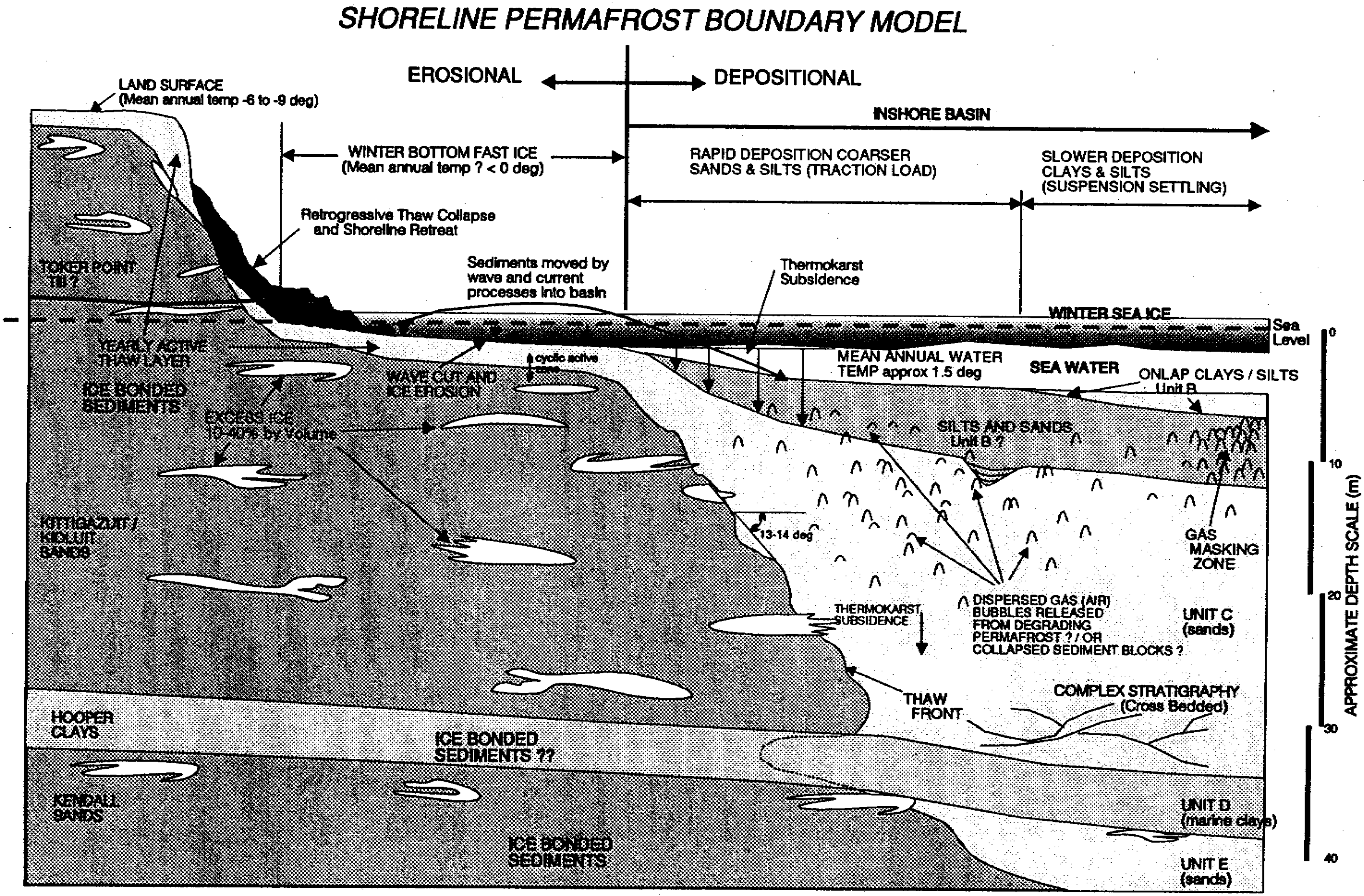

Figure 30: Schematic representation of the near shoreline permafrost transition which indicates the inshore edge of the Nearshore Basin along the Mackenzie Delta Coastline.

Implication on the Beaufort Sea Geological Model

The data displayed and described above has the following implications with regard to the GSC geological model for the Central Beaufort Shelf region.

Principally there is no significant change to the offshore stratigraphic section beyond 6-8 m water depths with regard to the GSC model. The primary modification falls is in the shallow water zone and this change is totally a function of the extensive talik across approximately the 16-18 km wide inshore basin feature. First the Units C, D and E sediments within this basin are unfrozen to depths in the order of 80 to 90 m below the seabed which is a basic change from the HAPF and stratigraphic APF (frozen) characteristics associated with the offshore model for these materials. With this variation the stratigraphic section is identical however as far as can be determined from the seismic and borehole data. Secondly, the resulting thermokarst subsidence in the basin has provided a huge catchment basin formation that is currently thought to be the trapping area for most of the coarser grained faction of materials that are being eroded from the shoreline and that may be brought down by the rivers. As a result only fine grained materials are transported to the offshore environments at present and are being deposited mainly as Unit A marine clay materials, predominantly in water depths greater than 15-16 m. The exception to this would be small amounts of coarser materials that are transported by ice rafting as the grounded sea ice along the coastline breaks free in the spring and drifts further offshore before melting. In itself this would likely represent only a small proportion of the bottom fast ice each year as the majority would likely melt in place or in the nearshore zones.

The inshore Holocene depositional regime does not completely conform to the standard offshore model because of this extensive catchment basin. For description purposes we refer to this environment as the Beaufort Sea Inshore Thermokarst Basin Model. The primary difference is the addition of the local basin scale thaw subsidence of the basin which was not occurring in the offshore regime during it's transgression. Sediments infilling the basin primarily conform to Unit B seismo-stratigraphic definition though entrainment of basal lacustrine and or riverine materials (Unit C?) would still be likely within the basin on the U/CL unconformity horizon that are difficult or impossible to distinguish from Unit B materials.

In this region of the Mackenzie coastal plain the basin is continuing to subside and as a result is continues to provide accommodation space for sedimentation (thus the onlapping seismo-acoustic horizons seen on both onshore and offshore sides of the basin). Thermal models on continuing rates of degradation of the deeper permafrost would be required to model rates of subsidence in the central basin (if at all). At the same time it is believed that the basin continues to grow wider with shoreline retreat and wavebase erosion to regions below the 1.5-2 m ice freeze limits. Thus lateral growth along with continued subsidence provides additional deposition space for the new sediments transported into the region or generated through shoreline erosion.

This inshore basin is clearly noted in the area directly to the north of Pullen Island, and if the assumption of shallow gas associated with this basin is correct, the Inshore Thermokarst Basin is prevalent to the west as far as the mouth of the main western channels of the Mackenzie River. Toward the east gas is prevalent throughout the inner portions of Kugmallit Bay and along Tuk Peninsula at least as far as the town of Tuktoyaktuk. Further east the gas appears to be less prevalent and therefore the inshore basin model may not be appropriate for this region. To the west along the Yukon coastline, gas is not prevalent and this model probably does not apply. These two regions are thought to represent areas that are not influenced by the warm water outflow of the Mackenzie and therefore represent coastal areas that are primarily influenced by relative sea level rise only with a more restricted thaw front because of the generally colder seawater temperatures.

A basic question that these observation raise is that of why is the offshore boundary of this basin at approximately the 6-8 m water depth limit (16-18 km from shore), and what environmental and/or physical changes occurred and at what point in time such that this basin feature began to form. The following two brief postulations are presented that may account for the formation of the inshore basin feature:

1 Prior Large Lake or Embayment

It has been postulated that the basin was actually formed as a large thermokarst lake or side embayment of the Kugmallit Channel that was separated by a series of offshore Barrier Islands that presently constitute the Akpak Plateau. The argument for this is the existence of Pullen Island, Breakers Shoal and the offshore permafrost (sub-seabed) high region. Overall the argument against this scenario is that there is virtually no remnant submarine high areas across the Akpak Plateau that are prevalent on the bathymetric record which would indicate the existence of these barrier islands. The seabed rises gently and continuously to the shoreline from beyond the 15 m contour. Also the inshore basin feature surrounds Pullen Island at present indicating at least that this island was not a part of the offshore barrier group. If there had been significant barrier islands across the Akpak Plateau it is felt that there would have to be significant remnant highs in the bathymetric record which are not seen.

2 RSL Change along with Mackenzie Discharge Variations

It is postulated that in the region beyond the present day 6-8 m depth contours, sea levels rose rapidly across the shelf and that the sea water encroaching the shore was primarily cold Arctic waters (approx -1°C) that did not significantly degrade the permafrost table. During this time period (approx 2,500 to 6,000 yrs bp, Hill, 1991 modified RSL curve) most or all of the warm water outflow of the Mackenzie was bypassing the shelf areas to the east of the Ikit Trough. A mechanism that may have resulted in this condition would have virtually all of the Mackenzie flow coming down the Main West Channel and into the Mackenzie Trough. These waters would then mix with the larger volume of arctic waters within the deep trough basin and be cooled to the point that when these waters circulated to the eastern shelf they did not cause significant degradation of the permafrost table. Evidence for this may be the extreme sedimentation rates within the inshore delta portion of the Mackenzie Trough which indicate up to 120 m of sediments deposited through the Holocene (Blasco, pers. comm.).

The other major change associated with the 6-8 m water depth contour is a significant change in the rate of relative sea level rise that occurred approximately at the time that this region would have been inundated. Figure 31 is a revised Relative Sea Level curve for the Beaufort Sea (reproduced and modified from Hill, 1991). This curve indicates a significant slowing in the rate of sea level rise at approximately 3000 yrs bp. From 0 to approximately 2100 yrs bp. the rate of sea level rise has been about 0.32 mm/yr while from 3000 to 6000 yrs bp the rate of rise was much faster at approximately 1.6 mm/yr. This slowed rate of sea level rise likely accounts for an increase in the amount of erosional shoreline retreat that has occurred which would result in the decrease in seabed slopes seen across the inshore basin region. Also the slower sea level rise would increase the exposure times of the underlying sediments to the warmer shallow coastal waters and thus likely increase the propagation of the thaw front to considerable depth.

Because of the observed steepness of the thaw front (13-15°) within the present inshore basin it is assumed that even though RSL rates were approximately 5 times higher before 2500 yrs bp. there must have been additional influences besides faster sea level rise that affected the thawing of the permafrost during inundation. Thus it is likely the some form of diversion of the warm Mackenzie waters during the middle Holocene was occurring as well.

The other main aspect of this study has been that there is no observed discontinuity in the stratigraphy from the onshore to offshore sections. This implies that the geologic sections are continuous and thus should be of the same age.

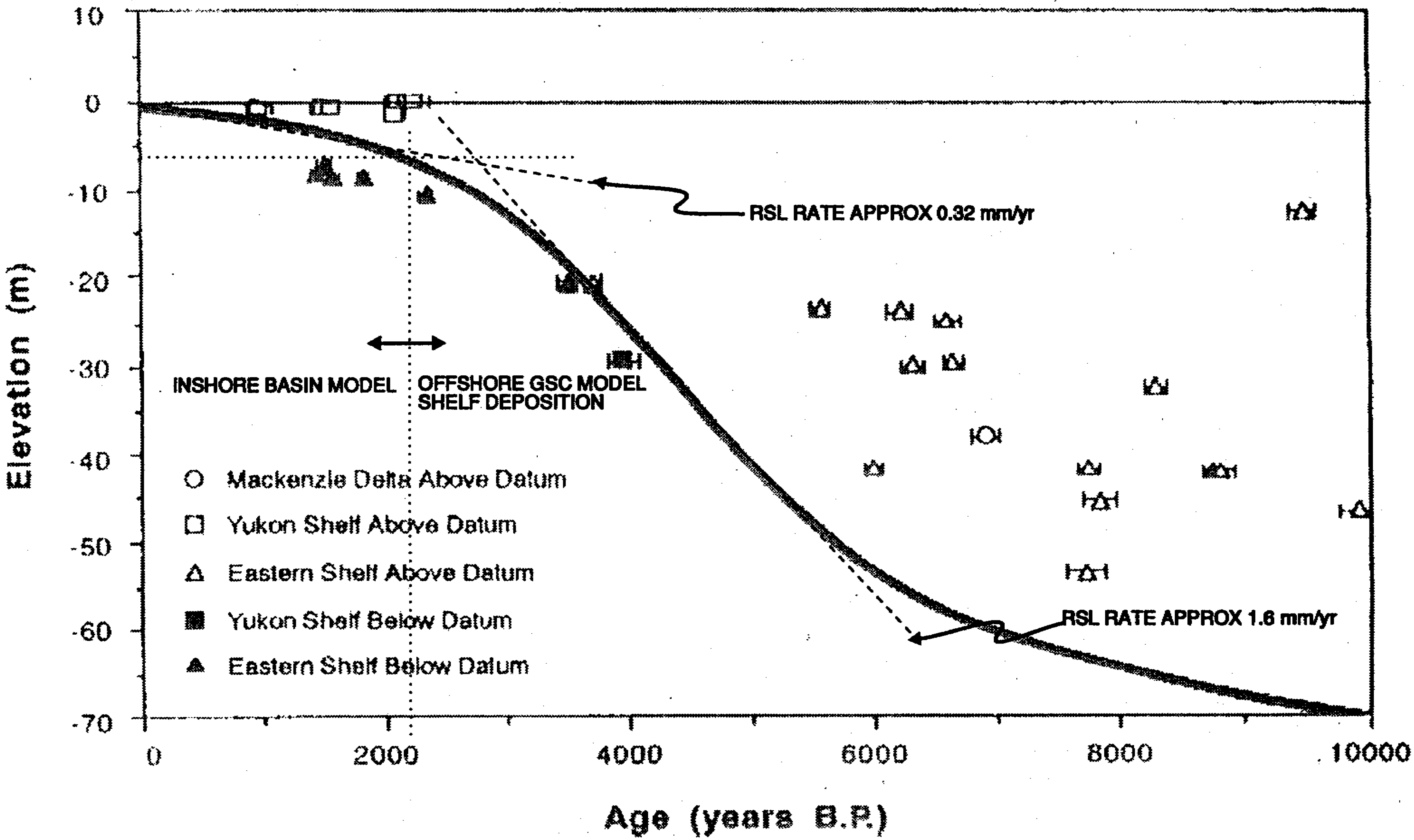

Figure 31: Revised Holocene relative sea level curve for the Canadian Beaufort Sea (reproduced and modified from Hill et.al., 1991 and based on Carbon 14 dates presented in that and earlier papers)

Conclusions

This study has outlined the existence of a major inshore thermokarst basin within the shallow water section of the Mackenzie Delta coastline. The thaw basin extends from the nearshore zone at approximately 0.5 to 1 km from shore where water depths exceed the depth of winter bottom fast ice (1.5 to 2 m of water) to a distance of 16-18 km from the shore. The thaw within this talik extends to a depth of 80-90 m below the seabed and the thawing of the 60-70 m of sediments in the talik has resulted in thermokarst collapse subsidence of these sediments of from 12 to 18 m throughout the basin. The sediments infilling this basin are Unit B marine transgressional silts and clays which are derived from erosional retreat of the shoreline and the outflow of the Mackenzie river.

The inshore permafrost degradation thaw front dips to seaward from the basin edge at a dip angle of between 13° and 15° and the resulting thaw subsidence of this boundary results in a steep, well defined inshore boundary of the inshore basin. The offshore boundary of the Thaw Basin is not well defined at this time because of the often unclear definition of the basin edge associated with offshore channel and thermokarst lake basins within the Akpak Plateau.

Throughout the interior portions of the basin feature the acoustic section is significantly degraded by shallow gases trapped beneath the surficial silt and clay layering in the shallow sediments. Gas samples from boreholes in the region do not indicate high concentrations of methane or ethane gases within these sediments. It is speculated that these acoustic gas masking concentrations may primarily represent "air" within the sediments that have been released by the thawing of the underlying materials. These gases likely also include some proportion of authogenic or petrogenic gases resulting primarily from the decay of organic matter that is entrained within the Unit B sediments during their rapid deposition.

The basin has formed a significant catchment area for the sedimentary materials transported into and through the area. We believe that the majority of the coarser faction of these sediments are entrained within the basin in the very nearshore region, just after the initial and major subsidence that occurs along the shoreline thaw front. The finer silt and clay factions are transported in suspension load initially to the central portions of the basin that is thought to be subsiding more slowly based on gentle onlap reflecting horizons seen along the onshore and offshore edges of the basin. The very fine clay materials are transported further to the

Recommendations

From the interpretation models and seismic observation presented through this study the following list of potential further study recommendation is presented:

1 Thermal modelling study of the continued rate of subsidence within the basin. This model should assume an angle of approximately 13-15° at the seabed for the thaw front at the inshore boundary and would likely shallow with depth as thermal condition equilibrated. Also the model should account for the latent heat of melting of the permafrost ice which is apparently 15 to 20% by volume of the total sediment column (possibly with a higher concentration near the top and decreasing with depth.

2 Get detailed information on rates of sedimentation within the inshore basin (2 mm/yr Solomon pers comm assuming C14 residual effects etc) - from this make assumptions regarding rates of basin subsidence less sea level rise assuming the seabed slopes are in a depth equilibrium conditions.

3 Look at sedimentation rates specifically within the shore-edge permafrost degradation zone -(first 200-300 m of the inshore basin at the thaw boundary) these potentially could be in the range of cm/yr associated with the rapid thaw subsidence. This might be possible using diver emplaced measurement stakes and looking at the region over a period of a few years.

4 Re-evaluate gas content tests on inshore basin sediments - it is possible that the "acoustically gassy" zones are not methane related but may be "air" filled void spaces resulting from release of air that was entrained in the ice and frozen sediments being released on thawing. Should be looking at air filled void space within the sediments as opposed to methane contents ??

5 The offshore boundary of the basin feature is currently poorly mapped on the acoustic records. This relates to high variability in the seismic qualities of the offshore data sets and the fact that only the local region of the pipeline corridor has been adequately mapped in relation to the Inshore Thermokarst Basin interpretation model. A more thorough review and mapping of the offshore data might be undertaken and it is felt that

this would lead to the necessity of additional survey lines in this region. (Note: if the mid - early 70's Esso data sets (Huntec I think) could be located it may be possible to map these area. Last reported use was O'Connor, 1985)

6 It was noted that the ubiquitous gas region of the inshore basin was not as prevalent in the inner portions of the southern Arktos survey line into Mason Bay. It therefore may be possible to obtain a continuous offshore to onshore seismic line transect from the Kugmallit Channel region into the shoreline. This would assist in confirming the continuity of the geological sections through this region. It would therefore be realistic to attempt some survey lines in these regions to confirm if this is possible (alternately spend some additional interpretation effort in this area using presently available data though most is of lower quality)

7 Additional inshore (Arktos Beta type) survey lines within the inshore areas would be useful in further defining the permafrost thaw front. These lines should incorporate high res multi tipped sparker data (salt bagged or tube sparker for use in fresh water) as well as boomer data to provide additional depth of penetration in order to attempt to define the deeper thaw front conditions. Survey lines should either be run obliquely to the shoreline or preferably at survey speeds of approximately 0.5 knot (15 to 20 m per minute) perpendicular to the shore to properly define the slope of the thaw front. Survey should be conducted on both protected (slow retreat) and open (fast retreat) shorelines and possibly within a thermokarst lake to determine if differing thaw front slopes are produced under the varying conditions. Also, survey lines onto outbuilding sand bars might determine if local areas of permafrost aggradation are occurring as well. Ideally these surveys should be conducted in the form of a local grid survey with 25 to 50 m line spacing such that a 3D representation of the thaw front could be produced and subsequently thermally modelled.

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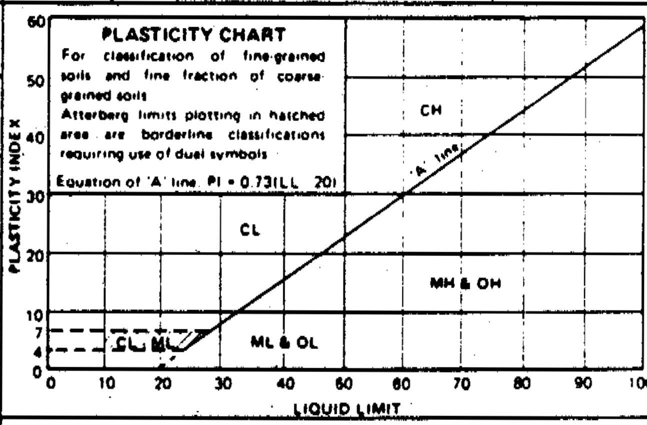
outer shelf where they are deposited as the fine clay Unit A materials predominantly in water depths of greater than 15 - 17 m.

There has been no evidence observed to indicate a discontinuity in the stratigraphic sections from the onshore to the offshore regions through this review of the seismic and borehole data available in the region. The seismic and borehole similarities in these sections strongly imply continuity of the sections. Therefore it is concluded that the offshore Unit C sediments correlate to the onshore Kittigazuit and Kidluit Formation. The offshore Unit D and Unit E sediments correlate with the marine clays and underlying sands that have been tentatively defined as the Hooper Clays and Kendall Sand on the North Point borehole sections. Note: because of stratigraphic relationships in the offshore we feel that these Hooper and Kendall sediments below Richards Island are not correlative with those at Rampton's type areas on Hooper and Kendall Islands to the west.

Since the onshore and offshore sections are stratigraphically correlative and therefore should have been deposited contemporaneously there is a significant discrepancy in the presently interpreted ages of one or both of these areas. It is beyond the scope of the present study to resolve which of these areas may be in error. It is suggested that the age and formation mechanism of the Toker Point till(?) diamict formation of the onshore section may hold the key to this discrepancy.

APPENDIX A

UNIFIED SOIL CLASSIFICATION†

MAJOR DIVISIONS			GROUP SYMBOLS	TYPICAL NAMES	CLASSIFICATION CRITERIA		
COARSE-GRAINED SOILS More than 50% retained on No. 200 sieve*	GRAVELS 50% or more of coarse fraction retained on No. 4 sieve	CLEAN GRAVELS	GW	Well-graded gravels and gravel-sand mixtures, little or no fines	Classification on basis of percentage of fines: Less than 5% pass No. 200 sieve: GW, GP, SW, SP; More than 12% pass No. 200 sieve: GM, GC, SM, SC; 5% to 12% pass No. 200 sieve: Borderline classification requiring use of dual symbols	$C_u = D_{60}/D_{10}$ Greater than 4; $C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}}$ Between 1 and 3	
			GP	Poorly-graded gravels and gravel-sand mixtures, little or no fines		Not meeting both criteria for GW	
		GRAVELS WITH FINES	GM	Silty gravels, gravel-sand-silt mixtures		Atterberg limits plot below "A" line or plasticity index less than 4	Atterberg limits plotting in hatched area are borderline classifications requiring use of dual symbols
			GC	Clayey gravels, gravel-sand-clay mixtures		Atterberg limits plot above "A" line and plasticity index greater than 7	
	SANDS More than 50% of coarse fraction passes No. 4 sieve	CLEAN SANDS	SW	Well-graded sands and gravelly sands, little or no fines		$C_u = D_{60}/D_{10}$ Greater than 6; $C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}}$ Between 1 and 3	
			SP	Poorly-graded sands and gravelly sands, little or no fines		Not meeting both criteria for SW	
		SANDS WITH FINES	SM	Silty sands, sand-silt mixtures		Atterberg limits plot below "A" line or plasticity index less than 4	Atterberg limits plotting in hatched area are borderline classifications requiring use of dual symbols
			SC	Clayey sands, sand-clay mixtures		Atterberg limits plot above "A" line and plasticity index greater than 7	
FINE-GRAINED SOILS 50% or more passes No. 200 sieve*	SILTS AND CLAYS Liquid limit 50% or less		ML	Inorganic silts, very fine sands, rock flour, silty or clayey fine sands			
			CL	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays			
			OL	Organic silts and organic silty clays of low plasticity			
	SILTS AND CLAYS Liquid limit greater than 50%		MH	Inorganic silts, micaceous or diatomaceous fine sands or silts, elastic silts			
			CH	Inorganic clay of high plasticity, fat clays			
			OH	Organic clays of medium to high plasticity			
HIGHLY ORGANIC SOILS			PT	Peat, muck and other highly organic soils	*Based on the material passing the 3 in. (75 mm) sieve †ASTM Designation D 2487, for identification procedure see D 2488		

GROUND ICE DESCRIPTION

ICE NOT VISIBLE

GROUP SYMBOLS	SYMBOLS	SUBGROUP DESCRIPTION
N	Nf	Poorly-bonded or friable
	Nbn	No excess ice, well-bonded
	Nbe	Excess ice, well-bonded

VISIBLE ICE LESS THAN 50% BY VOLUME

GROUP SYMBOLS	SYMBOLS	SUBGROUP DESCRIPTION
V	Vx	Individual ice crystals or inclusions
	Vc	Ice coatings on particles
	Vr	Random or irregularly oriented ice formations
	Vs	Stratified or distinctly oriented ice formations

VISIBLE ICE GREATER THAN 50% BY VOLUME

ICE	ICE + Soil Type	Ice with soil inclusions
	ICE	Ice without soil inclusions (greater than 25 mm (1 in.) thick)

NOTE:
1. *Dual symbols are used to indicate borderline or mixed ice classifications*
2. *Visual estimates of ice contents indicated on borehole logs ± 5%*
3. *This system of ground ice description has been modified from NRC Technical Memo 79, Guide to the Field Description of Permafrost for Engineering Purposes*

LEGEND

Soil Ice

APPENDIX B

Pipeline Corridor Geotechnical Zone Considerations

Along the pipeline corridor the section can be separated into six distinct zones based on the seismic data and supported by the borehole data available at present. Within these zones (particularly zone 3) the geotechnical characteristics could quite likely be further subdivided on a scale in the order of 100 to 200 m based on the highly variable structures within that area.

Kugmallit Channel

approx 25.7 → 45.6

Zone 1 Offshore zone km __ to __ within Kugmallit channel - 2-4 m of soft unit A 1- 30 kPa - >50% water content - overlying stiffer unit B materials 30-80 kPa with

Approx 23 → 25.7

Zone 2 Outcropping of Unit B within Kugmallit Channel - probable shear strengths in the range of 30-100 kPa - mixed silt sand and clay composition - local regions of shallow gas and subsurface permafrost but below any region likely to be affected by trenching.

Offshore ridge

18.5 23

Zone 3 km _ to _ Compacted firm sands ice is shallow in the section in some places coming to within 4-8 m of the seabed particularly in the region km _ to _. Highly variable strengths and compositions particularly within Unit B infilled channel features in at km _ to _ ..... possible gravels at seabed km ...

Inshore Basin

13.3 18.5

Zone 4 km - to km - region of silts and sandy silts of Unit B shear strengths in range of __ to __ kPa with variable composition silts, clays and occasional sandy zones. Recent sediments of Unit B composition to thickness of typically greater than 5 m and up to 15 m - soils are predominantly cohesive in character and there are no indications of permafrost for considerable depths - local regions of shallow gas are apparent on the seismic sections but borings and CPTs indicated no blowout problems or anomalous zones of unusual weakness and therefore gas concentrations must be low but high enough to affect the seismic sections

Zone 5 From km 1.2 __ to 13.3 __ the region is acoustically masked by shallow gas within the section. Local area of sandy gravelly seabed km 3 to 6 boreholes PS8801, PS88S08 and PS88S02 (EBA) - gravels were reported by Gilbert 1990 based on a sidescan and 3.5 kHz profiler run in 89 from a launch operated from Nahidik (on seabed grab sample showed gravels though not reported in boreholes) . From borehole data the basin is filled with clay and silt primarily with a lenticular sand body at the seabed as mentioned above. Acoustics indicate virtually no penetration throughout most of this region. Boreholes indicate basin contains 8 to 18 m of clays over an irregular U/CL unconformity surface.

Zone 5a inshore km 1-2.~~2~~ 6 is an acoustic window showing shallow gasses on both sides over an area of _ to _ m of unconsolidated Unit B materials - unconformity approx 5-6 m below seabed on inshore end and dips to a basin at a thickness of 13 m at approx km 1.6 and remains level from there. Overlies 23 m of Unit C sands on 8 m of Unit D clays on top of Unit E, Kendall sands - sediments are unfrozen to depths of at least 50 m through this zone based on seismics (possibly deeper though not detected with the system used).

Zone 6 Shoreline to approximately 1 km along transect - frozen sands of Unit C (Kittigazuit Formation) - **? borehole BH-8 inshore unfrozen to 15 m???**

0 → 1.2 km