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Geological investigations of proposed pipeline channel crossings in the vicinity of Taglu and Niglintgak islands, Mackenzie Delta, Northwest Territories

S. Traynor, S.R. Dallimore

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NOTE TO READER

To aid the reader in understanding and interpreting the figures presented in this report, a few background notes are highlighted below:

A) All channel profiles include a shaded box representing an average (1.8m) ice thickness for these channels during the winter months.

B) The direction of flow in all the channel cross-sections is into the page, such that, the left bank will always be on the left side of the page.

C) Slope values for the channel sides are maximum values.

ABSTRACT

This report reviews investigations of geological and geotechnical conditions at two proposed development sites in the vicinity of Taglu and Niglintgak Islands in the Mackenzie Delta. Pipeline channel crossing sites have been assessed by characterizing channel morphology and stability over a twenty to thirty five year time span. Other studies included investigations of bank geology, surficial features such as landslides and characterization of near-surface ground thermal regime.

High rates of channel shifting and bed degradation predominate at both sites with the Niglintgak site showing significant change as flow is diverted from Middle Channel near the mouth into the underfit Kumak Channel. Bottom-fast ice present during most of the winter months in areas with water depth less than 2m, plays a significant role in channel morphology and the development of shallow permafrost. Ground ice in a variety of forms was noted in the upper 6m of bank sediment and below some shoal areas. The role of the Pleistocene upland outliers is also identified, particularly as a control on channel migration and a source area for the introduction of a coarse fraction to the bed load of the channels.

The findings of the report have significant implications for future development of hydrocarbon resources in the area. When designing pipeline crossings across channels, special consideration must be given to the location of shallow permafrost below channel banks and shoal benches. These considerations include possible thaw settlement, frost heaving, bed degradation and rapid erosion of channel banks.

ACKNOWLEDGEMENTS

Field work conducted as part of this project utilized the Geological Survey of Canada launch J.Ross Mackay. The authors are indebted to R. Good who was responsible for maintenance of the launch and to L. Dyke who assumed captain duties for most of the work. Field assistance during this work was ably provided by J. Bisson, J. Shimeld, J. Hanright and V. Sloan.

The work would not have been possible without logistical assistance and access to the fine facilities at the Inuvik Research Centre and the Polar Continental Shelf base in Tuktoyaktuk. J. Weaver of Esso Resources and P. McLellan of Shell Canada are acknowledged for providing background information on geotechnical and hydrologic studies conducted at the Taglu and Niglintgak sites. Larry Dyke generously provided unpublished ground temperature data from the field sites.

Review comments on a draft manuscript provided by J. Jasper, M. Carson, J. Hanright, P. Egginton, A. Heginbottom, and S. Lord are gratefully acknowledged. Finally, the assistance of S. Edwards and B. Nesbit in administering the project is appreciated.

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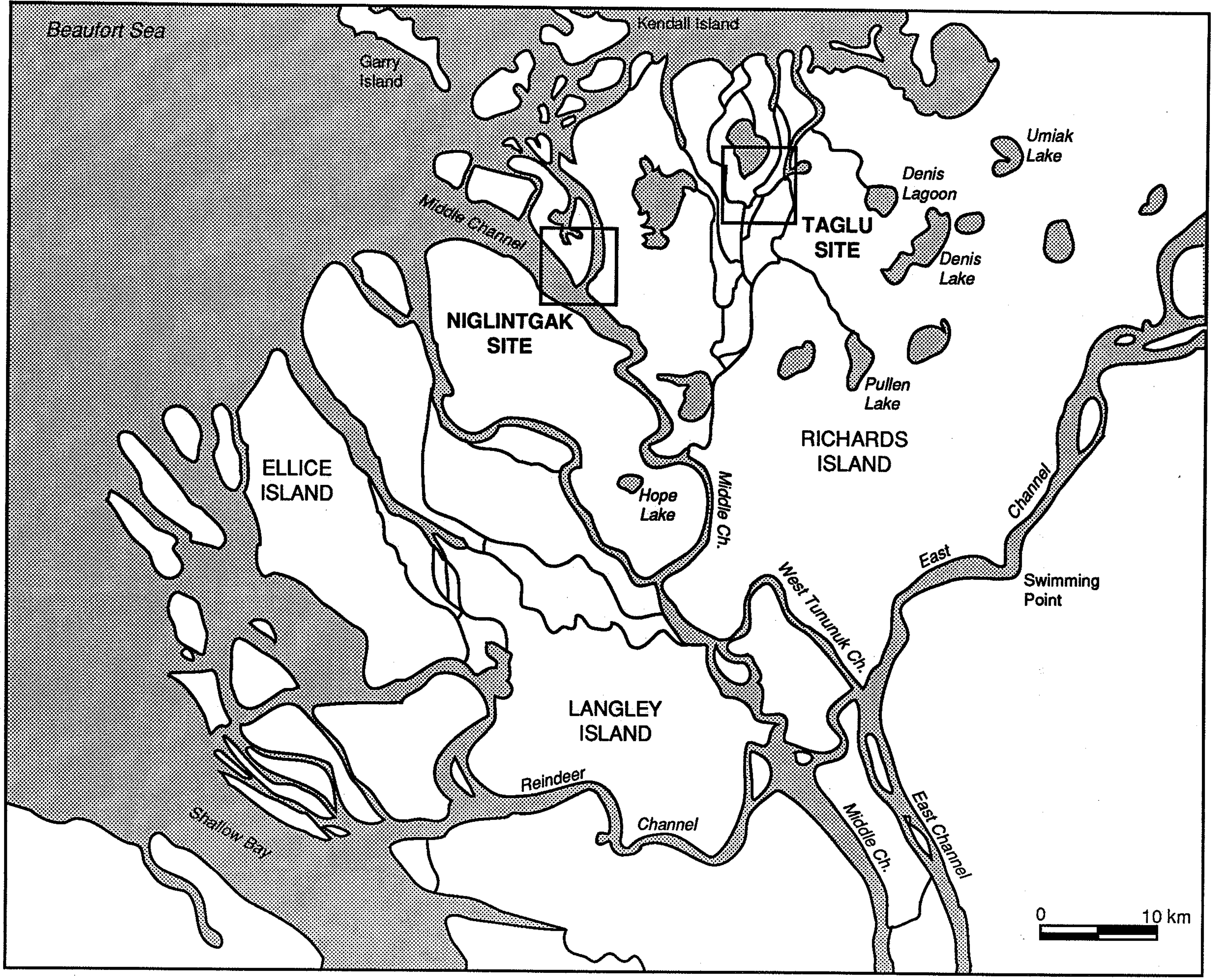
1.0 INTRODUCTION

1.1 General

The Mackenzie River Delta is the second largest delta in North America and the second largest delta in the world located in an arctic or subarctic climatic region. The complex geomorphic processes involved in delta formation, the climatic conditions and the widespread periglacial conditions combine to create a unique diversity of physical and biological environments. Major discoveries in this area of oil and gas have been made in the past twenty years with at least four major fields identified in the outer delta region. Proposed development of hydrocarbon resources within this region include major engineering structures such as feeder pipelines, production wells, docks, and other supporting facilities. The effective design, construction and operation of these facilities require detailed information on the impact of the structures on the environment and also, the impact of geologic and hydrologic processes on the structures themselves.

The purpose of this report is to describe investigations of channel stability, near-surface geology and permafrost conditions of several reaches in the vicinity of two of the major proposed hydrocarbon fields, the Taglu field and the Niglintgak/Kumak field. The two study sites discussed in this text are designated as the Taglu Site and the Niglintgak Site (Figure 1). The hydrologic and geologic conditions at each site were studied by industry in the early and mid-seventies, providing a data base on which to compare current studies and augment research of conditions found at the study sites.

Figure 1: SITE LOCATIONS - RICHARDS ISLAND, OUTER MACKENZIE DELTA



1.2 Funding For Research

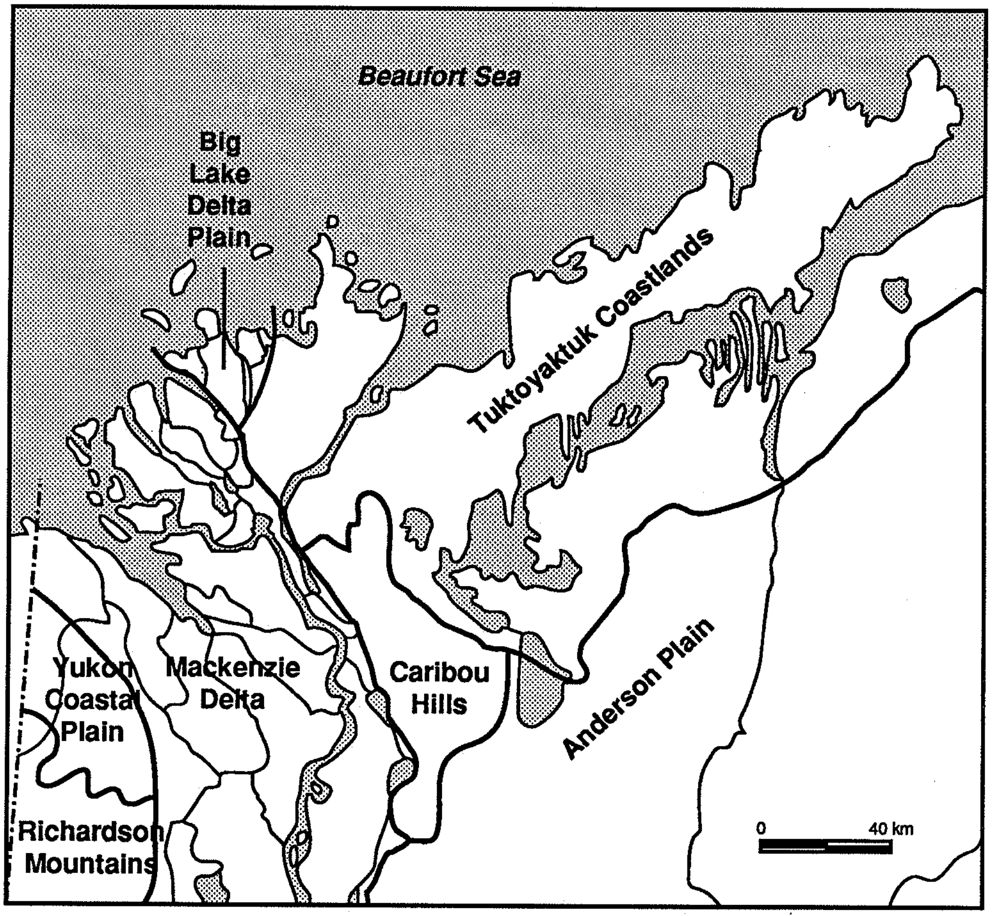
The research described in this report represents a continuation of regional geological investigations conducted in the Mackenzie Delta area over the past thirty years by the Terrain Sciences Division of the Geological Survey of Canada. The present study forms part of an A-base funded project directed by S.R. Dallimore investigating geological and geotechnical conditions of the Beaufort Sea coastal zone. Field work during the 1990 field season was funded largely by the Environmental Studies Research Fund as part of the project "Geoscience Issues Related to Gas Developments in the Mackenzie Delta Area". Field work during 1991 was funded by the Northern Oil and Gas Action Program through Renewable Resources and Environment, Indian and Northern Affairs Canada as part of Project A.20 "Water Management: Preparation for Mackenzie Valley Pipeline, Subproject A20-20 Survey of river channels on pipeline route to identify location of major ground ice".

2.0 PHYSIOGRAPHIC AND GEOLOGICAL SETTING

The Mackenzie River basin is the second largest basin in North America encompassing an area of 1,842,000 km^2 and draining 18% of the total land area of Canada (Lewis, 1988). The subaerial delta plain (modern delta) starts at Point Separation and extends to the Beaufort Sea, 210km downstream. The modern delta has developed in the low-lying Mackenzie trough bounded on the west by the Richardson Mountains and Yukon Coastal Plain and on the east by the Caribou Hills and the Tuktoyaktuk Coastlands (Figure 2). The Taglu site is located within the Big Lake Delta Plain physiographic sub-region while the Niglintgak site straddles this sub-region and the main Mackenzie Delta region to the west. While deltaic conditions dominate the low-lying areas in both regions, the main difference between the two is the presence of uplands comprised of older Pleistocene-aged sediments in the Big Lake Delta Plain region.

Both study sites are generally characterized by outer delta conditions undergoing continued adjustment under the constraints and limitations of sub-aerial growth through river dominance. The distributary channel network is anastomosing in form with no extensive inactive areas. Along channel meander sequences tend to be irregular with considerable variance in both wavelength and amplitude. Regular textbook sequences do occur but are not common (Mackay, 1963) because of the complex changes in flow due to channel branching and rejoining. This reflects the lower energy levels in the outer delta and hence, a tendency towards straighter channels and the need for more time to elapse before newer channels at the delta front can develop into a full meandering form (Lewis 1988).

Figure 2: PHYSIOGRAPHIC REGIONS OF THE OUTER DELTA



(Adapted from Rampton, 1988)

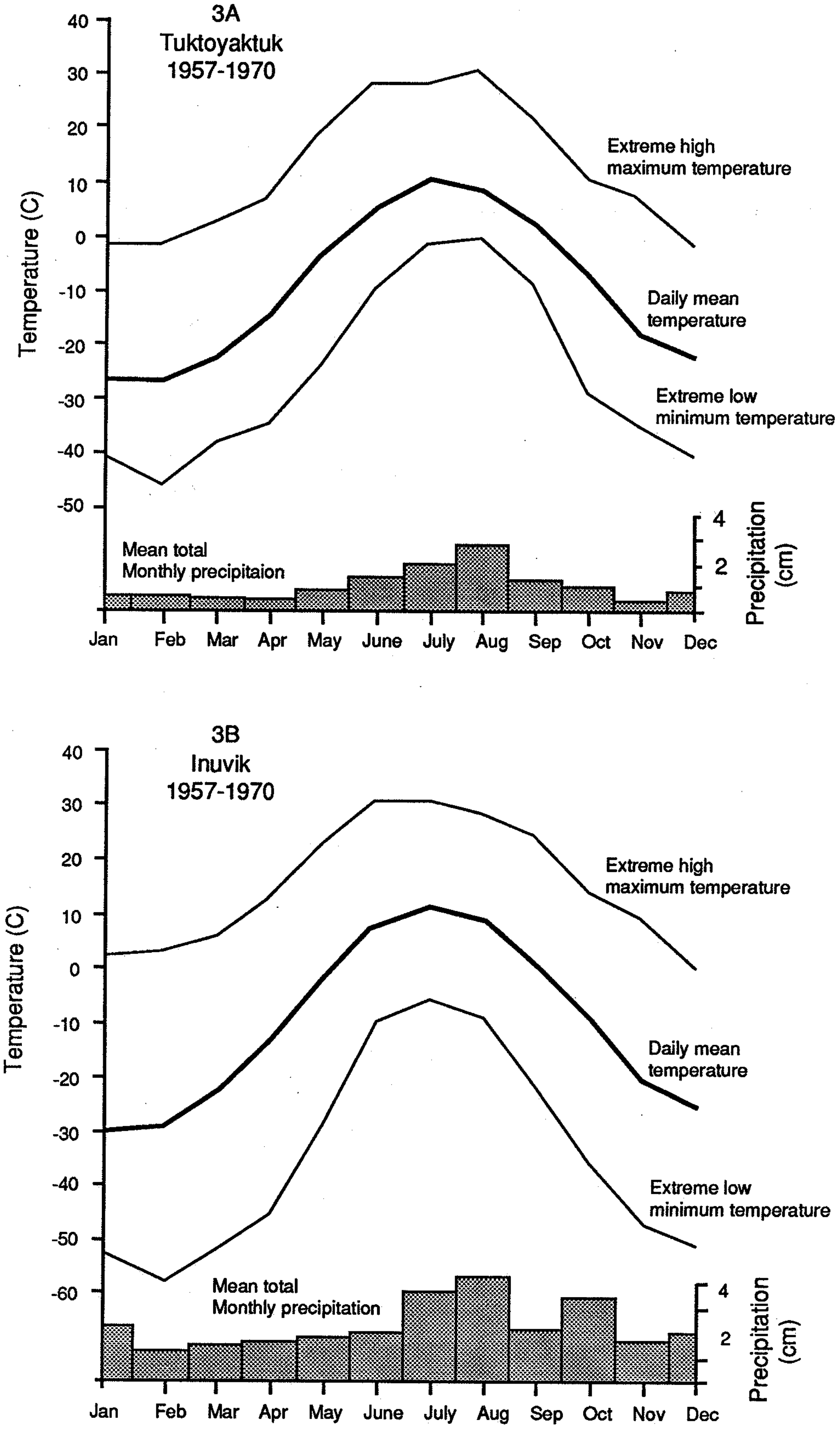
2.1 Climate

The modern Mackenzie Delta traverses the Arctic and Sub-Arctic climatic zones. The Big Lake Delta Plain is situated near the southern limit of the Arctic zone (Prowse and Ommanney, 1990). The Arctic classification refers to a region where the mean temperature for the warmest month is below 10°C and the mean annual temperature is below the freezing point. July temperatures between 5°C and 10°C further classify the Big Lake Delta Plain as "Low" Arctic. This climate is characterized by long winters (October to April) interrupted by short cool summers (Ritchie, 1984). Ice cover on the outer delta channels persists from early October to late May while cover on the Beaufort Sea begins to form several weeks later and persists to late June.

Temperature and precipitation data from Tuktoyaktuk, approximately 70km east of the Big Lake Delta Plain, typify the Low Arctic Coastal climate (Figure 3A). Daily mean temperatures peak in late June between 5°C and 10°C while winter months (December to April) attain daily mean temperatures below -20°C (Burns, 1973; 1974). Yearly precipitation totals are low although cyclonic activity in the summer accounts for a small peak in August. Snowfall, which mainly occurs in October, is often redistributed and compacted by wind (Rampton, 1988). Cloud and fog are also common along the coast in the summer (Burns, 1974).

Temperature and precipitation data recorded at Inuvik (80km to the southeast) characterize the northern limit of the Continental Subarctic climate (Figure 3B). Winters may be colder with stronger temperature inversions that occur along the coast (Rampton, 1988). The spring melt occurs earlier and proceeds more rapidly than along the coast as

Figure 3: CLIMATIC DATA FOR TUKTOYAKTUK AND INUVIK
(Adapted from Burns. 1973; Rampton, 1988)



spruce trees counter the albedo effect of snow (Ritchie, 1984).

2.2 Permafrost

The entire outer delta area is within the continuous permafrost zone. Permafrost thickness varies substantially between the two study sites in response to geological setting, presence of lakes and river channels and ground surface temperature regime. In the Big Lake Delta Plain physiographic region, relic permafrost is often preserved within the older Pleistocene sediments to a depth ranging from 200m to 600m of permafrost. In the Mackenzie Delta physiographic region, permafrost thicknesses are generally less than 100m. In both areas, if a river channel or lake deeper than 2m has persisted for more than a few decades, a thaw bulb or talik will be present beneath it. Depending on the size of these water bodies and duration of thawing, the taliks may extend through the permafrost body or be perched at the top of permafrost.

Mean annual ground surface temperatures in terrestrial areas are generally between -4°C and -7°C responding to microclimatic conditions such as vegetation and snow cover, standing water, elevation and proximity to the coast. Active layer thickness may vary from less than 50cm on fine grained ice-rich soils to more than 2m in areas close to sea level which are covered by water for much of the summer.

2.3 Hydrology

2.3.1 Flow Characteristics

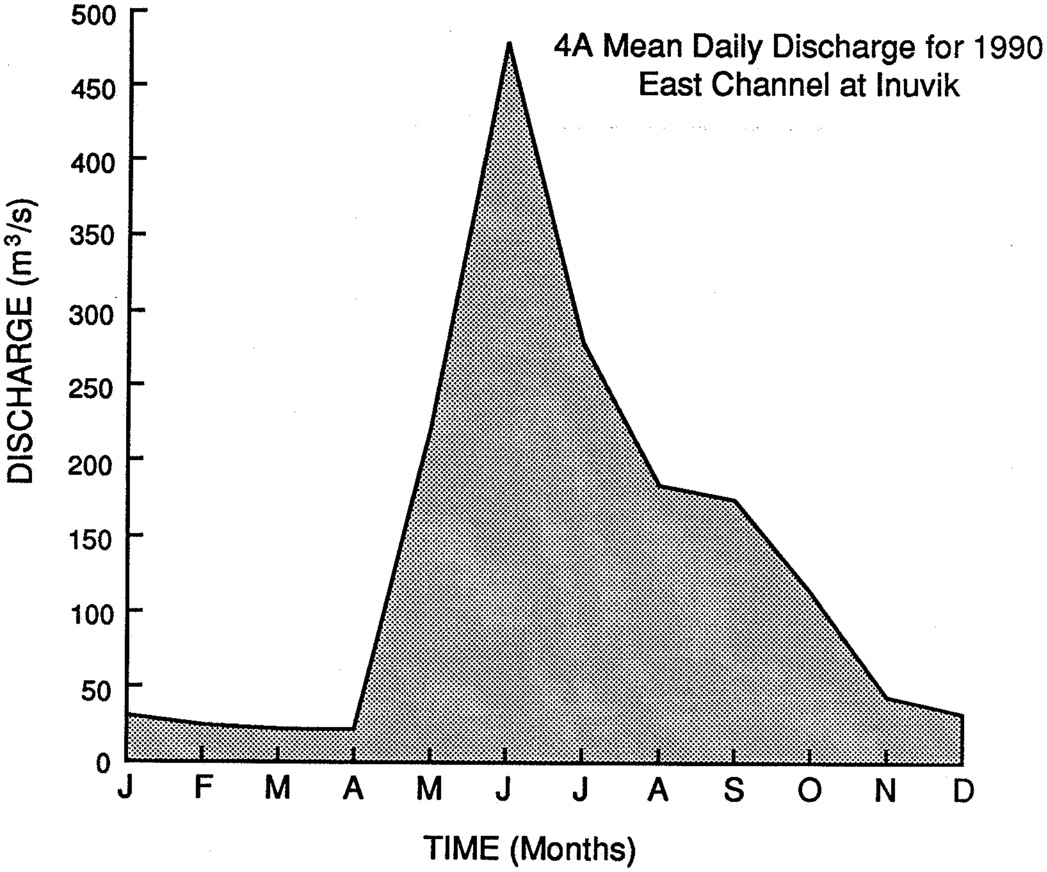
The Mackenzie River discharges at peak flows of approximately 28,000 m^3/s into the

Beaufort Sea and transports 200 million tonnes of sediment per year (Hollingshead and Rundquist, 1977). The distribution of flow through the delta has been studied by Anderson and Mackay (1973), Anderson and Anderson (1974), and NESCL (1976). The consensus, based on studies upstream of Tununuk, indicates that 20% of the flow follows East Channel through Kugmallit Bay; 30% follows Middle Channel (also referred to as Langley Island Channel); 20% follows North Reindeer Channel and 30% flows through Shallow Bay. These values represent an average and undoubtably vary seasonally; during the winter for example, East Channel accounts for 25-35% of the flow through the delta (Anderson & Anderson, 1974). Current research projects directed by Environment Canada should aid in achieving a better resolution of hydrological data near the outer delta (J. Jasper, pers. comm., 1991).

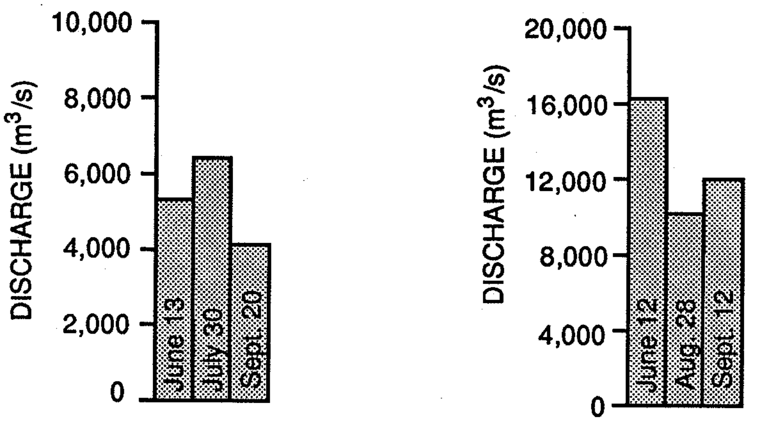
The seasonal flow pattern of the Mackenzie River is characteristic of a "nival" runoff regime (Church, 1974) in which the spring break-up flood is usually the dominant hydrologic event (Figure 4A). The peak water level of the Mackenzie River occurs on June 3 on average, with a standard deviation of only 4 days. The spring break-up is always larger than the summer peak, with average mean water levels of 5.6m asl and 2.8m asl for East Channel at Inuvik, respectively (Marsh and Hey, 1989). Miscellaneous measurements of daily discharge for Middle Channel show a summer average of 5,000 m^3/s with a July peak of 6,420 m^3/s (Figure 4B). Analysis of Slaney's (1975) data for the Niglintgak site show a discharge rate of 4,700 m^3/s in late July which appears consistent with the above data.

Arnborg et al. (1966 and 1967) define four seasonal flow regimes for the Colville River delta on the Alaskan Beaufort Sea coast. These were outlined as: winter, where sub-

Figure 4: DISCHARGE PATTERNS IN THE OUTER DELTA



4B Miscellaneous Daily Discharges for 1991



Middle Channel
near Langley Island

Middle Channel
near Raymond Channel

Note: Data provided by Water Survey of Canada, Inuvik, NWT.

ice flow is limited under the ice or absent; spring, characterized by peak flows during the spring break-up; summer, which is dominated by declining water flows and frequent storm surges; fall, where continuing low stage levels lead into freeze-up.

Lewis (1988) suggests that these regimes can also be used to describe the Mackenzie system. The flow regimes have been discussed in general for the Mackenzie Delta and its tributaries (Mackay and Mackay, 1973; Kerfoot, 1975; Anderson, 1982; Parkinson, 1982; Lewis, 1988; Marsh and Hey, 1989; and Prowse, 1989) therefore, each period will be discussed in the context of the study sites described in the following chapters.

2.3.2 Bank Stability

Bank stability research in permafrost regions has focused on the thermal and mechanical erosion of bluffs through undercutting, a process called thermoerosional niching (Walker, 1969; Outhet, 1974; Are, 1977; and Scott,1978). Generally, permafrost and streambank erosion studies have initiated a wide diversity of opinion. McDonald and Lewis (1973) believe that permafrost retards erosion over short time spans. In contrast, Walker and Arnborg (1966) and Ritchie and Walker (1974) emphasize the role of permafrost in promoting erosion by lateral undercutting, particularly during spring break-up of the Colville River in northern Alaska. Most research details erosive activity on the base of bluffs at specific localities. Few observations have been made to document the variability in erosion by hydraulic conditions and wave action along a reach (Lawson, 1983).

Lawson (1983) separates streambank erosion into two components, the bluff zone (thermoerosional niching) and the bank zone (thermoabrasion). The bluff zone refers to the upper section of the streambank exposed to the air, while the bank zone is the lower submerged section. Fluctuating water levels necessitate the addition of a transitional zone between these two zones. The streambanks of the outer delta alluvial plain rarely exceed 1.5m, resulting in the domination of bank zone erosion (Plate 1). Mackay (1963) identifies Richards Island as an area of extensive channel shifting. In this study, an attempt is made to link the erosional variability along the study reaches with thermoabrasion of the bank zone.

2.3.3 Channel Morphology

The subaerial Mackenzie delta plain has developed an anastomosing network of channels. Mackay (1963) highlights a number of channel characteristic of an anastomosing system. Distributary channels, typically, diminish in water volume in the outer delta as smaller channels branch off the main channel (Middle Channel for example). The remaining channel types represent ancillary channels within the anastomosing system. *Network channels* link the main distributary and tributary channel systems. These channels rarely meander, in a geomorphic sense, although they may be sinuous with meander-like bends. *Lake channels* interconnect lakes with other types of channels or lakes. Lake channels may reverse as water flows into the lakes at high water levels and out again at low water levels. These reversals commonly occur during break-up but can also take place during heavy precipitations and storm surges. In contrast, *reversing channels* (Aklak Channel for example) have a frequent and sufficiently strong discharge from two independent channel systems to reverse flow during discharge irregularities. Flow reversals in this channel type occur frequently during

Plate 1: BANK STABILITY

Extensive bank calving dominates the southern tip of Niglintgak Island.

summer months in response to only minor variations in water levels.

Cross-sections of the various channel types differ, and do not necessarily mirror classical symmetrical or asymmetrical forms. Some channels show an inner channel inset within the main channel (Mackay, 1963; Cooper and Hollingshead, 1973), while others with reversing flow have a more uniform cross-section, typically u-shaped. In addition, extensive shoal benches have been described by Mackay (1963), Lapointe (1984) and others. Despite their prominence, a study has never been done to demonstrate their formation and evolution. They remain, however, significant morphological features for ice partially or completely covers the entire width of shoal benches less than 2m deep, forming bottom-fast ice. This process promotes the growth of permafrost within the channel margins, creating an additional factor in the development of channel profiles.

2.3.4 Ice Conditions

Ice coverage is variable depending on winter temperatures, the depth of water and amount of insulating snow cover in the channels. Ice thicknesses along the outer delta channels range between 1m to 1.8m (Slaney, 1975) and are generally higher than those to the southwest (Anderson and Mackay, 1973). Channels typically freeze to the bottom at any shallow points (approximately 1.5m to 2m) restricting some or all water passage. Slaney (1974) noted that flow in relatively large outer delta distributaries like Middle Channel may cease completely with the growth of ice in winter, particularly downstream of Kumak Channel. Linking channels, reversing channels and lake streams are especially susceptible to bottom-fast ice (Slaney, 1975). Generally, any water on the shoals becomes bottom-fast with the flow limited to the thalweg zone. The ice itself is sediment free and cloudy to clear. The ice surface is generally smooth and regular (few cracks), indicating little shearing or heaving during its formation.

Ice jams are an important phenomena as flooding behind the jams, as well as the passage of ice, can create hazardous conditions for structures located on channel banks. Jams can also cause flow restrictions creating atypical scour zones. On the Mackenzie River, the ice jams vary according to flood levels (Mackay & Mackay, 1973). In high water years, ice jams are of greater size but fewer in number. Miscellaneous records indicate that ice jamming in the delta occurs most frequently at channel junctions, sharp bends, and shallow sections (Kerfoot, 1975). Except for a brief airborne observation survey by Slaney (1974, 1975), few reports exist on outer delta ice conditions, so the extent of potential problems there is largely unknown.

2.4 Methods Employed in Current Research

Data collection involved an office and a field component. An extensive literature search was conducted in order to compile a listing of relevant documents and data. Time-lapse air photo studies and the resurveying of channel cross-sections provided the framework for the analysis in this report. Cross-sections at new locations within the study areas augmented previous surveys and provided greater resolution on the downstream variability in channel form.

Air photos from 1950, 1985 and a SPOT satellite image from 1991 were interpreted for planform changes including levees, chutes, channels, lakes and any other relevant morphological features. Shoals and sub-aerial bars were also noted, along with the location of all historical cross-section surveys. The 1985 air photos were photographed in August but no date is given for the 1950 photos, although they were taken in the summer.

To determine the bank stability of the area, the rates of bank erosion and accumulation were estimated by a comparison of air photographic coverage from 1950 and 1985. Enlargement of the air photos using an air photo image projector facilitated the measurement of bank margin changes with lakes providing a standard reference point. Bank margins were defined as the water/land interface at the time of photography. Given fluctuating water levels and extensive shoals on point bars, these margins represented an approximation.

Cross-sections for the 1991 field program were recorded using an Eagle Mach I sounder mounted in a Zodiac. A Zodiac equipped with a transducer and the sounder provided the most efficient means of traversing the wide, shallow channels of the outer delta. In the 1990 survey, a Raytheon subbottom profiling device with a 20 mHz and 30 mHz transducer was also utilized. At the Niglintgak site in 1990, an electronic theodolite was used to survey bank margins, transect sites and water elevations from bench marks established by industry. Markers positioned on each bank enabled the boat to maintain a perpendicular route between each bank as it crossed the channel. Accurate field measurement of horizontal distances could not be ascertained at all locations in the field so air photos and maps were used.

The selection of cross-section locations was based on a need to provide a complete framework of data on the reaches to be analyzed. As such, 14 cross-sections were resurveyed, while 33 new sites were selected to complement the historical data and create a more representative spacing of cross-sections. Although no markers were set in place by Slaney (1975), numerous landscape features were identified on maps and air photos to ensure an accurate positioning of comparative cross-sections. At least two traverses were recorded at each cross-section in the 1990 and 1991 G.S.C. field program for completeness.

All channel cross-sections were replotted into a standardized format for use in the report. Vertical control for these studies is estimated to be only ±0.3 due to uncertainties of datums from the industry surveys and variations in water levels between 1990 and 1991. During the 1991 field program, the water level fluctuated 50cm over a two month period (July and August). Where comparative cross-sections were superimposed onto the same scale, the profiles were adjusted to incorporate bank retreat rates researched for each site. Each profile also displays a shaded box representing an average ice thickness of 1.8 m, typical of this region (Slaney, 1974). Since all cross-sections were recorded at midsummer levels, they display minimum level of ice cover as the lowest water levels generally occur at the time of freeze-up.

Descriptions of the associated bank morphology were also recorded along with associated sediment type and vegetation. Where exposed, bank sediments were analyzed for ice lenses or wedges. A frost probe was used to measure the depth to the active layer, providing some data on the relationship between the channel and ice bonded sediments in the bank margins.

3.0 TAGLU SITE

An important element in understanding the hydrology of the Taglu site is delineating the drainage systems contributing to the flow (Figure 5). Harry Channel carries the flow into the Taglu Island area from the south and bifurcates into two channels separated by the island containing Big Lake. The western branch, Kuluarpak Channel, flows as a single channel northward to Mackenzie Bay with no additional tributaries. Harry Channel, the eastern branch, changes to a multi-channel morphology at Big Horn Point and back to a single channel before entering Mackenzie Bay. Harry Channel, downstream of G-33, receives contributions from two distinct drainage basins. The first basin encompasses Fish Island and interconnecting lakes to the east with contributions as far southeast as Pullen Lake (18km SE). This drainage basin flows into Harry Channel at Big Horn Point. The second basin joins Harry Channel via a lake channel extending from the Denis Lagoon drainage basin to the east.

3.1 Landforms and Associated Sediments

The Mackenzie Delta alluvial plain dominates the Taglu Site with isolated Pleistocene uplands providing local relief (Figure 6). The low-lying alluvial plain is frequently inundated during spring thaw and periodic storm surges contribute sediment (mainly silt) to low-lying areas. In many areas, standing water remains during most of the summer. Low-centred polygons are a common feature of the alluvial plain. Other geomorphic features identified in the Taglu site, include abandoned channels and features related to channel migration, such as ridge and swale topography. Levees can be discerned

Figure 5: TAGLU SITE

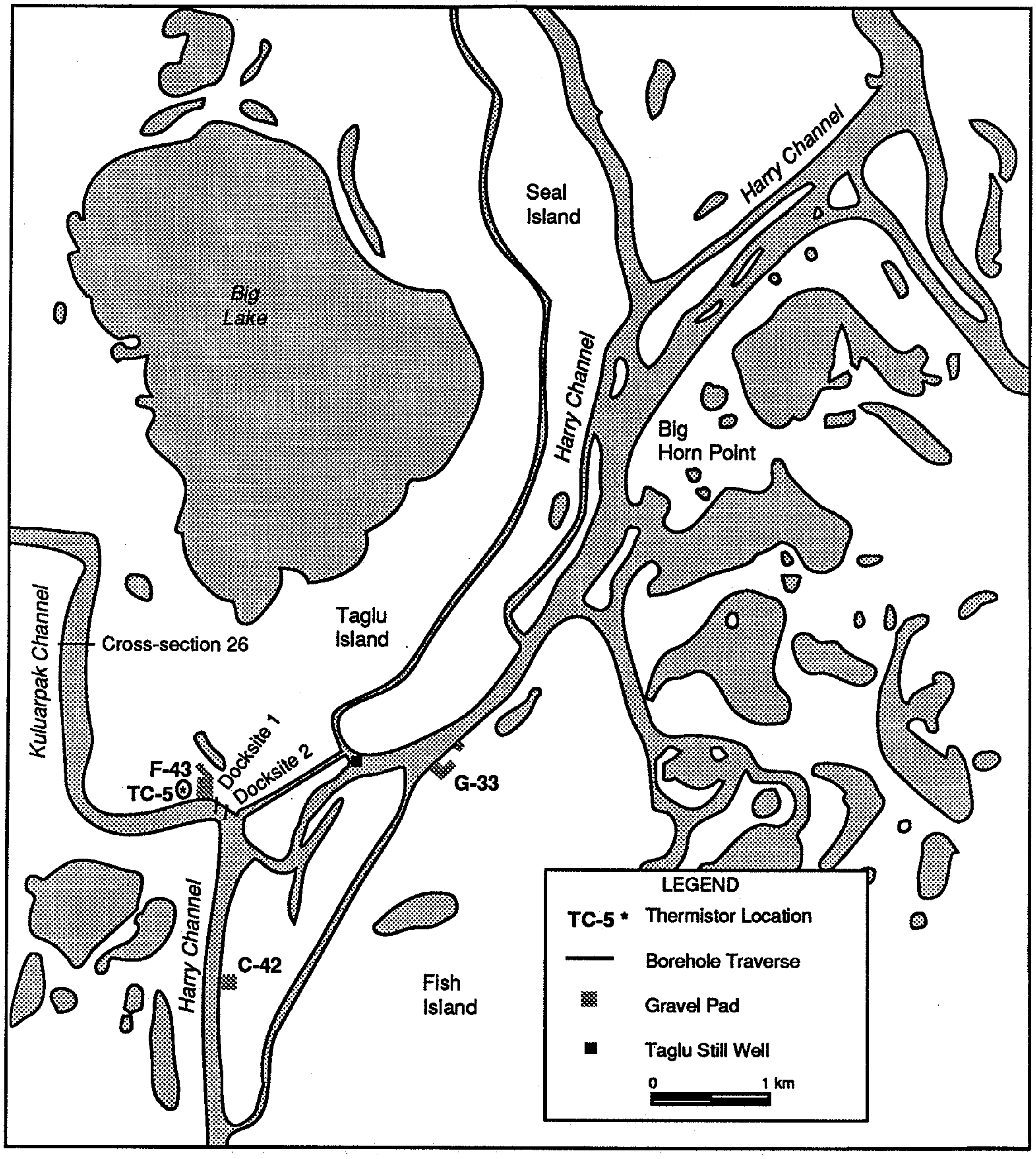
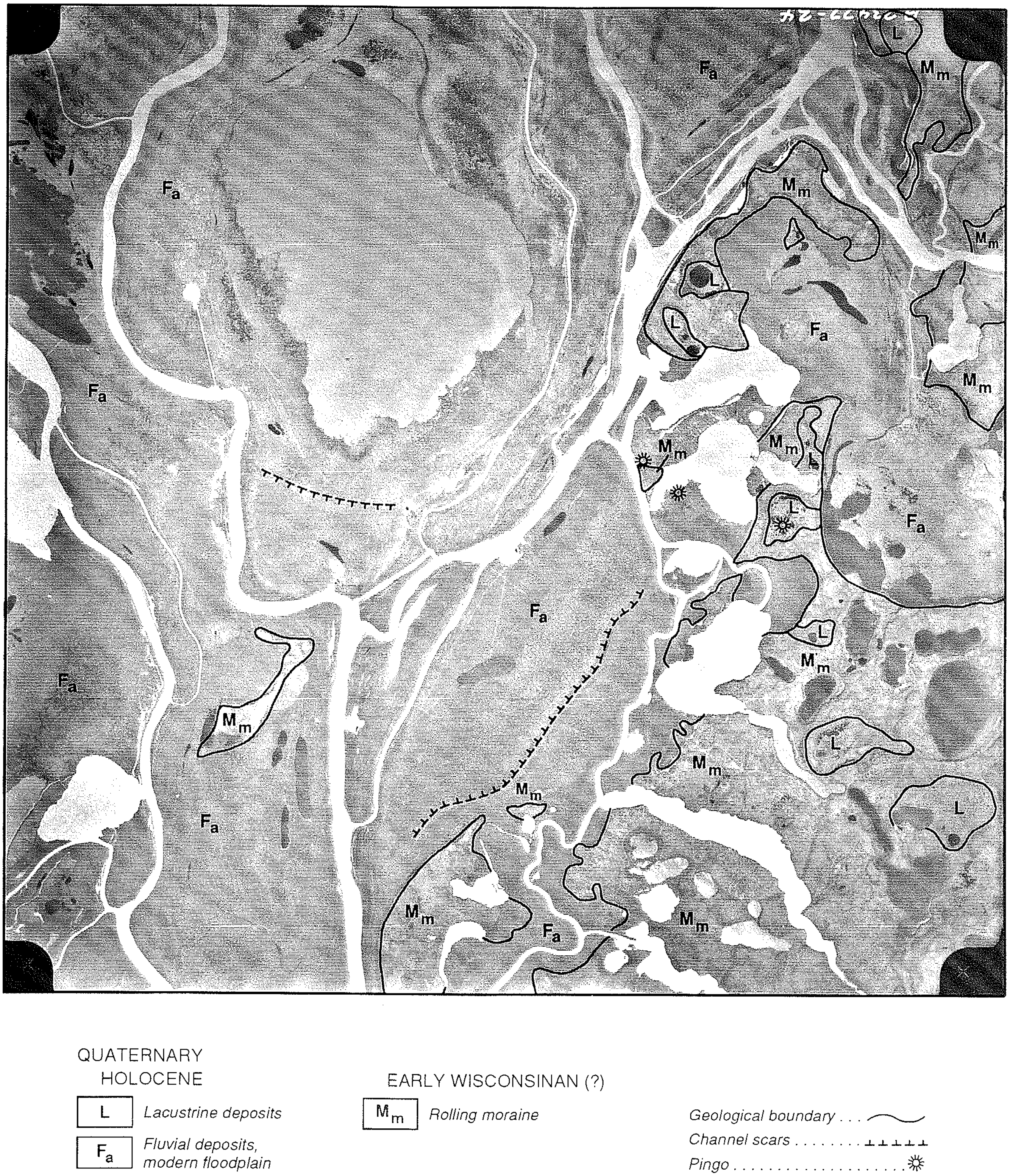


Figure 6: SURFICIAL GEOLOGY OF THE TAGLU ISLAND AREA



along the channel edges but this principally has to be done by field survey as low relief and willows make air photo identification difficult. Broad bars of low relief, replace the usual well-defined distributary levees at the delta front because of wide dispersal of the fine sediment load (Lewis, 1988).

The other dominant landform feature is the Pleistocene uplands which rising up to 30m asl. The uplands are comprised primarily of Pleistocene-aged glacial moraine and glaciofluvial outwash. The moraine is typically a silt-rich diamicton, forming a thin irregular cover over the outwash sands and gravels. Thermokarst processes have been active in many areas resulting in indented lacustrine basins and re-working of the diamicton by solifluction and retrogressive thaw flow slides. Where the upland areas intersect the deltaic floodplain, a gravel-lag beach generally is formed.

Big Horn Point forms the most prominent Pleistocene upland in the vicinity of the Taglu site. Exposures in this area indicate a 3m to 5m thick cover of moraine, over 10m to 15m of glaciofluvial sand and gravel. The moraine is often ice-rich with 10 to 50 percent excess ice (ice in excess of pore space). Four active retrogressive thaw flow slides were active in 1991 in the Big Horn Point area along the eastern edge of Harry Channel. Additional remnant scars, visible on aerial photographs, suggest that this process has been active episodically between 1950 and 1991.

The main consequence of the Pleistocene deposits in terms of fluvial geology is the contribution of a coarse sand and gravel fraction to the bed load of Harry Channel. The outwash sands and gravels are also relatively resistant to erosion and thus, tend to limit channel migration and channel deepening. In contrast, the ice-rich moraine may undergo relatively rapid erosion, as a result of undercutting and destabilization initiating flow slide activity.

3.2 Geotechnical Conditions

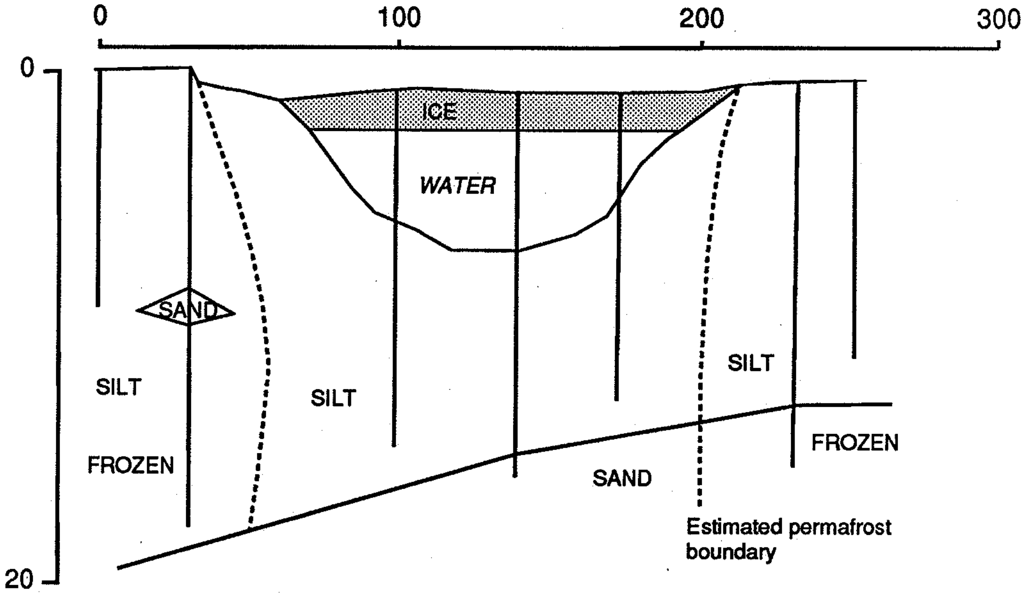
Geotechnical studies in the outer delta have mainly been conducted in relation to the potential development of production sites, drill pads and pipeline corridors. As such, EBA (1974) reports on shallow borehole data in the Taglu area at proposed pipeline crossings and docksites. The borehole data was obtained at cross-section 26 and at two potential docksites adjacent to Taglu D-43 (see figure 5 for locations). Generally, the stratigraphy is interpreted as consisting of deltaic silt over very fine-grained deltaic sand. In terrestrial areas where permafrost is present, ice contents in the upper 6m ranged between 20-50% primarily in the form of thin lenses of segregated ice (Figure 7)

The data collected in the vicinity of cross-section 26 indicates that the bank materials are basically a thin layer of peat (likely organic silt), up to 0.60m thick, overlying approximately 14m of deltaic silt followed by very fine deltaic silty sand (Figure 7A). A thin sand lens was also noted in borehole XA1-6 from 8.2m to 9.8m. Although the lower permafrost boundary was not encountered in any of the boreholes beneath the channel, it is assumed to descend steeply from each of the banks as no lateral movement of the river is evident for the past 35 years. The bed material consists of a 9.1m dark grey silt with clay traces underlain by dark grey fine sand.

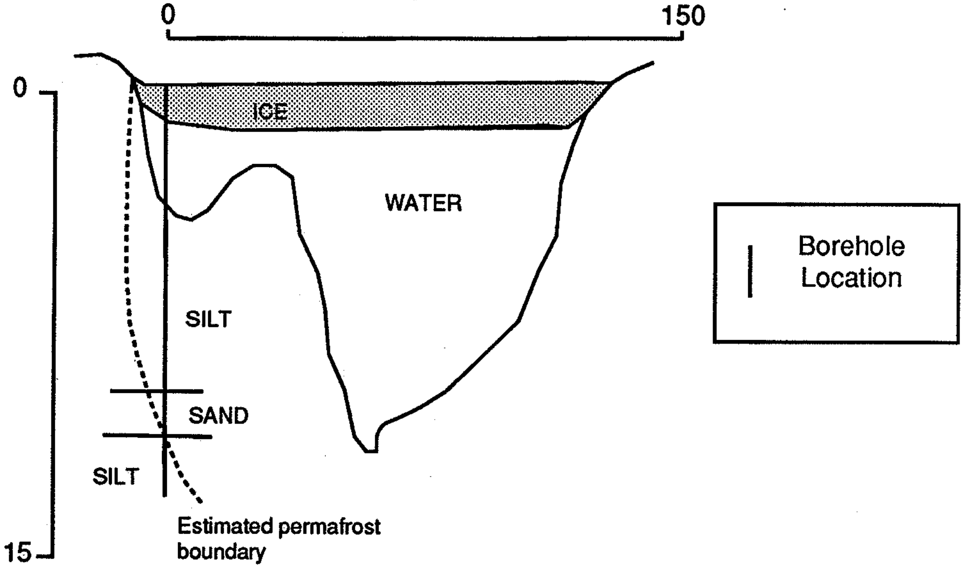
Bank and near shore conditions were investigated for two potential docksites; docksite 1 (Figure 7B) located at cross-section 20 and docksite 2 (Figure 7C) just upstream

Figure 7: BOREHOLE TRAVERSES - HARRY and KULUARPAK CHANNELS

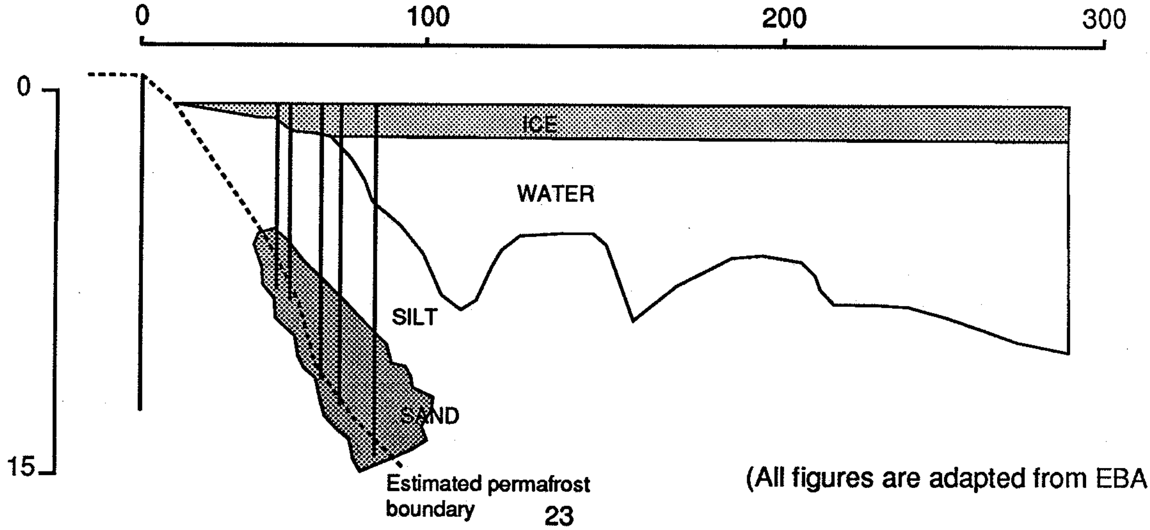
7A - CROSS-SECTION 26



7B - DOCKSITE 1



7C - DOCKSITE 2



(All figures are adapted from EBA, 1974) of cross-section 20 near the start of Kuluarpak channel. The docksite 1 borehole contains 10.4m of grey silt underlain by 1.5m of sand followed by another silt unit (Figure 7C). A permafrost boundary is encountered at a depth of 11.3 m. The permafrost table appears to be relatively steep at this location. This is expected as the location is further around the bend where the rate of bank erosion is not as rapid.

Ground temperature measurements (courtesy L.D. Dyke, GSC) on the bank in the vicinity of Docksite 1 at F-43, show mean annual ground surface temperatures in vegetated areas are approximately -2°C to -3°C (Figure 8). Active layer thicknesses in this area and others in the vicinity of Harry Channel are generally about 0.8 to 1.0 m.

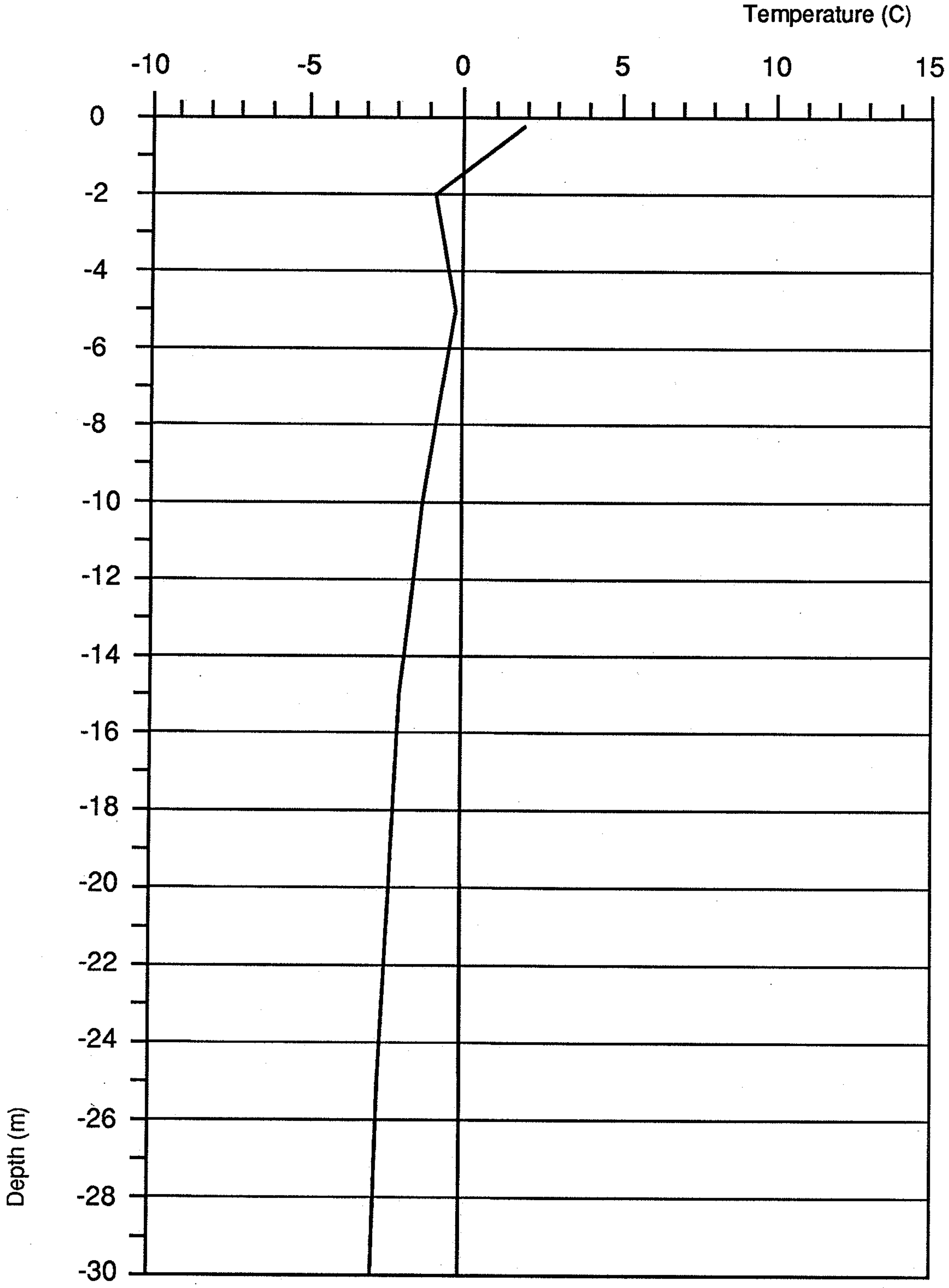
At docksite 2, approximately 6m of dark grey silt overlies an unknown thickness of dark grey silty sand and silt. At this site, the top of permafrost extends out beneath the channel responding to the effects of the shoal where ice is bottom-fast in the winter.

3.3 Vegetation

The low alluvial islands of the outer delta support a number of vegetation species in what is characterized as a treeless tundra (Lambert, 1972; Ritchie, 1984). Vegetation varies according to the physiographic area and local variations. In this study, vegetation has been delineated by mapping units defined in terms of vegetation grouping, species composition, and landform association (Figure 9).

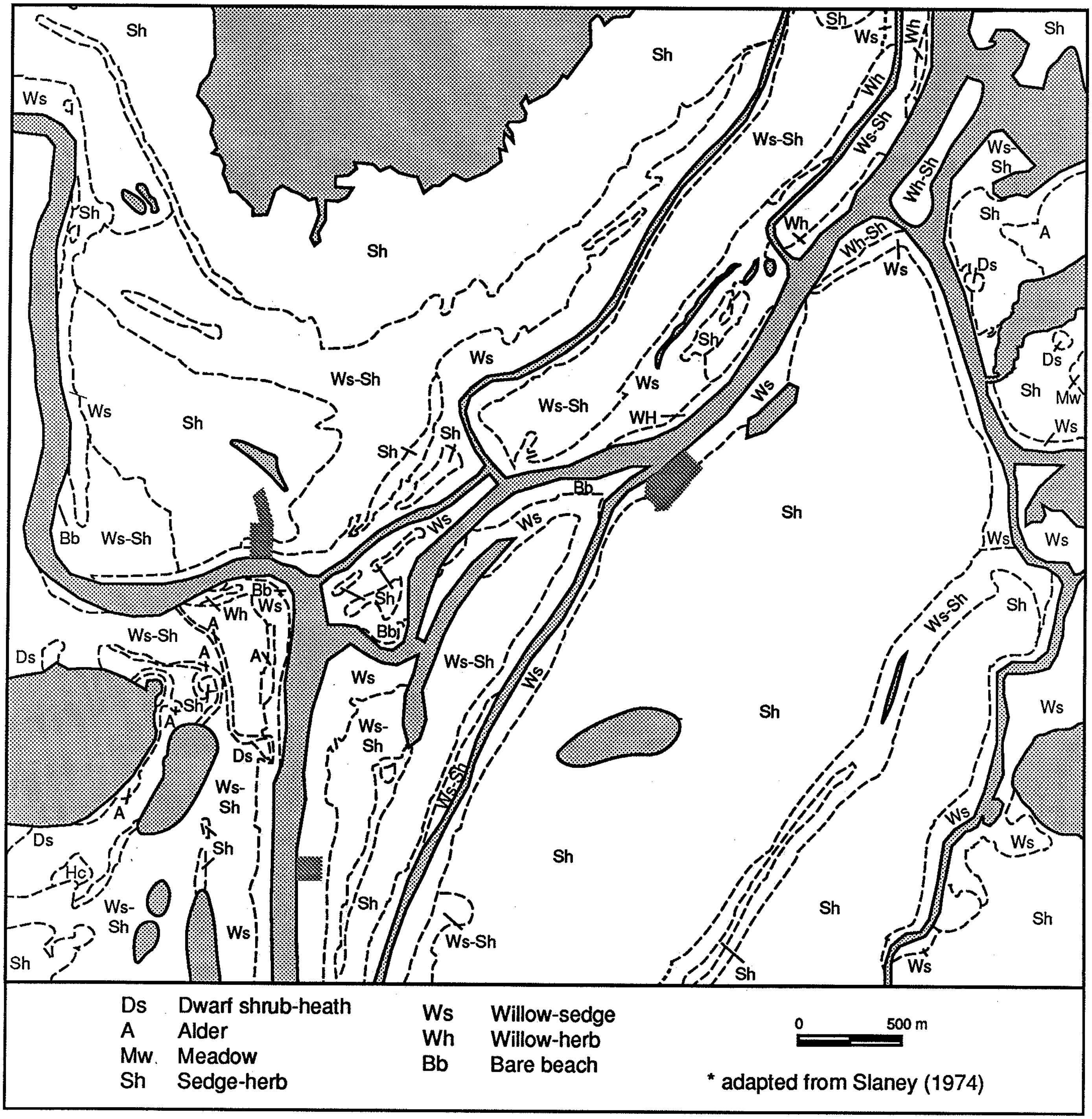
The major vegetation groups can be broken down into two basic units, alluvial plain and Pleistocene Uplands. The alluvial plain includes sedge herb (Sh), willow-sedge (Ws) and willow-herb (Wh). The Pleistocene uplands are vegetated with dwarf shrub-heath (Ds),

Figure 8: GROUND TEMPERATURE DATA
TC-5



(Data courtesy of L.D. Dyke)

Figure 9: VEGETATION DISTRIBUTION
TAGLU SITE



* adapted from Slaney (1974)

alder (A) and meadow (Mw) vegetation.

The distribution of vegetation in the study area is dominated by drainage. Drainage is determined zonally by the texture of the surface material and locally by topography. Microtopography becomes important in areas with impeded drainage. Hence, vegetation on polygon rims can be vastly different from vegetation on the centres although there is a relief of only a few inches (Slaney, 1974).

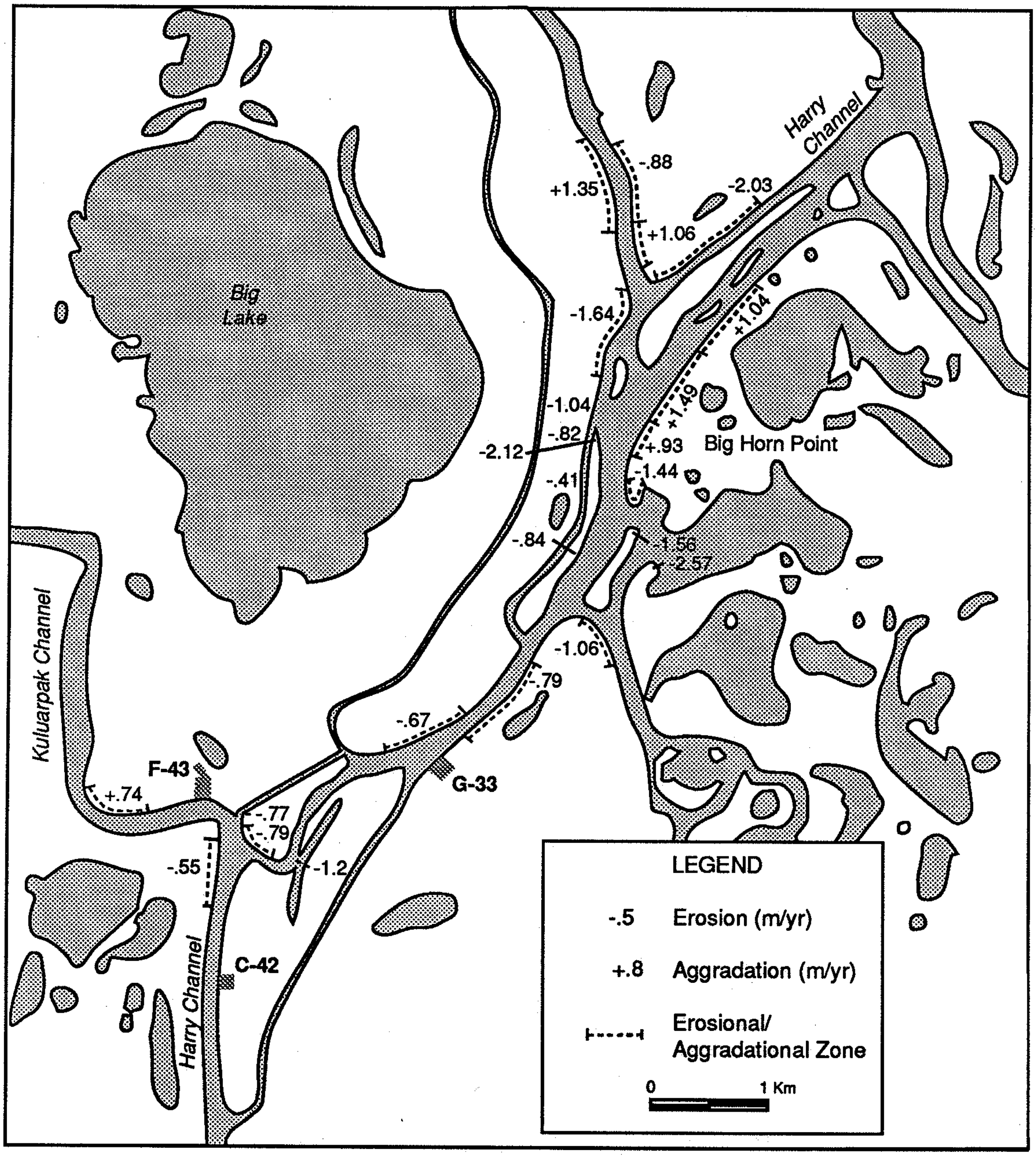
3.4 Bank Stability

The bank stability analysis at the Taglu Site highlights the channel morphology change from single channel to multi-channel along Harry Channel, the result of the emergence of numerous mid-channel bars (Figure 10). Harry Channel upstream of the Harry/Kuluarpak bifurcation and meander bends immediately downstream, displays localized erosion along the outer bends. The abrupt-angle bend of Harry Channel at the Harry/Kuluarpak Channel bifurcation averages 0.79m/yr of erosion over 35 years along the outer bend.

The first meander bend, downstream of the bifurcation along Harry Channel, has retreated to the extent that it has breached the outer bank into a small, linear lake (1.2m/yr). This break occurred sometime between the 1973 and 1985 air photo coverage. Minor zones of retreat are noted on the left and right banks of Harry Channel at Taglu G-33 with erosion rates of 0.67m/yr and 0.79m/yr, respectively.

In an earlier bank retreat study of the outer delta channels by Lapointe (1986), similar erosional zones are identified yet Lapointe reports slightly higher erosional values

Figure 10: BANK STABILITY FROM 1950 TO 1985
TAGLU SITE



(Note: Where a zone is identified, the associated value represents an average value.)

over a shorter period of time (1950-1981). Given Lapointes 0.2m/yr accuracy range, water levels and time differences, the values are essentially similar.

Harry Channel towards Big Horn Point is characterized by rapidly coalescing mid-channel bars and variable retreat rates on the outer banks. Pleistocene uplands dominate the Big Horn Point area itself, preventing any movement of Harry Channel eastward. With the exception of the south tip of Big Horn Point which is retreating at a rate of 1.44m/yr, the east shore of the channel in this area is aggrading at rates between 1 and 1.49m/yr. The channel itself changes just upstream of Big Horn Point, instead of the single channel morphology exhibited upstream, it changes into a multi-channel form with mid-channel bars. The mid-channel bars play a key role in directing flow through the area. The rates of change of the midchannel bars are high, significant migration was noted, for instance, between the 1990 to 1991 field observations. This type of instability is indicative of a shallow, low energy environment.

3.5 Channel Morphology

Channels in the Taglu site were characterized through the systematic study of channel cross-sections (Figure 11). Three reaches are described; Harry Channel, upstream of the Kuluarpak Channel bifurcation, Harry Channel, downstream of the bifurcation and Kuluarpak Channel.

Three cross-sections (1, 2 and 3) describe the channel morphology upstream of the Harry/Kuluarpak Channel bifurcation (Figure 12). All three profiles exhibit a symmetrical form but vary in depth and channel bed topography. Cross-section 2 shows an approximate

Figure 11: CROSS-SECTION LOCATIONS
TAGLU SITE

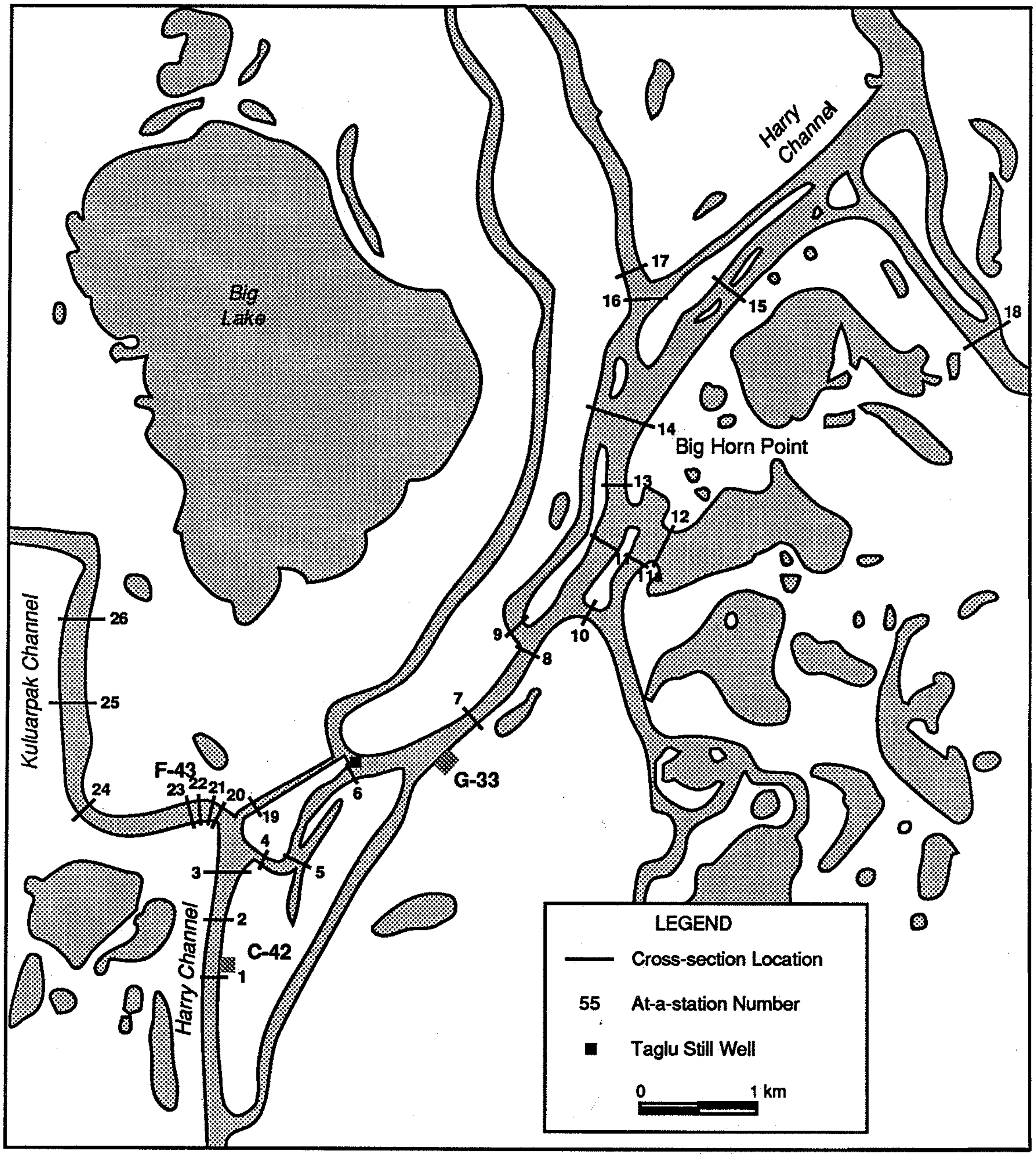
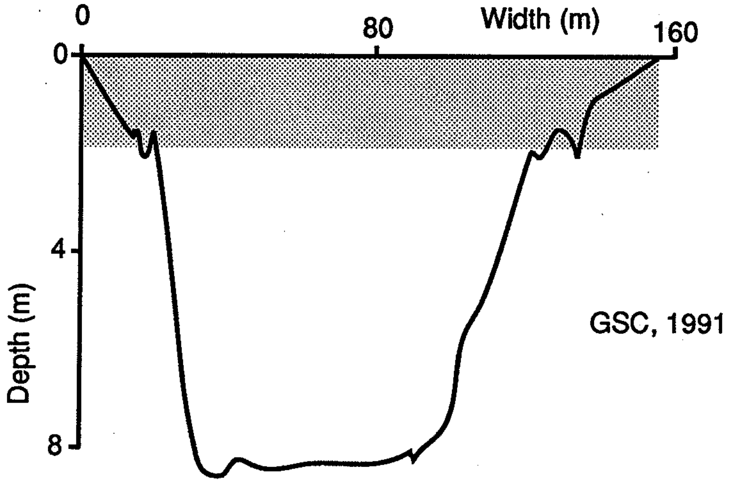
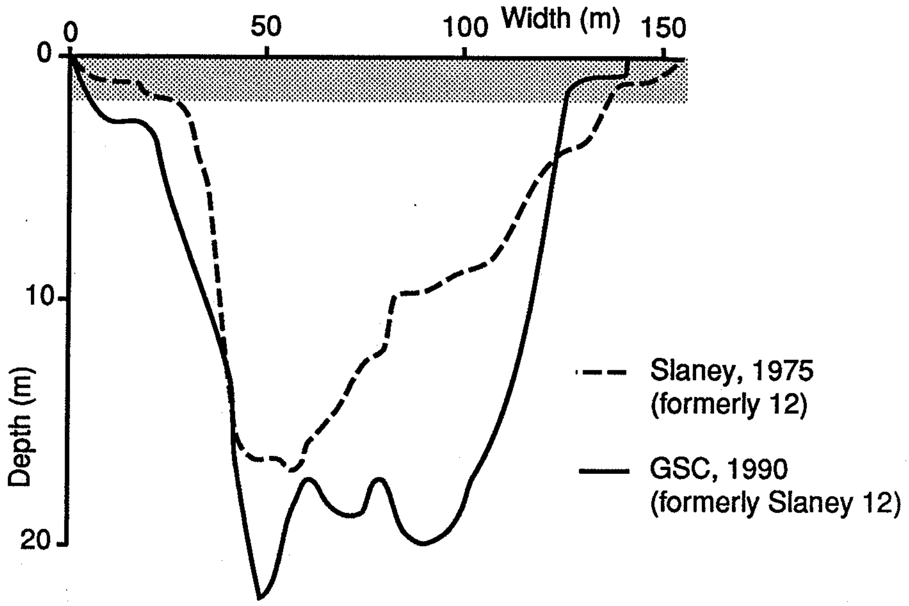


Figure 12: CROSS-SECTIONS 1, 2, AND 3

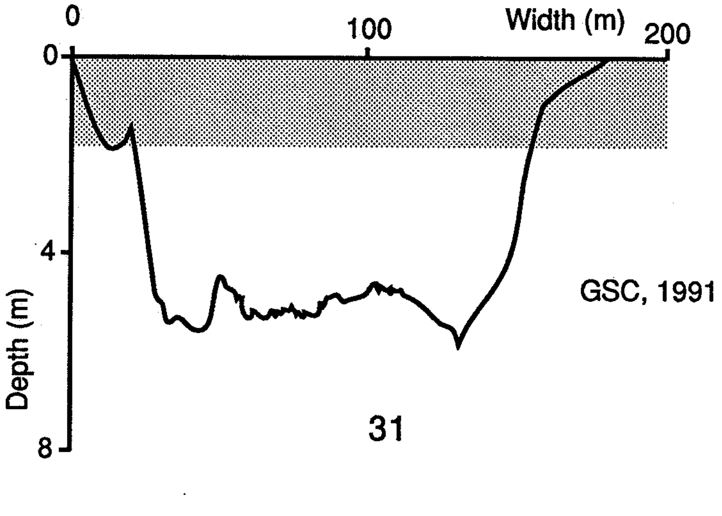
CROSS-SECTION 1 - Harry Channel



CROSS-SECTION 2 - Harry Channel



CROSS-SECTION 3 - Harry Channel



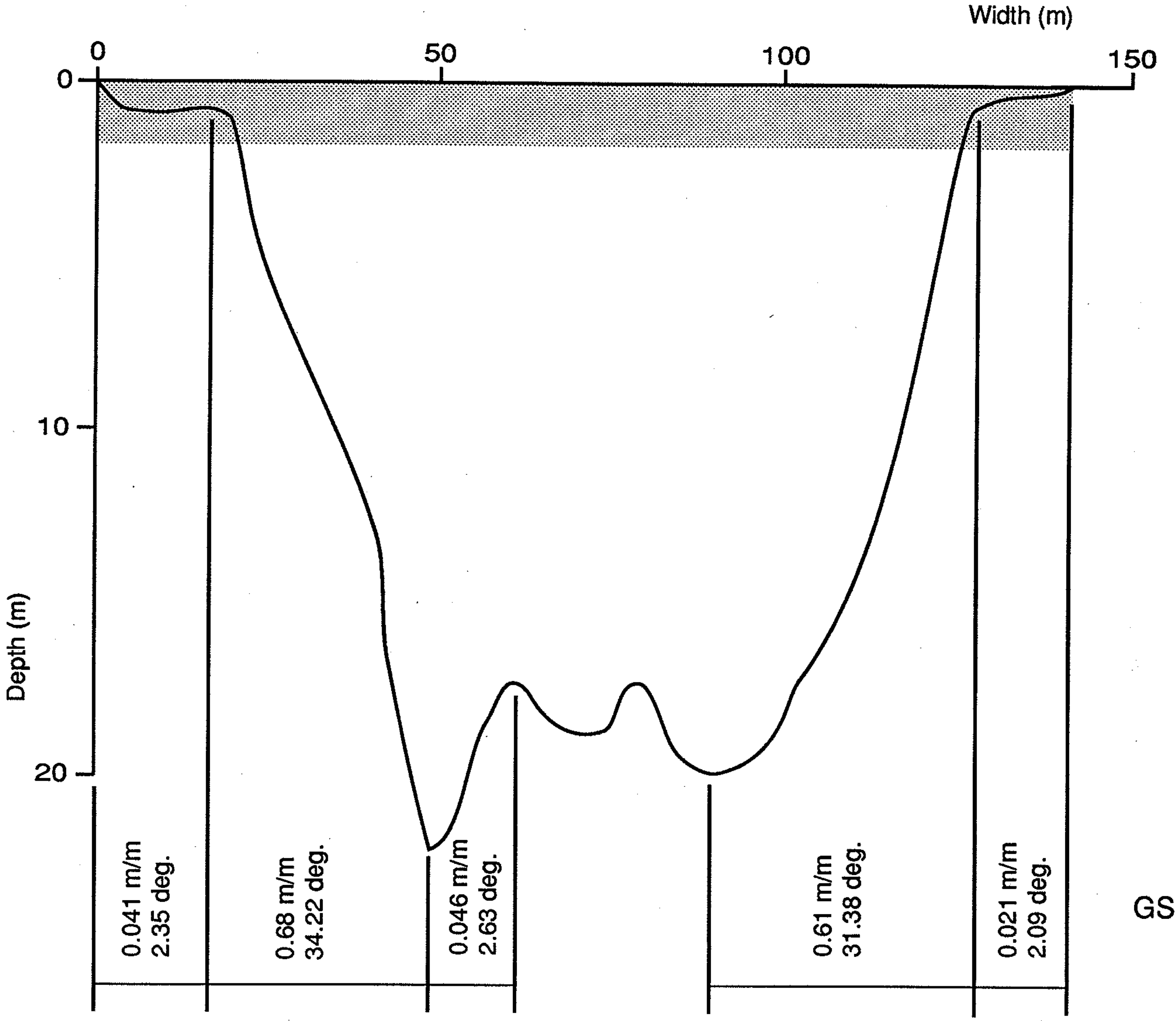
deepening of 4.8m between 1975 and 1990. This value is significant when compared to the 8 and 6m maximum depths recorded on the profiles upstream and downstream, respectively. This suggests an active scour zone at cross-section 2 which presents an interesting anomaly. There is no evidence of channel bank enlargement but the subaqueous channel sides have enlarged significantly.

The slope values for the channel sides at cross-section 2 are presented in Figure 13. The left channel side shows a maximum slope of 34° while the right side is 31°. These values are extremely high for a low gradient delta setting, although Hollingshead and Rundquist (1978) note a 45° slope in a profile on Kumak Channel.

At F-43, Kuluarpak Channel branches off Harry Channel flowing westward around Taglu Island. Cross-sections 21 and 23 illustrate the channel profile along the initial bend of Kuluarpak Channel (Figure 14). Comparative cross-sections at 21 illustrate an aggradation of 2.8m of the channel bed, creating a symmetrical form having a maximum depth of 12.1m. With the exception of a 12m shoal on the left bank, the thalweg zone spans the entire channel width eroding a 23m shoal previously recorded on the right bank. The slope values for cross-section 21 illustrate the symmetrical form with values of 16° (left) and 13° (right).

Cross-section 23 also displays a shallowing (1.1m) and an enlargement of the thalweg zone. A deep thalweg (11.1m) still prevails despite aggradation of the left bank. A 2m mound along the right bank margin, has been eroded to form an underwater bench, 6.8m deep. The development of the channel profile at cross-section 23 indicates a change in morphology to a symmetrical form.

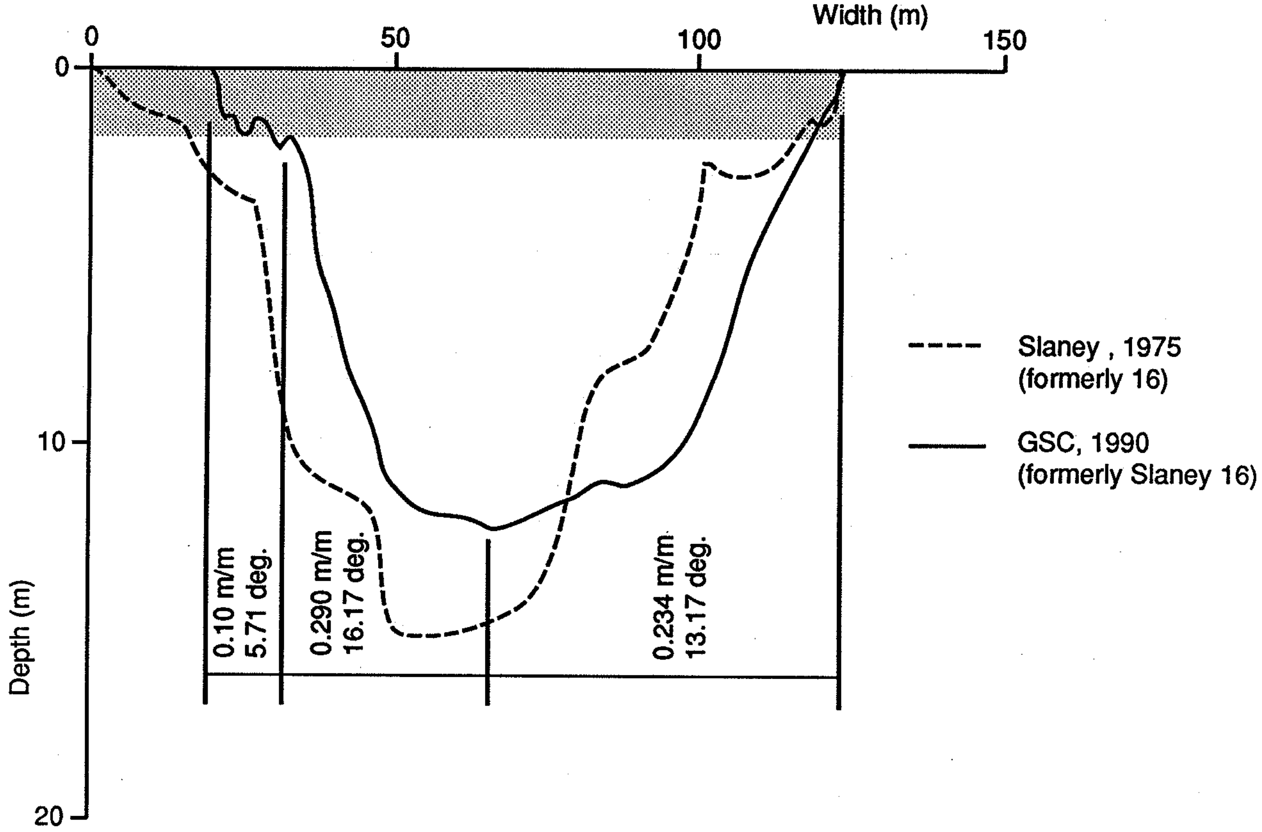
Figure 13: CHANNEL BED AND BANK SLOPES - CROSS-SECTION 2



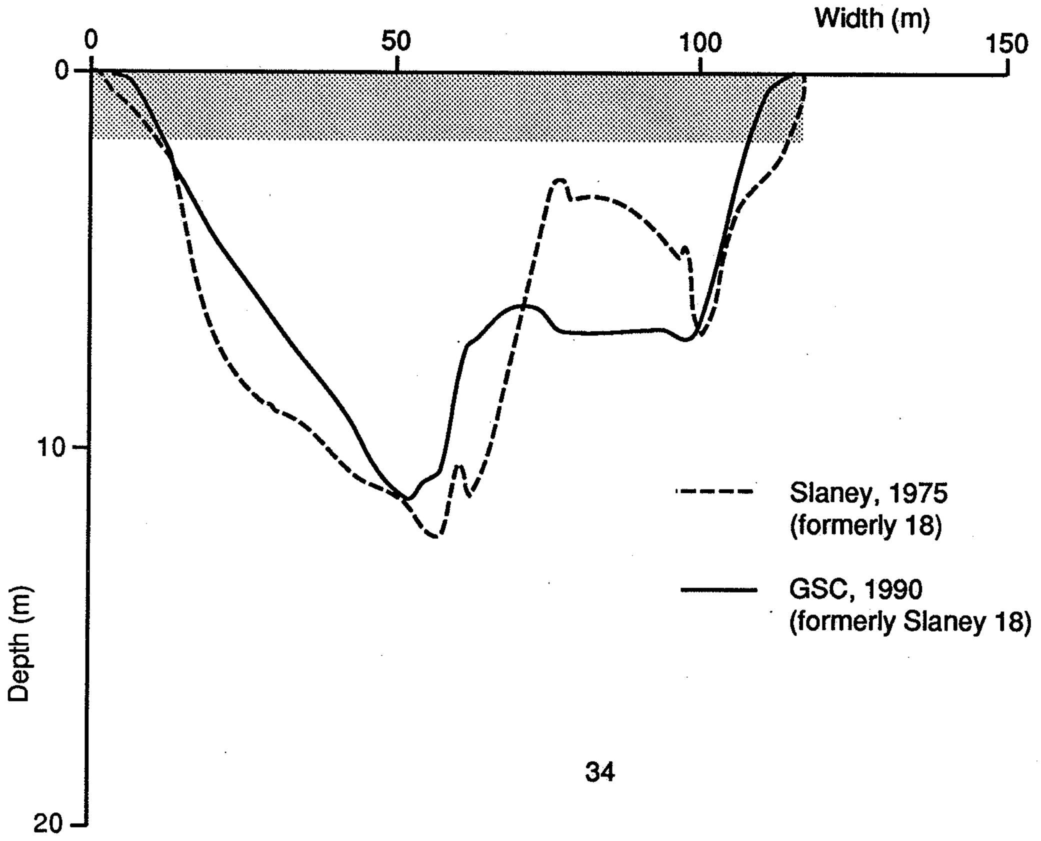
GSC (1990)

Figure 14: CROSS-SECTIONS 21 AND 23

CROSS-SECTION 21 - Kuluarpak Channel



CROSS-SECTION 23 - Kuluarpak Channel



Cross-section 24 is situated at the apex of the second bend, where the channel begins to flow northward (Figure 15). The box-like profile features a slightly irregular bed which slopes towards the right bank, attaining a maximum depth of 8.2 m. The right channel margin decreases in slope as it rises to form a beach on the inside of a meander bend. The left bank increases in slope above the water level to form a vertical bank 1m high.

Cross-section 26, located on an extensive straight reach downstream of 24, displays a symmetrical form with a convex bed and a trough below each bank (Figure 15). The right bank trough is slightly deeper, giving the cross-section a maximum depth of 7.2m. An earlier cross-section (EBA, 1974) outlines a u-shaped symmetrical profile at this location. The depth has remained the same (approximately 7.0m), however, the thalweg zone has expanded and the channel margins have steepened.

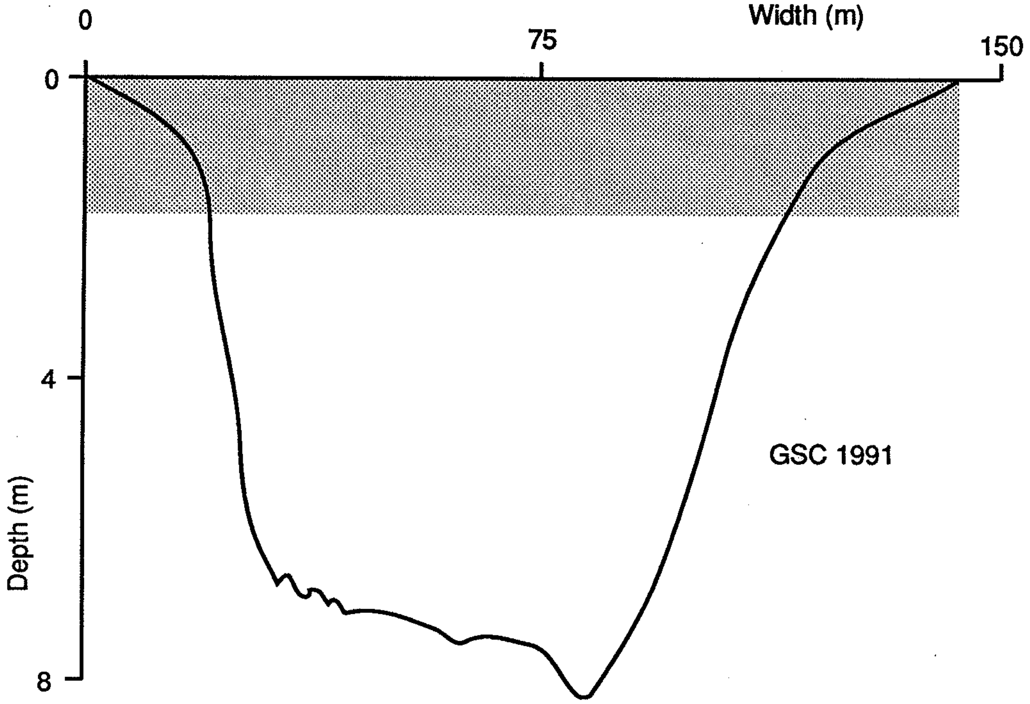
The remaining cross-sections highlight the profile of Harry Channel downstream of the bifurcation. Comparative profiles at cross-section 4 demonstrate a 2.7m decrease in channel depth which results in a reduction of the cross-sectional area (Figure 16). Overall, the asymmetrical form is maintained with an inner channel developing at the thalweg. The left bank has been reduced in slope while the width has remained unchanged.

Cross-section 6 illustrates a well developed asymmetrical form with a maximum depth of 7.4m (Figure 17). The gradually sloping right channel margin rises onto a beach along the inner bank of a meander bend. The left bank maintains a steep slope leading up onto a vertical channel bank 1m high.

Downstream of G-33, cross-section 7 profiles Harry Channel at the exit of a meander bend. Comparative cross-sections identify a 15m shift in the thalweg zone towards the right

Figure 15: CROSS-SECTIONS 24 AND 26

CROSS-SECTION 24 - Kuluarpak Channel



CROSS-SECTION 26 - Kuluarpak Channel

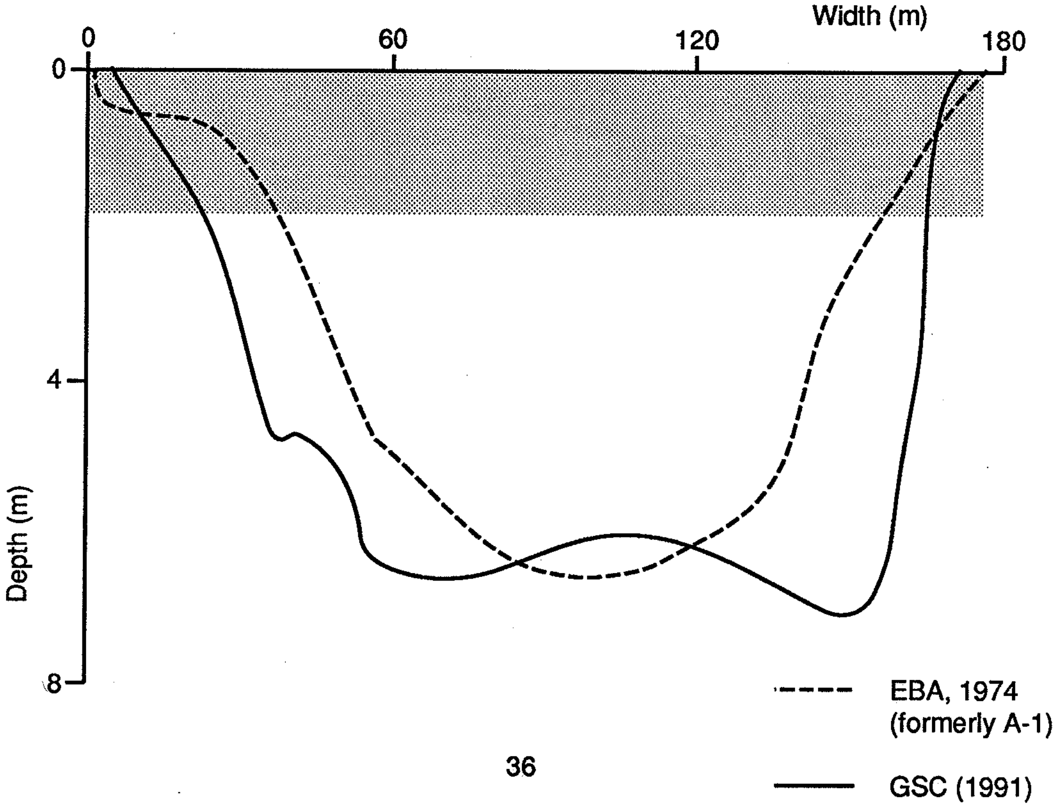


Figure 16: CROSS-SECTION 4 - Harry Channel

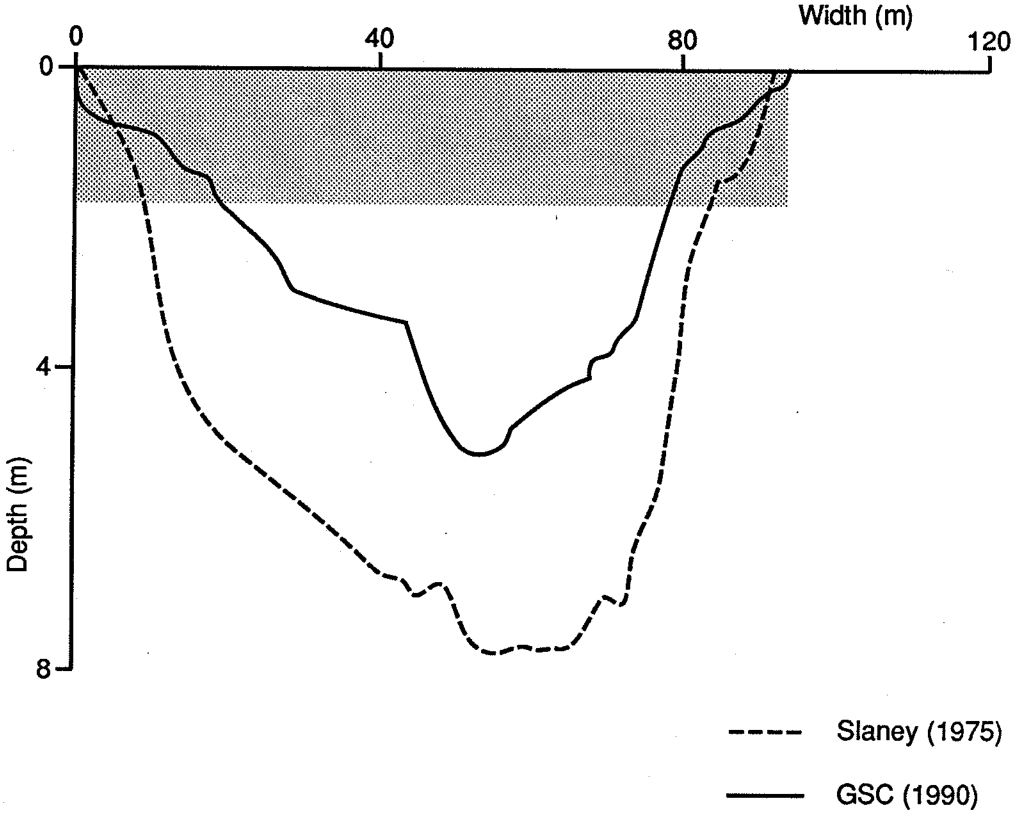
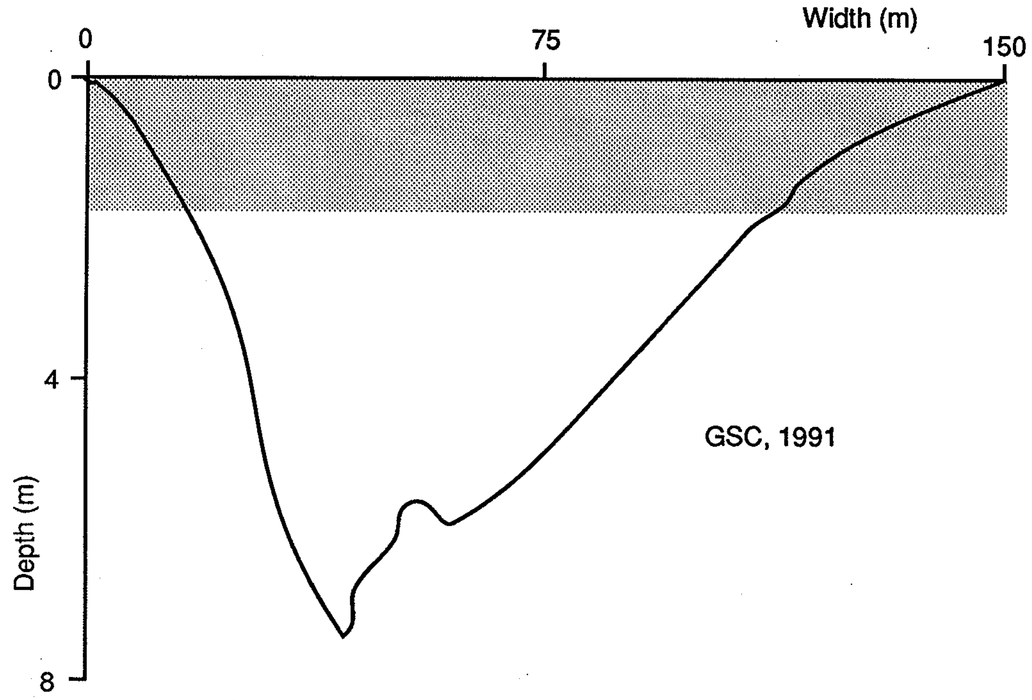
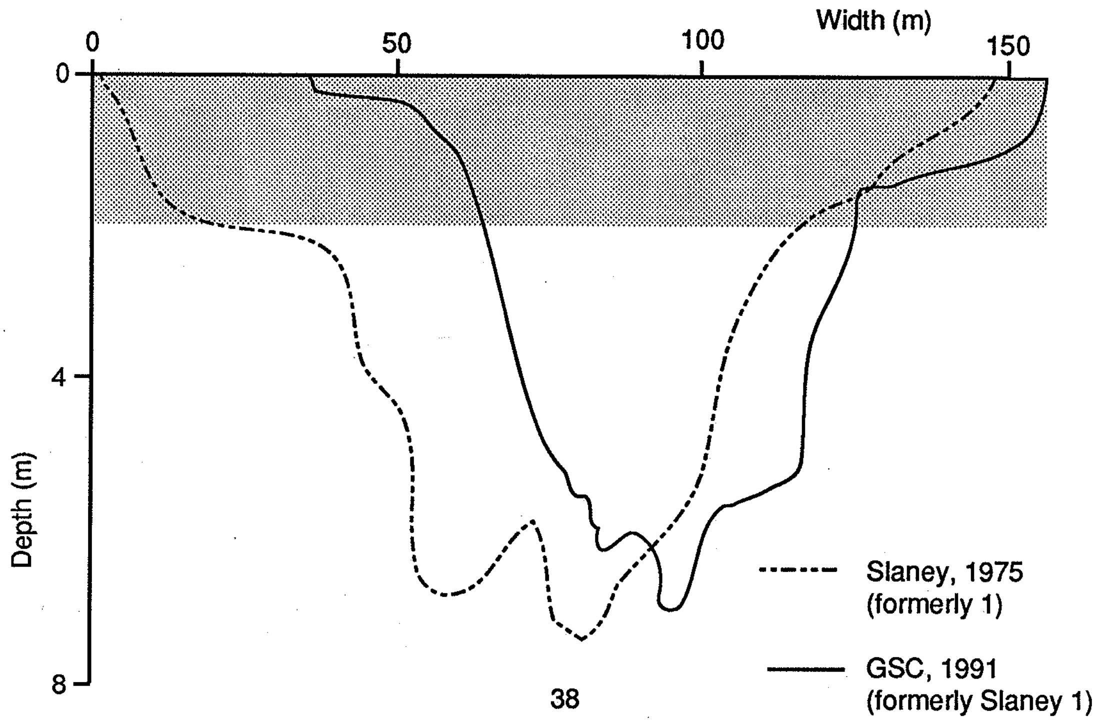


Figure 17: CROSS-SECTIONS 6 AND 7

CROSS-SECTION 6: Harry Channel



CROSS-SECTION 7 - Harry Channel



bank and profile modifications. The 1975 profile shows a 1.5m high mound between two troughs. The subsequent 1991 profile shows an aggradation of the left trough and the left bank, particularly in the ice cover zone. The right slope has steepened and a 32m shoal has developed. The left bank rises onto a 19m beach while the right bank is delineated by a 1.2m vertical face.

Downstream, in the Big Horn Point area, the channel morphology changes from a single channel form to a multi-channel form with rapidly shifting and coalescing mid-channel bars. Cross-sections 11, 13 and 14 outline the channel profile along the meander bend at Big Horn Point (Figures 18 and 19). Cross-section 13 shows an asymmetrical form with an irregular bed which attains a maximum depth of 5.5m. The right channel margin rises to an 8m wide gravel beach at the base of a Pleistocene upland. The left channel margin gradually rises onto a vegetated mid-channel bar.

Cross-section 14 represents the most extensive profile in the Big Horn Point area, as it outlines the entire width of the channel. A convex channel bed separates two troughs. The left trough clearly dominates with a depth of 4m. The wider and shallower right trough is 2m deep and likely, contains bottom-fast ice during the winter months. Likewise, ice dominates cross-section 11 except for a small area in the thalweg zone.

Downstream, a distributary channel branches off Harry Channel to the east. This distributary channel narrows from 120m (Cross-section 16) to approximately 78m (Cross-section 17) resulting in a corresponding increase in depth from 5.5m to 7.3m. The symmetrical profile of cross-section 16 displays an irregular topography with mounds standing 1.2m high and 6m wide (Figure 20). During winter months, the symmetrical forms

Figure 18: CROSS-SECTION 13 - Harry Channel

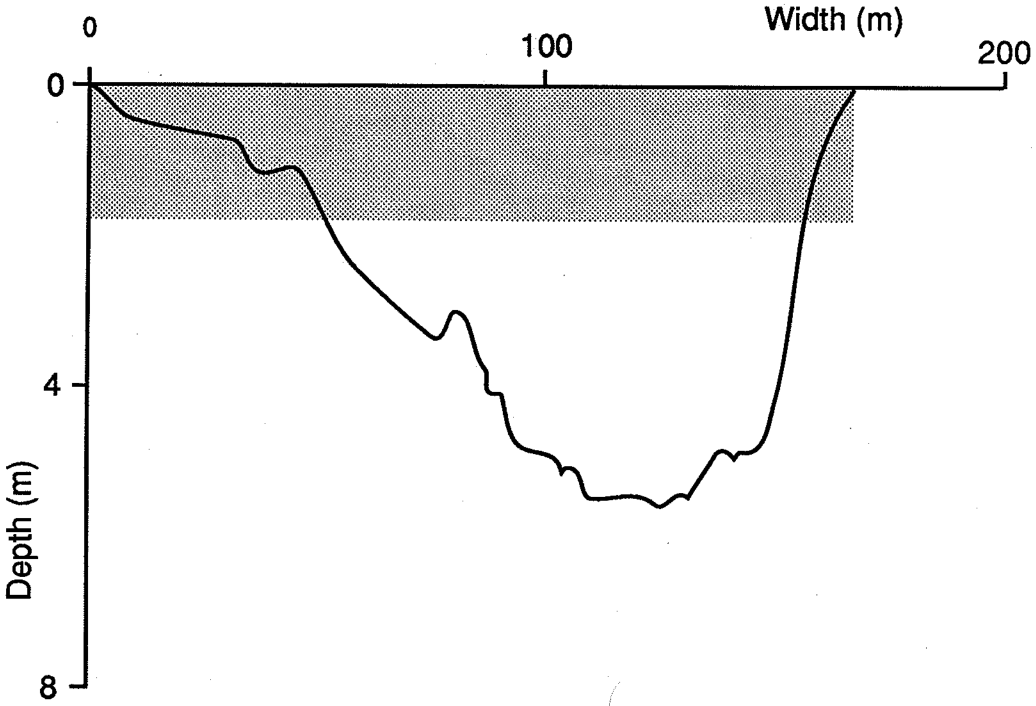
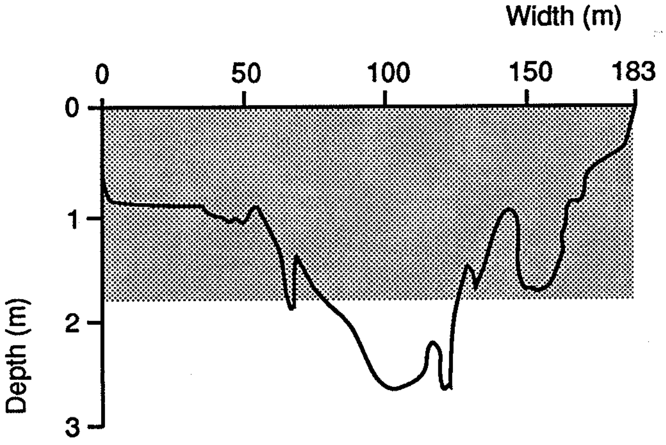


Figure 19: CROSS-SECTIONS 11 AND 14 - HARRY CHANNEL

CROSS-SECTION 11 - Harry Channel



CROSS-SECTION 14 - Harry Channel

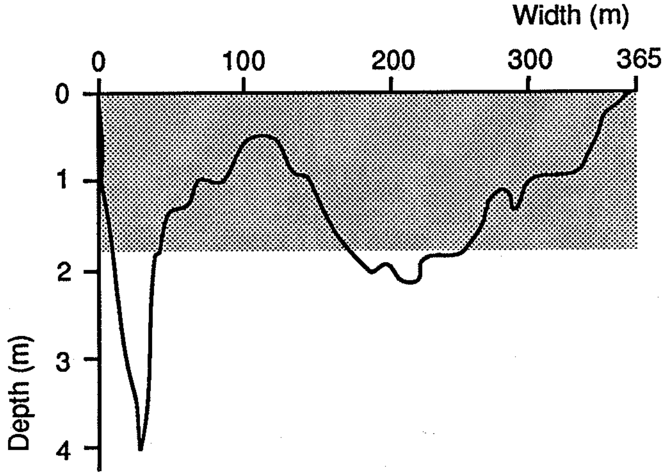
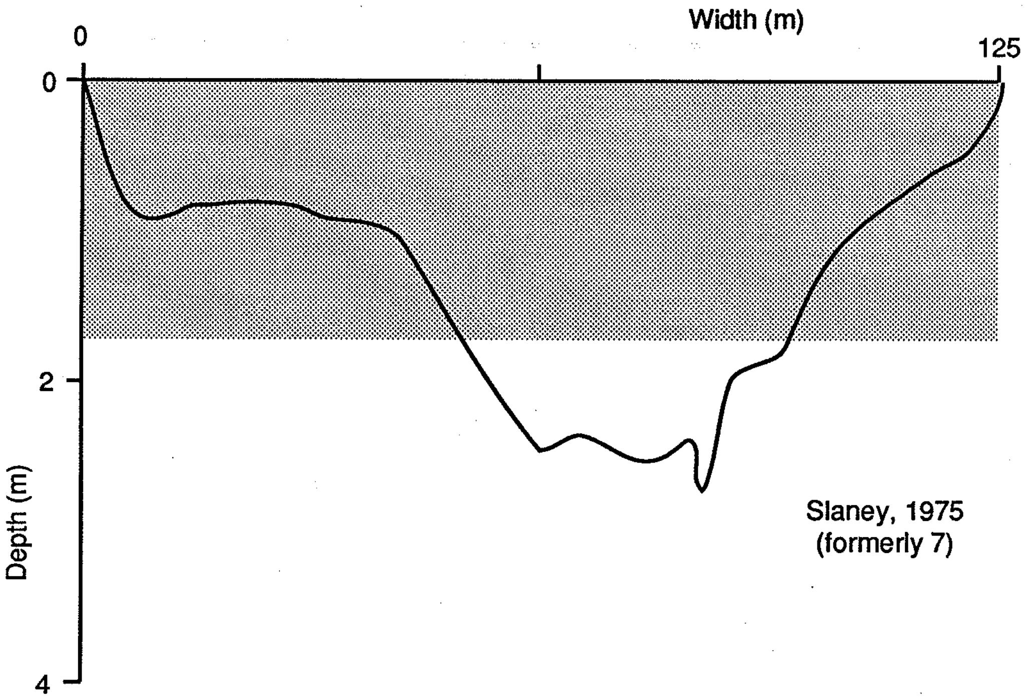
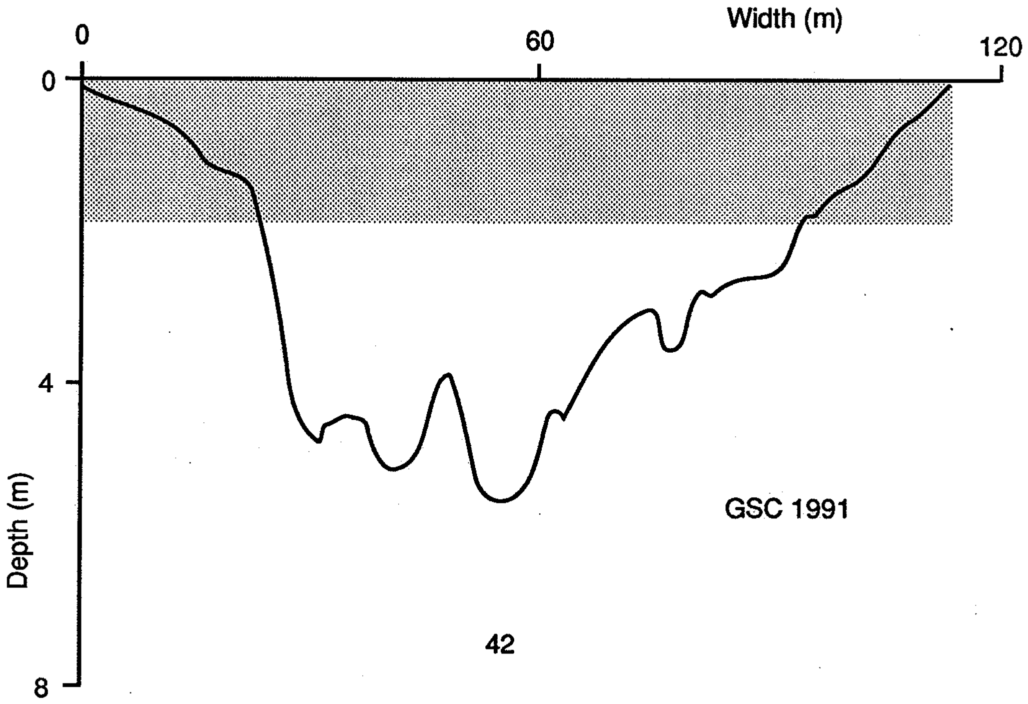


Figure 20: CROSS-SECTIONS 15 AND 16

CROSS-SECTION 15 - Harry Channel



CROSS-SECTION 16 - Harry Channel



permits the channelization of sub-ice flow along the distributary.

The farthest downstream profile of Harry Channel is outlined in cross-section 15, an asymmetrical profile with a 40m shoal extending from the left bank (Figure 20). The shallow channel (2.7 m) suggests a limited role in supporting flow from this point downstream. Low water levels in the fall would suggest that Harry Channel is bottom-fast at this location and any sub-ice flow is channelized along the unnamed distributary profiled in cross-section 16.

3.6 Ice Conditions

Given the extensive shallow channels within the Taglu site, the availability of free-flowing water under the ice cover is limited during the winter. For instance, no sub-ice flow was detected in Harry Channel at Taglu G-33 in early January (1972), as a result of extensive shallows and restrictions upstream between F-43 and G-33 (Slaney, 1974). In late January, a minimal sub-ice flow was detected in Harry Channel at Taglu G-33 and studies in May revealed no flow upstream or downstream of F-43 along Harry channel (Slaney, 1974). Because of the shallow depth in Harry Channel downstream of Big Horn Point, bottom-fast ice is likely common. In contrast, Kuluarpak Channel is deep enough that flowing water is maintained beneath the ice throughout the winter.

Slaney (1974, 1975) observed ice jams occuring in the vicinity of the Taglu site break-up. A major ice jam was also noted on Kuluarpak Channel during the 1975 survey. The jam extended from approximately cross-section 23 to cross-section 24. A second ice jam was observed on Harry Channel at the first bend downstream of the Harry/Kuluarpak bifurcation during a 1975 break-up survey.

The occurence of major ice jams and bottom-fast ice zones can be expected to have a major effect on channel hydraulics during the break-up period in the Taglu site. Ice jams, for instance, dramatically restrict flow causing substantial surface flooding and increased localized scouring beneath the ice. Bottom-fast ice will generally tend to persist during breakup, protecting the bed from scour. The combined effect of these factors will tend to concentrate flow in the thalweg zone and result in erosion of the deeper channels.

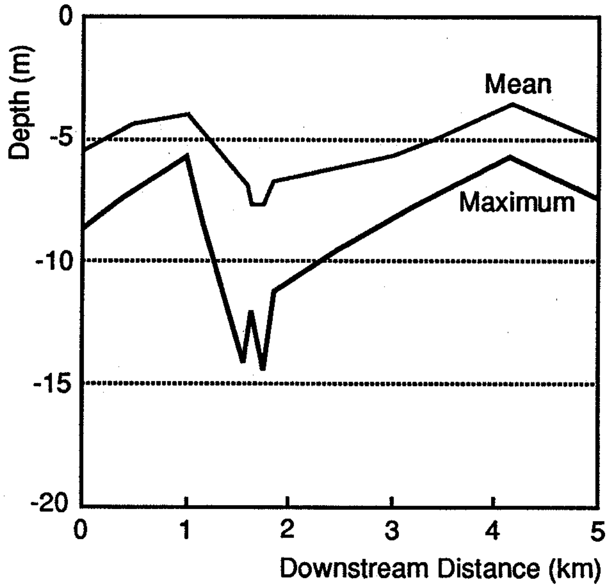
3.7 Bedforms and Fluvial Processes

The Taglu site is characterized by two contrasting channel reaches which are linked in terms of fluvial hydraulics. Harry Channel carries the flow into the study area basically as a distributary channel with a single channel morphology. Downstream of C-42, Harry Channel bifurcates into two channels, Harry and Kuluarpak. Kuluarpak Channel, the northwest distributary, retains most of the flow as a function of downstream depth and cross-sectional area. Figure 21A shows the mean and maximum downstream depths of Kuluarpak Channel ranging between 4m and 10m with a sharp increase in depth at the first bend. In contrast, Harry Channel shows a trend towards shallowing downstream, to the point where bottom-fast ice likely dominates during the winter months (Figure 21B).

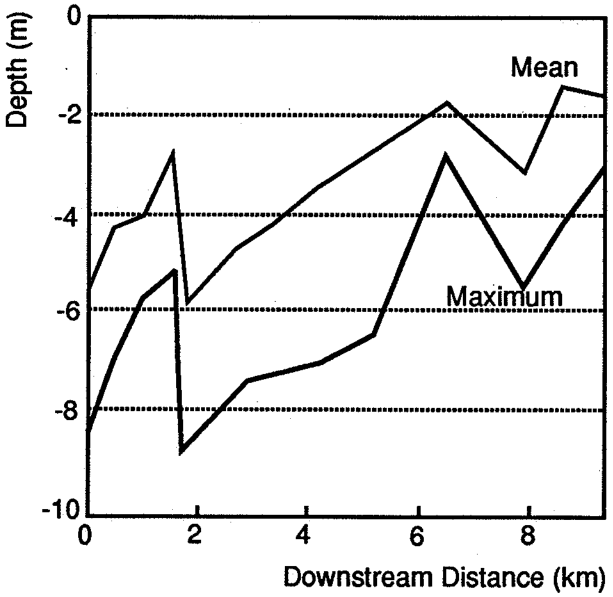
Harry Channel continues northeast shallowing gradually as it flows towards the Beaufort Sea. In the vicinity of Big Horn Point, the channel becomes wider with rapidly forming and coalescing mid-channel bars giving this part of the channel a multi-channel morphology. Contributing factors causing this, include sediment from erosion of the Pleistocene uplands and diversion of flow into the lakes to the east and southeast.

Figure 21: MEAN AND MAXIMUM CHANNEL DEPTHS

TAGLU SITE - KULUARPAK CHANNEL



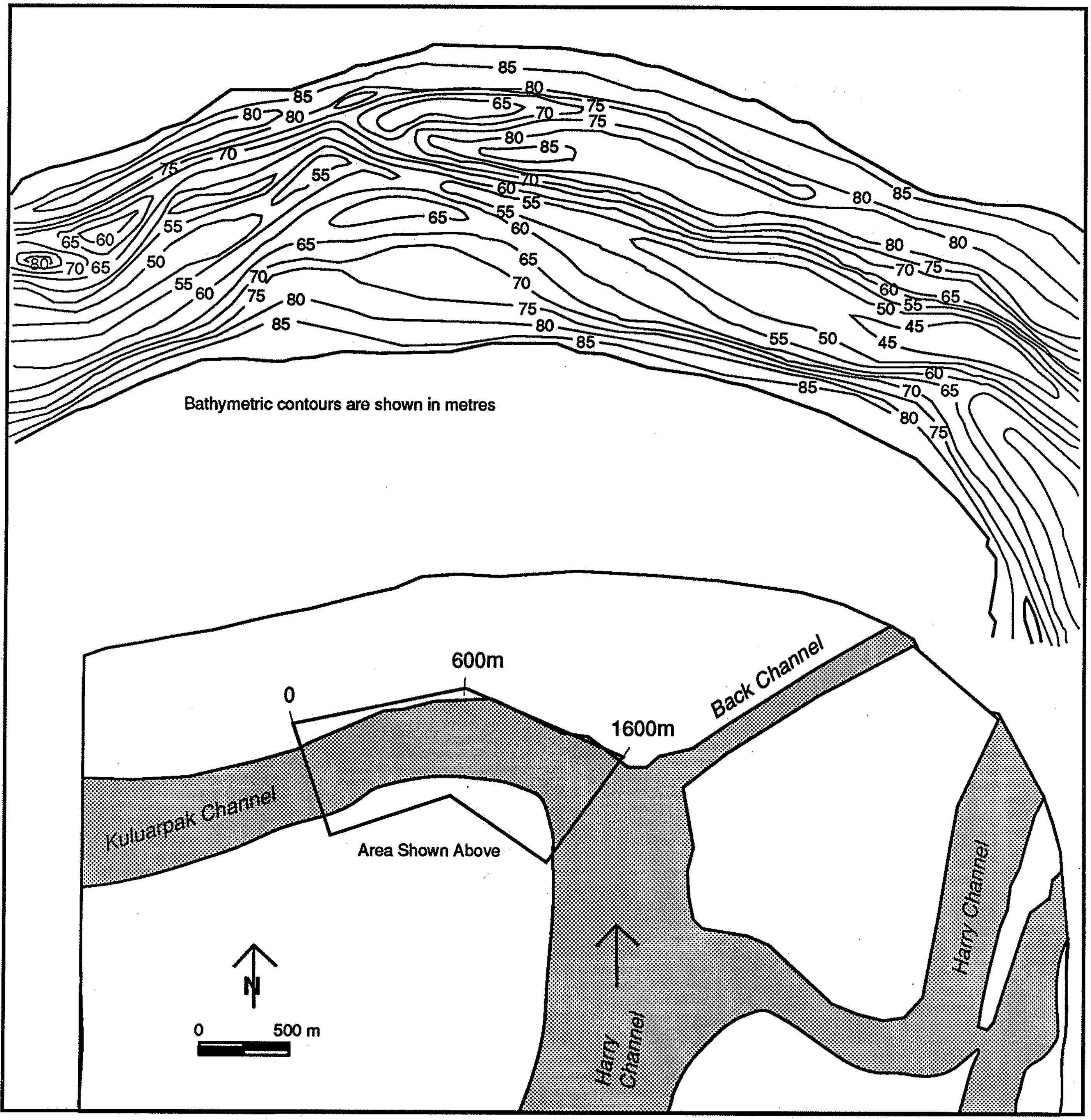
TAGLU SITE - HARRY CHANNEL



Downstream of Big Horn Point, an unnamed distributary channel branches off to the west diverting the main flow from Harry Channel.

The only detailed bathymetric map of the channels within the study area was prepared by the consultants to the Oil Industry. This map outlines a hole and mound bed topography (Figure 22) around the first meander of Kuluarpak Channel at the bifurcation. This type of bed topography is common in other channels within the delta and suggests chaotic hydraulic conditions. Under these hydraulic conditions, there is not enough hydraulic force on the outside bend to create a linear scour pool which is common along meander bends. With insufficient hydraulic force, the outer bank will remain relatively stable with only minor bank retreat as indicated by the lack of any appreciable deepening at cross-sections 20-23.

Figure 22: MACROBEDFORMS - KULUARPAK CHANNEL



Bathymetric contours are shown in metres

4.0 NIGLINTGAK SITE

The Niglintgak site is located at the south end of Niglintgak Island (Figure 1). In this area, Kumak Channel branches of from Middle Channel, which carries flow from the south. At least 90% of the flow follows Kumak Channel, while downstream of the junction, Middle Channel shallows out to form a funnel-shaped mouth common to other large distributaries of the Mackenzie Delta (Figure 23). Kumak Channel maintains a single channel form with additional contributions from two sources, Aklak Channel and an unnamed lake channel from Logan Lake. Aklak, a reversing channel, primarily flows westward into Kumak Channel (Slaney, 1975).

4.1 Landforms and Associated Sediments

Surficial materials in the Niglintgak site consist of modern alluvial deposits and older Pleistocene uplands (Figure 24). The Pleistocene uplands, in particular, play an important role in channel morphology, forming the right bank of Kumak channel upstream of Aklak Channel and forming the uplands on Niglintgak Island. The uplands consist of a combination of glaciofluvial outwash and glacial moraine. Generally, the outwash sediments tend to be slightly lower in elevation with flat, gently sloping surfaces. Morainal areas are, generally, more rolling in surface expression. Thermokarst features, such as retrogressive thaw flow slides, are less common at the Niglintgak site than the Taglu site. Because of the coarse texture of the upland sediments, they have a restricting effect on the channel migration. In general, sand and gravel beaches dominate the channel margins, where the channel has impinged against the upland.

Figure 23: NIGLINTGAK SITE

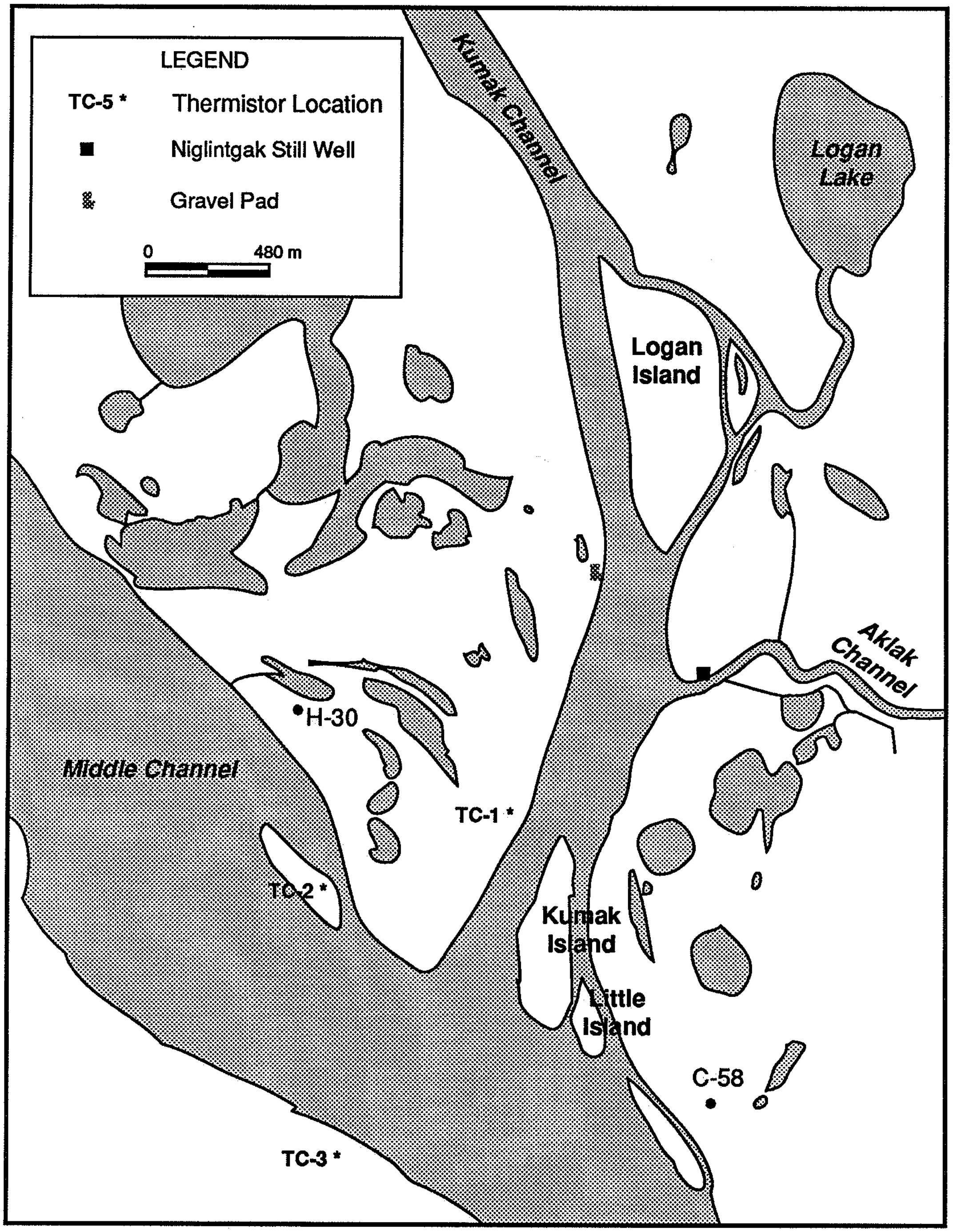
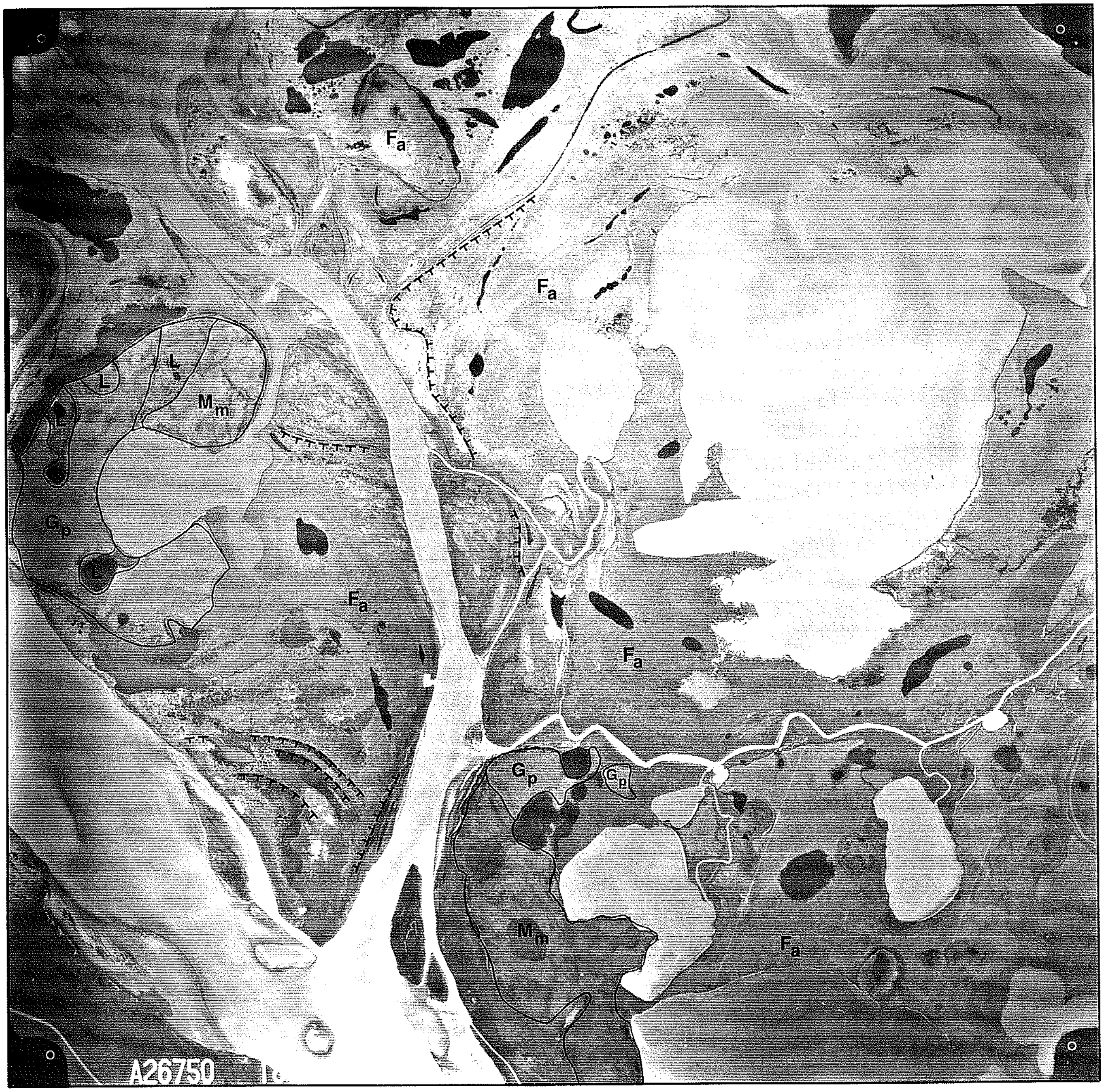


Figure 24: SURFICIAL GEOLOGY OF THE NIGLINTGAK ISLAND AREA



QUATERNARY
HOLOCENE

L	*Lacustrine deposits*
F_a	*Fluvial deposits, modern floodplain*

EARLY WISCONSINAN (?)

G_p	*Outwash plain*
M_m	*Rolling moraine*

Geological boundary . . . ⁓

Channel scars . . . . ⊥⊥⊥⊥⊥

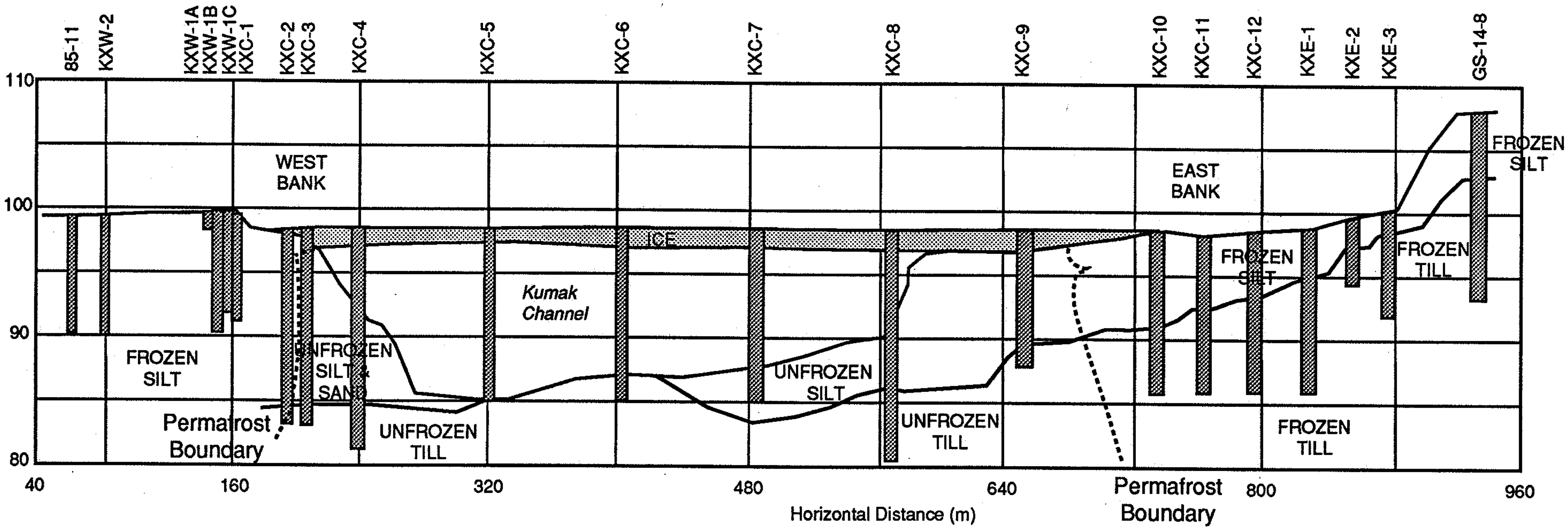
Geomorphic features common on the alluvial plain include abandoned channels, ridge and swale topography and delta lakes. Ice wedge polygons are not well developed but can be distinguished in some areas by subtle variations in vegetation cover. Surface sediments are almost entirely coarse silt with only a very thin organic mantle.

4.2 Geotechnical Conditions

In 1977, boreholes were drilled across Kumak Channel at cross-section 34 (Hardy and Associates, 1977). The resulting geological cross-section (Figure 25) outlines the generalized units and the approximate permafrost boundaries below each bank. The ice content of the two banks was found to differ significantly. The west bank (left) has excess ice contents ranging between 20-70% in the upper 1m (KXW-1C) on the top of the bank. At the ice margin (KXC-2 and KXC-3), ice contents range between 15-60% in the first metre of sediment below the ice (75cm thick). Borehole KXC-10, on the east bank (right), is comprised of 25cm of ice underlain by 1m of silt with no ice. Beneath this layer is 4m of sediment having 5-50% ice content.

Figure 26 is a Raytheon subsurface image of cross-section 34. A distinctive horizontal lineation appears on the right bank at an approximate depth of 21m. Unfortunately, borehole data at this cross-section does not reach this depth. A general assumption would be that this layer represents either a gravel zone or the top of a sand layer which formed an older delta sequence. This lineation is also present at 21m in subsurface profiles of cross-section 35 (Figure 27) and cross-section 36 (Figure 34).

Figure 25: BOREHOLE DATA for CROSS-SECTION 34
HARRY CHANNEL



(Adapted from Hardy and Associates, 1977)

Figure 26: RAYTHEON PROFILE OF CROSS-SECTION 34

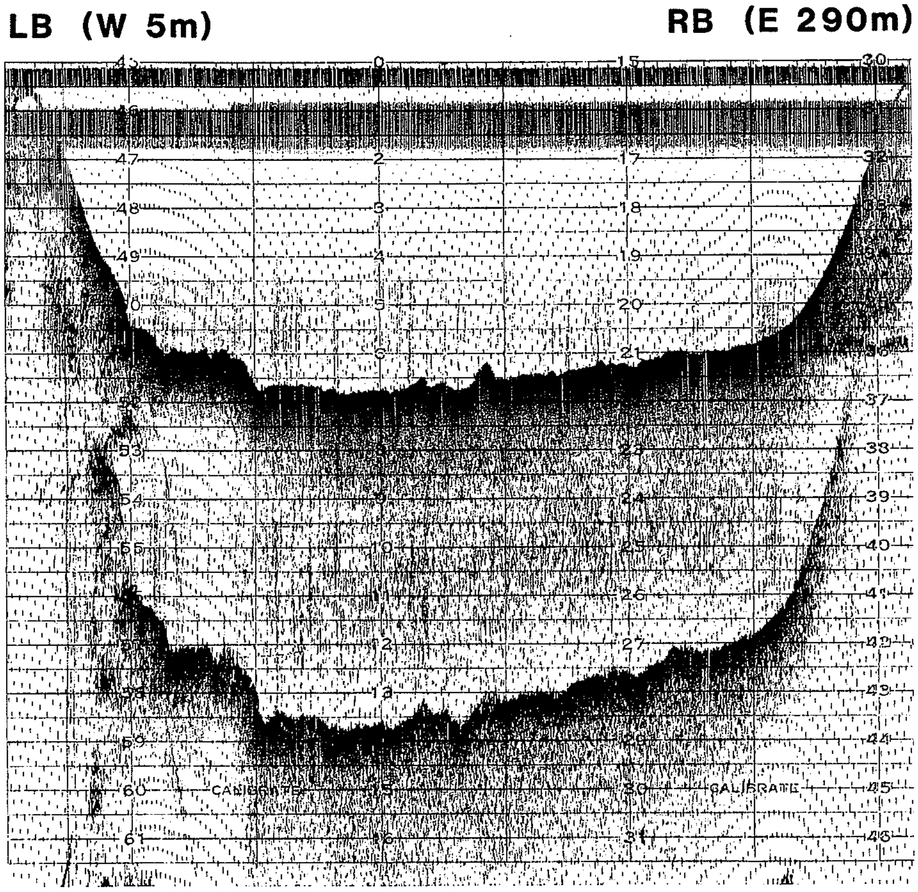
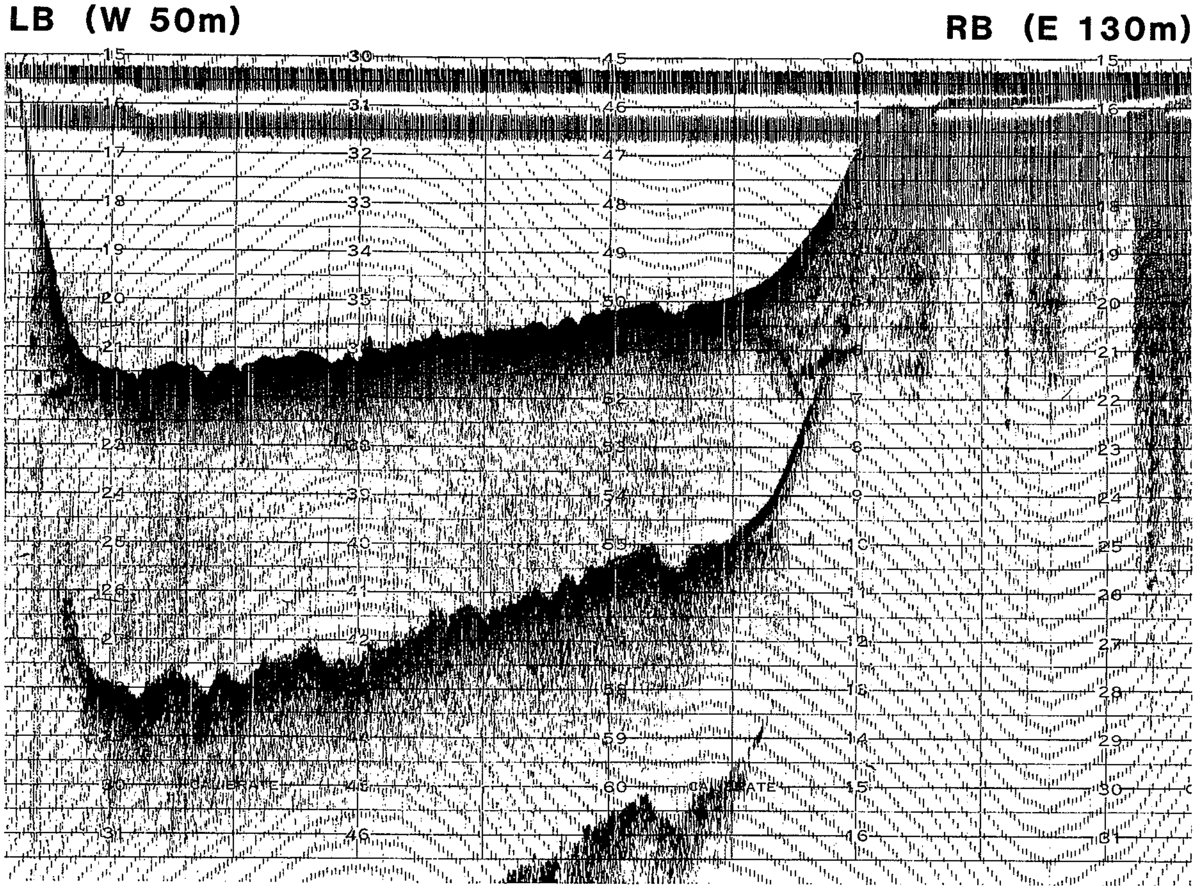


Figure 27: RAYTHEON PROFILE OF CROSS-SECTION 35



At hydrologic cross-section 40 (EBA, 1974 station D2), 13 boreholes were drilled across Kumak Channel (EBA, 1974)(Figure 28). The channel banks consist of a 15m to 20m thick sequence of deltaic silts and sands overlying a basal sand. The coarse texture of the basal sand and an inclusion of till-like material in borehole XD2-15, indicate that this sand is glaciofluvial outwash and therefore, part of the Pleistocene uplands sequence exposed a short distance upstream on east bank.

The permafrost boundary was well identified by the borehole transect across the channel. Borehole XD2-8 on the west bank was frozen from the surface to a depth of 15.5m, where a thin unfrozen zone was encountered at the bottom of the borehole. Borehole XD2-3 and 3a located on the east side of the channel encountered approximately 6m of unfrozen silt over frozen sand. This suggests an asymmetric thaw bulb beneath the channel consistent with channel migration from west to east.

The ice content of the bank material is significantly different from bank to bank. The west bank has excess ice contents in the order of 10-45% in the upper 6m of sediment, primarily in the form of segregated lenses and ice inclusions. Beneath this depth, no excess ice was encountered. The east bank has approximately 1-5% excess ice in the upper 6m with no excess ice beneath this depth.

Ground temperature data (courtesy L.D. Dyke) is available from three instrumented sites, located on southern Niglintgak Island and on the west side of Middle Channel (Figure 29). In addition, temperature data is also available from the detailed geotechnical studies conducted by EBA (1974). In general, mean annual ground surface temperatures of vegetated areas vary from approximately -2°C to -4 °C, while unvegetated areas are

Figure 28: BOREHOLE DATA for CROSS-SECTION 40 - KUMAK CHANNEL

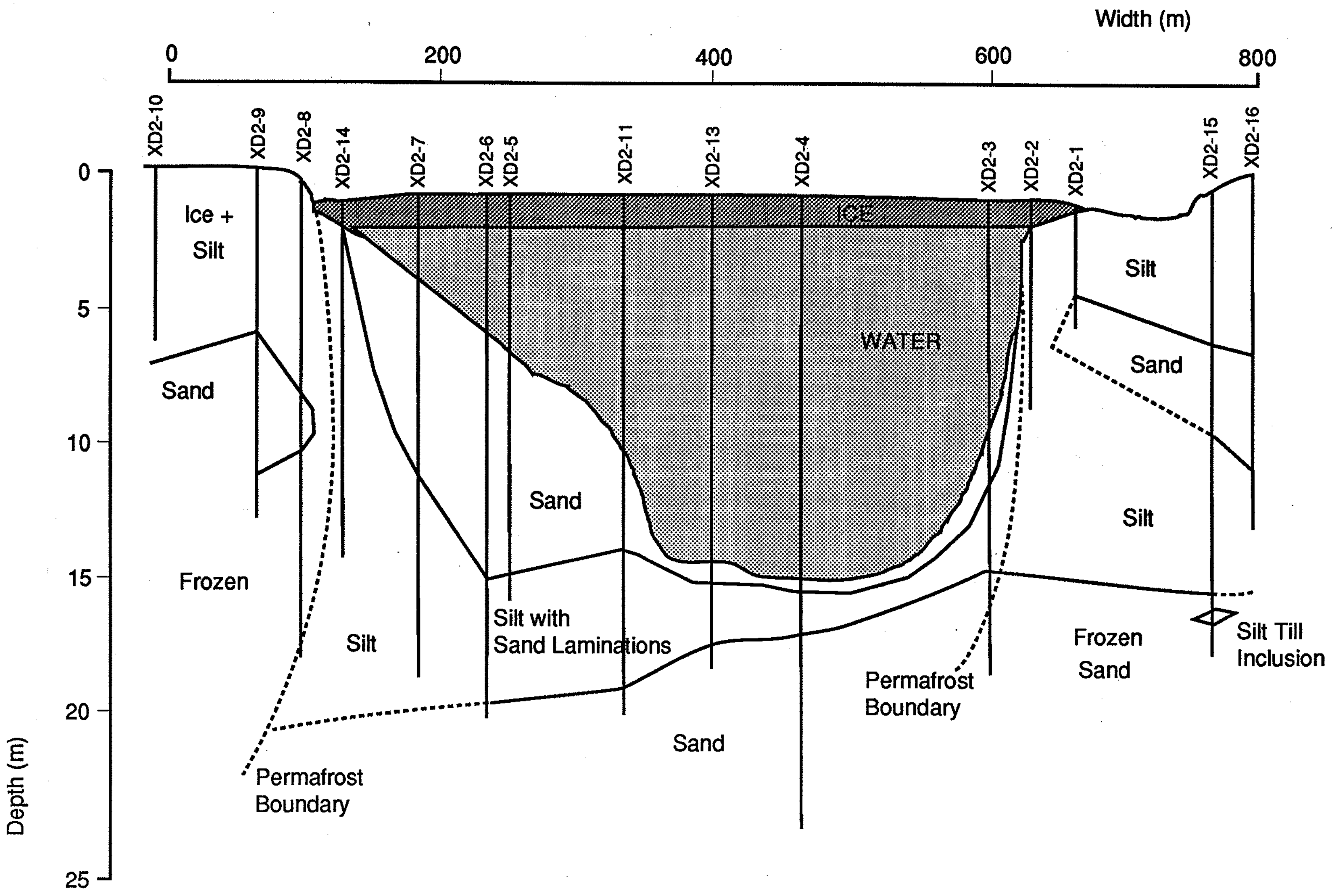
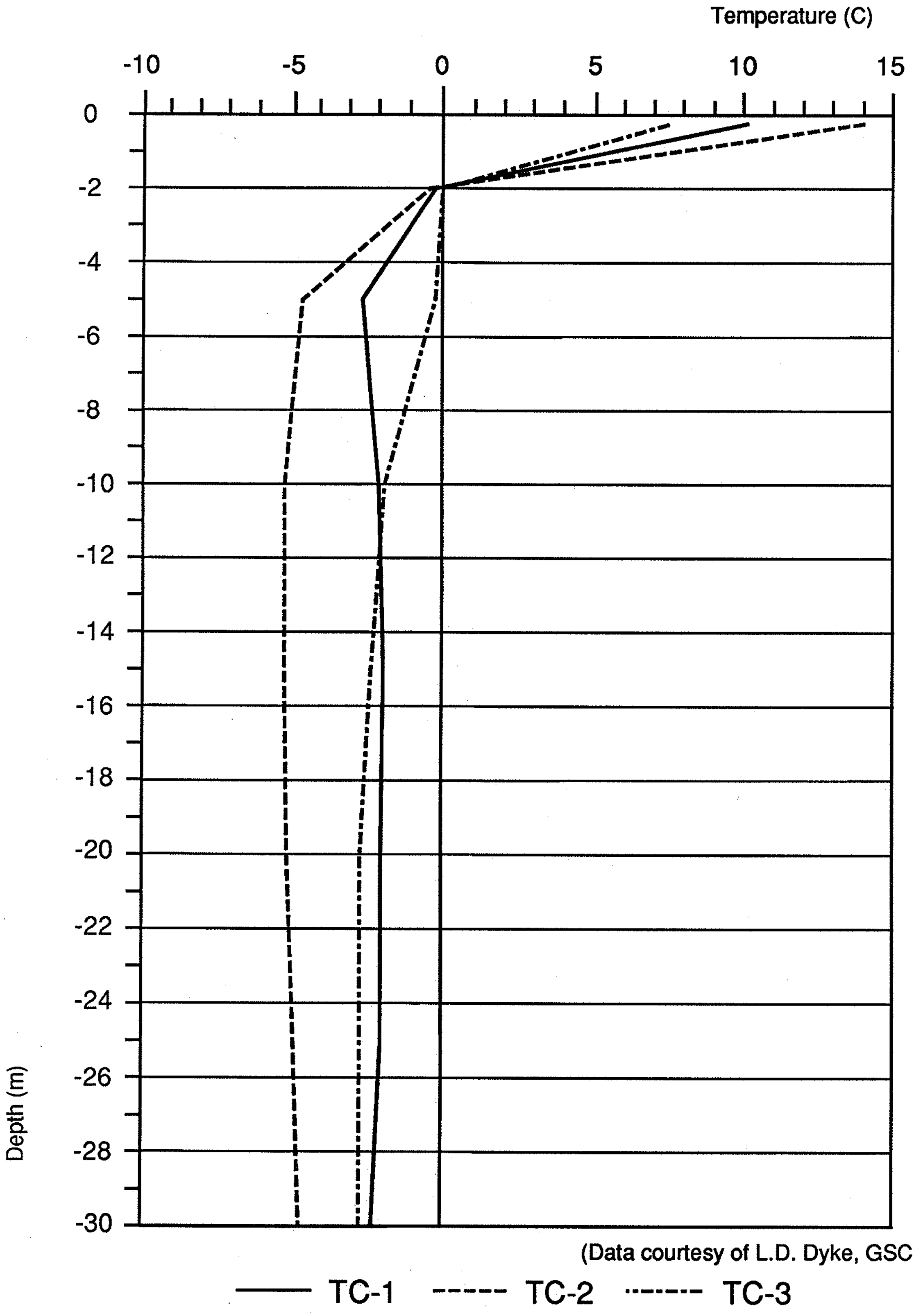


Figure 29: GROUND TEMPERATURE DATA for TC-1, TC-2, and TC-3



(Data courtesy of L.D. Dyke, GSC)

—— TC-1 ----- TC-2 ·-·-·- TC-3

somewhat colder (L.D. Dyke, pers. comm., 1991). Active layer thickness varied from 0.8m to 1.2m beneath vegetated sites.

4.3 Vegetation

The general description of vegetation units for the Niglintgak site (Figure 30) is similar to that of the Taglu site (Section 3.1.3), but in general, much more dense. Willow areas on the west side of Middle Channel for instance, may be over 5m in height while at Taglu they are rarely more than 3m high. In the fluvial plain area, the vegetation is controlled mainly by elevation and subtle variations in soil texture. Well drained swales, for instance, are covered exclusively by willows, while low-lying wet areas are covered by sedge-herb species.

4.4 Bank Stability

This section will present data on the rates of streambank erosion and its distribution within the Niglintgak site (Figure 31). The left bank of Kumak Channel at the Kumak/Middle Channel junction forms a 800m erosional zone retreating at an average rate of 2.2 m/yr (Plate 2). In this zone, the bank is 1 to 1.5m in height and is constantly calving, primarily by undercutting, in blocks 1 to 4m^2 in size. The left bank of Kumak Island, displays a 1.7 m/yr average rate of retreat. This rate is probably more indicative of a fluctuating water levels at the time of the aerial photography along a wide shoal as opposed to active bank erosion. Channel cross-sections presented in the following section will outline the predominance of shoals at this location.

Figure 30: VEGETATION DISTRIBUTION
NIGLINTGAK SITE

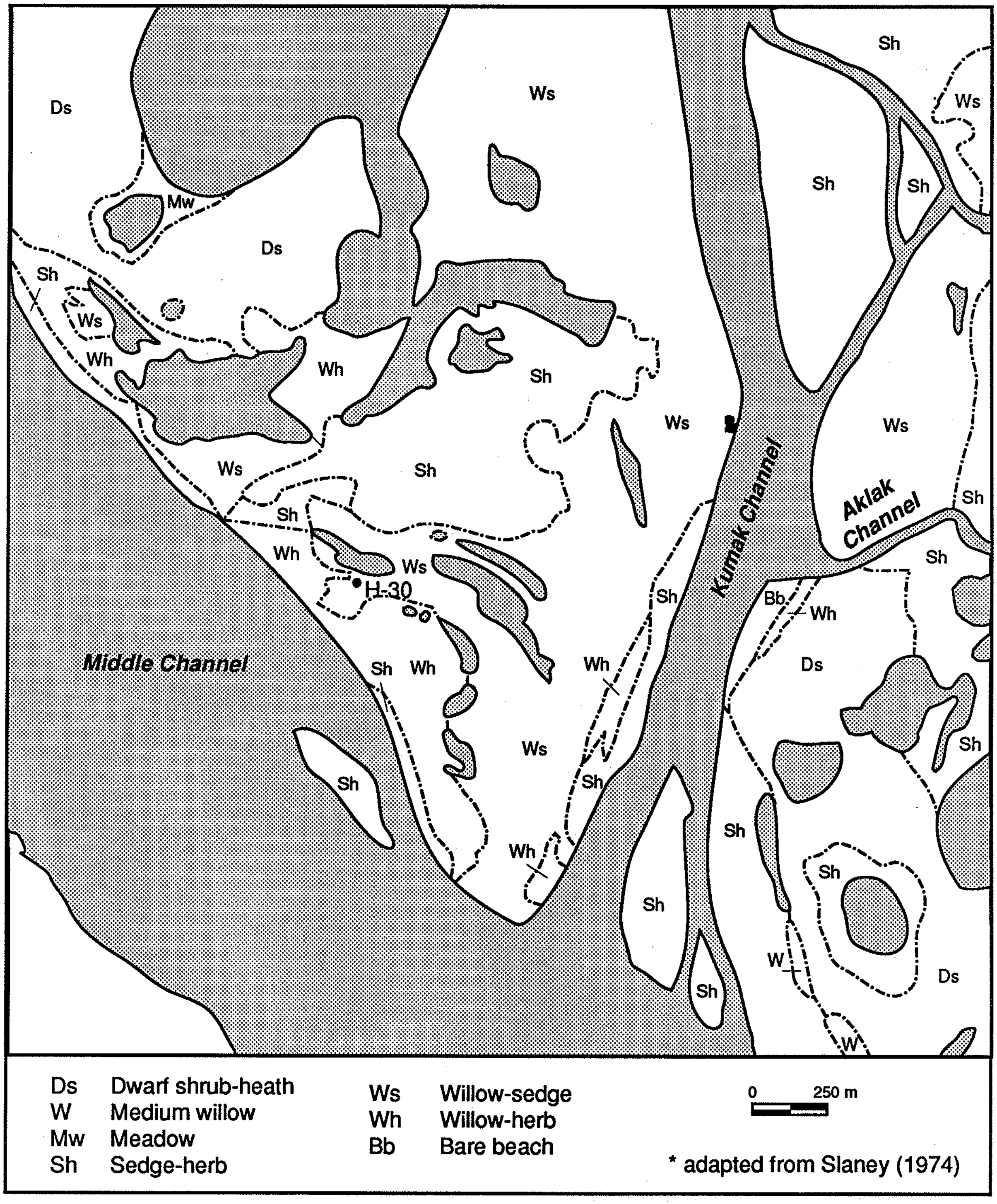
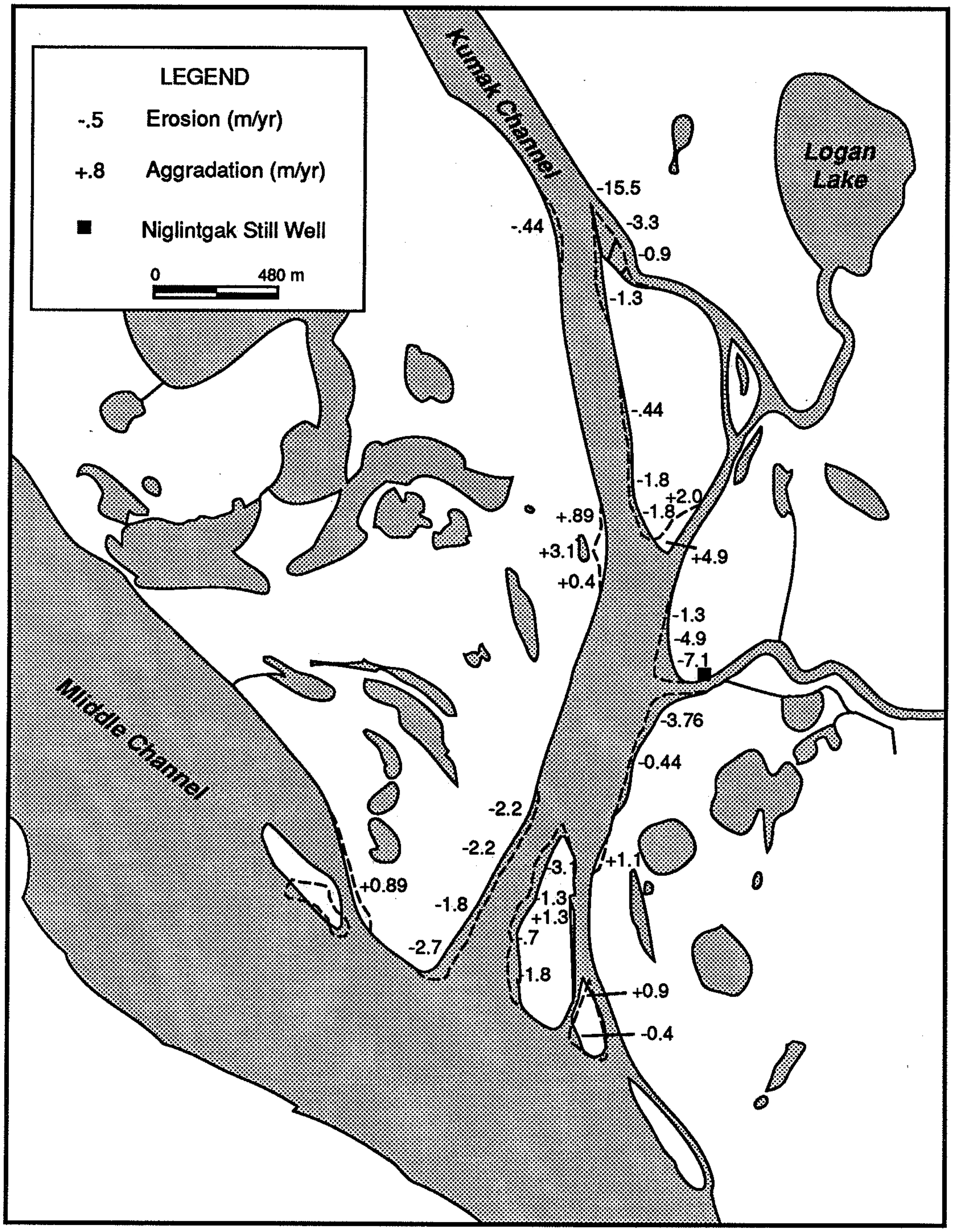
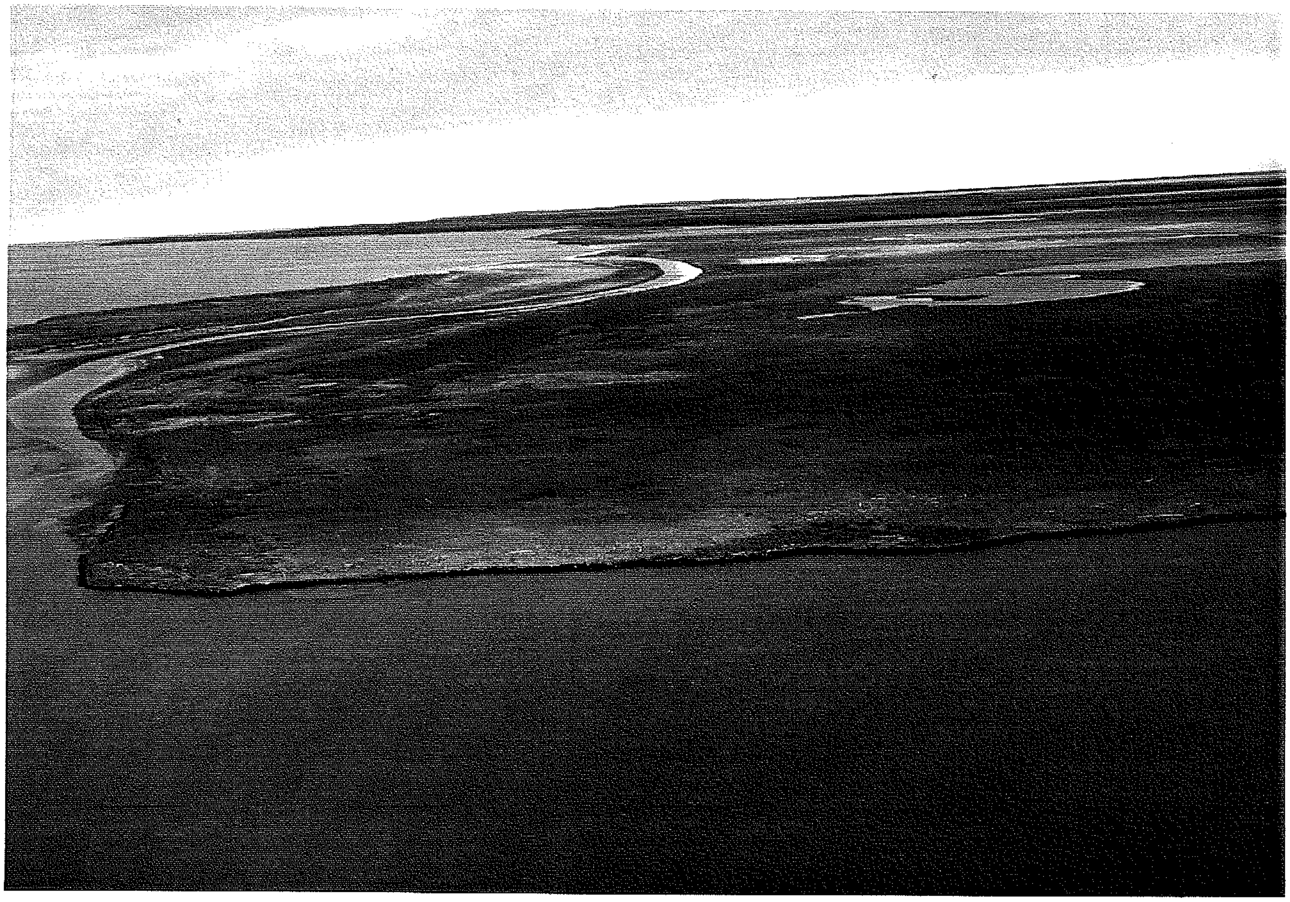


Figure 31: BANK STABILITY FROM 1950 TO 1985
NIGLINTGAK SITE



(Note: Dashed line represents formert bank margin, 1950)

Plate 2: BANK STABILITY - SOUTHERN TIP OF NIGLINTGAK ISLAND



Farther downstream, bank erosion rates are also influenced by water level fluctuations and the presence of extensive shoals. This accounts for the anomalous high rates of retreat in the vicinity of Aklak channel (7.1 and 3.76 m/yr). At the confluence of Kumak Channel and the lake channel from Logan Lake, it appears a different process has resulted in a high rate of retreat (15.5 m/yr). This high rate of retreat appears to be more a function of the stream adjusting course within it's own meander plain over time than any significant adjustments by Kumak Channel.

A bank stability study of the outer delta by Lapointe (1986) provides limited data on erosional zones in the Niglintgak site. The few values presented are within the erosion zones identified on figure 31. Except for the southern tip of Niglintgak Island, Lapointe's values are significantly lower than those noted in the present report.

Areas of aggradation are less extensive and more difficult to assess from air photos. Shoals, which are clearly evident at low flows, are extensive throughout the area . The right channel margin at the downstream tip of Kumak Island displays an increase of +1.1m. Downstream, the inner bank (left) of the meander bend shows a range of accumulation between +0.4m and +3.0m (Plate 3). On the outside bend of the meander, the left bank of the unnamed lake channel, rates of accumulation reach 4.9 m/yr.

4.5 Channel Morphology

A concerted effort was made to duplicate crossings previously recorded in order to obtain a time-lapse comparison. Additional cross-sections were added to present a more concise description of the downstream profile variability (Figure 32). The increased density

Plate 3: POINT BAR AGGRADATION

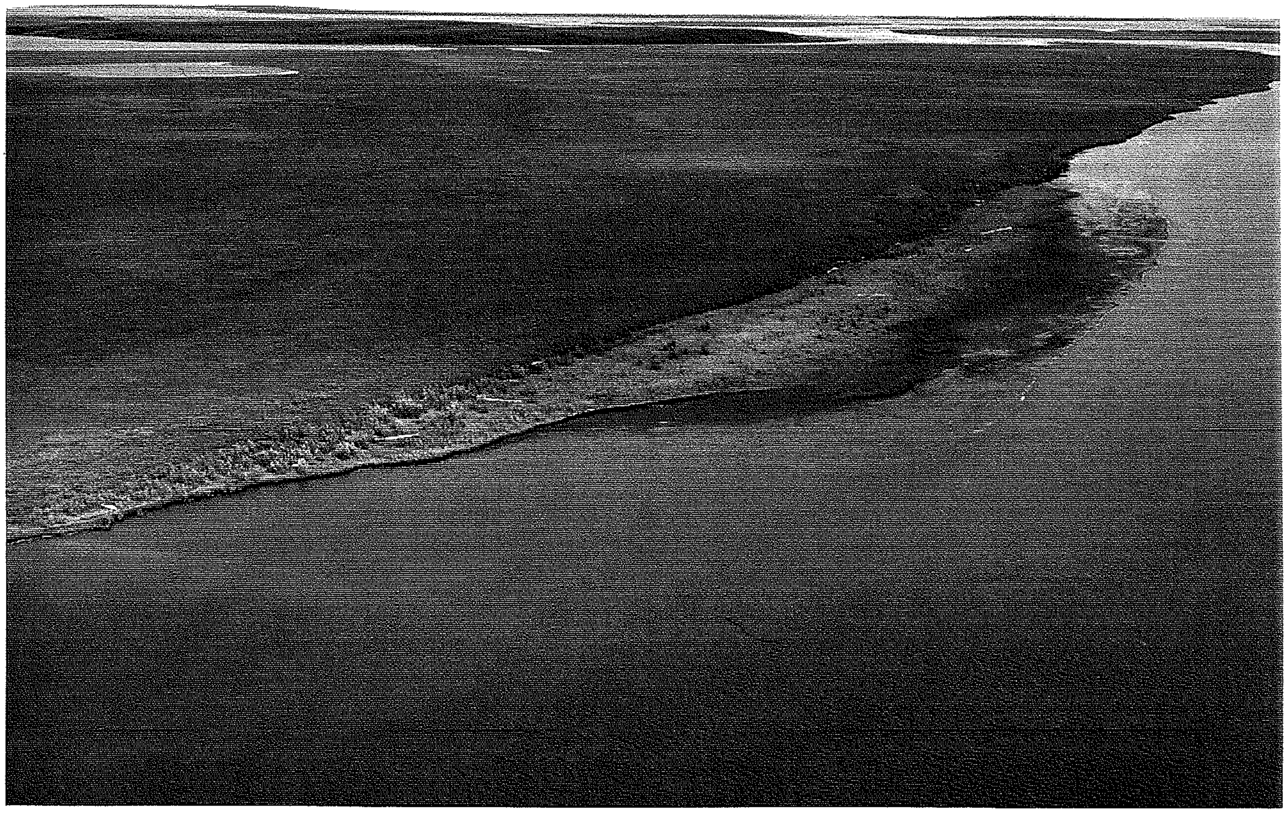
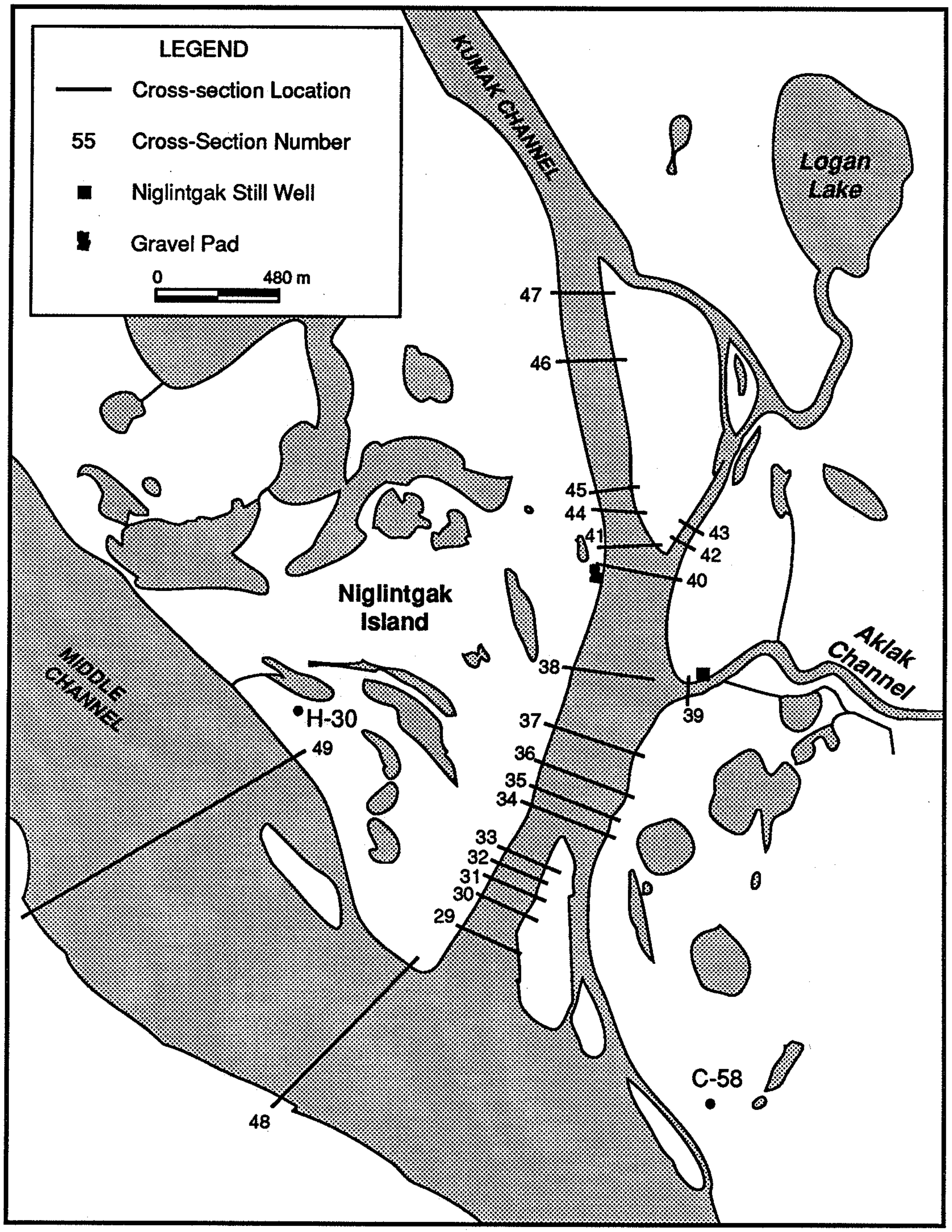


**Figure 32: CROSS-SECTION LOCATIONS
NIGLINTGAK SITE**



of cross-sections between cross-sections 29 and 37 represents an historical area of interest, namely proposed pipeline crossings and associated shore-based facilities (Plate 4).

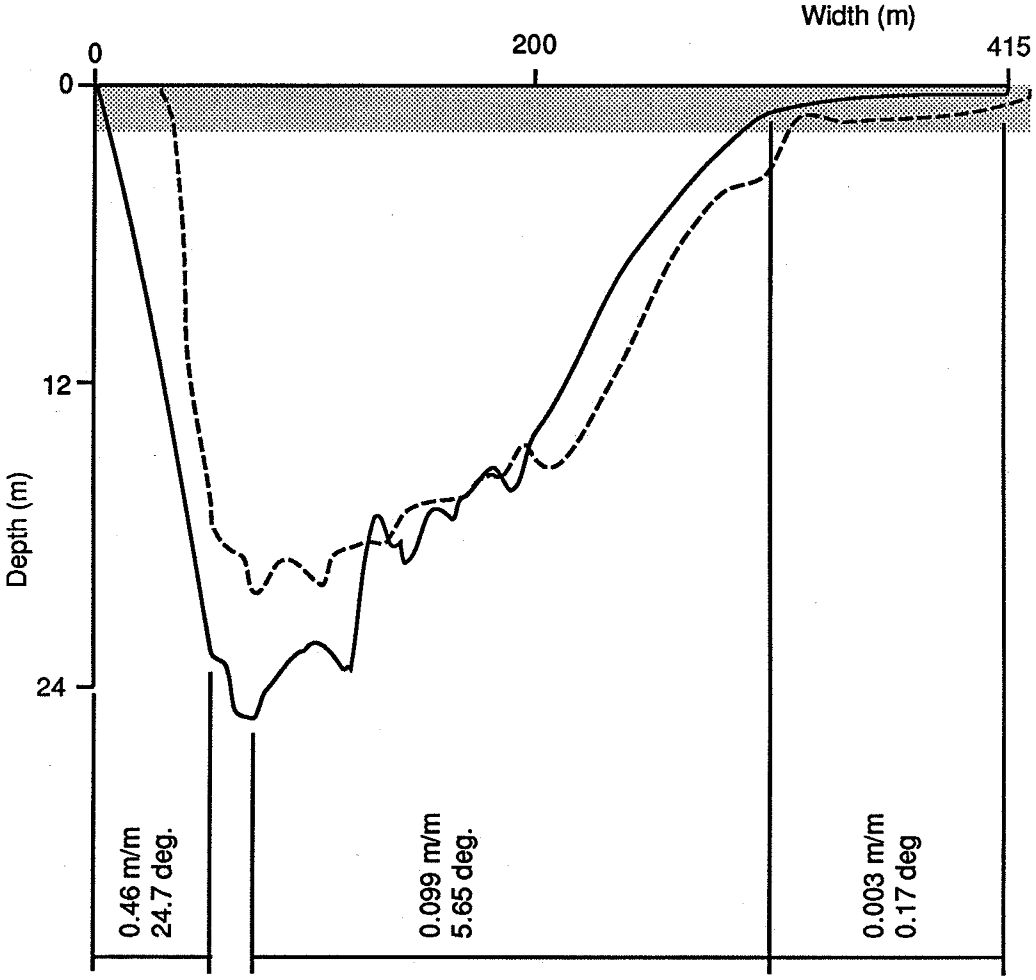
At the entrance to Kumak Channel, the flow from Middle Channel is diverted around Kumak Island forming an initial meander bend. Cross-section 33 illustrates an asymmetrical profile surveyed by Slaney in 1975 and the GSC in 1990 (Figure 33). The profiles show a bank and bed shift of approximately 33m and a deepening of the thalweg zone from 19.8m to 24.8m. The profile is asymmetric with a steep eroding bank on the left side (24.7°) and a 100m shoal on the right bank. The right channel side has a slope of 5.65° while the shoal is only 0.17°. The unique feature of this present profile is the development of an inner channel reaching a maximum depth of 24.9m. The 86m wide inner channel extends 4m deeper than an underwater bench on the right slope of the thalweg zone. The irregular bed topography displays several mounds and troughs averaging 1m high and 30m wide.

Figure 34 is the sounding profile produced by the Raytheon sub-surface sounder at cross-section 36. The image shows a u-shaped profile with a wide shoal on the right bank. A dark subsurface lineation (shown by arrow) below the right channel margin is interpreted as the sand contact noted in the geotechnical section (section 4.2). It is interesting to note that this contact is at the same depth as the channel bed, suggesting a possible resistant layer given the present hydraulic conditions at this location.

Cross-section 37 displays a deep u-shaped morphology (Figure 35). At this site, while the bank has remained stable, the 400m wide thalweg zone has shifted 150m towards the left bank and deepened by 7.7m between 1975 and 1990. The shift has resulted in the development of a symmetrical form compared to the previous asymmetrical form. The large

Plate 4: OBLIQUE AERIAL VIEW OF CROSS-SECTION LOCATIONS

Figure 33: CROSS-SECTIONS 33 - KUMAK CHANNEL



- - - - Slaney, 1975
(formerly Slaney 30)

—— GSC, 1990
(formerly Slaney 30)

Figure 34: RAYTHEON PROFILE OF CROSS-SECTION 36

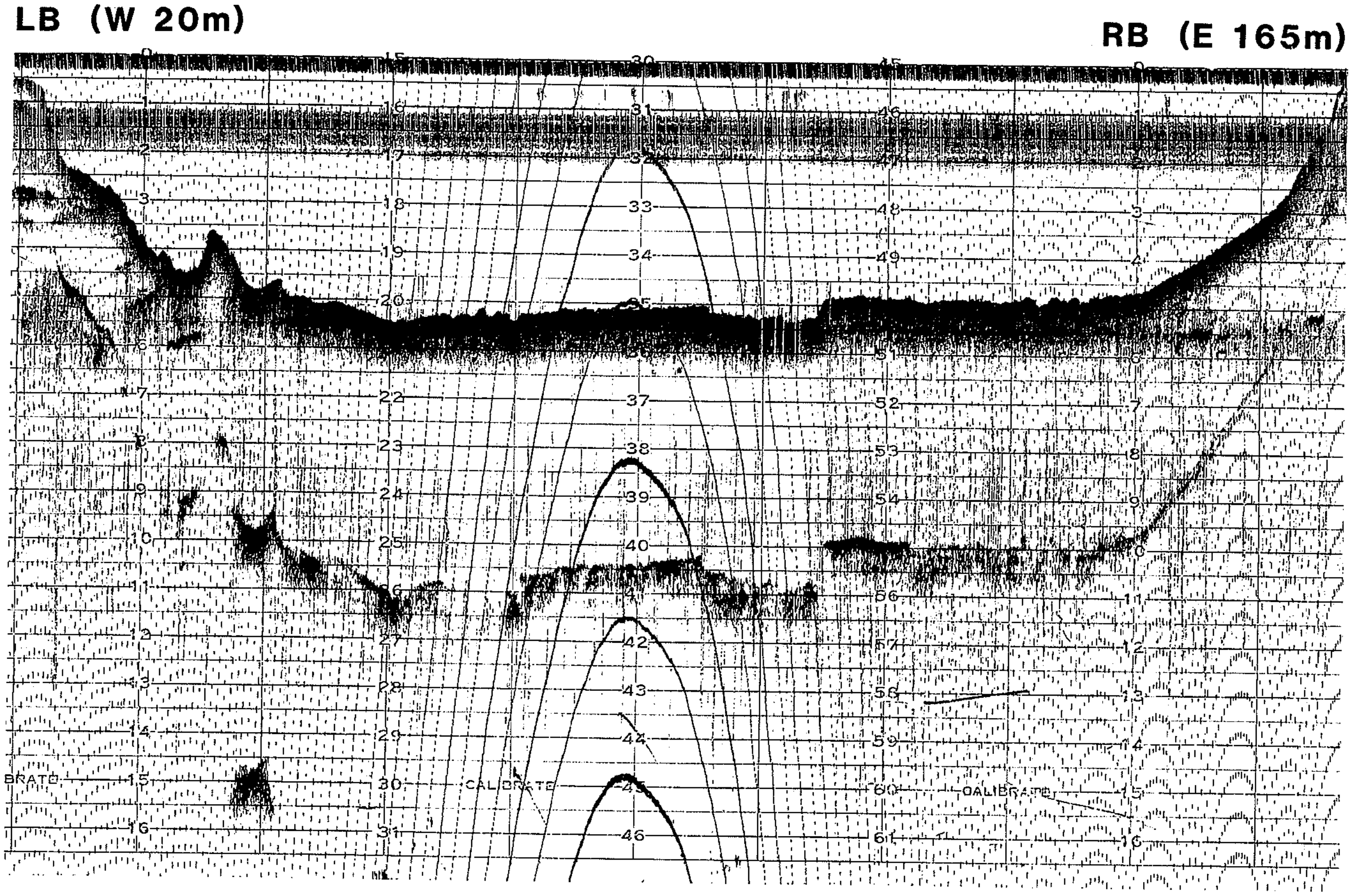
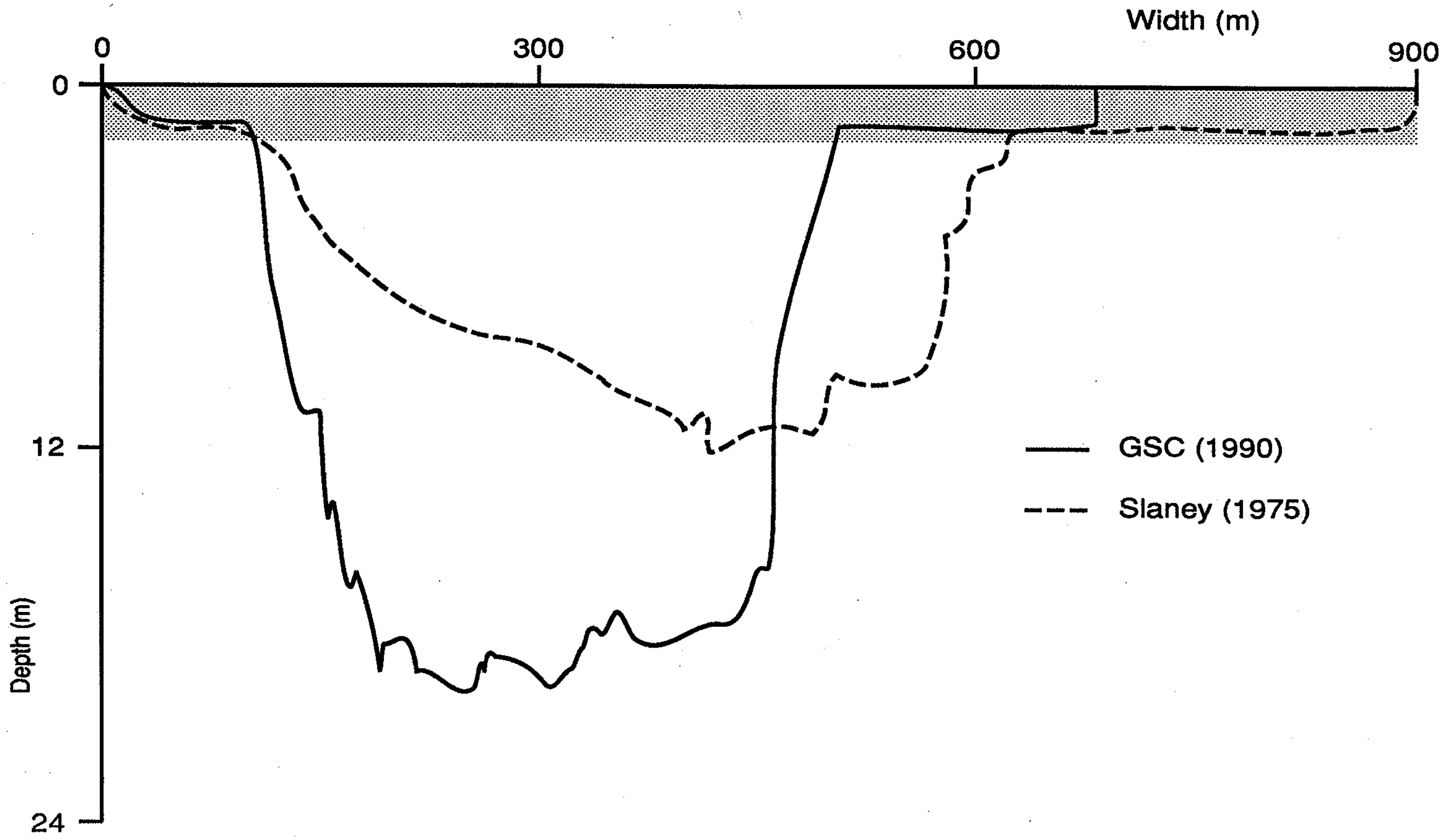


Figure 35: CROSS-SECTION 37 - Kumak Channel



shoal on the right bank has widened by 120m. The channel bed is irregular with mounds averaging 50m wide and 2.5m high.

Cross-section 40 is a comparative profile of 3 cross-sections recorded 17 years apart (Figure 36). The channel outline trends towards a deepening of the thalweg from 14m to 20m, an increase of 0.35 m/yr. The asymmetrical thalweg zone has enlarged in conjunction with the increase in depth. The steep right slope remained fairly stable while the left slope increased in steepness. Shoals extend 62m and 92m from the left and right banks, respectively. The asymmetric profile characterizes a pool morphology near the apex of a meander bend.

Cross-section 45 was surveyed at the downstream end of a meander bend leading into a 1km straight reach (Figure 37) Comparative profiles surveyed over 15 years illustrate a channel shift (27.5m) towards the right bank while maintaining the same overall width (270m). The thalweg zone has been reduced which has resulted in the extension of the left bank shoal to 98m. The maximum depth of 22.1m represents only a 0.5m reduction, however the profiles indicate aggradation of the channel bed. The cross-section morphology is indicative of an asymmetric form.

The farthest downstream profile is cross-section 47, which is located at the downstream end of a straight reach (Figure 37). The channel cross-section outlines a symmetrical form with a convex bed and two troughs below each channel bank. The maximum depth (12.0m) occurs in the right trough where an irregular bed compared to the left scour indicates active erosion. This suggests a shift in the thalweg as it enters a downstream meander. Steep slopes are noted along both channel banks. The thalweg zone

Figure 36: CROSS-SECTION 40 - Kumak Channel

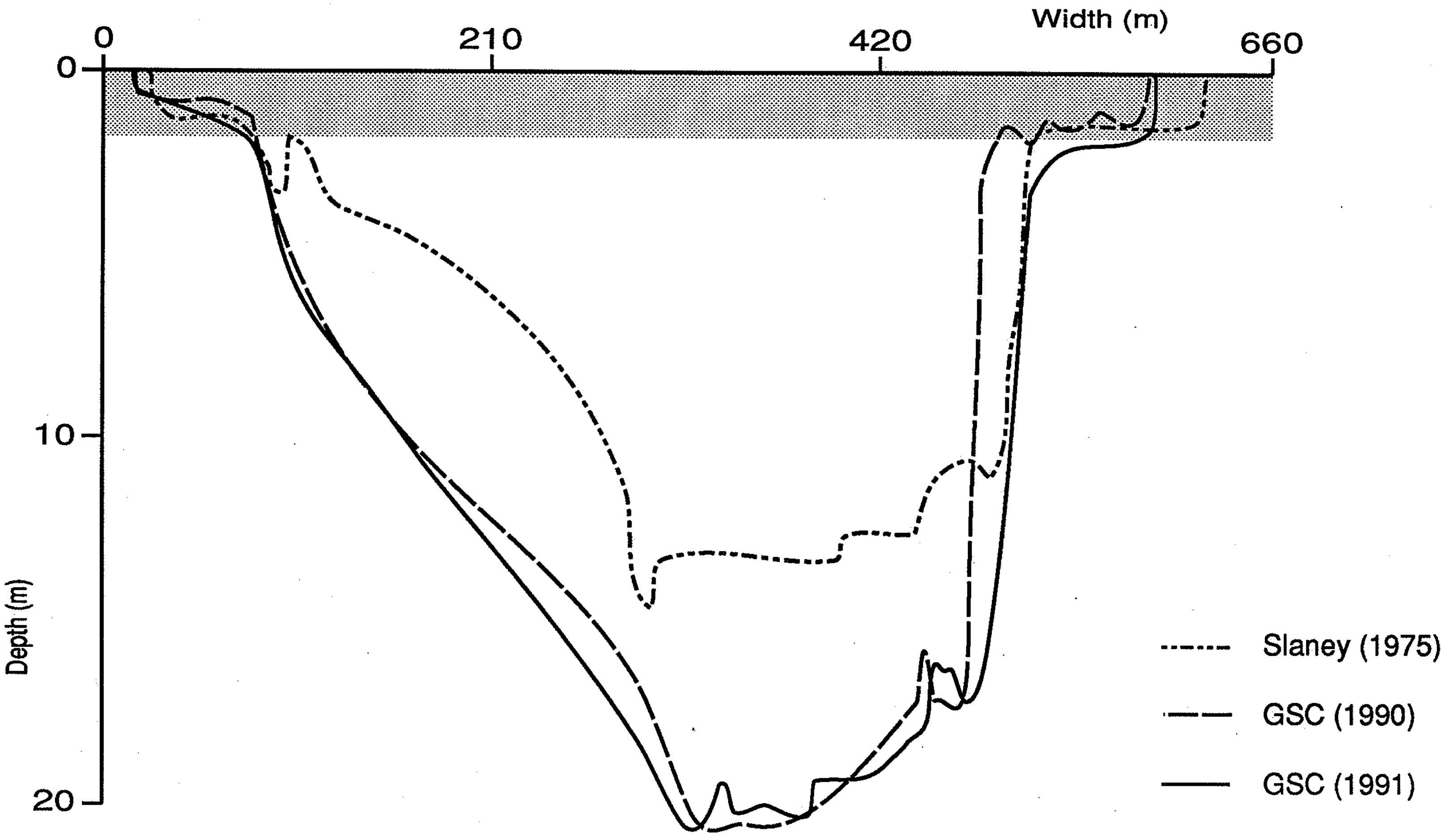
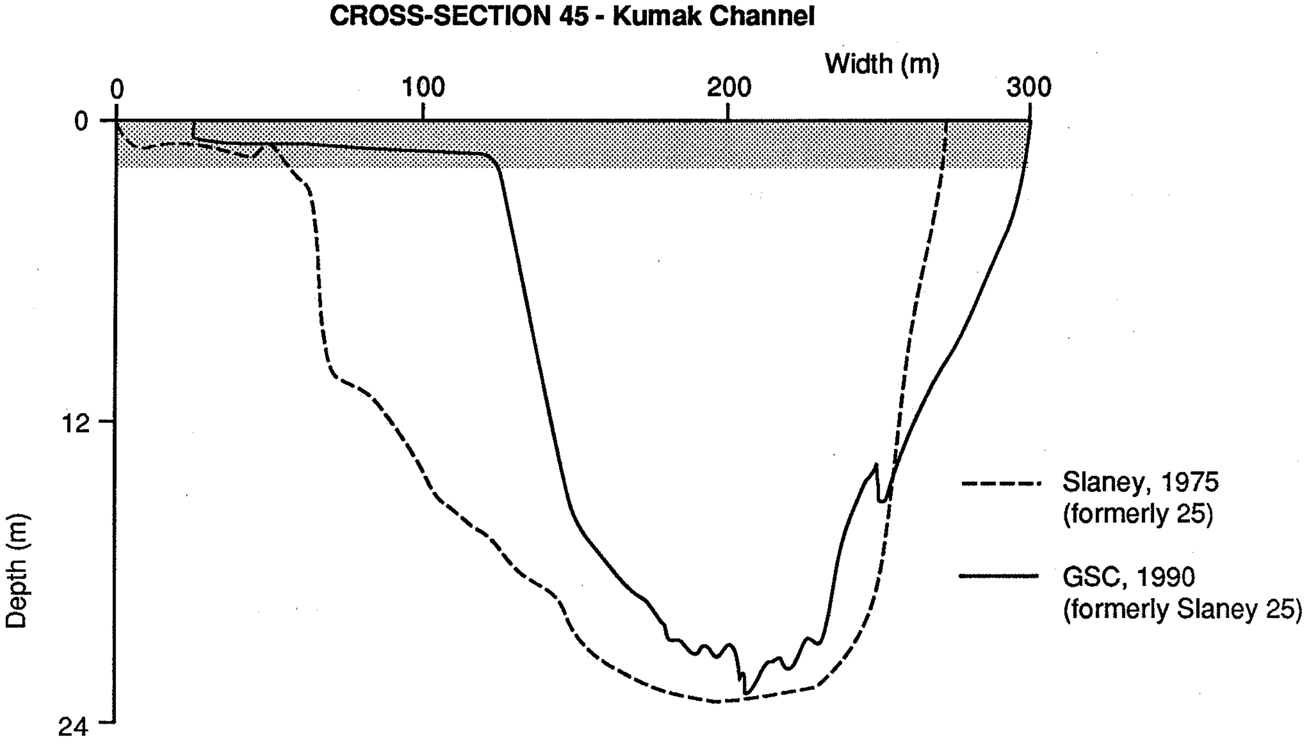
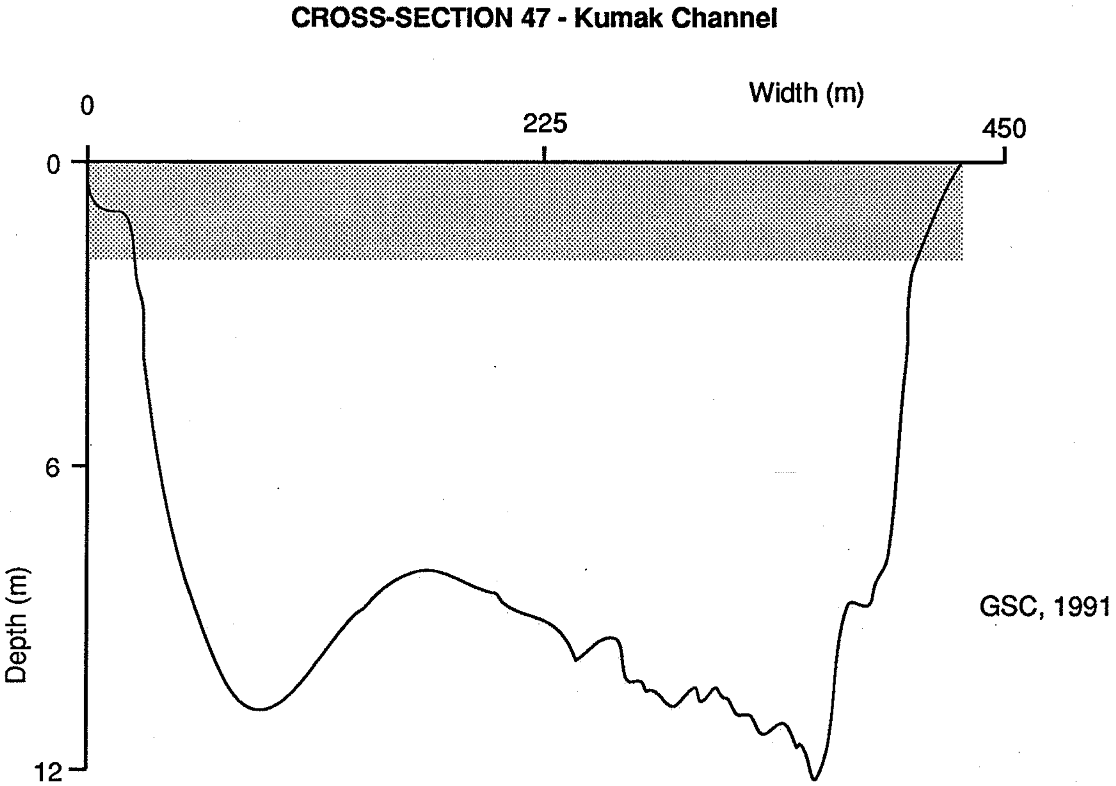


Figure 37: CROSS-SECTIONS 45 AND 47





encompasses the entire width (434m) of the channel except for a minor 19m shoal. Both channel banks above the water line are vertical with a height of approximately 1m.

4.6 Ice Conditions

Winter conditions and flow differs markedly from the summer flow regime in the Niglintgak study site. Middle Channel, north of the Kumak junction, is assumed to be covered by bottom-fast ice for most of the winter. Spot measurements, in April, of flow in Kumak Channel (Slaney, 1975) record flow at one-fifth the summer velocity (Slaney, 1975). Many of the shallow contributing channels, such as Aklak channel, are dormant in winter, constrained by bottom-fast ice. Sub-ice water temperature profiles ranged between -0.2°C and -0.3°C indicating isothermal conditions top to bottom (Slaney, 1975).

Relatively little is known about the ice jamming conditions in the vicinity of the Niglintgak site, however, the combination of high velocities, gentle bend curvatures, and a deep thalweg zone reduces the potential for ice jamming at least for Kumak Channel. The only ice jams observed in the study area were located along Aklak Channel (Slaney, 1975).

4.7 Bedforms and Fluvial Processes

Meander bends represent the most dynamic segment within the reach. The potential for erosion is greatest at these locations. Cross-sections 28 to 33 highlight the initial meander bend as Kumak Channel branches off Middle Channel. Middle Channel is shallowing, resulting in a diverging of flow into Kumak channel (Plate 5). Both the bank retreat rates and channel depth increase reflecting adjustments to channel form required to

Plate 5: MID-CHANNEL BAR BLOCKING FLOW TO MOUTH OF MIDDLE CHANNEL

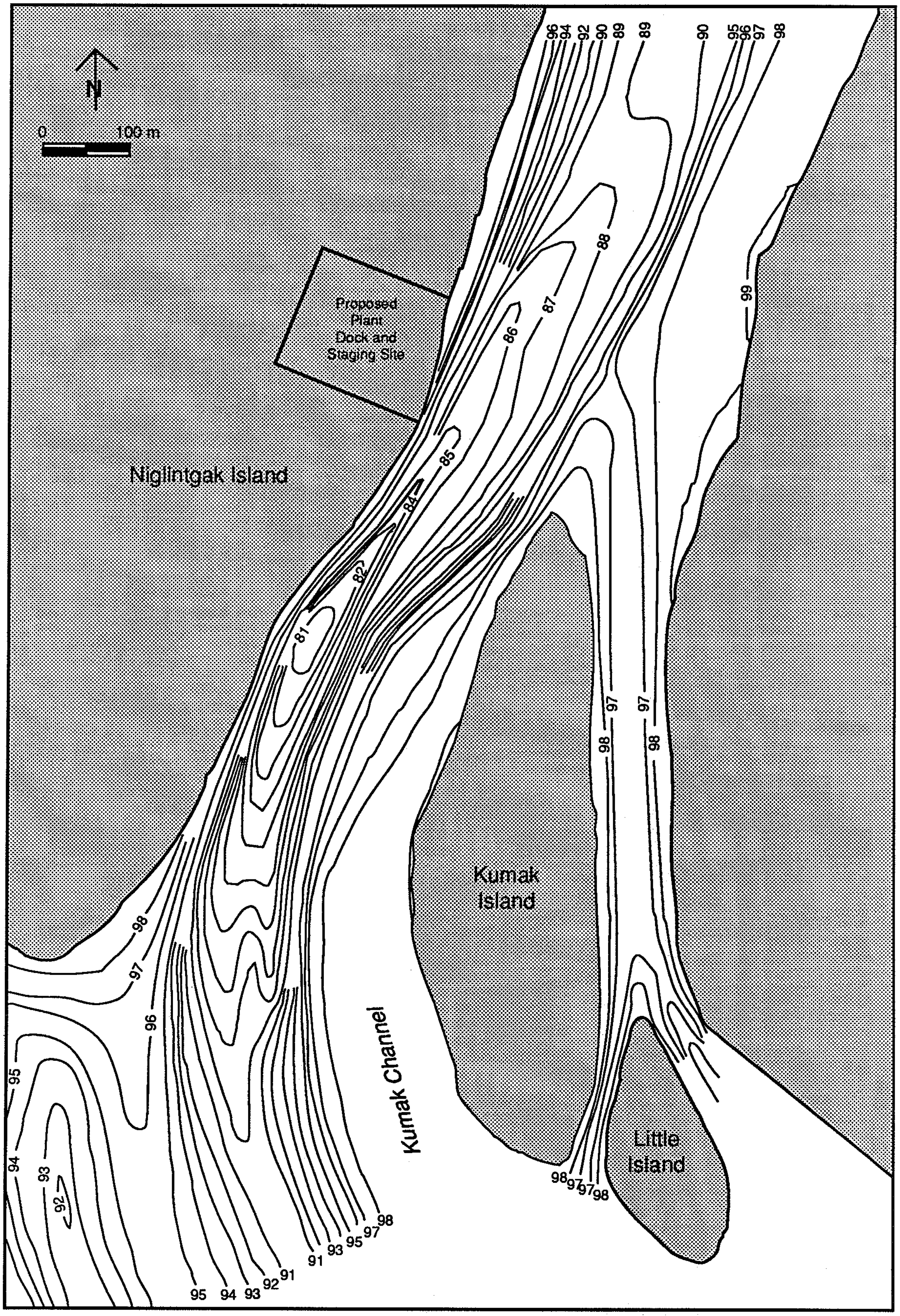
accommodate the increased discharge. The pool is enlarging in depth and the thalweg zone width is also increasing. The deepest segment is located at cross-section 33. The scour pool is linear (Hardy and Associates, 1977), in contrast to the hole and mound bed morphology found along Kuluarpak Channel (Figure 38). This linearity likely results from the significant erosion and large discharge at this site.

The concentration of flow on this outer bend has created channel deepening and is in fact forcing the issue. The only restraint on erosion appears to be the ice-bonded banks. The scour hole is lengthening downstream and deepening.

Downstream, especially identified in cross-section 40, there has been a significant increase in scour depth around the bend with cross-section 40 being the locus of the bend. Continuing downstream, the channel shallows and appears to resume a normal course of events. However, no time-lapse profiles are available to make an accurate estimation of change.

Kumak Channel is being significantly altered through the channelling of Middle Channel flow through the hydraulically underfit Kumak Channel. The morphology is changing as rapidly as the physical environment will allow. The main thrust of change occurs during the peak run-off which happens only once a year. The remainder of the time the channel is reacting through minor changes to the major yearly change and seasonal erosion, i.e. some thermoerosional niching along channel banks.

Figure 38: MACROBEDFORMS - KUMAK CHANNEL



5.0 DISCUSSION

5.1 Fluvial Geomorphology of Taglu and Niglintgak Sites

The fluvial processes described in the Taglu and Niglintgak sites are complex because of the large number of variables and their interrelationship. While the two sites contrast in flow volumes and surficial setting, they display many similarities. Some of the main characteristics displayed at these sites are discussed below;

5.1.1 Channel Stability

Both sites display high rates of localized bank and channel erosion. At the Niglintgak site, an active scour zone has been identified where the flow from Middle Channel is diverted into Kumak Channel. Bank retreat rates averaging 2.2 m/yr at this bend have been measured since 1950, while resurveying of bathymetric cross sections indicate up to 10m deepening of the channel and 150m lateral migration of the thalweg zone. This thalweg migration at the bend has also resulted in substantial bed change several kilometres further downstream. These high rates of change over a relatively short period demonstrate the general instability of the upper Kumak Channel area in response to the flow constrictions at the Middle Channel/Kumak Channel junction. This trend can be expected to continue in the future.

At Taglu, the rates of bank retreat are similar but the channel erosion and adjustment have been less due to lower flow rates. The main areas of significant channel bed change are centred on Harry Channel south of the Harry Channel/Kuluarpak Channel bifurcation and in the upper portions of Kuluarpak Channel. Harry Channel, downstream of the confluence, shows evidence of shallowing as a result of reduced flow.

Ancillary channels including stream channels, lake channels and reversing channels are common at each site, however, because of their limited cross-sectional areas and shallow depths they are expected to be relatively stable.

5.1.2 Winter ice conditions and break-up period

Bottom-fast ice

Because of the extensive shallow water areas common in the ancillary channels such as lake channels and reversing channels and in the main channels where flow has been diverted (Middle Channel north of Kumak Channel), ice cover during the winter has a dramatic effect on both winter and breakup flow characteristics of both study sites. The 1.5 to 2m isobath is critical for channel dynamics in this regard, since it, in general, is the depth of annual winter ice. These areas can be expected to be covered by bottom-fast ice effectively stopping winter flow or dramatically restricting it to the deepest part of the thalweg zone. Where bottom-fast ice is present for a significant part of the winter, sediments beneath the channel may freeze bonding the ice to the sediment and possibly inducing permafrost aggradation. Permafrost has been observed for instance, in drill holes in the shallow benches along the main channels.

Bottom-fast ice and the ice bonding of shallow bottom sediments is important for several reasons. Immediately following break-up, bottom-fast ice is frozen to the base effectively protecting these areas from fluvial erosion and ice rafted scour. With time the bottom-fast ice will melt, however, the bed sediments will be ice-bonded and much more resistant to erosion than the adjacent thawed sediments in deeper water. This process can be expected to stabilize shoal and bank areas relative to the thalweg zone.

Ice jams

Ice jams can be expected at both sites, especially in the vicinity of abrupt bends such as the Harry Channel/Kuluarpak Channel bifurcation. These jams have flow implications both upstream and downstream. In some instances, flow can be expected to be confined such that substantial overland flooding occurs. In other instances, enhanced scouring may occur due to increased flow velocities. In addition, jams often break-up catastrophically causing substantial ice block erosion of banks and scouring of bed topography.

5.1.3 Role of Pleistocene Uplands

Unlike areas of the Mackenzie Delta to the south and west, channels in the vicinity of the Taglu and Niglintgak sites have been influenced by outliers of older Pleistocene sediments which may occur as uplands or may occur at a shallow depth beneath the delta plain sediments. The Pleistocene sediments are typically much coarser grained consisting mainly of a pebble-rich diamicton or coarse sand and gravel. Pleistocene sediments may also be ice rich with retrogressive thaw slides in some instances massive ice.

The role of uplands in terms of channel development, is two fold, they can control channel migration and they introduce a coarse fraction in to the bed load of the channels. In terms of channel migration, upland areas at both sites effectively limit erosion on one side of the channel and force flow around them. In addition as discussed earlier, there are subbottom reflectors at both sites that may indicate buried Pleistocene sediments. These units restrict depth of scouring because they are more erosion resistant than the deltaic sediments. In terms of bed load, a coarse boulder beach, generally occurs where the alluvial plain intersects the upland. In addition, coarse sand and fine gravel is likely redistributed downstream.

5.1.4 Role of Permafrost

Deltaic and Pleistocene sediments occuring subaerially in the vicinity of the two sites, are underlain by permafrost. Typically, both sediments can be expected to contain substantial amounts of excess ice especially in the upper 6m. Ice may occur in a variety of forms including thin horizontal lenses,irregular veins and inclusions, ice wedges and in the case of the Pleistocene uplands anomalous bodies of more or less pure ice. This has substantial implications for the development of channels in the area. Because the upper 6m of sediment typically contains 50% by volume excess ice, this means that eroded bank material actually only contributes half its volume as sediment to the bed. In addition, once the channel has eroded the bank material to a depth greater than 2m (maximum winter ice thickness) permafrost can be expected to begin to degrade resulting in thaw settlement of the bed. If even a modest ice content of 10% by volume is assumed for these sediments, the implication is for every 10m of thaw, there will be 1m of thaw settlement. This may to some degree account for some of the rapid bed adjustments and scour rates noted at each sites and reported in other areas of the Mackenzie Delta.

5.2 Implications for Pipelines and Shore Based Facilities

Development structures planned for the Taglu and Niglintgak sites are likely to include shallow founded structures such as pipelines, pump stations and dock sites and deep foundations such as production wells. Because of the numerous channels located in the vicinity of the Taglu and Niglintgak hydrocarbon reservoirs, design information on the stability of the channels, surficial sediments and permafrost conditions is critical.

5.2.1 Channel stability

Initial design scenarios for pipeline crossings proposed by industry for the Taglu and Niglintgak areas in the early seventies called for burial beneath the bed below the depth of estimated maximum scour during the design life of the structure. Due to a lack of quantitative data, this value was generally chosen somewhat arbitrarily and was typically equal to 1.5 to 3.5m (EBA, 1974). The results of this study have allowed quantification of many reaches in the vicinity of the two fields and have demonstrated exceptionally high rates of local scour in some areas. Rates such as 0.51 m/yr at Niglintgak would likely require burial at least 13m beneath the bed and burial 55m inland of the present channel bank to protect a pipeline during a 25 year operating period. Similarly, land-based production facilities would have to be set back a considerable distance from the bank in these areas. Unstable areas, however, have been shown to be relatively limited and more or less predictable based on a study of bank stability and the general character of river hydrology. In most instances, a modest change in the pipeline route would avoid unstable areas.

5.2.2 Thaw Settlement and Frost Heave

An important consideration in the design of structures in the vicinity of the Niglintgak and Taglu sites is the influence of the structure on the ground thermal regime. Structures such as warm oil pipelines and production wells can be expected to cause local permafrost degradation. In the case of channel crossings, the top of permafrost is close to the surface beneath shallow benches where seasonal river ice is bottom-fast but it drops off at a steep angle beneath deeper parts of the channel. A warm pipeline would induce melting where the permafrost is close to the surface. Because surficial sediments may contain in excess of 50% by volume excess ice, thawing of the permafrost will induce vertical displacement and pipe strain. In terms of river hydraulics, thaw settlement in the vicinity of the pipeline may locally deepen the channel, such that, it remains unfrozen year round. This is likely to create a local scour zone.

The converse of a warm oil pipeline would be a chilled gas pipeline. This would result in local frost heave where unfrozen sediments are encountered. Nearly all of the deltaic sediments found throughout both study areas could be deemed very frost susceptible. A reflection of the natural processes of frost heave, for instance, is shown by the high contents of segregated ice in the upper 6m which have been shown in many instances to exceed 50% by volume. Once again, the abrupt thermal transition at the edge of the deeper channels is of concern, since in this area the pipeline would be restrained within the permafrost and experience frost heave in areas beneath the channel.

5.2.3 Deep Foundations

Deep foundations, such as production wells, pose challenging geotechnical problems in the Taglu and Niglintgak areas. Although not the focus of this study, it is well known that both areas are underlain by many hundreds of metres of relic permafrost. Since formation temperatures in production zones are above freezing, the most cost effective foundation design would be a warm foundation. Very little is known about the ice content of these soils and as a result, at the present time, it is impossible to predict the amount of thaw consolidation which may result due to production. However, several important points merit consideration in terms of surface processes. The first is that because of the low elevations of these areas, any thaw consolidation resulting from single production wells (or especially the case for multiple wells) will increase the likelihood of flooding and inundation during storm surges. Likewise, settlements occurring due to hydrocarbon extraction can be expected to change the regional character of the area. Many hydrocarbon developments, such as the Ekofisk field in the North Sea (Blasco, 1989), have induced settlements of more than 1m in the vicinity of the production zone. Since many areas of the Niglintgak and Taglu fields are only 1 to 1.5 m above sea level, this may have a dramatic effect resulting in increases in standing water, changes in vegetation patterns and possibly changes in the character of channel migration.

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APPENDIX A: Other Methods Used to Obtain Cross-Sections

EBA (1974)

At least one hollow stem borehole and several dynamic cone penetrometer tests were performed at each major crossing to determine the material types and density profile of the river bed. One or two continuously cored boreholes were drilled on each bank of the crossing to determine the soil type, ice content and permafrost regime. Soundings were taken at 100 foot intervals across the channel to obtain a bottom depth profile. No geodetic link is given for the height of the ice at the time of sounding nor is there an exact locational reference.

Slaney (1976)

Measurements of channel depth and cross-sectional profiles were carried out using a portable Furuno FG 200 echo sounder and a 6 metre aluminum boat equipped with a 20 hp outboard. Channel widths were surveyed with a Topofil chain. The recorded width only measures the water surface and not the bank heights. The water levels at the time of study are linked to the Shell M-19 and Taglu G-33 wellheads where the flange is measured as 100 foot.

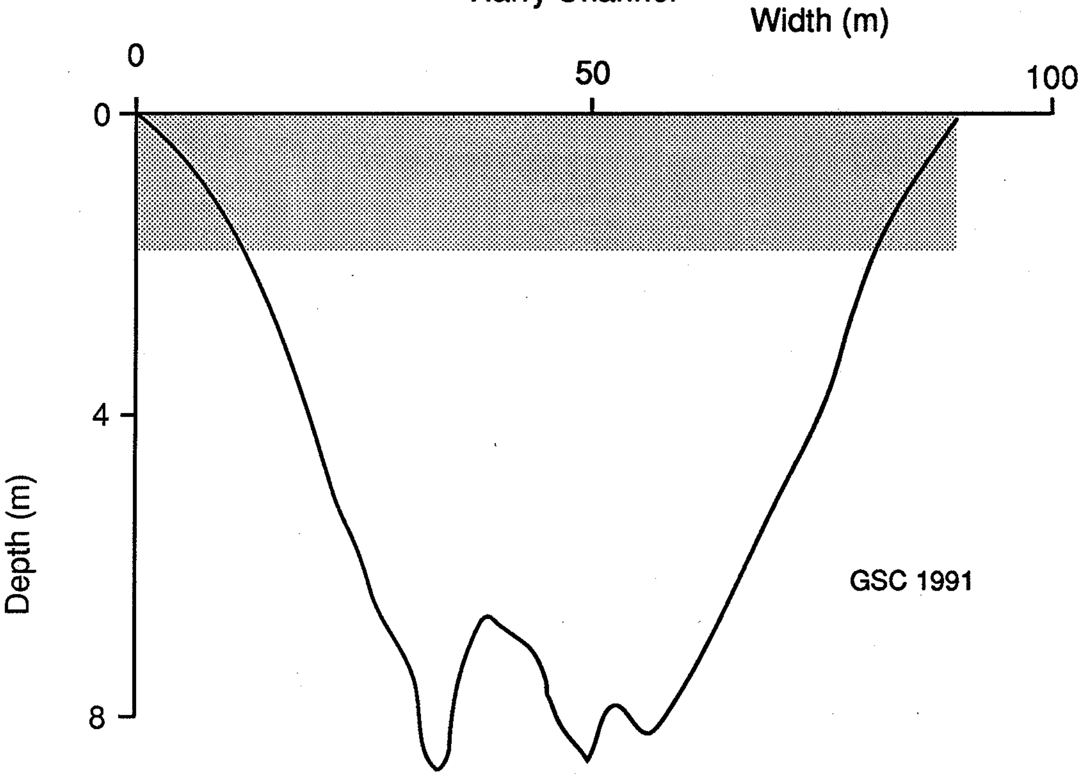
Hardy (1977)

Depth soundings were performed to determine river bed and lake bed profiles in several areas. The method used was to drill a series of holes through the ice at preestablished spacings and lower a heavy weight attached to a cable through the ice. Where sharp changes in water depth were noted, additional holes were drilled and sounded to complete the river or lake bed profile.

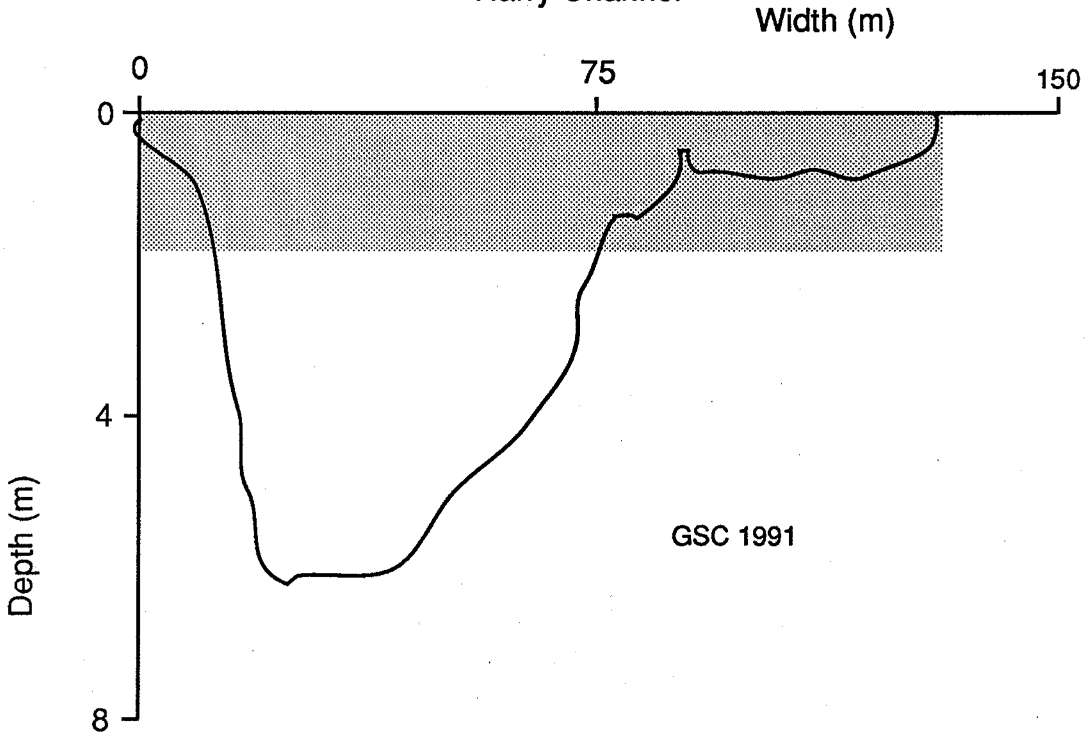
Measurements were calibrated with known water depths to make an allowance for currents in the channels. Two benchmarks were constructed at the proposed docksite location on the left bank of Kumak Channel downstream of Kumak Island. These two benchmarks were calibrated to the M-19 wellhead. All bathymetric surveys relate to these two benchmarks. However, the bathymetric surveys are either too general (Figure 37) or only record the depth along the first 50 m from the left bank.

APPENDIX B: Channel Cross-sections

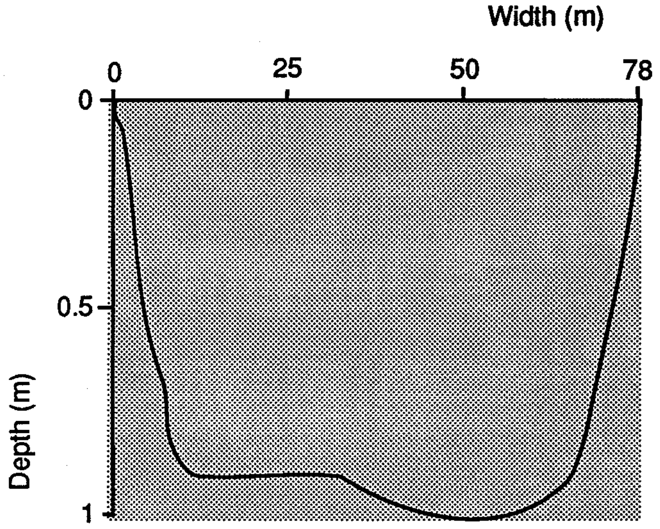
CROSS-SECTION 5
Harry Channel



CROSS-SECTION 8
Harry Channel

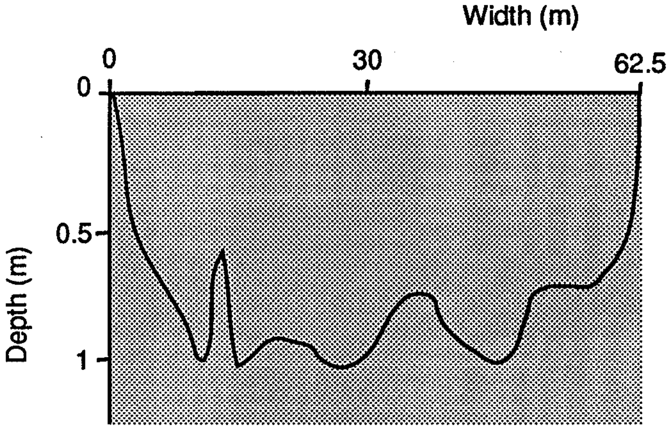


CROSS-SECTION 9
HARRY CHANNEL



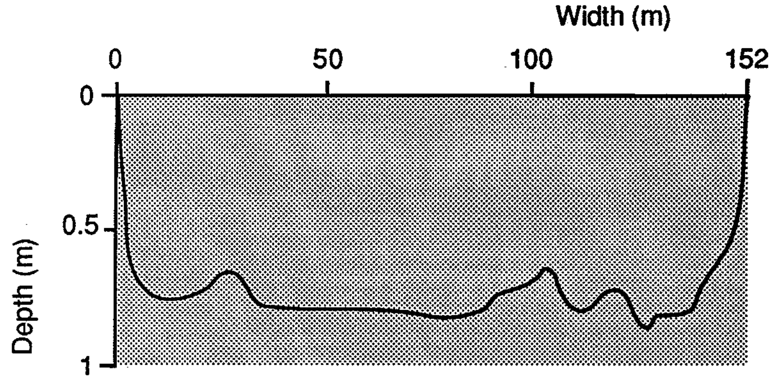
Slaney, 1975
(formerly 5)

CROSS-SECTION 10
HARRY CHANNEL



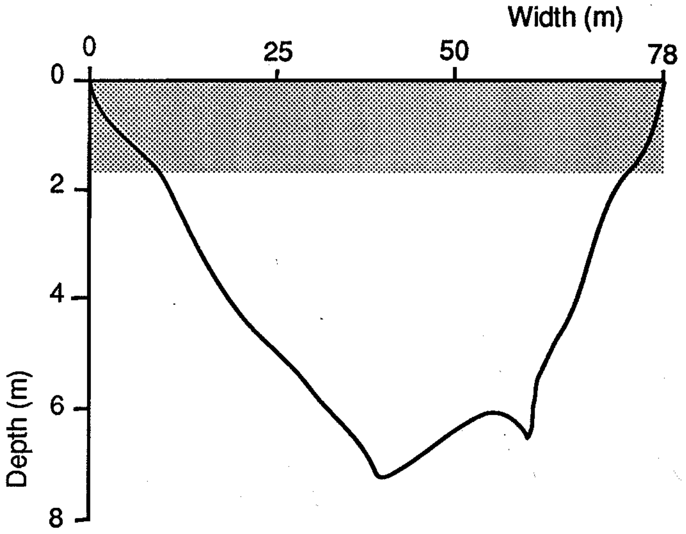
Slaney, 1975
(formerly 9)

CROSS-SECTION 12
HARRY CHANNEL



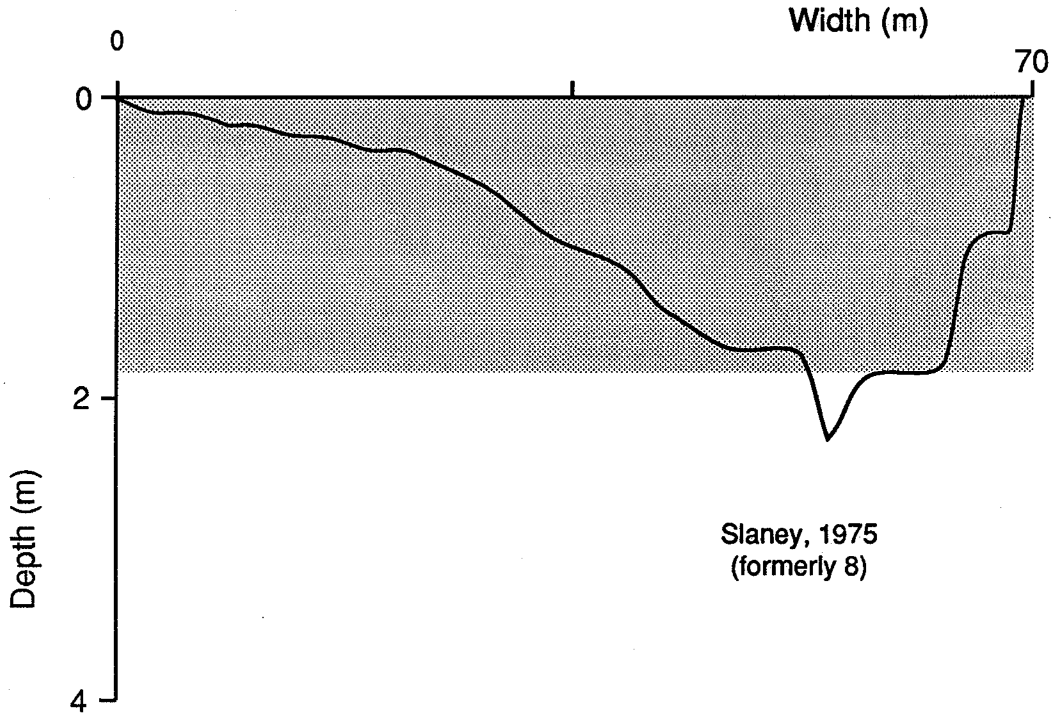
Slaney, 1975
(formerly 10)

CROSS-SECTION 17
HARRY CHANNEL



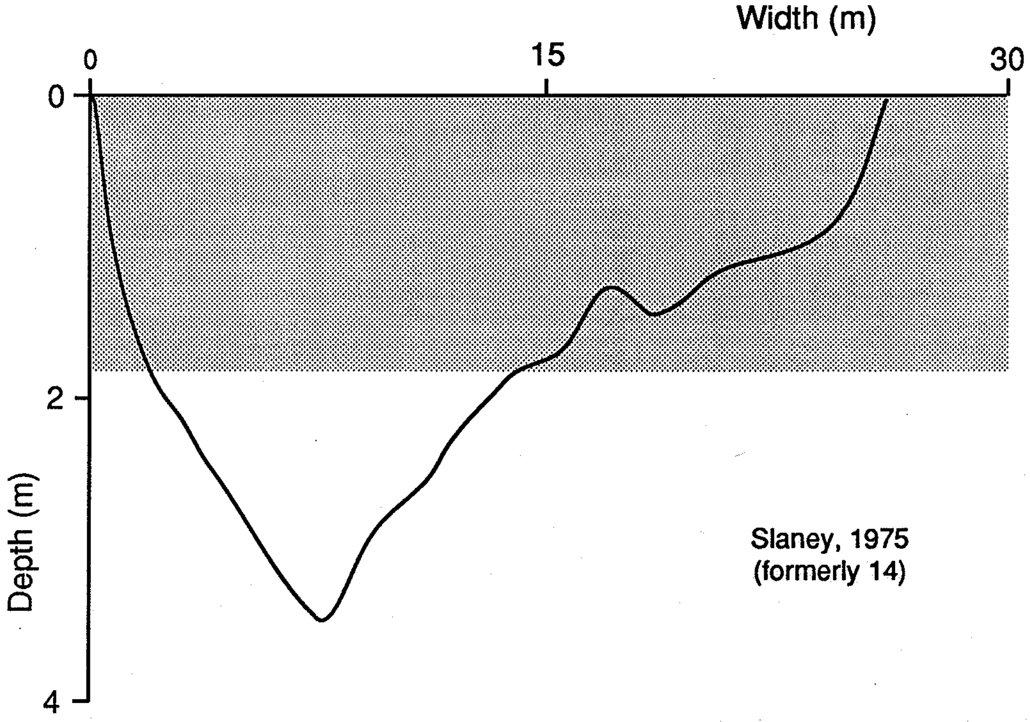
Slaney, 1975
(formerly 6)

CROSS-SECTION 18
Harry Channel



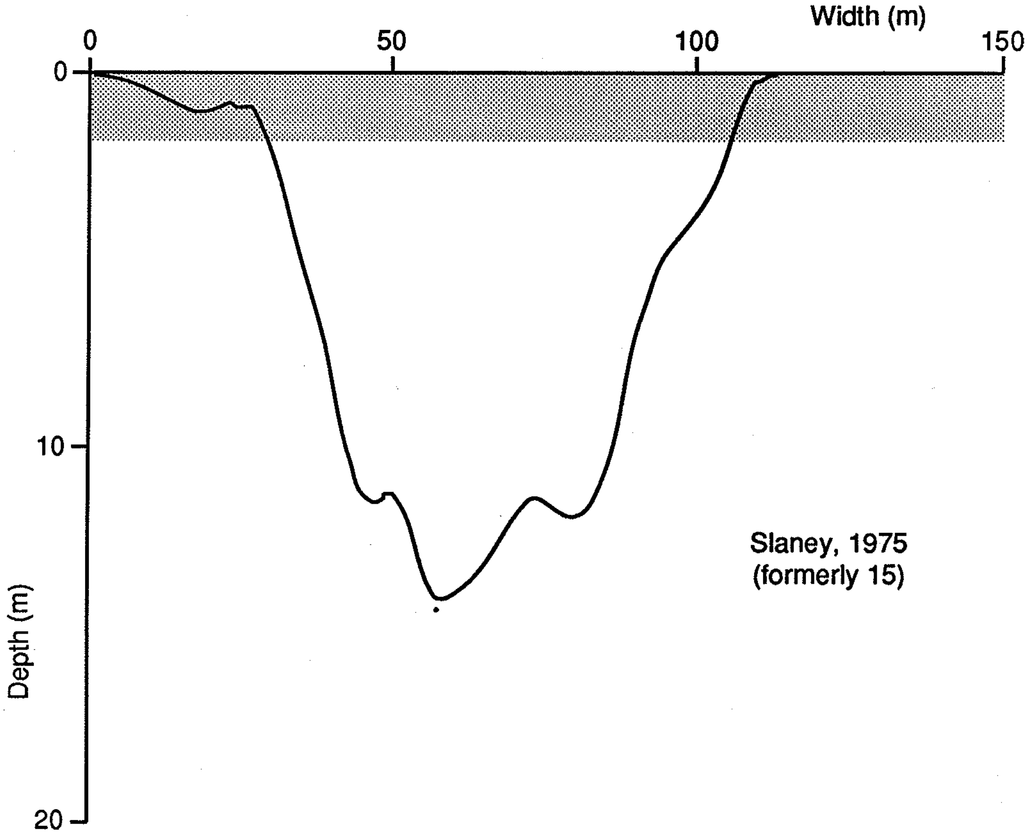
Slaney, 1975
(formerly 8)

CROSS-SECTION 19
Back Channel

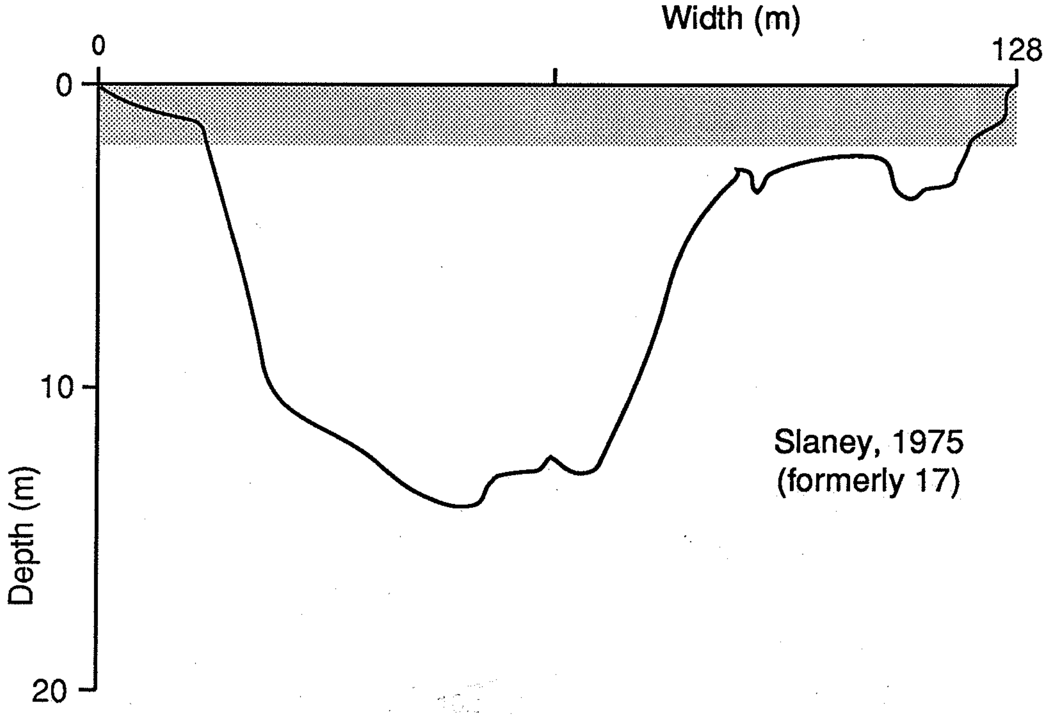


Slaney, 1975
(formerly 14)

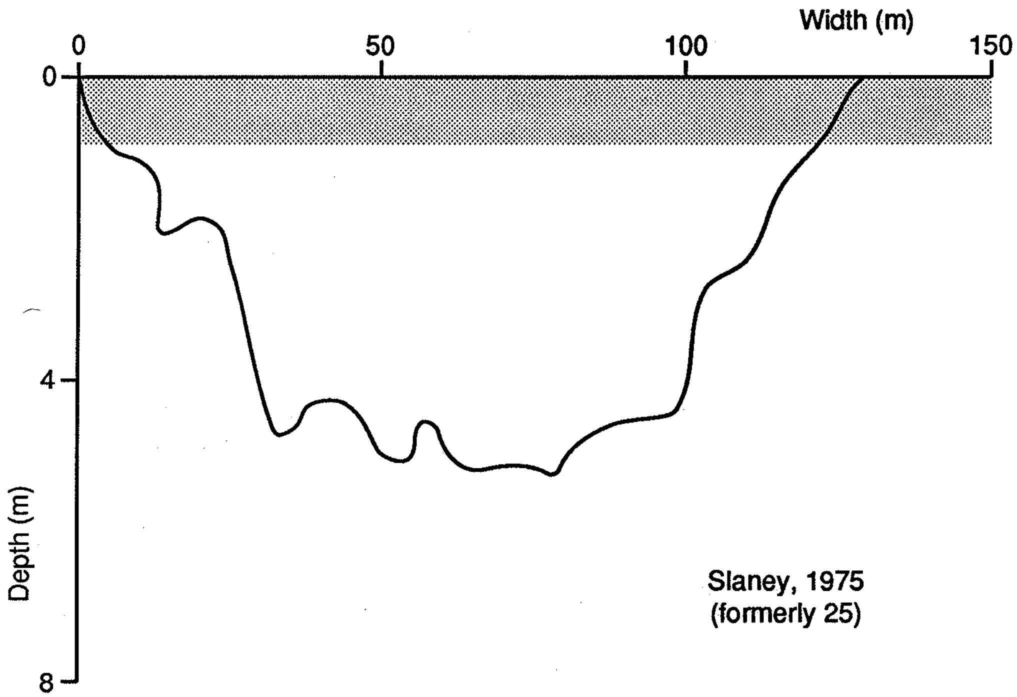
CROSS-SECTION 20
Kuluarpak Channel



CROSS-SECTION 22
Kuluarpak Channel

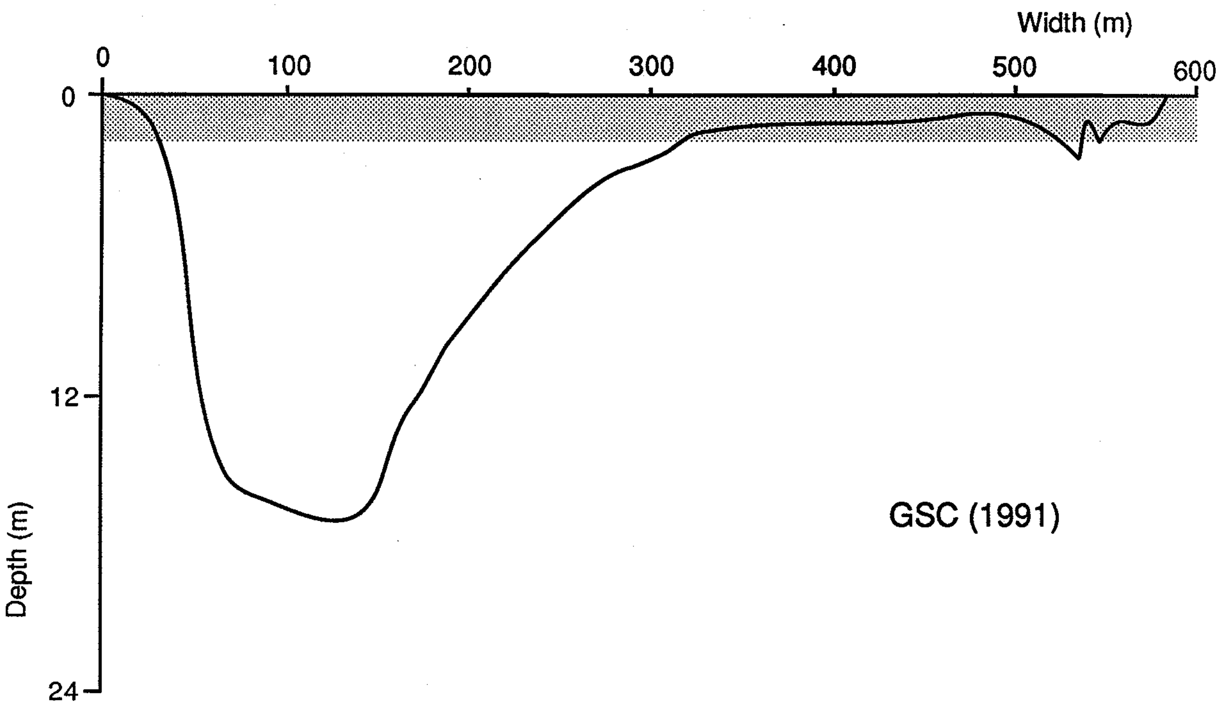


CROSS-SECTION 25
Kuluarpak Channel

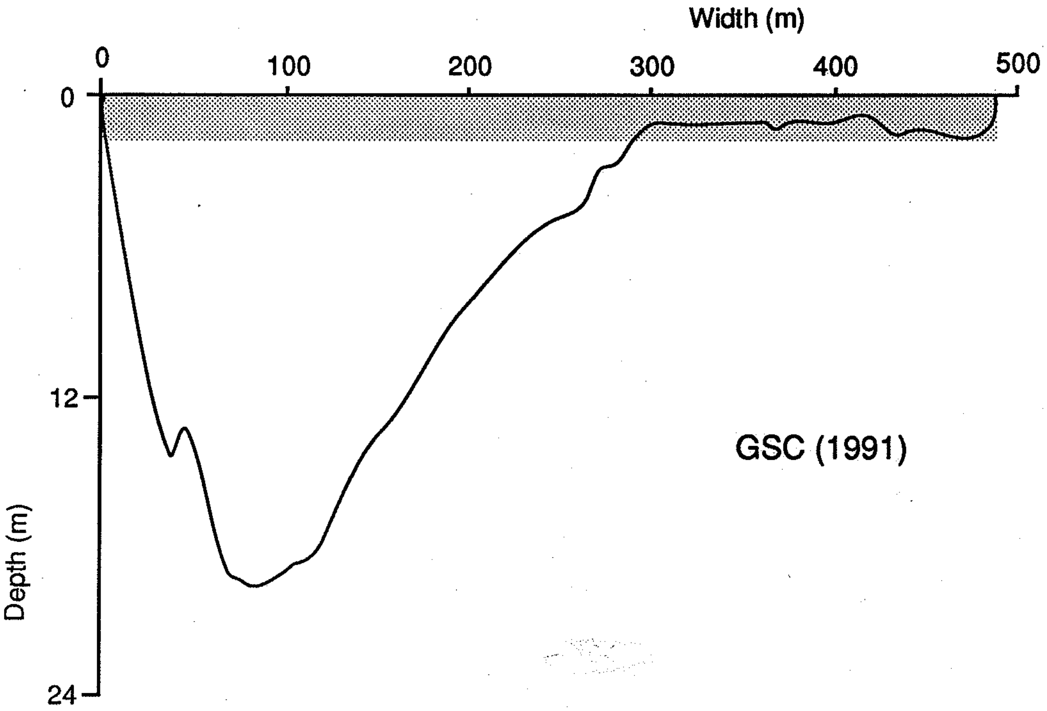


Slaney, 1975
(formerly 25)

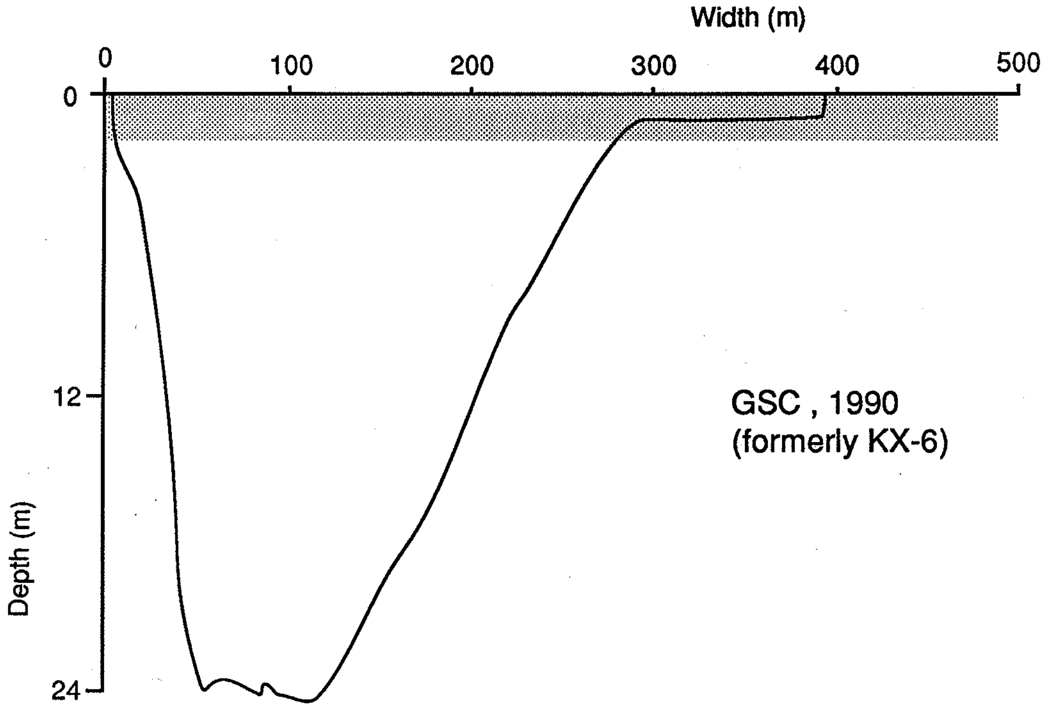
CROSS-SECTION 29
KUMAK CHANNEL



CROSS-SECTION 30
Kumak Channel

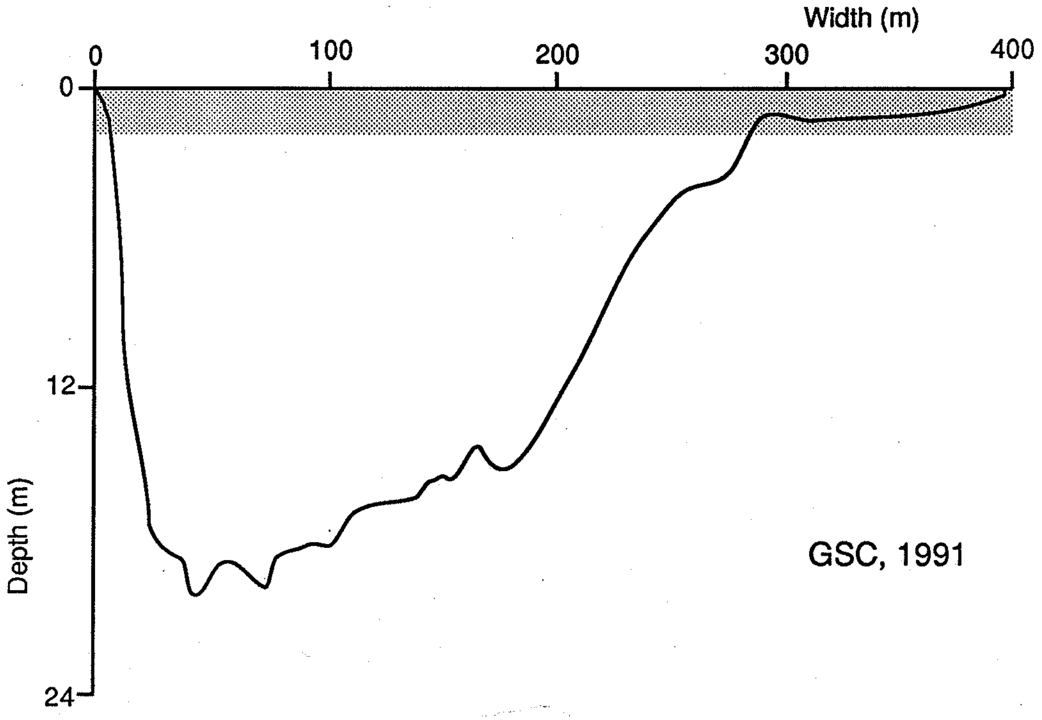


CROSS-SECTION 31
Kumak Channel



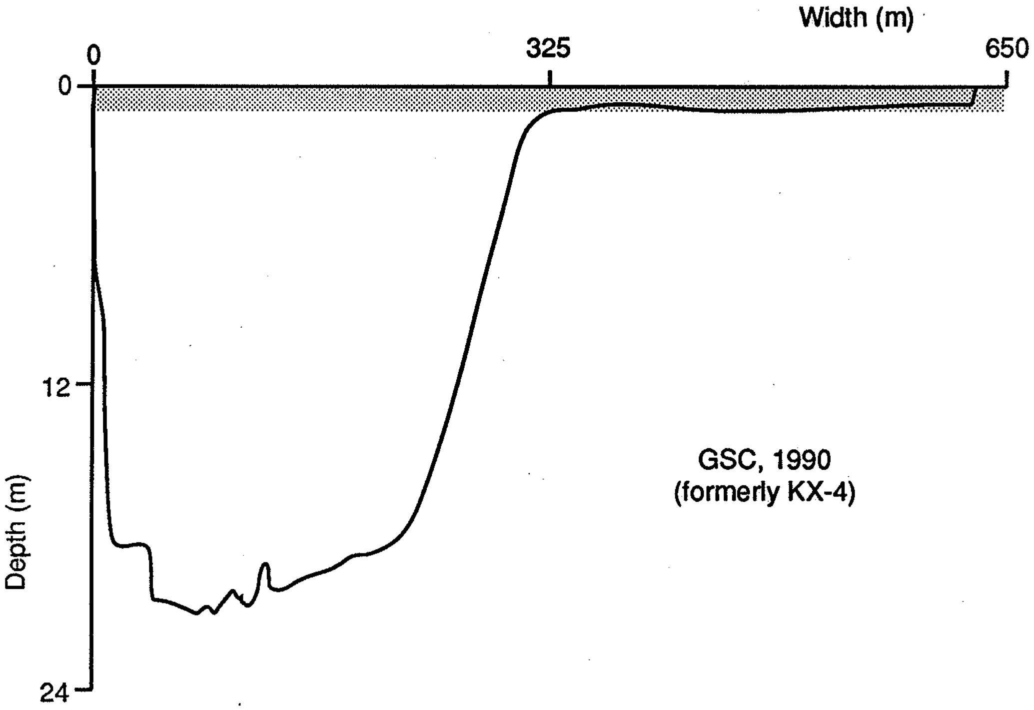
GSC , 1990
(formerly KX-6)

CROSS-SECTION 32
Kumak Channel



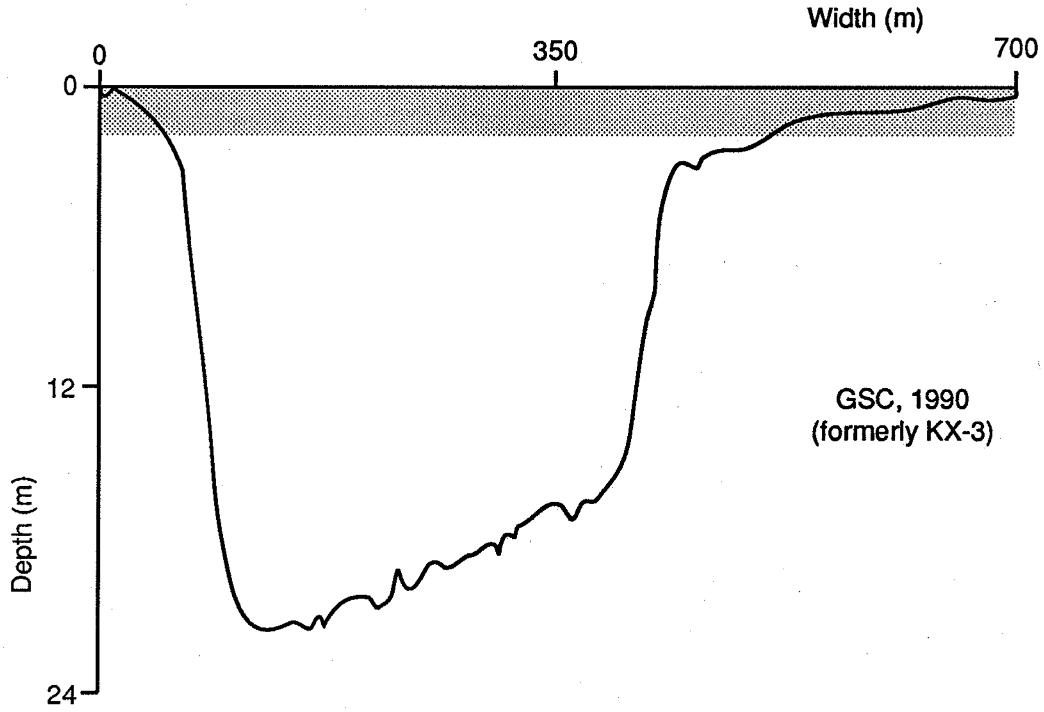
GSC, 1991

CROSS-SECTION 34
Kumak Channel



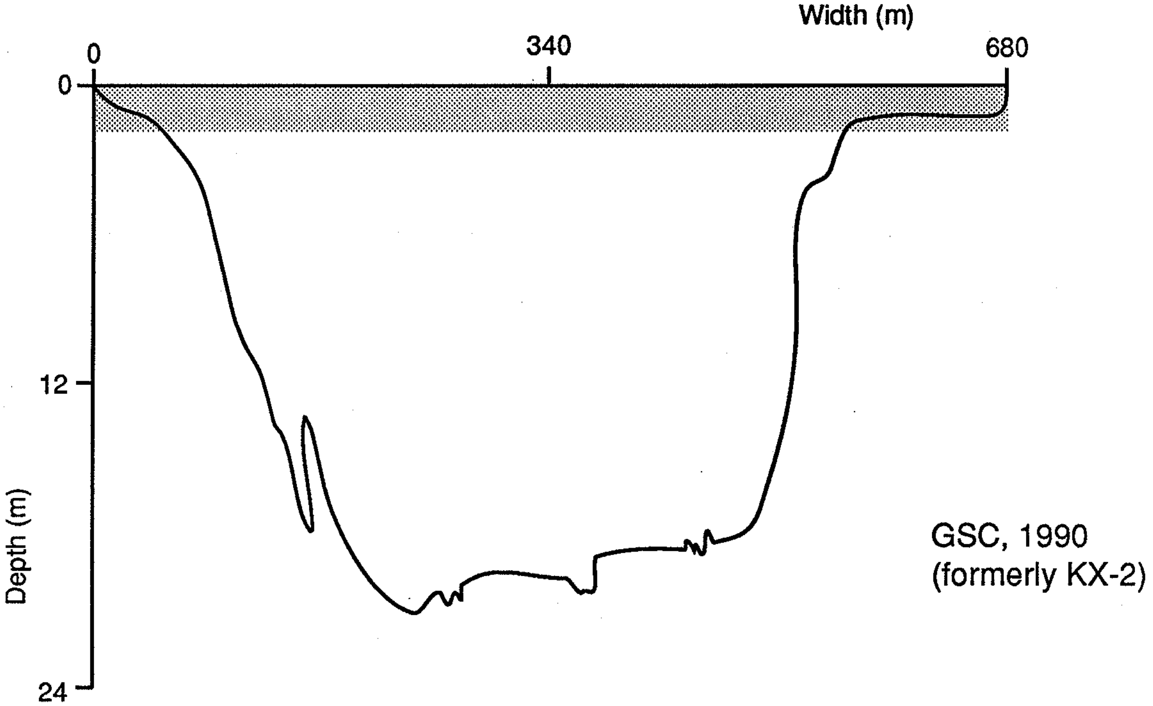
GSC, 1990
(formerly KX-4)

CROSS-SECTION 35
Kumak Channel

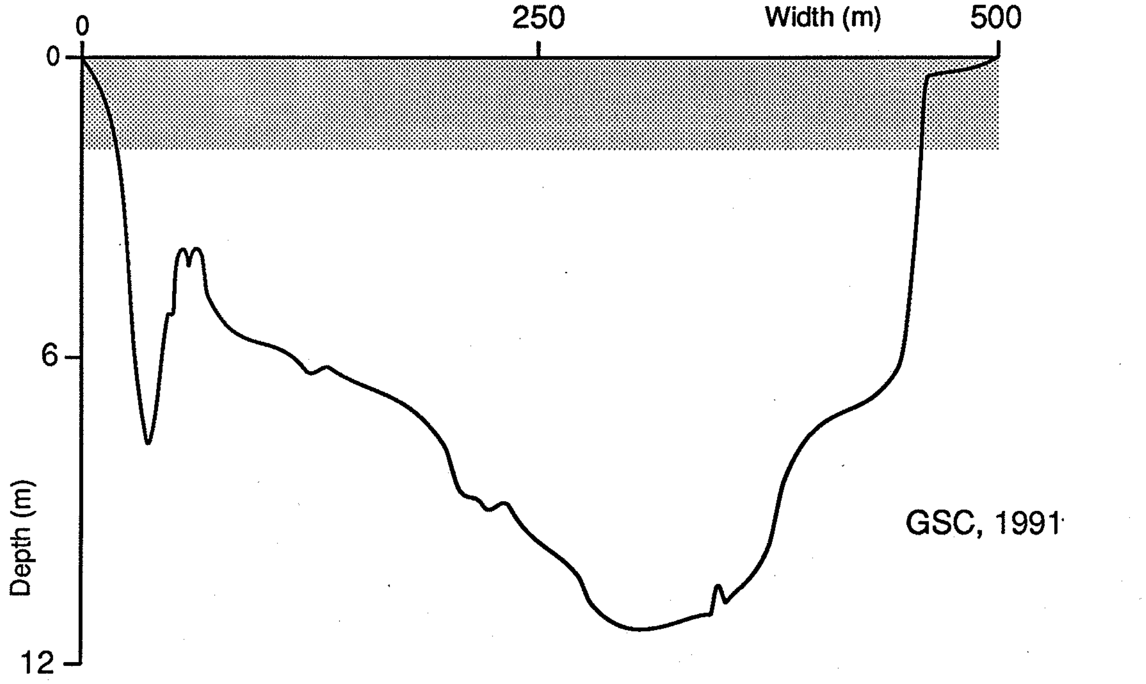


GSC, 1990
(formerly KX-3)

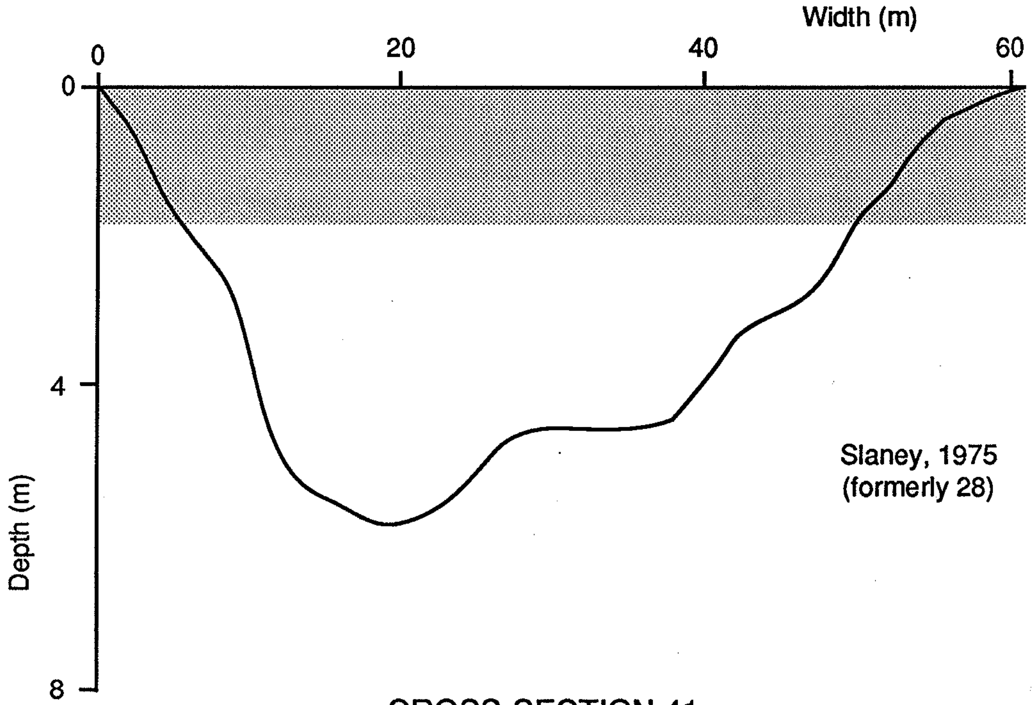
CROSS-SECTION 36
Kumak Channel



CROSS-SECTION 38
Kumak Channel

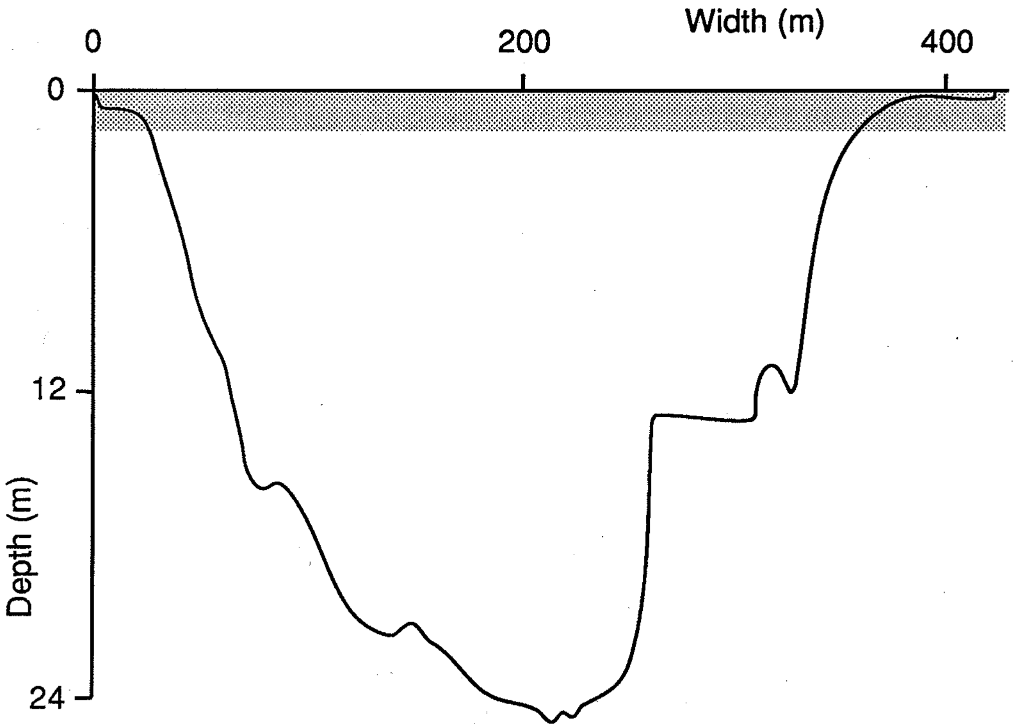


CROSS-SECTION 39
Aklak Channel



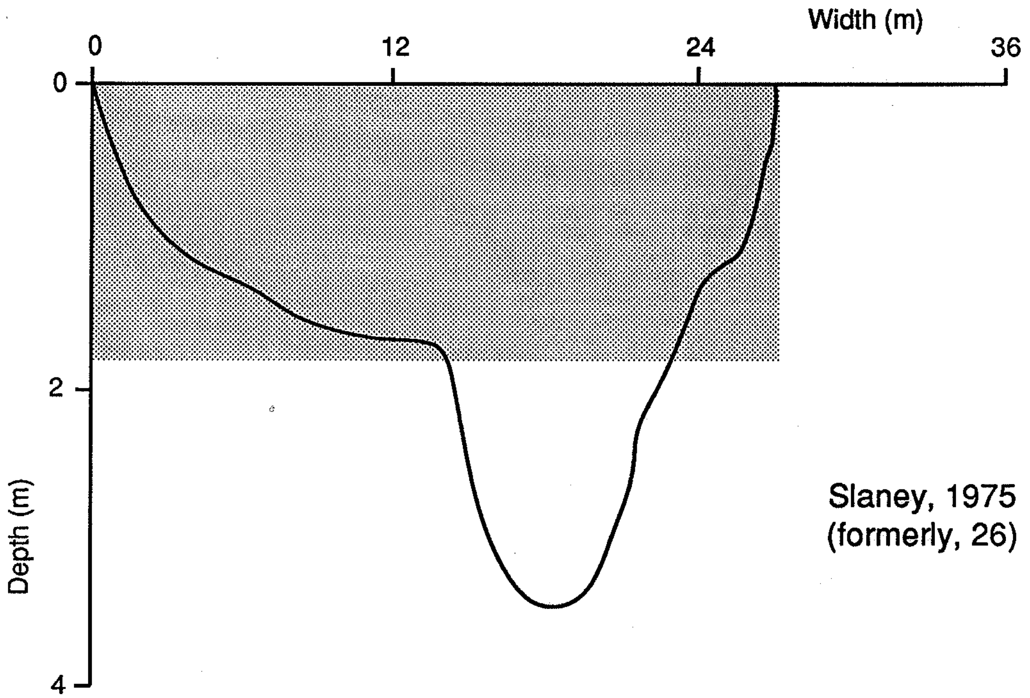
Slaney, 1975
(formerly 28)

CROSS-SECTION 41
Kumak Channel

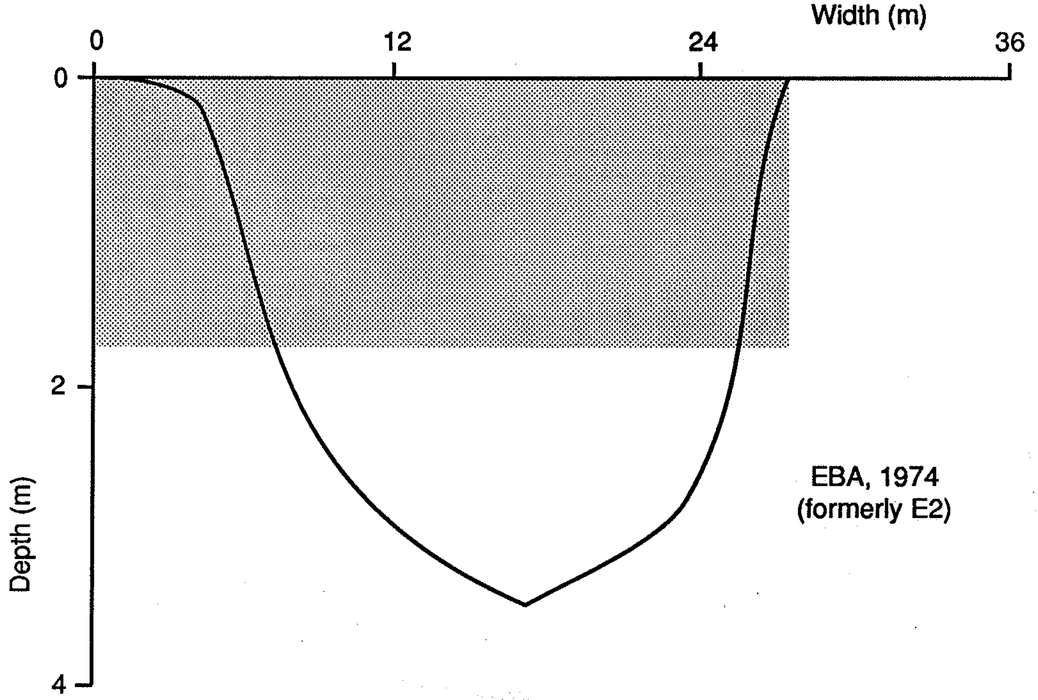


GSC, 1990

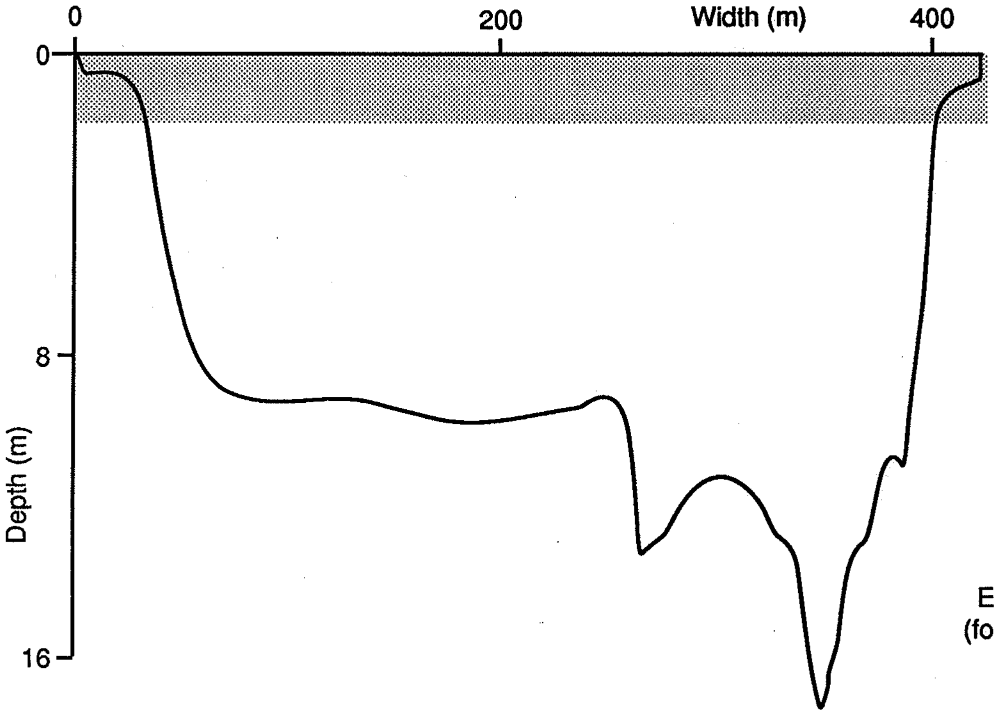
CROSS-SECTION 42
Kumak Distributary Channel



CROSS-SECTION 43
Kumak Distributary Channel

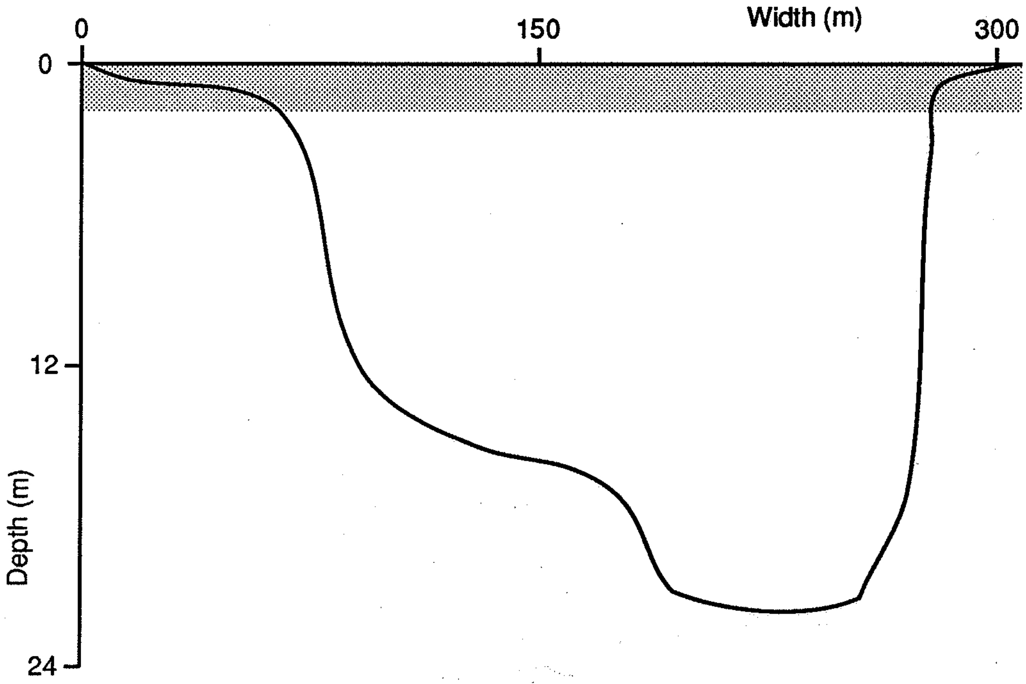


CROSS-SECTION 44
Kumak Channel



EBA, 1974
(formerly E3)

CROSS-SECTION 46
Kumak Channel



GSC, 1991