CHANNEL STABILITY IN THE MACKENZIE DELTA, NWT: 1992/93 UPDATE

(IWD-NWT NOGAP Project 11.6)

by

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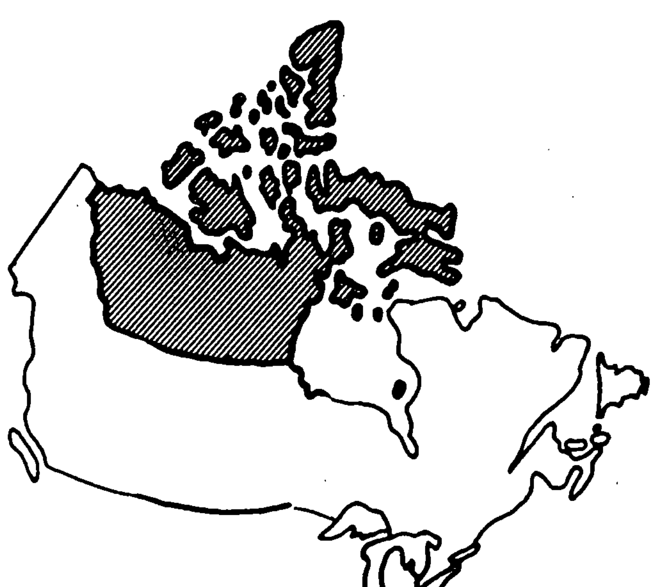

CANADA'S GREEN PLAN
LE PLAN VERT DU CANADA

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Executive Summary

This report is an update of a previous report on channel stability in the Mackenzie Delta, prepared in 1991 as part of the first year of the three-year NOGAP-funded program of IWD Yellowknife dealing with sediment-related aspects of northern hydrocarbon development.

The present report supplies the following information: an overview of proprietary literature from industry in the 1970's dealing with channel stability in the outer delta; and a review of the work of the Geological Survey of Canada in 1990-1991 dealing with channel stability at proposed pipeline crossings in the Niglintgak, Taglu and Swimming Point areas; a search of Russian literature dealing with hydrothermal erosion as it might assist channel stability studies in the delta.

An overview of the proprietary literature is provided in the first chapter. The next three chapters deal separately, in some detail, with channel stability issues in the three separate areas of Niglintgak Island (Kumak Channel), Taglu Island (Harry and Kuluarpak channels) and Swimming Point (East Channel).

A short concluding chapter considers possible further involvement of Inland Waters Directorate in this work.

All appendices are provided in a second report (Carson, 1993) which is not intended for general circulation, due to the inclusion of proprietary information released to the author for use in this contract. This contains listings of Russian references (App. I), current meter data for the Taglu area (App. II) and borehole data and cross-sectional data found for the Swimming Point area (App. III-VIII). The emphasis given to Swimming Point in the appendices reflects the limited information provided by the GSC open-file for this area compared to the open-file on Niglintgak and Taglu.

Acknowledgements

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Much of the material used in the present study was taken from proprietary reports prepared as part of the Canadian Arctic Gas Study Limited investigations of sites for hydrocarbon extraction and transport in the Outer Delta undertaken in the 1970s. Thanks are due to Esso Resources Canada Ltd. in Calgary (Evan Birchard and Ken Croasdale) for permission to use these reports and to Ross Goodwin of the Arctic Institute of North America, University of Calgary for making them available. O.M. Kaustinen of the Polar Gas Project kindly provided the cross-section of the Swimming Point crossing shown in Fig. 4.9.

Open file reports on the work done by the Terrain Sciences Division of Geological Survey of Canada in 1991-1992 were supplied by Scott Dallimore, GSC, Ottawa, who is also thanked for providing clarification of many points in these reports.

The computer search of Russian literature on hydrothermal erosion was undertaken by the Canada Institute for Scientific and Technical Information in Ottawa. Thanks are extended to Carol Fairbrother, Sandy Mish and Claude Larriviere for their help in that search.

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1. INTRODUCTION

1.1 Updating of previous report

A preliminary overview of channel stability in the Mackenzie Delta was prepared last year (Carson, 1991a) as part of Year 1 of IWD's three-year NOGAP-funded program dealing with "Sediment-related aspects of northern hydrocarbon development" (Jasper, 1991). In part, the purpose of this overview was to assist in the planning of IWD's program of hydraulic and morphologic surveys (HMS) in the delta, an introduction to which was provided by Carson (1991b).

The purpose of this update report in Year 2 is threefold:

- to provide a review of proprietary reports undertaken for the oil\gas\ pipeline companies, most of these reports being unavailable during the preliminary review;

- to provide a review of the work done by the Geological Survey of Canada (GSC) in 1990-92 in relation to river cross-section surveys and terrain evaluation in the vicinity of potential channel crossing sites; the results of this work were incomplete at the time of the initial review;

- to provide a review of work dealing with hydrothermal erosion by channels in permafrost areas, published in technical literature translated from Russian sources, which might assist in dealing with these issues in the Mackenzie Delta.

The first of these tasks is summarized in the main body of the present chapter (1.2). A summary of Russian literature is given at the end of this chapter (1.3).

Those reports that deal in detail with the three main areas of likely channel crossings by pipeline (Niglintgak Island, Taglu Island and East Channel at Swimming Point) are explored in greater depth, together with the GSC reports, and form the main body of this report: Chapter 2 (Niglintgak), Chapter 3 (Taglu) and Chapter 4 (East Channel). The locations of these areas are indicated in Fig. 1.1.

1.2 Review of Mackenzie Delta reports

This section provides, firstly an overview of the reports consulted in the preparation of this document, and secondly, examination of a number of general channel stability issues in the outer delta that are not specific to any particular crossing site: "scour holes", delta-front sedimentation and changes in water levels.

1.2.1 Overview

Many of the reports prepared for the oil\gas\ pipeline companies during the 1970s are not directly related to the general issue of channel stability in the outer delta, nor do they provide geotechnical and hydrological data that refer to the main areas now regarded as the prime candidates for channel crossings by pipelines.

Investigations for the now-abandoned "cross-delta alternative" route from Shallow Bay to East Channel downstream of Tununuk Point, for example, provided information on channel crossings that are well south of the three areas listed in Section 1.1 (e.g. Wyder, 1974). Some of the findings of reports dealing with this route were noted in the earlier channel stability report, particularly the work by NESCL (1976) and the article by Hollingshead and Rundquist (1977): see Carson (1991a, p. 6-8). However, some of this information is still useful in the present context: the work done as part of the cross-delta project by Hardy (1974a) in East Channel just downstream of Tununuk Point provides some perspective for conditions further downstream at Swimming Point (Chapter 4).

Most of the information gathered for Swimming Point originates in reports that deal with conditions at major river crossings along the Arctic Gas Pipeline proposed by Canadian Arctic Gas Study Limited (CAGSL) in the mid-seventies. This route extends from Prudhoe Bay to the west side of the Mackenzie Delta with a proposed crossing of the Peel River about 5 km downstream of Fort McPherson and of the Mackenzie River just upstream of Point Separation. It then stays on the east side of the Mackenzie River until upstream of Camsell Bend, crossing to the west bank at Burnt Island, and then crossing the Liard River in the vicinity of Poplar River before entering Alberta. A route from Richards Island, which crosses East Channel at Swimming Point, ties in with the main route just east of the Point Separation crossing. The crossings studied in detail were: East Channel at Swimming Point; Peel River and the Mackenzie River above Point Separation; Great Bear River; Mackenzie River at Burnt Island and the Liard River.

Three reports by Hardy (1973a, 1973b and 1974b) deal with geotechnical conditions at these crossings. Hardy (1973a) provides an overview of the route which is primarily a collection of low-level oblique aerial photographs. Hardy (1973b) provides detailed borehole logs of the channel banks at these cross-sections; while Hardy (1974b) gives similar data for boreholes drilled through the river beds. None of these reports is discussed further in this chapter, but the Swimming Point data are included in Chapter 4.

Three reports by Blench (1973, 1974a, 1975) examine channel stability issues at these same crossings. Blench (1973) examines river engineering aspects; Blench (1974a) looks at breakup conditions; and Blench (1975) considers the effects of freeze-up on channel stability. Again, these reports are only relevant here in relation to the Swimming Point crossing (Chapter 4).

Most of the reports dealing with the Niglintgak and Taglu areas were previously noted (although not seen) in the original Channel Stability report.

1.2.2 Investigations into "scour holes"

It was previously noted that deep, steep-sided "holes" are fairly frequent in the channel bed in parts of the the Mackenzie Delta (Carson, 1991a, p. 10-11). Observations by Lapointe (1986) seemed to indicate that they were most abundant south of the Aklavik-Inuvik line and rather uncommon north and east of Shallow Bay, but his study did not extend north of the latitude of Tununuk Point.

Examination of the proprietary literature indicates that similar concerns have, nonetheless, been raised about deep scour holes - often termed "channel anomalies" - in the Outer Delta as well. Blench (1974a,b, 1975) and NESCL (1975) have all considered the problem from different aspects.

The report by Blench (1974a) does not refer specifically to scour holes but includes in its objectives measurements of bed geometry and surface velocities during and after major ice jam releases that might occur along the Mackenzie system. It involved pre-breakup winter surveys of the channel bed at the three major proposed northern river crossings (Peel, Point Separation and Swimming Point) followed by observations on breakup during spring of 1974 and resurveys. No resurvey was done at Swimming Point because of the mild nature of breakup. The other resurveys were done a week after breakup. The report summary notes:

- numerous moderate-sized ice jams developed in 1974, but none were comparable with the 1973 ice jam at Point Separation; the most severe jam was a 13 m buildup of water level above winter stage at Point Separation. Release of the jam did not produce severe conditions, but another jam at the same site led to surface water velocities of 4.3 m/s;

- ice-gouging of banks was observed at several places, the maximum depth of gouge being less than a metre; no direct measurements could be made of the depth to which ice-gouging of the bed occurred;

- resurveys of the bed, a week after breakup (not possible earlier because of floating ice), "did not indicate severe net erosion", though maximum local erosion amounted to 3 m in some places.

The scope of the report was limited to presentation of the results, the synthesis of findings being deferred to a later report (Blench, 1974b) which has not been seen. However, the conclusions seem to be outlined in the introduction to the report by Blench (1975):

> *" Several deep holes are known to exist in the channels of the Mackenzie Delta area. Breakup observations in 1973 and 1974 ... indicated that development of these holes is not likely associated with ice breakup."*

The report went on to note that the possibility of scour beneath hanging ice dams formed from frazil ice generated during late freezing or in ice-free water areas remained a possibility. The work during 1974 freeze-up described by Blench (1975), however, seemed to rule this out. In the summary, they note:

> *"Small open water areas observed in the lower delta on October 18 covered quickly by deposition of floating snow and frazil ice. Open areas in the island complex near Point Separation, over 100 miles upstream from proposed crossings, may remain open until January or later. Stream gauging observations in the mid-delta area (by IWD) indicate that frazil ice from this source near Point Separation does not reach the lower delta so that no source of frazil ice exists to form hanging dams in the pipeline crossing area in the lower delta."*

The introduction to the NESCL (1975) report states:

> *"Studies of the Mackenzie Delta area undertaken for the design of the proposed gas pipeline revealed substantial irregularities in the depths and configurations of some of the channels. The origins of these anomalies are important considerations in the design of pipeline channel crossings in the Mackenzie Delta. It has been suggested that melting of ground ice beneath the channels could cause the variations in channel depth, and a deep hole drilling and sampling program was proposed to investigate this hypothesis."*

The report provides detailed borehole data for three holes located along the banks of the East Twin Channel (upstream from IWD station 10MC901 Middle Channel near Langley Island) and one hole close to the IWD station. The report does not provide any analysis of the findings; these were to be "documented separately in a report on the origin of these channel depth anomalies and their implications to the proposed routing" (NESCL, 1975, p.1). This report, the title of which was not given, has not been found. The author of the NESCL (1975) report was not identified, but Hollingshead and Rundquist (1977) subsequently summarized most of the work done on the cross-delta alternative route on which the East Twin Channel crossing is located (see Carson, 1991a, Fig. 2.3). As noted previously (Carson, 1991a, p. 7), Hollingshead and Runquist (197 ·rovided no mechanism for the creation of these deep scour holes.

Examination of the data contained in the report by NESCL (1975) certainly provides no obvious evidence in support of the view that melting of ice-rich sediment beneath channels is the cause of these holes. Beneath the top 3m, gravimetric moisture contents (weight of all (frozen and liquid) moisture to weight of dry sediment) of frozen samples (usually silt) did not exceed 50%, and was generally in the range 35-40%. These are not especially high values. It should be recognized that these values are not volumetric moisture contents.

Volumetric ice content in borehole specimens (estimated visually) usually refers to "excess" ice content, i.e. the volume of segregated ice (expanded into volumes beyond the normal pore space) as a percentage of the specimen volume. The NESCL (1975) report gives data on ice type and visual ice percentage and indicates visible ice to be restricted to near surface sediment only. No visible ice was found below 12m (in N74-D1 down to 56m); none below 13m in N74-D2 (down to 30m);

and none below 11m in N74-D3 (down to 18m). Some visible ice was found sporadically in N74-D4 down to 44m. Visible ice amounts greater than 10% of the core were found only in D2 (above 7m depth), D3 (above 3m) and D4 (above 13m). Simple melting (without thaw-consolidation) of sediment with 10% excess ice would require 100m of sediment to produce a bed lowering of 10m.

Other data collected in the Niglintgak and Taglu areas (Chapters 2 and 3) tend to support the view that simple melting of ice-rich sediment beneath channels is insufficient to produce deep holes in the channel bed, at least in those areas where data have been collected.

1.2.3 Sedimentation at the delta front

Recent work by Jenner and Hill (1991) provides observations on estuarine sedimentation in the Mackenzie Delta. Though not central to issues of channel stability, the work marks an important contribution in attempts to determine the fate of suspended sediment delivered to the delta. The study documented the landward growth of the Olivier Islands (west of the northern part of Ellice Island: Fig. 1.1) in the estuary of Reindeer Channel based on a comparison of aerial photographs taken in 1954 and 1985. Further work might lead to some indication of the volume of input, on an annual basis, of sediment to the area. The authors argued that most spring and early summer sediment inputs to the Outer Delta bypassed the area and were deposited offshore. Estuarine deposition is apparently restricted to the late summer open-water season when storm surges from offshore slow down, and even reverse, fluvial currents. Some of the estuarine sediment is presumably derived from offshore during such events.

1.2.4 Water levels in the Outer Delta

Assessment of channel stability in the Outer Delta is hampered by the meagre data available on channel hydraulics, i.e. discharges, currents and stages. Though data certainly exist for mid-delta sites in the Mackenzie system (e.g., Davies, 1975), corresponding data for the channel outlets are extremely scarce.

This is important given the dramatic increase in total channel width and total channel cross-section area at the delta front compared to updelta: there must be a marked decrease in stage fluctuations in the outer delta channels. Lewis (1988, Chap.3) notes that this increase in total channel width through the delta increases markedly at the 3m levee height (Carson, 1991c, Fig. 2.3: about the head of Shallow Bay) and hypothesizes that the greatly increased total channel width north of this line should permit discharge increases to be accommodated with smaller increases in water level.

"This, in turn, should affect overbank flooding and sedimentation, and we might expect a relatively abrupt drop in levee heights on the lower plain";

this agrees with observations by Mackay (1963).

In addition, because of water "losses" into the numerous lakes connected with the delta distributary system, there must be considerable dampening of discharge peaks in moving north through the delta, even without channel splitting. Lewis (1988, Ch. 3), for example, notes that the aerial extent of lakes in the mid-delta alone (between a SW-NE line through Inuvik and one through the head of Shallow Bay) would, with a 1m rise in level, take the **entire volume** of the Mackenzie River at mean annual flood (28,600 m3/s) for almost half a day, even without taking into account the accompanying expansion in lake area.

For these reasons, stage fluctuations in the outer delta must be expected to be much less than in mid-delta and at the delta head, and there is some evidence to support this view. Fig. 1.2 shows fluctuations in stage at different points in the Mackenzie Delta during the summer of 1973. The changes on Harry Channel at Taglu are minor in comparison with those on the Mackenzie above Arctic Red River. In fact the changes on Harry Channel are dictated almost entirely by those at Tuktoyaktuk (tides [about ± 1 ft maximum], wind surges and atmospheric pressure effects [about 1 ft due to pressure drop]: Slaney, 1976), and show little relationship to those at the delta-head.

Peak daily river flow on the Mackenzie River above Arctic Red River in that year was 26,600 m3/s on June 26. Peak stage at Taglu was on June 1 with levels at Taglu during the June 23 peak (89.5 ft stage: Fig. 1.3) lower than the 94.5 ft peak. All stages below about 92 ft stage appear to be confined to the channel itself, without overbank flooding. This is based on observations by Slaney (1976) in the 1975 breakup. That work showed that overbank flooding was widespread on June 6 (Fig. 1.4) at a stage of 93.5ft (Fig. 1.5) but had shrunk considerably by June 9 (Fig. 1.6) when stage had dropped to 92.5 ft.

In short, the limited fluctuation in stage showed by Harry Channel in Fig. 1.2 during 1973 is not the result of local overbank flooding in the Taglu area, but simply a result of limited fluctuations in the discharge of the channel compared to the magnitude of flood pulses at the delta head.

For perspective, the peak flow on the Mackenzie River at Arctic Red River in 1975 (34,000 m3/s) was the highest on record (1972-1990). However, peak 1975 stage at Taglu D-43 was about 0.5 ft less than that recorded there in 1973, when discharge was much lower. Slaney (1976, p. 44) also notes that peak channel discharges at Niglintgak occurred after water levels had dropped below minimum bank heights and after downstream jamming had disappeared.

Storm surge calculations by Slaney (1976, p. 39-41) indicated the 50-year flood level (from storm surges) to be about 6 ft above mean sea level, comparable with the 1975 breakup peak. The Slaney report also notes that this level is still 2 ft to 4 ft below maximum levels of driftwood on the delta front.

In short, in the Taglu area, the strength of fluvial currents must be expected to be much weaker than near the delta head, and offshore effects on discharge need to be taken seriously. It would have been interesting to plot the stage record for Kumak Channel and East Channel (where the impact of fluvial events would be expected to be much greater) on Fig. 1.2, but no data have been found. However, on Kumak Channel in 1975, two peak water levels in August (Fig. 1.7) were only about two feet less than the peak level of June 7.

The observations above provide an important perspective for assessment of channel stability in the Outer Delta channels undertaken in the next three chapters.

1.3 Russian literature on hydrothermal erosion

In view of the large experience of Russian scientists and engineers in dealing with channel stability in rivers flowing through permafrost areas, it was proposed to search existing databases to ascertain whether or not any of this material would be useful to work in the Mackenzie Delta.

After discussion with technical staff at the Canada Institute for Scientific and Technical Information (National Research Council) in Ottawa, two searches were made using the databases GEOREF (1968 to present) and COLD (1951 to present). The keywords used were "permafrost" and "erosion". Little useful material was found in the GEOREF index, but 60 Russian listings were found in COLD. These listings are provided in Appendix I (Carson, 1993).

Many of these listings do not deal with hydrothermal river erosion of permafrosted channel banks. Some deal with the thermal erosion of land slopes leading to rivers. Many deal with "shore erosion" in reservoirs.

Several of the listings do, nonetheless, appear very relevant in the context of river hydrothermal erosion, especially those of F.E. Are (Accession numbers 5, 21, 34, 37, 45 and 50). In particular, two books by Are appear to deal in detail with this topic. One is a collection of papers by several authors edited by Are

(Acc. No. 5) titled "Shore processes in the cryolithozone" published in 1984. The other, published in 1985, is entitled "Essentials of forecasting thermal abrasion of shores" (Acc. No. 21).

Unfortunately, with the exception of a brief paper by Are in the 2nd International Conference on Permafrost in 1973 ((Acc. No. 45), and one item not in the COLD database (Are, 1977), it appears that none of the relevant literature has yet been translated into English. The material is therefore of limited immediate use.

2. CHANNEL STABILITY IN THE NIGLINTGAK AREA

2.1 Introduction

The Niglintgak area of the outer Mackenzie Delta, the site of Shell Canada's proposed gas field, is shown in Fig. 2.1. It occupies low-lying terrain at the bifurcation between Middle and Kumak channels. Kumak Channel represents the seaward continuation of most of the river flow of Middle Channel, the extension of Middle Channel south of Niglintgak being heavily shoaled.

The proposed development (Hardy, 1977) indicated the plant site and dock site to be located in the vicinity of TC-1 on Fig. 2.1, immediately downstream of the north end of Kumak Island. A pipeline crossing of Kumak Channel will be required. The location has not been finalized but the most likely site (Deyell, 1991, pers. comm.) appears to be between Aklak Channel and Logan Island (Fig. 2.1) about 1.5 km downstream of the bifurcation.

A very brief summary of previous work on channel stability in the Niglintgak area of the outer delta was provided in the Year I Channel Stability report (Carson, 1991a, p. 22). Suggestions regarding IWD fieldwork were provided in the Year I HMS report (Carson, 1991b, p.12-13).

Detailed fieldwork pertaining to channel stability in the Niglintgak area has been undertaken by EBA (1974), Hardy (1977), Slaney (1974, 1976) and the Terrain Sciences Division of Geological Survey of Canada (Traynor and Dallimore, 1992). None of these reports was available during preparation of the Year I Channel Stability report.

This chapter provides an integrated review of these reports in the context of channel stability in the area.

2.2 Overview

2.2.1 Vegetation

The vegetation map (Fig. 2.2) provided by Slaney (1974) shows most of the low-lying delta area to be covered by a willow-sedge complex (Ws). Lower-lying areas flanking channels and lakes are represented by sedges and herbs (Sh). This complex covers the islands at the entrance to Kumak Channel as well as flanking both sides of the channel upstream of the Aklak branch-off.

2.2.2 Surficial deposits

The surficial deposits of the area have been discussed by Rampton (1972) and are shown in the 1985 aerial photograph of Fig. 2.3 (Traynor and Dallimore, 1992). Most of the area is made up of low-lying recent fluvial deposits of the modern floodplain of the outer Mackenzie River. There are two exceptions to this pattern: one is west of the large unnamed lake on Niglintgak Island; the other is on the east side of Kumak Channel between Middle and Aklak channels. Here the ground surface is higher and made up by either rolling moraine or outwash sands.

The origin of these older deposits is summarized by EBA (1974, p. 4-9). The residual highs (about 15 m above the delta plain) are essentially outliers of the fine-grained till which blanketed Richards Island during the Pleistocene when sea level was much lower than today. Subsequent retreat of the ice front cloaked much of the till with outwash sediments which were later dissected to produce the present outliers. After the post-glacial rise in sea level, the northward expansion of the delta front enclosed these outliers in much the same way that Kendall Island is being surrounded today. This till deposit underlies the entrance to Kumak Channel (Hardy, 1977) as noted later.

The 1985 aerial photograph of Fig. 2.3 (Traynor and Dallimore, 1992) shows the sedge-herb complex on the channel margins downstream of Kumak Island to correspond to assemblages of long lateral bars separated from higher terrain away from the channel. On the right side, the changeover corresponds with the western margin of a Pleistocene outlier. On the left side, the edge of the Sh complex is indicated by the margin of a channel scar.

The channel-margin deposition represented by these left-bank bars downstream of Kumak Island belongs to a former period of channel activity. Towards the south end of Kumak Channel (opposite Kumak Island) these channel-margin deposits have been truncated by bank erosion, accompanied by lateral accretion against Kumak Island itself. The morphology of the Kumak Channel entrance area seems to correspond to a typical meander bend site.

2.2.3 Hydrology

Slaney (1976) provides preliminary flow data for three days in 1975 for Kumak Channel and for several small channels in the Niglintgak area, but not for the Middle Channel outlet downstream of the Kumak branch-off. The early summer flow in Kumak (June 9) was given as 5130 m3/s indicating the major size of the Kumak Channel outlet. Reference to the maps of flooding in the outer delta by Slaney (1976), shown previously as Figs. 1.4 and 1.6, indicate that the river was at or below bankfull stage during the June 9 measurement.

Independently in that year, Davies (1975) was coordinating a hydrological study of the Mackenzie Delta by Water Survey of Canada. The data provide some perspective for the single-flow value for Kumak Channel. The mean flow in June 1975 in Middle Channel in the mid-delta (above Napoiak Ch.) was 22,700 m3/s with a daily peak of 31,400 m3/s on June 3 (IWD, 1989). Thus the Kumak flow represents about 23% of the mean June flow for that year and about 16% of the daily maximum. It is not clear whether these data have been used by WSC in its calibration of the 1-dimensional flow model for the delta. Assuming that they were not, the data provide an opportunity to assess the success of the model in hindcasting.

In a more detailed study of the outflow channels in winter (restricted to March 1975), Davies (1975) estimated that 20% of the mid-delta Middle Channel flow stayed in that channel as far as Mackenzie Bay. This is comparable with the breakdown in the previous paragraph.

Only limited other flow data for the Mackenzie Delta are available, but the 1975 data can be placed in further perspective by examining the inflow record (1972 to date) for the Mackenzie River at Arctic Red River. IWD (1989) indicates the peak daily flow on record to be in 1975: 34,000 m3/s on May 28. This figure has not been changed during subsequent revisions of the data and has not been exceeded since (up to 1990).

Though the June 1975 data were extreme, it is evident, nonetheless, that Kumak Channel is a major outlet of the Mackenzie Delta, comparable in size with Reindeer Channel and East Channel below Tununuk Point.

2.2.4 Hydrological controls on channel stability

The key issues here are:

(a) To what extent (i.e. at what rates) is meander bend erosion, indicated by channel morphology, being continued at the present time?

(b) Given that the future strength of these erosion processes will be largely controlled by the amount of Middle Channel flow that is forced into Kumak Channel, what is the future allocation of flow between these two outlet channels likely to be?

(c) What changes can be expected in the flow of the incoming Middle Channel, upstream of Kumak Channel, as a consequence of changes in flow branch-offs in other parts of the delta upstream?

The various reports considered here provide important data that bear directly upon the first of these questions. The topic is examined reach by reach along Kumak Channel from its mouth to the downstream end of Logan Island. Prior to that, however, brief comment is made on the overall pattern of bank-stability along Kumak Channel as derived through comparison of air photograph traces.

2.3 Stability of channel banks: air photograph data

Assessment of longterm bank erosion rates in the Niglintgak area was undertaken by Traynor and Dallimore (1992) as well as by Lapointe (1986) as part of his overview of the whole Mackenzie Delta. In both cases, the air photographs used date from 1950 and the mid-1980s. However, different photographs were used in the latter case: those of Lapointe were taken in 1984, and those of GSC in 1985. The methodology employed in the two studies was also different and this has led to some differences in the results.

Lapointe's data were previously given in the Year I Channel Stability report (Carson, 1991a, Fig. 3.5). The scant data were based solely on sites showing undercut banks. The findings indicated longterm retreat rates of about 1.6 m/yr at the upstream end of Little Island, 1.0 m/yr at the southern tip of Niglintgak Island, 0.5 m/yr on the west bank of Kumak Channel opposite Kumak Island and opposite Aklak Channel, and 1.0 m/yr at the upstream end of Logan Island. Accuracy of rates was given as ± 0.2 m/yr.

The more detailed GSC data are mapped in Fig. 2.4. These data were derived from the position of water's edge; they include sites on shoals as well as cut banks. The data show much higher rates of bank erosion. These average 2 m/yr along the west bank of Kumak Channel opposite Kumak Island and also indicate bank top erosion along the western margin of Kumak Island.

The GSC data must be used with caution: they are based on water's edge position without any adjustment for difference in water level between the two sets of photographs.

[The 1950 photographs were taken on August 2, and the 1985 photographs were taken on August 3. Though water levels at Niglintgak during these periods are not known, theoretically they should be attainable by reference to the tidal record at Tuktoyaktuk. As noted in Chapter 1 (Fig. 1.2), river stage in the outer delta is largely controlled by sea level fluctuations rather than by river discharge. Unfortunately, the tide records at Tuktoyaktuk are not available in 1950. Moreover, the tide data for August 3 1985 indicated a fluctuation of 0.5m (Sargeant, 1992, pers. comm.), emphasizing the need for precise water level data locally at the time of photography.]

Traynor and Dallimore (1992, p. 62) readily acknowledge the uncertainties in their air photographic data for shoal channel margins, but believe that the data are reliable when they indicate erosion. This is a valid argument where water's edge abuts a near-vertical bank, but is less so in areas of gentler undercut slopes.

2.4 Cross-section surveys

As indicated in Fig. 2.5, 21 cross-sections have been surveyed in the vicinity of Niglintgak Island, mostly along Kumak Channel. (It should be noted that the numbering system in Fig. 2.5 (based on the final version of the GSC report) is quite different from that in the Year I HMS report (Carson, 1991b) and Channel Stability report (Carson, 1991a) which was based on the draft GSC report.)

Of these sections, four were surveyed in the mid-1970s only (CS 39, 42-44) either in 1974 (EBA, 1974) or in 1975 (Slaney, 1976). The rest were surveyed by GSC in 1990 or 1991. These include four sections (double-lined in Fig. 2.5) that were resurveys of lines used by industry in 1975. These provide important information on channel stability. Both sets of survey were undertaken from a boat using an echo-sounder.

Interpretation is, to some extent, complicated by lack of control for both water level and horizontal positioning of the cross-section end points. As to the former, GSC states:

> *"Vertical control for these studies is estimated to be only ± 0.3 (m) 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 50 cm over a two month period (July and August)." (p. 17).*

Presumably, more accurate comparison is, in fact, possible, given that Slaney's water levels were tied in to the Shell M-19 well-heads (Traynor and Dallimore, 1992, p.88).

Perhaps more serious is uncertainty in the horizontal control. Traynor and Dallimore (1992) state:

> *"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." (p. 17).*

However, the accuracy possible in restoring the original endpoints of the 1970s survey seems uncertain, and this must have posed problems in the superimposition of the 1970s and 1990s profiles. In fact, Traynor and Dallimore (1992) go on to comment:

> *"Where comparative cross-sections were superimposed onto the same scale, the profiles were adjusted to incorporate bank retreat rates researched for each site" (p. 17).*

It is not clear how such adjustment could be made given that the only reliable data for such bank retreat rates would come from a correct superimposition of the two sections in the first place. It is presumed that the "bank erosion rates researched for each site" are those that were previously obtained from the air photograph comparisons. These have already been questioned as to their accuracy.

Three of the four repeat cross sections also have geotechnical data, either on the line or near to it. The four reaches are considered below.

2.5 Channel stability opposite Kumak Island

No subsurface sediment data are available for the entrance reach of Kumak Channel, but a prior cross-section survey at the downstream end by Slaney (1976) allows documentation of channel stability in the last 15 years. The comparison is made (CS 33) in Fig. 2.6.

The left bank of this section shows appreciable retreat in the 15-year period. The indicated bank retreat of 2 m/yr on section 33 matches the rate indicated on Fig. 2.4. However, this is presumably because of the "adjustment" in the positioning of the GSC profile rather than an independent verification of the rate derived from air photographs.

These comments are not meant as a challenge to the view that the left bank of CS 33 is retreating. Clearly, from field inspection, the banks are undercut. What is at issue here is the rate of this retreat, given that GSC's estimate of 2.2 m/yr is more than four times that of Lapointe (1986) in the vicinity of CS 30.

On the right hand side of the channel (west side of Kumak Island) the GSC air photo comparison indicates **banktop** erosion, while comparison of cross-sections points to bankside deposition below water level.

In terms of channel deepening, the GSC data are more convincing: the amount indicated for the thalweg is 4.5-5.0 m, substantially in excess of the indicated error of 0.3 m, and the deepening corresponds to the creation of a distinct "inner channel". The geomorphic and engineering significance of this deepening is not entirely clear: much depends on the mechanisms involved in the deepening. In this context, the overall bathymetry of the area shown in Fig. 2.7 (taken from Traynor and Dallimore, 1992) is pertinent, revealing a distinct "hole" at contour 81.

Unfortunately, the date and methods employed in this survey were not indicated by Traynor and Dallimore, nor the isobath units, nor the reference datum. It is presumed that the survey was done by Hardy (1977) based on the hydrological sounding profiles shown in Fig. 2.8. (The relevant data - Fig. A-26 - are missing from the only copy currently available). It is assumed that the isobath units are metres, and that they are bed surface elevations referred to the Niglintgak datum (Hardy, 1977, p. 51-52). The thalweg bed on CS 33 in 1975 was about 19 m below water level which would correspond to about 81 m elevation.

The bathymetric map provides some perspective for the changes at CS 33. Is the deepening indicated by the comparison of the 1975-1990 surveys a short-term pattern of alternating scour-fill at this site, or an ongoing long-term process at the cross-section (implied by Traynor and Dallimore, 1992, p. 73-75), or does it simply involve a systematic shift in the position of the scour hole. The latter process certainly exists in the sand-bedded reach of the Mackenzie River upstream of the Lower Ramparts (Carson, 1991c, Fig. 6.11 and 6.14): there, a bed geometry dominated by linear scour holes is systematically moving downstream as the upper end of each hole is infilled by sediment from upstream and the downstream end of the hole is subject to scour.

At present it appears as though the proposed plant and dock site (shown on Fig. 2.7), and the possible crossing site north of Kumak Island (Hardy, 1977, Fig. 1.2), are both located safely downstream of the zone of active bed (and bank) erosion. This confidence would be misplaced, however, if, in fact, there is a systematic migration northwards of the scour hole shown in Fig. 2.7.

The data published by GSC do not allow this question to be addressed. Yet, in fact, it should be possible by comparison of GSC's profiles with those of the KXS series of Hardy (1977) shown in Fig. 2.8. It appears from Appendix B of the GSC report that GSC did do resurveys on the KXS sections (GSC 31 on KX-6; GSC 34 on KX-4; GSC 35 on KX-3 and GSC 36 on KX-2), but the original 1977 profiles were not included in the GSC report (nor have they been found in the present study). Additionally, resurvey of all nine of the GSC sections in five or so years, would provide assessment of current changes. Benchmarks put in by Hardy for the KX series were relocated by GSC in 1990 (Dallimore, 1992a, pers. comm.).

2.6 Kumak Channel between Kumak Island and Aklak Channel

This reach is of potential significance to the gas industry because Hardy (1977, Fig. 1.2) shows a possible pipeline crossing just north of Kumak Island. This crossing corresponds to a section somewhere between GSC cross-sections 34 and 35 (Fig. 2.5). A geotechnical survey was undertaken along this crossing line by Hardy (Fig. 2.9: bottom) and affords some perspective for the bathymetric changes that were monitored slightly downstream on CS 37 (Fig. 2.9: top).

The left bank in this reach is downstream of a "point" in the shoreline (near CS 34) and might be expected to be relatively stable at the moment. The bathymetric profiles in Fig. 2.9 tend to confirm this: the 1975 and 1990 LB positions are coincident, though uncertainty still exists because of the lack of true horizontal control.

The two profiles nonetheless do show major changes in bathymetry with a deepening of the thalweg zone by about 8 m, and a general shifting towards the left bank. What was previously a relatively shallow asymmetric profile with a left bank shoal (as expected from the plan geometry of the reach) is now a deep symmetric profile, the right bank shoal having apparently prograded about 120 m to the left. The magnitude of these lateral shifts is significant and it is unfortunate that the horizontal control points for Slaney's 1975 work could not be found in order to provide more confidence in the comparison. As previously noted, the report by Hardy (1977) shows that four hydrological sounding profiles were made in this reach in 1977, and it would be useful to examine these data in the hope of finding definite horizontal controls. The surveys were done from the winter ice surface. Unfortunately the profiles and data were missing from the only copy of the report available.

The new increased depth of channel at this CS 37 site is about 5 m less than in the previous CS 33 at the downstream end of Kumak Island. The location of CS 37 has been marked on the 1970s bathymetric map of Fig. 2.7, from which the impression gained is that the increase in depth at CS 37 - as in the case of CS 33 - is the result of downstream migration of the longitudinal scour hole that abuts the left bank opposite Kumak Island.

This interpretion of the changes at CS 37 allows for deepening of the channel at this site without significant migration to the left bank. However, the overall downstream extension of the scour hole implies that the zone of bank undercutting will also have moved downstream, presumably encroaching upon the dock site. This process clearly needs to be monitored further. Associated with the bank migration there will be migration of the near-vertical permafrost front with attendant problems resulting from thaw of the ice-rich upper sediments of the west bank (Hardy boreholes KXW-1C, -2 and 3).

The stratigraphy across the channel along a line through the dock site is shown in the bottom part of Fig. 2.9 in the mid-1970s when the thalweg depth was only about 15 m. The main part of the channel is shown to be made up of unfrozen till described by Hardy (1977) as stiff to very stiff clay till. The unfrozen silt overlying this till along the right side of the channel was described as very loose with a trace of fine sand and is presumably alluvial.

The GSC report includes Raytheon subsurface images for CS 34-36 which show a distinct horizontal lineation at about 21 m depth. The report suggests that the layer may represent "either a gravel zone or the top of a sand layer which formed an older delta sequence" (Traynor and Dallimore, 1992, p. 51). It should not be forgotten, however, that the Hardy report (Fig. 2.9) shows clay till to underlie the whole channel to a depth of at least 20 m below the level of the west bank surface.

In discussing the Raytheon image for CS 36, the GSC report notes:

"A dark subsurface lineation below the right channel margin is interpreted as the sand contact noted in the geotechnical section. 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 conditons at this location."

(Traynor and Dallimore, 1992, p.65) The justification for this comment is, however, not clear. There is, in fact, no sand layer in the Hardy geotechnical section in this reach; there is further downstream (at CS40) but this is not located beneath till. In any case, it is not clear why sand would constitute a resistant layer, unless the particles were for some reason cemented; a sand layer would normally be much more erodible than clay till. It is true that the 1990 thalweg depth in CS 34-36 is consistently about 21 m, whereas that on CS 33 was 25 m and that on CS 37 was about 19 m; but it is not clear whether this indicates any structural control or simply represents the general shoaling of the longitudinal scour hole in the downstream direction (Fig. 2.7).

The nature of this deeper material therefore remains unclear and needs to be examined further if a pipeline crossing is indeed proposed in this reach. It is evident that the till that formed the bed in the reach at the time of the 1970s surveys is not sufficiently strong to withstand the scouring force of the river at these sites.

2.7 Aklak Channel to Logan Island

This reach is the thought to be the most likely for a pipeline crossing under Kumak Channel (Deyell, 1991, pers.comm.) with a site in the general vicinity of CS 40 (Fig. 2.5) just upstream of Logan Island. This corresponds with crossing D2 in the EBA (1974) report.

The profiles for CS 40 are given in Fig. 2.10 (top) and, again, indicate a marked deepening (7m) and enlargement of the cross-section between 1975 and 1990. The location of the thalweg on the right side of the channel is consistent with the left-to-right crossover in the reach in front of Aklak Channel as shown by the 1970s bathymetry in Fig. 2.7. The thalweg depth in Kumak Channel opposite Aklak (CS 38) was, in fact, only 12 m when surveyed in 1991.

The steep, undercut right bank contrasts markedly with the shoaled (very loose, fine sand) margins of the left side of the channel. The profiles indicate little undercutting of the right bank between 1975 and 1991, but this may be an artifact of the "adjustment" process noted in Section 2.4. EBA (1974, p.33) remarked that "no evidence of bank instability was noted on either slope." Almost 30 m of (submerged) bank scour is indicated, however, between 1990 and 1991, even though EBA (1974)'s geotechnical profile shows this to be in permafrost near the bank top (Fig. 2.10 bottom). GSC provided no discussion of this apparent bank retreat, but Dallimore (1992b) now believes that this is an error, probably due to lack of EDM work in the 1991 survey.

Comparison of the 1990 profile with the geotechnical section beneath indicates that channel deepening has extended through the laminated silt layer well into the underlying sand. It is interesting to examine the geotechnical log of boreholes XD2-4, -11 and -13 in this zone of deepening. The top few metres of the bed itself in 1974 were composed of very loose, fine grained alluvial sand. Underneath were about 3 metres of stiff silt with a dynamic cone penetrometer resistance increasing with depth from about 10 blows per foot to about 30. Beneath this silt band, the penetrometer resistance increased abruptly to 40-60 blows per foot, corresponding to the top of the underlying fine sand body. The bed scouring since 1975 has extended through these relatively resistant (to penetrometer) strata. Indeed, it is worth noting that EBA (1974, p. 16) use a penetrometer resistance of 5 blows per foot as the limit of frequently scoured material. This should, quite clearly, not be used as anything other than a very crude index of potential bed scour.

The reasons for this marked deepening of the channel at CS 40 are unclear. The GSC report suggests that, throughout Kumak Channel, there is significant alteration of the bed associated with the "channelling of Middle Channel flow through the hydraulically underfit Kumak Channel" (Traynor and Dallimore, 1992, p. 75). Yet the bed scour in the two previous reaches seems to be related primarily to downstream migration of the longitudinal scour pool, and the documented change in the next reach of Kumak Channel (CS 45) in the 1975-90 period shows slight aggradation rather than channel deepening (Section 2.8).

Slaney (1976) provided current-meter data for CS 40 on two days in 1975. These are summarized in Fig. 2.11 (top), the June 9 velocities corresponding to very high flows through the Mackenzie Delta, and a discharge past Kumak Island of about 5100 m3/s. Near-bank velocites at this time, along the vertical closest to the steep right bank, averaged about 1.5 m/s (1 knot = 0.51 m/s). To provide some perspective for these observation, the velocities are substantially higher than found by GSC on June 13 1991 in East Channel below Tununuk Point (mean vertical velocities about 0.8 m/s at 3950 m3/s) and Middle Channel near Langley Island (maximum vertical mean of 0.75 m/s at 5350 m3/s). However, the gauged discharge for the incoming Mackenzie at Arctic Red River at this time (June 4) was only 17,600 m3/s, about half that in the peak June flow of 1975. A more realistic comparison of velocities at the various delta stations requires data for higher flow events at WSC stations. None seems to be available at the moment.

2.8 Kumak Channel opposite Logan Island

This reach corresponds to crossing E3 in the EBA (1974) report. There must be an aprupt bend in the Kumak flow immediately downstream of CS 40. The flow at CS 40 hugs the right side of the channel and there is little outflow available to the right of Logan Island where CS 42-43 show the side channel to be very small (3.5 m deep). Lapointe (1986) indicated an average bank erosion rate of about 1 m/yr at the upstream west side of Logan Island.

From the plan geometry of this reach it might be expected that the right-side flow at CS 40 would be shunted across to the left bank between CS 45 and 46. Yet, in fact, this is not the case, CS 45-46 both (except for CS 45 in 1990) showing the thalweg zone in the right side of the channel. However, EBA (1974, p. 36) observed no instability on either bank, and commented that the shift of the river towards the right bank is probably extremely slow.

There was no deepening of the channel on CS 45 between 1975 and 1990, in contrast to the three previous resurveyed cross-sections (Fig. 2.12). The result is perhaps not surprising since channel depth was already 23 m at CS 45 in 1975, essentially the maximum noted in Kumak Channel in all the surveys. Indeed, the apparent infill of sediment at CS 45 in this period seems to be consistent with the upstream bed configuration as noted below.

The 20-m deep channel at CS 40 deepens to 24 m in the narrower CS 41, then shallows to 12-16 m at CS 44 before abruptly increasing in depth to 23 m at CS 45. Unfortunately there is no bathymetric map to provide a three-dimensional image of the bed in this reach comparable with that done near Kumuk Island (Fig. 2.7). The impression gained, however, is that of a bar-pool sequence (44-45). Under normal circumstances, what typically happens in this situation (in an essentially straight reach) is that sediment is scoured from the upstream side of the bar and redeposited downstream in the pool, especially in sand-bed channels. These changes cause a downstream translation of the bar-pool morphology. This pattern is consistent with observed changes at CS 45.

Unfortunately no subsurface data exist at CS 45, and even at the EBA (1974) E-3 crossing (which is roughly at CS 44 on Fig. 2.5) the only sub-channel geotechnical data are penetrometer profiles (XE3-5 and -6).

2.9 Conclusions

The GSC report provides extremely important data regarding changes in bed configuration along Kumak Channel, indicating marked deepening in some areas. Data for bank shifting are, unfortunately, unreliable. The bed level data must be taken very seriously by those involved with planning of pipeline crossings and dock and plant facilities in this area, especially given the severity of change in the vicinity of Kumak Island.

2.9.1 Bed instability

The GSC data certainly provide a new perspective to channel stability in the area. For example, in comparing the merits of Kumak crossings at CS 40 (=D2) and CS 44 (=E3) (see Fig. 2.5 for locations), EBA (1974, p. 37) commented:

> *"It is believed that section D is a more favourable alternative than Section E. Although crossing D2 is longer than the combined crossings E3 and E2, it is also much shallower. Thus the amount of excavation for the approach trench will*

be less for Crossing D2 than for E3. The materials and ice conditions at both crossings are similar, however, a larger erosion potential exists at crossing E3 because the smaller cross-section results in greater water velocity."

Yet, comparison of the 1975 and 1990 profiles indicates that it was D2 (CS 40) that showed severe bed scour (8m) while the nearest section to E3 (CS 45) showed slight deposition on the bed. EBA (1974, p. 37) were cautious to qualify their opinion with the rider:

"These findings were based on only one cross-section. Several depth profiles should be obtained parallel to the river to delineate any scour holes which migrate towards the crossing."

There is little fluvial geomorphological interpretation of the data in the GSC report. Its general conclusion is that extensive scour is taking place along Kumak Channel as a result of shallowing of Middle Channel west of Niglintgak Island and increasing diversion of flow into Kumak Channel (Traynor and Dallimore, 1992, p. 73-75).

The shallow nature of the Middle Channel outlet is certainly a significant feature of the area and has led to permafrost development as noted by Hardy (1977) and shown in Figs. 2.13 and 2.14. The permafrost layer is about 13m thick with visible ice contents of 5% to 30% in the top 3m, below which ice was less than 5% to non-visible. Shallowing of the Middle Channel outlet is thus a function of both sedimentation and bulking by ice lens growth in the upper permafrosted alluvial silt. A proposal to create a well-site on an artifical island in this outlet in the vicinity of BH AI-4 (Fig. 2.13) was being considered (Hardy, 1977, p.128), but no details have been seen regarding the probable size. The possibility of further reduced cross-sectional area of flow in the outlet as a result of such an island, together with resulting increased sedimentation, needs to be borne in mind.

The present rate of shallowing of the outlet (and therefore the rate of enlargement of Kumak Channel) is unknown. Though Kumak Channel has clearly been enlarged by the past shallowing of the Middle Channel outlet, the general conclusion put forward in the GSC report may be too simplistic. The siting of present reaches of active bank and bed erosion may be more dependent upon the overall channel (bed and bank) configuration and the downstream translation of mega-bedforms. Unfortunately a detailed bathymetric map of Kumak Channel is not available (except for the Kumak Island reach in Fig. 2.7) and there is little information on bed sediment to assist in the prediction of bed sediment movement.

At the downstream end of the active scour zone at CS 34, the bed is non-alluvial till, but the right bank shoal is apparently largely silt (Fig. 2.9), whereas downstream of Aklak Channel at CS 40 the veneer of bed sediment in the thalweg and the left bank shoal are apparently sand (Fig. 2.10). No other bed sediment data apparently exist.

2.9.2 Bank instability

The marked bank scour along the left side of Kumak Channel, opposite Kumak Island, has already been emphasized, although actual rates differ between Lapointe (1986) and the GSC report. Perhaps what is more important here is the rate of extension of the undercut bank northwards towards the proposed dock site, but no data are available on this.

The uncertainty of the existing data describing bank retreat rates makes it difficult to assess the relationship between bank scour and excess ice contents in the channel banks. Some comment is in order, however, on the relationship between bank geometry in undercut areas and the ice content profiles in the three sections with geotechnical data.

The first point is that in only one of the three geotechnical sections (CS 40: Fig. 2.10) does it appear that scour of undercut banks has actually encroached upon permafrost, and even in that case only in the upper few metres. At the other two sites, scouring is in previously permafrosted bank material that has already been thawed by the river, though at CS 44 (Fig. 2.12) it appears that the bank is close to the permafrost boundary near the base. Thus, even in the active Kumak Channel, the influence of bank properties on deep-seated bank scour seems to be more through the strength of thawed sediment than any influence of permafrost per se. This conclusion should not be extended to shallow banks, flanked by shoals or ledges, where banktop erosion appears to be occurring in permafrost.

The second point is that in all three sections, visible excess ice (which on thaw weakens bank sediment) is prominent only in the top few metres of the bank.

At CS 34 (Fig. 2.9: KXC-2) high visible-ice contents were restricted to the top 5m; gravimetric moisture content (w%) in the adjacent unfrozen borehole (KXC-3) was as high as 50% in the top 3m, decreasing abuptly to 20-30% beyond that depth. At CS 40 (Fig. 2.10: XD2-15), visible excess ice generally ranged 1-5% in the top 6m, but with no excess ice in the rest of the borehole (15m depth), though the mid-depth was in sand rather than silt. Gravimetric moisture content ranged 30-80% in the top 3m, then stayed at 30% below this level until decreasing further in the compact till near the base of the borehole. At CS 44, the right bank borehole (Fig. 2.12: XE3-2) showed 20-70% segregated ice in the top 2.5 m, but no excess ice beneath that level, though much of this is sand.

This characteristic ice profile would be expected to lead to more erodible sediment in the upper few metres, which, in turn, should lead to high-level ledges in undercut zones. To some extent this is the case.

The third point is that there seems to be some evidence that excess visible ice contents on the undercut sides of the river are less than on the prograding shoaled side.

At CS34 (Fig. 2.9 bottom), the area behind the undercut left bank shows only the top metre to contain 50% excess ice (borehole KXC-2), whereas on the prograding right bank, there is a 4m layer of permafrost with up to 50% excess ice. At CS 40 (Fig. 2.10), the borehole behind the undercut right bank (XD2-15) shows excess ice of only 1-5% in the top 3m, whereas the borehole behind the prograding left bank (XD2-8 and 2-9) show 10-40% excess visible ice down to 6 m depth. At CS 34 (Fig. 2.12) the borehole on the undercut bank (XE3-2) shows excess ice up to 50% in the top 2.5m, whereas on the opposite bank (XE3-3) the same high ice contents extend down to 4m.

The significance of these observations - from the standpoint of both geophysics as well as statistically - is unclear.

2.10 Future work

Additional work is clearly necessary in Kumak Channel, and IWD might be able to play a useful role here in attending to some of the deficiencies just noted. The following recommendations are made for future work in this area, some of which could be undertaken by IWD in Year III of the NOGAP program unless already planned by GSC.

1. Ideally, reference locations (horizontal control markers) for the Hardy and GSC sections need to be located in the field, and clearly identified (and modified if necessary) to ensure that they are capable of relocation in the years ahead. Future surveys could then be redone after major flows through the reach to determine more recent bed changes. This is part of longterm planning.

2. Additional surveys should be undertaken to fill in the gaps in the GSC traverses (e.g between 37 and 38, 38 and 40, and 45 and 46) in order that a complete bathymetric map be obtained for the reach. Such a map is essential for proper interpretion of the bed changes that will take place on the surveyed sections. It is recommended that IWD consider this work for inclusion in its Year III program.

Almost all of this work could be done using an updated version of IWD's HYDAC-HYDRA system as previously described in a morphological study of the Squamish River estuary by Zrymiak and Durette (1979).

3. Bank erosion appears to be an issue of some importance opposite Kumak Island and careful monitoring is required of the apparent encroachment (from upstream) of bank instability on the proposed dock site. This may not be central to IWD's concerns in the area.

4. Bearing in mind that the hydraulic strength of flow in Kumak Channel is in part controlled by the degree of shoaling of Middle Channel outlet downstream of the bifurcation, longterm monitoring of the bathymetry of the outlet (southwest side of Niglintgak Island) would be useful. Hardy (1977) surveyed one cross-section there (Fig. 2.8) and GSC has undertaken two profiles (Fig. 2.5). Provided that vertical control were carefully established with respect to the local datum, a repeat survey in the mid-1990s would be useful at these sites, though the amount of change may be small. This work is lower in priority than that indicated in (2) above.

5. Additional information on bed sediment is needed. Initially what is required is not data from deep coring, but samples from more sites on the bed surface, where sediment is being scoured and deposited. This is needed in order to properly interpret bed level changes. Initially, these data are most needed in the two sections being considered as pipeline crossings: downstream of Kumak Island (at CS 33, 35, 36 and 37) to supplement the data for CS 34; and downstream of Aklak Channel (at and downstream of CS 38) to supplement the borehole data for CS 40. This work could be done by IWD in Year III of the NOGAP program.

Undertaking this work will, clearly, not satisfy the basic requirements for any detailed assessment of long-term channel stability at a specific cross-section. This would require deep coring to determine the exact nature and strength of subsurface "resistant" layers, as previously noted.

The work would, however, build upon the observations of EBA (1974), Slaney (1974, 1976), Hardy (1977) and GSC (1992) in providing an integrated assessment of the reach, and in allowing a more informed interpretation of what is actually happening to bed sediment and channel margins.

3. CHANNEL STABILITY IN THE TAGLU AREA

3.1 Introduction

The location of the Taglu Island area of the Mackenzie Delta, the site of Esso Resources gas exploration, is shown in Fig. 1.1.

A map of the area is provided in Fig. 3.1. The local drainage is dominated by the incoming Harry Channel (from the south) which continues, after an abrupt left hand bend, as Kuluarpak Channel, flanking the west side of Taglu Island. Two small channels branch off to the right at this bend. The smaller of these two, flowing on the west side of Seal Island (Fig. 3.1) has been named Back Channel. The larger channel, flanking the east side of Seal Island retains the name of Harry Channel. It should be clearly recognized, however, that Harry Channel downstream of the Kuluarpak branchoff, is substantially smaller than upstream.

The proposed gas plant is located immediately north of the Kuluarpak-Harry channel bifurcation and south of Big Lake. The proposed docksite locations are shown in Fig. 3.1 at the bend entrance to Kuluarpak Channel on the outer right bank of the channel.

The proposed raw gas pipeline from Niglintgak would cross Kularpak Channel in the vicinity of GSC Cross-section 26 shown on Fig. 3.1. Two possible pipeline routes out of the Taglu plant across the Harry Channel complex, in the vicinity of the south end of Seal Island, are indicated in Fig. 3.1, based on information supplied by Esso Resources (Deyell, 1991, pers. comm.).

A very brief summary of previous work on channel stability in the Taglu area of the outer delta was provided in the Year I Channel Stability report (Carson, 1991a, p. 22-23). Suggestions regarding IWD fieldwork were provided in the Year I HMS report (Carson, 1991b, p.14).

Detailed fieldwork pertaining to channel stability in the Taglu area has been undertaken by EBA (1974), Slaney (1974, 1975) and the Terrain Sciences Division of Geological Survey of Canada (Traynor and Dallimore, 1992). None of these reports was available during preparation of the Year I Channel Stability report.

This chapter provides an integrated review of these reports in the context of channel stability.

3.2 Overview

3.2.1 Vegetation

The vegetation map of the area prepared by Slaney (1974) is shown in Fig. 3.2. As at Niglintgak, most of the low-lying area away from channels is dominated by a sedge-herb complex (Sh). As noted in Chapter 1, these low-areas are frequently inundated during spring breakup and also during occasional summer storm surges. The willow-sedge complex (Ws), found on slightly higher parts of the modern delta, is much more restricted here than at Niglintgak and forms much narrower strips (presumably levees) next to channels. Raised areas in the southwest and northeast parts of the map are covered with alder.

3.2.2 Surficial deposits

The two higher areas of alder correspond to inliers of moraine in the modern alluvium of the Mackenzie Delta (Fig. 3.3). These silt-rich moraine exposures are relatively rare in the immediate vicinity of the proposed Taglu plant, but are extensive in the eastern part of the area adjoining the western margins of Richards Island. The prominent exposures at Big Horn Point show a 3m to 5m thick cover of till over 10m to 15m of glaciofluvial sand and gravel (Traynor and Dallimore, 1992, p. 21).

Such deposits do not appear to affect channel stability conditions at the Harry-Kuluarpak bifurcation, but they do form much of the right bank of the lower Harry Channel. Traynor and Dallimore (1992, p. 21) comment:

> *"The main consequence of the Pleistocene deposits in terms of fluvial geomorphology 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 (overlying) ice-rich moraine may undergo relatively rapid erosion."*

These deposits may also have influenced channel stability in the upper Harry Channel (Fig. 3.3), but no discussion of this has been found.

3.2.3 Hydrology

Slaney (1974) provided preliminary discharge data for the region from 1973 with gaugings on the incoming Harry Channel (1.5 km above F-43 on Fig. 3.1), and the lower Harry Channel (0.2 km downstream of G-33); the flow in Kuluarpak Channel was taken as the difference between the two. For comparison, flows were also gauged on Middle Channel, 7.5 km upstream from C-58, and East Channel at Swimming Point.

July 6	Incoming Harry Channel	481 m3/s
	Lower Harry Channel	169 m3/s
	Kuluarpak Channel	313 m3/s
July 8-10	Middle Channel	3564 m3/s
July 10-12	East Channel	5055 m3/s
October 6	Incoming Harry Channel	277 m3/s
	Lower Harry Channel	57 m3/s
	Kuluarpak Channel	220 m3/s
October 7	Middle Channel	1667 m3/s
October 8	East Channel	3522 m3/s

Unfortunately there are few years of additional hydrological data for the delta to provide a perspective for the 1973 observations, though examination of the incoming Mackenzie River at Arctic Red River is again useful. Reference to the 1988 yearbook (IWD, 1989) indicates a peak daily flow on the incoming Mackenzie in 1973 of only 26,600 m3/s (June 26). This was the third lowest on record after 1987 and 1984, and substantially less than the peak of 34,000 m3/s in 1975. On the other hand, the mean June flow for 1973 was about 2,000 m3/s above the longterm mean, and the mean July flow was essentially the same as the longterm July average.

The July data above, therefore, seem to be reasonably representative of mid-summer conditions. They emphasize the much weaker flow in Kuluarpak Channel, and especially lower Harry Channel, compared to the flow of Kumak Channel alongside Niglintgak Island.

3.2.4 Hydrological controls on channel stability

In examining channel stability in the Taglu area, there are several central themes that need consideration:

- To what extent is the flow of the incoming Harry Channel (as a percentage of the Middle Channel flow at the WSC gauging station 10MC901 near Langley Island) affected by changing morphologic and bathymetric conditions at the Middle-Harry bifurcation and at branch-offs between Middle Channel and Taglu (Fig. 1.1)?

- What was responsible for the abrupt left hand bend at the start of Kuluarpak Channel and the associated right-hand branch-off of lower Harry Channel? And how stable is the bifurcation today in terms of the allocation of flow between the two channels?

Virtually no work appears to have been done on the first of these topics. Nor has fieldwork been undertaken to specifically address the second. However, data collected by industry and government in the 1970s and in 1990-91 do provide some information that bears on the second topic, and this is examined in the sections below.

3.3 Stability of channel banks: air photograph data

Assessment of longterm bank erosion rates in the Taglu area was undertaken by Traynor and Dallimore (1992), shown in Fig. 3.4, as well as by Lapointe (1986) as part of his overview of the whole Mackenzie Delta. In both cases, the air photographs used date from 1950 and the mid-1980s. However, different photographs were used in the latter case, those of Lapointe being from 1984 and those of GSC being 1985. As noted in Section 2.3, the methodology employed in the two studies was also different, and this has led to some differences in the results.

Lapointe's data were previously given in the Year I Channel Stability report (Carson, 1991a, Fig. 3.5). The scant data were based solely on sites showing undercut banks. The data indicated longterm retreat rates of about 0.5 m/yr in the vicinity of the Kuluarpak-Harry divergence, being somewhat higher (about 1 m/yr) on the outer left bank of Kuluarpak Channel downstream of the divergence, and in Harry Channel immediately downstream of the branch-off (about 1.3 m/yr). Bank erosion rates along lower Harry Channel in the reach covered by Fig. 3.4 averaged about 1 m/yr except on the left bank opposite Big Horn Point where rates of 3 to 4 m/yr were indicated. The latter area corresponds to a significant bifurcation in lower Harry Channel, an irregular mid-channel bar complex, and the exposure of coarser-grained Pleistocene deposits in the right bank.

The more detailed GSC data were derived from the position of water's edge and include sites on shoals as well as cut banks. At Niglintgak, the GSC data showed much higher rates of bank erosion, but this is not true at Taglu. The GSC rates at Taglu are generally slightly lower than those of Lapointe.

It might seem strange that the discrepancy between the GSC data and those of Lapointe should be in the opposite direction from that at Niglintgak. However, given that water levels at Taglu (and Niglintgak) are dominated by tide and wind effects (Chapter 1), and given different times of travel of these effects to the two areas, the different results in the two areas are perhaps not surprising.

As noted in the discussion of Niglintgak (Section 2.3), the GSC data are based on water's edge position without any adjustment for difference in water level between the two sets of photographs. Dallimore (1992b, pers. comm.) points out that most banks, in areas of retreat, were 0.5m to 1.5m high. Thus, provided that water level fluctuations did not drop below these steep banktops, the effect of water level change on apparent retreat data would be minimal in such areas.

The data compiled by GSC for the Harry-Kuluarpak divergence are of particular interest here, though no information was obtained for the proposed docking sites near F-43 (Fig. 3.4). The data do show, however, widespread scour on banks of Harry Channel: along its left bank before the divergence (0.5 m/yr), along the new left bank as the channel "doubles-back" into the Harry branch-off (0.8 m/yr) and along the right bank immediately after the branch off (1.2 m/yr). At the latter site, bank scour has impinged on a small linear lake, producing a complex bank outline at the present time (Fig. 3.4).

Though the rates of bank scour at the Harry-Kuluarpak divergence may seem relatively small, the resultant changing configuration of the area must eventually affect the percentage allocation of flows along the different channels.

3.4 Cross-section surveys

As indicated in Fig. 3.5, twenty-six cross-sections were surveyed in the vicinity of Taglu Island, along both Harry and Kuluarpak channels. Again, it should be noted that the numbering system in Fig. 3.5 (based on the final version of the GSC report) is quite different from that in the Year I HMS report (Carson, 1991b) and Channel Stability report (Carson, 1991a) which were based on the draft GSC report.

Most of these sections were non-repeated surveys either by industry (especially in the Big Horn Point area) in 1975 or by GSC in the early 1990s. However, six of the cross-sections (double-lined in Fig. 3.5) were resurveys by GSC of lines used by industry in 1975. These provide important information on channel stability: one (CS 2) is on the incoming Harry Channel; three (CS 21, 23 and 26) are on Kuluapak Channel; and two (CS 4 and 7) are on lower Harry Channel. Both sets of survey were undertaken from a boat using an echo-sounder.

As noted in Section 2.4, interpretation is complicated by lack of horizontal and vertical control.

The three resurveyed sections on Kuluarpak Channel roughly correspond with three geotechnical sections drilled by EBA (1974). No other borehole data have been found.

3.5 Incoming Harry Channel

The upper part of Harry Channel, before the abrupt bend into Kuluarpak Channel, is essentially straight for 5 km including the reach shown in Fig. 3.5.

The three cross-sections surveyed in this reach are shown in Fig. 3.6. The sections are remarkably symmetrical (with relatively steep banks) as would be expected from the straight plan configuration of the channel.

The three sections are quite different in depth, however, the bed of CS 2 being 20 m below water level compared to only 8 m about 500 km upstream, where channel width is the same. The downstream section CS 3 is even shallower (5m) though this must, in part, be related to the widening of the section immediately upstream of the lower Harry Channel branch-off.

No bed sediment data are available. The variable depth along the reach seems to imply an active bed morphology, however, as confirmed by the changes in bathymetry at CS 2 between 1975 and 1991. Here, the slightly asymmetric 1975 section has deepened, especially along the right side of the channel (up to 10m deepening), becoming much more symmetric. How much of this bed sediment has been redeposited on CS 3 is not known, but, clearly, changing bed levels in the vicinity of the Kuluarpak-Harry divergence will have some effect on the proportion of flow following the two channels. The cross-sectional distribution of current speed in CS 2 on June 10, 1975 is given in Appendix II under the Slaney listing of station 12.

Ultimately what is needed in the divergence reach is a proper bathymetric map of the channel. The GSC report provides one for the area opposite the proposed docksites downstream (based on a mid-1970s survey by industry, source not stated) but not for the incoming reach.

3.6 Kuluarpak Channel entrance

Four cross-sections were sounded by industry in Kuluarpak Channel immediately after the divergence from Harry Channel, two of which were resurveyed by GSC. CS 20 (1975; not shown) was not appreciably different from CS 21; and CS 22 (1975; not shown) was not unlike CS 23. CS 21 and CS 23 are shown in Fig. 3.7 and the general 1970s bathymetry of the reach (original source not known) is given in Fig. 3.8. The figure is taken from the GSC report in which the contours are indicated to be in metres. This is somewhat surprising given that the maximum depth on the four sections in this reach is 15m, yet the contours on Fig. 3.8 range from 85 to 45 above datum. In addition, the geotechnical sections of EBA (1974), shown in Fig. 3.9, indicate depths no greater than 12m. It is assumed that the contour units are, in fact, feet.

The exact locations of CS 21 and CS 23 on Fig. 3.8 are unfortunately not known. The positions indicated are approximate only, and are derived by comparison of shoreline configuration in Fig. 3.5 and 3.8.

Fig. 3.8 shows a rather unusual channel bathymetry for a bend location. The thalweg enters the bend at mid-channel and essentially stays in that position through the reach, though its depth decreases from a contour of 45 near the entrance to a level of 50-55. There is some indication of a point bar against the inner left bank in the mid-reach area of Fig. 3.8, yet there appears to be a submerged linear shoal in the right hand (outer) part of the channel rising to a contour of 85 by midreach. At this point the "shoal" is separated from the right bank by a "hole" 20 (ft?) lower than the "shoal". The current distribution in CS 23 on June 10, 1975 is given in Appendix II, listed as the original Slaney station 18.

The changes shown for CS 21 between 1975 and 1990 (Fig. 3.7) are somewhat puzzling. There was, apparently, a shift of about 12m of virtually the whole section towards the right bank, eliminating the right-bank ledge shown in the 1975 profile. Yet there is virtually no difference in the slope of the left and right banks in the 1990 profile: some asymmetry should have developed if there had been undercutting of the right bank and accretion against the left bank. Though migration towards the right (outer) bank would certainly be expected in this bend, some doubt must exist regarding the superimposition of the 1990 and 1975 profiles, given the acknowledged lack of horizontal control in these surveys. The thalweg has infilled on CS 21 by about 3m. It seems likely that this is related to local infilling of the "scour hole" shown at the entrance to the reach in Fig. 3.8.

The changes on CS 23 are generally minor, except for the "planing down" of the right-side "shoal" (Fig. 3.7: bottom). There is no evidence to indicate whether this ridge represented a bar of alluvial sediment or a slumped block from the undercut right bank. The only geotechnical data (Fig. 3.9) relate to the bank itself rather than the channel bed. There appears to have been slight aggradation and a narrowing of the thalweg zone of Kuluarpak Channel at CS 23 between 1975 and 1990.

The GSC report notes the "hole and mound" bed topography of the reach and comments:

> "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." (Traynor and Dallimore, 1992, p. 46).

These remarks appear to overlook the apparent 12m migration of CS 21 towards the outer bank during 1975 and 1990 (Fig. 3.7), and the significant bed scour just upstream at CS 2 (Fig. 3.6).

On the other hand it is acknowledged that normal river forces are much weaker here than in Kumak Channel, discussed in Chapter 2, and may be countered or reversed at times by tidal surges moving up from Beaufort Sea. No data appear to be available regarding the latter.

Ice jams during breakup were reported by Slaney (1974, 1975) in this reach, with a major one in 1975 between the bend at CS 24 extending upstream to CS 23. The plan geometry at this site is certainly conducive to such jams, and it may well be that Back Channel and lower Harry Channel originated as avulsions at the time of ice jamming. The peculiar angle of departure of lower Harry Channel from the incoming flow certainly suggests unusual flow conditions.

3.7 Kuluarpak Channel at potential crossing site

The 1974 and 1991 profiles at CS 26, in a long straight reach, are shown in Fig. 3.10, together with the geotechnical section provided by EBA (1974).

The channel is, surprisingly, about 20m wider at this section than Harry Channel upstream of the divergence (Fig. 3.6) yet the summer flow data of Slaney (1974) show the flow to be about two-thirds of the incoming Harry Channel. The depth, at about 6m, was slightly less than upper Harry Channel at CS 1, and much shallower than CS 2.

Since 1974, there has been some accumulation of sediment in the mid-channel thalweg, accompanied by undercutting of both channel banks. It is possible that this lateral basal scour is related to flow divergence around a mid-channel bar, part of which shows in the 1991 profile. Without more bathymetric data for the reach, however, this is speculation. In general, there is little real instability of the channel cross-section at this site which is consistent with the straight plan configuration and the (assumed) slow movement of bed material. Nonetheless, given the distinct scour holes in the two previous reaches, a broad bathymetric survey up- and downstream of CS 26 is required before any reliable comment can be made about likely scour depths.

The subsurface stratigraphy appears to be relatively uniform and simple: about 12-18m of deltaic silt overlying silty, very fine-grained deltaic sand. The geotechnical properties, however, are more variable. The in-channel silt beneath the bed for about 6m is relatively soft, with less than 10 blows per foot, reflecting its weak consolidation (gravimetric moisture content (w%) = 45%). Whereas beneath this depth, greater consolidation (w% = 35%) has produced a much stiffer sediment (more than 20 blows per foot). The silt in the bank boreholes generally has frozen moisture contents that are similar to the more consolidated sub-channel sediment, but the top 5m, especially on the left bank, has been bulked with ice-lenses.

3.8 Harry Channel immediately downstream of divergence

The change in profile at CS 4 between 1975 and 1990 is shown in Fig. 3.11 (top). Massive deposition is indicated in amounts far in excess of any error due to lack of vertical control. Further downstream at CS 5 (Fig. 3.11 bottom) and CS 6 (Fig. 3.12 top) channel depth in 1990 is close to 8m comparable with that for CS 4 as recorded in 1975.

The GSC report interprets this deposition as the result of reduced flow (Traynor and Dallimore, 1992, p. 77-78); by this they are presumably referring to the reduced velocities at CS 4 compared to those of the incoming Harry Channel, rather than to a reduction in discharge in lower Harry Channel over time. Such a marked reduction in the cross-sectional area of flow at the entrance to lower Harry Channel is clearly important, especially given the inherently unstable nature of the high-angle branch-off. The current speed data for CS 4 in Appendix II (listed as Slaney station 13) show peak speeds (near the outer north bank) on June 10, 1975 of only 1.75 knots compared to 2.9 knots in CS 12. This apparent blockage of the channel entrance, if maintained, is likely to lead to further siltation in Harry Channel (with resultant permafrost aggradation in shallow places) and increased flow (and probably scour) along Kuluarpak Channel.

It would be interesting to repeat the 1975 survey at the entrance to Back Channel (CS 19: Fig. 3.5), 3.5 m deep in 1975, in order to discover whether similar deposition has taken place there.

3.9 Harry Channel opposite south end of Seal Island

The reach of Harry Channel in the vicinity of site G-33 and CS 7 (Fig. 3.5) appears to be the most likely candidate for a pipeline route eastwards from the Taglu plant based on discussions with Esso staff in 1991 (Carson, 1991a, Fig. 3.17). In this reach the flow of Harry Channel is augmented (by an unknown amount) with water from an unnamed channel that branches northeastward off incoming Harry Channel (Fig. 3.5). It is also affected by any inflow from Back Channel and any loss to the channel flowing between Taglu Island and Seal Island.

The comparison of 1975 and 1991 profiles at CS 7 is given in Fig. 3.12 (bottom). The figure shows a general shift of the profile towards the right (prograding of about 30m on the left bank and retreat of about 10m on the right) with little overall change in shape. Given the lack of horizontal control, this shift must remain uncertain. Lapointe (1986) has no bank scour data for this reach except at the ends: 1.3 m/yr opposite site G-33 and 1 m/yr on both banks at CS 8. The left bank bench of 1975 does appear to have shoaled while a new bench has apparently formed on the right bank since 1975.

No significant change in bed level is indicated, however, and channel depth (at 7m) is much the same as upstream at CS 5 and 6 and downstream at CS 8.

The reach appears to be generally stable, as would be expected from the weaker flows (compared to incoming Harry and Kuluarpak channels) and the (assumed) cohesive banks. In this respect, the reach is quite different from further downstream alongside Big Horn Point. Current speeds in CS 7 for June 10, 1975 are given in Appendix II under the original Slaney (1975) listing of staton 1.

3.10 Harry Channel in vicinity of Big Horn Point

Few soundings were done by GSC in this reach, and none at sites previously surveyed by industry; therefore no 15-year data on channel stability are available.

The soundings available indicate the wider river channel in this reach to be associated, as would be expected, with much shallower depths. The depth at CS 11 is only 2.5m (compared to 6m upstream at CS 8); at CS 13 it is 5.5m; and at CS 14 it is only 2m in the main part of the channel. The formation of mid-island bars and islands has produced a subsidiary channel to the left, and, though CS 9 at the entrance to this channel is only 1m deep, its continuation through CS 14 shows a depth of 4m.

The conditions in this reach are apparently controlled by exposures of coarse (Pleistocene) sediment along the right bank which results in local shoaling. In addition, channel velocities will be reduced by the loss of some floodwater into the large number of lakes breached by the right bank margin just upstream of Big Horn Point.

The generally shallow nature of the multiple channels in this reach suggest that much of it would be frozen with bottomfast ice in winter. This was in fact noted by Slaney (1974) in January of 1972. The presence of this bottomfast ice is likely to stablize the channel during breakup, though there may be localized scour in parts of the thalweg. The marked contrast in channel depth in the left-hand channel between CS 9 and CS 14 may be related to such under-ice scour. The generally shallow depths presumably lead to far more complex permafrost distribution in the near-channel region than in the deeper reach upstream.

3.11 Conclusions

As in the case of Niglintgak, and notwithstanding the limitations of the data due to lack of horizontal and vertical control during surveys, the GSC report provides important observations regarding channel stability in the Taglu area between 1975 and 1990.

3.11.1 Bed instability

The two reaches previously identified as likely candidates for pipeline crossings (Fig. 3.1) both appear to be relatively stable. In the case of Kuluarpak Channel at CS 26, this presumably reflects the generally straight configuration of the reach. In the case of Harry Channel near CS 7, this would seem to be the result of much weaker flows and the (assumed) cohesive character of bank and bed materials (in contrast to the Big Horn Point reach).

On the other hand, the marked changes apparent in the bed of upper Harry Channel at CS 2 since 1975 indicates that, even in a straight reach, substantial scour can still occur; and the contrasts in bed level between CS 1 and CS 2 confirm this view. The cause of these changes is unknown, but they may relate to downstream movement of large bedforms.
Ultimately, a proper bathymetric map of the bed (rather than isolated cross-sections) is needed to address this kind of problem.

3.11.2 Bank instability

In contrast to the two probable crossing reaches, channel instability in the vicinity of the proposed dock area would be expected to be more pronounced because of its location on the outside of a sharp bend. The GSC report does show marked (underwater) bank scour at CS 21 (about 20m in the 15-year period), but the accuracy of the comparison is not known. Bed geometry in the bend site is certainly complex and not consistent with classic outer-bank thalweg morphology. To what extent this is related to possible reverse flows at times of storm surges, and to chaotic conditions during known ice jams during breakup, is not known. Before-and-after monitoring of the bend during both types of events would be useful.

The fewer channel-bank boreholes available for this area (the only report seen with geotech nical data is that by EBA (1974) provide limited information on the relationship between ground ice profiles and bank stability. At the Kuluarpak entrance (Fig. 3.9), only one borehole is fully in permafrost, while neither bank at CS 26 (Fig. 3.10) is undercut. The various boreholes do, however, support two of the findings in the Niglintgak area, namely the thawed nature of the channel banks near the water and the dominance of ice-bulked sediment in the top few metres of banks of permafrost.

At Docksite 2, visible ice contents in the bank borehole ranged up to 95% in the top 3.5m corresponding to gravimetric moisture contents (w%) of 30-80%; while at greater depths excess ice was generally not visible and w% was 25-45% only. At CS 26, in the left deep borehole, excess ice contents of 20-40% were encountered throughout the top 6.5m, with little visible ice below that level. Gravimetric moisture contents decreased abruptly from 30-100% in the upper layer to 20-30% below that. In contrast, in the deep borehole on the right bank, excess ice (up to 35%) was found throughout the full depth of silt, corresponding to w% values of 30-50%, decreasing abruptly in the underlying sand to 20%. The greater depth of excess ice on the right bank may possibly be related to the shallower depth of the underlying sand, but this is speculation.

The lack of permafrost exposures in the banks is consistent with the (inferred) slower rates of bank scour in the smaller channels of Taglu compared to Kumak Channel. The apparently greater thickness of the surface ice-bulked sediment together with the smaller depth of channels implies that far more of the channel bank in the Taglu area is likely to be made up of ice-bulked (softened) sediment. However, more observations are needed before this generalization can be made with confidence.

3.11.3 Instability of channel junctions

The main concern at this site must be the inherently unstable character of the bifurcation, especially the doubling-back of Harry Channel at CS 4. Such geometry is probably not conducive to maintenance of an open channel at this branch-off and changes in cross-sectional area must affect the allocation of flow between the two channels. The changes at CS 4 between 1975 and 1990 indicate massive deposition which presumably has increased flows along Kuluarpak Channel at the expense of lower Harry Channel. Slaney (1974) noted that about 35% of the incoming flow continued along Harry Channel in July of 1973. Diversion of increased amounts of this flow into Kuluarpak Channel must be expected to augment scour in that channel, while leading to sedimentation, shallowing and permafrost aggradation in lower Harry Channel.

3.12 Future work

As in the Niglintgak area, additional work is clearly necessary, and IWD might be able to play a useful role here in rectifying some of the deficiencies just noted. The following recommendations are made for future work in this area, some of which could be undertaken by IWD in Year III of the NOGAP program, assuming that GSC has no further longterm interest in channel stability in the Outer Delta. However, in view of the more limited extent of channel instability indicated by the GSC report, these recommendations have much lower priority than those for Niglintgak, and none may warrant inclusion in the current NOGAP program.

1. Ideally, reference locations (horizontal control markers) for the GSC sections should be located in the field, and clearly identified (and modified if necessary) to ensure that they are capable of relocation in the years ahead. These surveys could then be redone after major flows through the reach to determine additional bed changes. This is part of longterm planning.

2. Additional surveys should be undertaken to fill in the gaps in the GSC traverses (e.g between 1 and 3 on the incoming Harry Channel and between 24 and 26 on Kuluarpak Channel) in order that a complete bathymetric map be obtained for the two reaches. Such maps are essential for proper interpretion of the bed changes that will take place on the surveyed sections. Almost all of this work could be done using IWD's HYDAC system as previously described.

3. Attention needs to be directed to ensuring permanence of horizontal control markers so that amounts of bank retreat are properly determined. In particular, careful monitoring is required of the apparent bank retreat near the proposed dock sites. This is probably not, however, of direct concern to IWD.

4. Bearing in mind that the hydraulic strength of flow in Kuluarpak Channel is in part controlled by the degree of shoaling of Harry

Channel downstream of the bifurcation, longterm monitoring of the bathymetry of the outlet (between CS 3 and CS 6, and including Back Channel) would be useful. Similar surveys could be done at the entrance of the first branch-off from incoming Harry Channel (northeast to G-33: Fig. 3.5). No data appear to exist on how significant the flow is in this channel (let alone changes in channel geometry over time), yet the flow must influence conditions at the proposed crossing site near CS 7 to some degree.

5. Additional information on bed sediment is needed. Initially what is required is not data from deep coring but more extensive data (more sites) on the shallow bed sediment that is being scoured and deposited. This is needed in order to properly interpret bed level changes. The highest priority for this sampling is where data are already available on bed profile changes: CS 2, 4, 7, 21, 23 (especially in the right bank shoal), 26.

As in the case of Niglintgak, the work would build upon the observations of EBA (1974), Slaney (1974, 1975), Hardy (1977) and GSC (1992) in providing an integrated assessment of the key reaches in the area, and lead to a more informed interpretation of what is actually happening to bed sediment and overall channel stability.

4. EAST CHANNEL AT SWIMMING POINT

4.1 Introduction

The Swimming Point reach of East Channel, located about 20km downstream of Tununuk Point (Fig. 1.1), is the likely crossing site for pipelines from Richards Island to the mainland and Mackenzie Valley for both the delta area (Niglintgak and Taglu) and offshore (via North Point). It was identified as the crossing route in the Polar Gas application to the National Energy Board and Indian and Northern Affairs Canada in 1984. A summary of channel stability aspects identified in that application was included in the original channel stability report (Carson, 1991a, Section 3.6.3).

Studies of channel stability at this site in the mid-1970s appear to have been undertaken largely by T. Blench and Associates, but a report describing work by that company for CAGSL in 1972-74 (cited by Neill, 1988: Carson, 1991a, p.26) has still not been seen. The only reports seen that deal with Swimming Point are Blench (1973, 1974a, 1975).

A detailed borehole program was undertaken by R.M. Hardy and Associates, the logs of bank sites being reported by Hardy (1973b) and the logs of river bed sites being given by Hardy (1974b). The logs for these boreholes are provided in Appendices III and IV respectively. Additional boreholes at bank and bed sites in the Swimming Point reach were done by GSC in 1985 and 1991 and included in the open-file report edited by Hanright and Dallimore (in prep.). These are given in Appendix V. Two bank borehole logs were published by Brooker (1972); the sites are shown in Appendix III, but the report has not been seen.

The report by Hanright and Dallimore (in prep.) summarizes a research program conducted by GSC in the spring and summer of 1991 in the vicinity of Swimming Point "to assess the local surficial geology, geothermal conditions and hydrologic conditions of the crossing area". The hydrological component was limited, however, to the surveying by echo-sounder of three cross-sectional profiles of the river; it did not involve comparison with previous surveys done in the mid-1970s by industry.

4.2 Overview

4.2.1 Hydrology

Information on the discharge of lower East Channel, as it relates to that of the incoming Mackenzie River at Arctic Red River, and in comparison with the two main other outflow channels (Reindeer and Middle Channel) is extremely meagre. Ultimately these flows will be simulated by IWD's one-dimensional model, based on the current program of spot gaugings.

The Year I Channel Stability report (p. 6) noted that the design discharge for estimates of maximum channel scour in studies leading up to the 1984 Polar Gas application to NEB and INAC was approximately 18,400 m3/s, based on half of the (estimated) 100-year flood entering the Delta at Point Separation. Mean annual maximum flow was believed to be about 10,000 m3/s.

The GSC report notes that Anderson and Mackay (1973) and Anderson and Anderson (1974) estimated that about 20% of the discharge of the Mackenzie River flows through East Channel to Kugmallit Bay, on average, though in the winter this figure might be as high as 25-35 percent.

Some data from isolated gaugings from the mid-1970s and from IWD's recent discharge program are given in the table below (discharges in m3/s):

1975.08.10	East Channel	3030	21 %
1975.08.13	Langley Is.	4450	
1975.08.14	Middle Ch.	14780	(upstream of Neklek Ch.) East/Langley68%
1991.06.13	East Channel	3950	22 %
1991.06.13	Langley Is.	5350	
1991.06.04	Mackenzie	17600	(above Arctic Red) East/Langley74%
1991.07.31	East Channel	4040	23 %
1991.07.30	Langley Is.	6420	
1991.07.30	3 outlets	17530	(East, Langley, Reindeer) East/Langley63%
1991.09.12	East Channel	2780	25 %
1991.09.20	Langley Is.	4120	
1991.09.20	3 outlets	11160	East/Langley67%
1992.08.06	East Channel	3240	21 %
1992.08.05	Langley Is.	6020	
1992.08.04	3 outlets	15300	East/Langley54%

These figures are reasonably consistent and agree with the estimates noted in the GSC report. However, the percentage figures refer to different totals in the three cases. There is, moreover, a substantial variation in the relative importance of East Channel compared to Middle Channel at Langley Island, the East Channel percentage ranging from 54% in the 1992 figures to 74% in the June 1991 data.

4.2.2 Surficial deposits and geomorphology

The valley bottom of lower East Channel and the general setting of the Swimming Point reach are shown in Fig. 4.1. On both sides of the river are permafrosted Pleistocene sediments of the Tununuk Low Hills (Rampton, 1988: see Fig. 3.21 of Carson, 1991a). Further south (upstream of Spruce Island in East Channel) is the northwestern end of the Caribou Hills. The surface sediments of the Tununuk Low Hills are largely glaciofluvial sand and gravel (mostly ice-contact deposits on terrain east of the river), believed by Rampton (1988: GSC Map 1647A) to date from the Early Wisconsin. Beneath them are older Pleistocene deposits, including brown sands overlying grey sands, and these form most of the exposures in the channel banks.

Whatever the exact history of these deposits (and the interpretation is still uncertain), they were subsequently incised by ancestral flows of East Channel to produce the present valley. River terraces, underlain by outwash, with associated high-level meander scars, occur throughout the valley (Fig. 4.1) and are evidence of this former period of downcutting.

Mackay (1963, p. 32), in attempting to explain these terraces (the problem being the much lower level of the Mackenzie Delta upstream), suggested that, south of Tununuk, the ancestral East Channel lay partially or wholly on a lobe of glacier ice lying in the Mackenzie trough. It is not clear at what date this might have been. Rampton (1988, Map 1647A), however, indicates the deposits underlying the 15m high terrace on the left side of the valley at Swimming Point to be outwash from the Toker Point Stade of the Early Wisconsinan glaciation. Rampton (1988, p. 67) also attributes low-level terraces (6.5m above sea level) along Lower East Channel (near the sea) to meltwater action during a period in the deglaciation of the Toker Point Stade ("Tuk" phase) when a glacier lobe stalled for a significant time south of Richards Island. The history after the Early Wisconsinan glaciation remains a mystery since the Mackenzie Delta area upstream was at a much lower level than it is today.

During the Late Wisconsin glaciation (Sitidgi Stade), when a lobe of glacial ice advanced down the Mackenzie Delta to about 10km south of Tununuk, Rampton (1988, p.69) described conditions in the area as follows:

"Along the west edge of Caribou Hills, meltwater channels were formed by streams paralleling the edge of the glacier, and flowing into the trench (exposed by lower sea level) now occupied by Mackenzie Delta."

At that time, then, presumably there would have been no flow from the Mackenzie basin along lower East Channel because the valley through the Tununuk Low Hills would have been perched well above the level of the delta area that lay in front of the glacier and southwest of Tununuk, this not yet having been infilled with alluvium.

Bed samples acquired by IWD in 1991 across the full width of East Channel at Station 10LC-901, just downstream from Tununuk Point (Fig. 4.1) are relevant here. These bed surface samples, located in water 5-6m deep, were all sandy gravel (much of it > 8mm), presumably a lag feature from ice-contact debris, rather than Recent alluvium. Whether they date from the Sitidgi stade or earlier is not clear.
Borehole logs at the margins of the channel close to the section, published by Hardy (1974a) and listed in Appendix VI, all indicate gravel in the top 6m below water level.

Accompanying the sea level rise of the last 10,000 years, there has been gradual aggradation over the delta. Radiocarbon dating of wood in the East Channel area near Inuvik (Johnston and Brown, 1965) indicates 38m of aggradation since 6900 BP. This aggradation would have raised the level of the main delta to that of the Lower East Channel trench and led to spillover of Mackenzie River flow through Tununuk Low Hills to produce the present Lower East Channel. It has presumably also involved some infilling of the channel bottom of Lower East Channel, but no attempt appears to have been made to separate Recent alluvium from the underlying Pleistocene sediments.

At the channel entrance, it is presumed that the surface gravelly bed material is Pleistocene and not Recent sediment. Upstream of Tununuk Point, Mackay (1963, p.40) noted that the long profiles of east bank streams (and now drowned by lakes) extend to 6m to 15m beneath the level of East Channel, indicative of the depth of deposition, but does not ascribe a date to either the valleys or the channel blockage. Rampton (1988, p.71), however, comments: "Many of the drowned valleys along the Yukon coast and throughout the Mackenzie Delta (including East Channel) .... were probably eroded during Late Wisconsin time, as they are all positioned beyond the limit of Late Wisconsinan ice and within the limit of Early Wisconsinan ice. The inference seems to be that the blockage of these east bank streams was the result of Recent aggradation.
Rampton (1988, p. 47), however, shows one of these drowned valleys as, apparently, being blocked by Toker Pt glaciofluvial sediment.

There is, finally, the question of how long Lower East Channel has been receiving water at Tununuk Point from Middle Channel via Neklek Channel. The drainage configuration (Fig. 1.1) in which Middle Channel splits into Reindeer Channel, lower Middle Channel and Neklek Channel, and in which Neklek Channel then splits around Tununuk Point into West Tununuk Channel and lower East Channel is amazingly complex. It stands out markedly in contrast to the simple alignment of the middle reach of East Channel (between Inuvik and Tununuk) and lower East Channel. The impression gained is that this outflow into East Channel via Neklek Channel occurred relatively recently. This has presumably affected the rate of aggradation in lower East Channel.

4.3 Bank sediments

The terraces on the west bank of East Channel at Swimming Point, about 15m above sea level, are shown in more detail in the aerial photography of Fig. 4.2. The proposed pipeline crossing leaves the west bank from the modern floodplain of the river and mounts the right bank at an undercut bank in sandy Pleistocene sediments.

The locations of H-series boreholes through bank sediments on the undercut right side of East Channel are given in Fig. 4.3 and details are provided in Appendix III.

Hole H72-112 was augered at the base of the exposed river bank approximately 1.8m above water level on October 24, 1972 (Hardy, 1973b). The hole was in permafrost through the full depth of 32 metres. Apart from a 60 cm surface layer of gravel (presumably beach material from the undercut bank) overlying 1.4m of silty, sandy peat, the entire log comprised fine sand (with some silt in upper 4m). The upper silty sand was dark brown and contained abundant visible ice (up to 70% visible); the light grey sand underneath contained little visible ice.

Testhole H72-113 was located about 300m from river edge at unknown elevation (but presumably about 20m above water level based on the contours on the 1:50,000 topographic map for Tununuk (107C/3E)). Since H72-113 was drilled to 22m it may have reached the level of the top of H72-112. The recurrent soil description in the log is "fine sand, trace silt" with occasional shale and wood fragments. The permafrost is bulked with ice in the top 7m, but beneath that level only two thin bands showed visible ice.

The GSC borehole (91-5), closer to the plateau edge and described as "several metres above river level", also indicated sand throughout the full 27m depth, apart from a surface 1.5m layer of sandy gravel (App. V).

The N-series boreholes in the right submerged bank (in area B: Fig. 4.3 and shown in section in Fig. 4.4) were not augered but drilled with a diamond core. Sampling was a problem and "most samples were obtained from the drilling return fluid or by split-spoon sampling" (Hardy, 1974b, p.23). This should be borne in mind in interpretation of the logs (App. IV). The deepest hole, N74-505 (extending to 21m below river level) shows a similar deposit to those logged on the exposed bank: "SAND, fine to medium, some silt" through the full depth, except for a layer of coarse-to-medium gravel in the top metre which may be part of the beach deposit. The shallower boreholes closer to the river edge are more complex and include silt and peat as well as gravel. These may be indicative of conditions in the submerged platform further upstream and opposite Swimming Point.

The lack of any detail in the log of the unfrozen N74-505 hole makes it difficult to comment on the stability of this bank. Only one actual sample is indicated as having been taken (immediately beneath the bed) and percentage recovery was shown as 0%.

4.4 Bed sediments

The locations of boreholes by Hardy (1974b) and GSC through the river bed are given in Fig. 4.3 and details are provided in Appendix IV. The GSC holes were primarily for the purpose of locating the boundaries of permafrost (Dallimore, 1992b, pers. comm.). No samples were actually taken, and sediment descriptions were based on continuous ejection.

No data have been found for the thalweg area. However, Blench (1973) indicates this to be paved with cobbles, beneath which is sand (see Section 4.5). The deepest part of the channel in Fig. 4.3 logged in boreholes is shown in inset Area A: borehole N74-501 begins on the bed 33.5 ft (10m) below the surface of river ice (Fig. 4.4). The log penetrated to 62 ft (19m) through unfrozen fine to medium (dark yellowish-brown) sand in a loose to medium-dense state of compaction, with a dense or coarse layer at the base. The deeper borehole near the right shore (N74-505: Area B), beginning at a depth of 7 ft (2m), penetrated to 70 ft (21) through essentially the same sediment (as noted in Section 4.3), though the sand was described as dark greyish-brown.

As Hanright and Dallimore (in prep.) remark:

> " ... borehole logs lack the detail required to distinguish between Pleistocene sands and silts and those deposited during Recent floodplain aggradation."

This comment applies to most of the boreholes in the area. The problem is compounded by the fact that on-land boreholes barely penetrate to a depth equivalent to the top of channel bed boreholes. And comparison between the two is made more difficult by the apparent absence of levelling data for the on-land holes. As noted previously, then, it is difficult to know how much of the channel bed sediment is Recent in age.

The left bank shoal appears to comprise about 10m of silt over fine sand (Fig. 4.4). The underlying sand appears to be continuous with the sand found at the surface of the channel bed right of the point bar.

Two GSC boreholes were located immediately north of borehole area A of Hardy (Fig. 4.3). GSC 91-4, at the edge of the shoal, and comparable in location with N74-501, showed 5m of brown sandy silt overlying unfrozen clay down to 13m. Dallimore (1992b, pers. comm.) believes that the log is primarily a reflection of the abrupt change to unfrozen sediment, and that, while the underlying unit may be somewhat finer-grained, the term "clay" may be misleading for the whole unit.

Perhaps more significantly, GSC 91-3, on the left bank shoal (Fig. 4.4), shows 16m of brown sandy silt separated from the underlying grey medium sand by two one-metre layers of pea-size gravel. And all four cone penetration tests done by GSC in 1985 in Area C, at the river edge of the left bank shoal, were stopped (at depths of 16m to 19m below the surface of river ice) in gravel (Fig. 4.4). This is probably the same layer as found in GSC 91-3. It is difficult to explain the presence of these gravel beds in terms of the present hydraulic regime of East Channel. Hanright and Dallimore (1993) make the comment:

> "Gravels found in boreholes within the channel, assuming that they are of fluvial origin, suggest a period of relatively high stream competency, high gradient and lower sea level. A sea level curve developed by Hill et al. (1985) indicates lower sea levels for at least the last 27,000 years. If the gravels were deposited during this period of emergence, then it is likely that they are related to some event of high discharge such as the retreat of Late Wisconsinan ice (Sitidgi stade) from the delta."

An alternative view is that they represent lag deposits (armour) during the Late Wisconsin downcutting envisaged by Mackay (1963), noted above, derived from the reworking of gravel in the glaciofluvial sediments into which meltwater had been downcutting.

Whatever the exact origin of these bed gravels, assuming that they do indeed date from the end of the Pleistocene, the 10-15m of overlying silty sands would represent a maximum rate of post-glacial aggradation of about 1 mm per year, substantially less than the 5 mm per year noted in the main part of the delta near Inuvik (based on the 6900 BP C-14 date for buried wood at 38m depth).

The lithostratigraphic section of Fig. 4.4 shows several other interesting features. One, in particular, is the occurrence of organic deposits and peat buried in the left bank shoal at about 3-4m below river ice level. This band extends riverward at the same level as the underwater ledge that was the site of boreholes 502 and 510. Significantly, the tops of these two boreholes are logged as peat.

It thus appears that the small ledge is the remaining part of a formerly more extensive floodplain surface that developed as a lower tread in the staircase of meander-plain surfaces previously noted in Fig. 4.1. As aggradation took place in the main channel (as part of more widespread deltaic deposition), river level has risen above the level of this old plain, and it, in turn, is now being buried by the progradation of the present point bar. The existence of this submerged floodplain remnant raises the question as to how many of the other "nearshore platforms" that are found throughout the delta (and which are usually regarded as modern erosional surfaces) have a similar origin.

A final point to emerge from the bed borehole data is the contrast between the GSC boreholes (91-3 and 91-4) and those of Hardy (1974b) in essentially the same location. Hardy's boreholes N74-502 and N74-501 (Fig. 4.4) were drilled at depths of 18ft and 30ft respectively. Yet all the GSC boreholes were located on land (not river ice), 91-3 and 91-4 being on the point bar. At first sight, it appears that there has been massive progradation of the point bar in the intervening period. However, this may be misleading because of the greater width of the point bar (Fig. 4.5) on Cross-Section I (on which the GSC boreholes were located) compared to Cross-Section B (which appears to be approximately the location of the Hardy boreholes). The 2m isobath shows a marked embayment on the Hardy line, whereas it extends much further into the channel on CS I.

4.5 Channel bathymetry and stability

Information on channel bathymetry in the Swimming Point region is, unlike at Niglintgak and Taglu, relatively sparse. There is the generalized bathymetric map of Canadian Hydrographic Service (6430) surveyed in 1975 (Fig. 4.5). In addition, several sections were surveyed by industry in the mid-1970s, and three sections were sounded by GSC in 1991, but none of the latter were resurveys along traverses established by industry.

Surveys were done by Thomas Blench and Associates (soundings at intervals across the ice), but only two reports which include reference to Swimming Point have been seen. One deals with channel stability and pipeline crossing design at the six river crossings on the CAGSL route (Blench, 1973). The other deals with breakup conditions, but also includes several profiles (Blench, 1974a).

The locations of sections surveyed by Blench (1973) are, for clarity, shown on Fig. 4.6 rather than Fig. 4.5. Also shown are the locations of four bed-material sampling sites. A bathymetric map based on these sections is given in Fig. 4.7. The sections themselves are given in Appendix VII. The bathymetric map shows much more detail of the crossing area than does the CHS map and indicates a scour hole more than 18m (60ft) deep on the site of the proposed crossing line.

The Blench (1973) report notes that scour depths of up to 70ft were found along this reach by Pemcan Services (1972), and these were thought (at that time) to result from river scour beneath ice. The report went on (p. 23):

> "Because of the possibility of deep scour related to river ice, it is recommended that the crossing be located in the narrow deep section at the sharp bend in the channel (as shown in Fig. 4.7). The existing depth at this location minimizes the possibility of further scour occurring as a result of ice conditions over the crossing."

> "Attempts to obtain bed samples in this deep channel indicated that the bed is paved with cobbles. However, subsurface soundings made during the survey described in Ref. 4 (Pemcan, 1972) suggest that this coarse granular paving is underlain by fine sand."

No samples could be obtained from sites S1, S2 and S3 on Fig. 4.6, and the inference regarding cobbles or boulders was based on the action of the supporting line for the sampler. The observations are consistent with GSC penetrometer records from 1985 noted previously.

The tentative design for the pipeline crossing by Blench (1973) is shown in Fig. 4.8. The marked steepness of the submerged right bank is due to vertical exaggeration. The final design submitted in the 1984 application (Fig. 4.9) shows the right bank without exaggeration: the slope is about 50ft rise in 150ft, or about 18 degrees.

The locations and profiles of the sections from Blench (1974a) are given in Appendix VIII, while the locations are also shown on Fig. 4.10. and the upstream-downstream sequence near the proposed crossing is given in Fig. 4.11.

It should be noted that there is apparently an additional report by this firm prepared in 1975 that summarizes channel stability findings. This report has not been seen. However, in view of the belief expressed in Blench (1973) that the deep scour holes are likely to reflect scour beneath ice, while the subsequent reports examining this possibility (Blench 1974a, 1975) dismissed this hypothesis, it would be interesting to see what the final views were regarding the origin of the scour hole at the Swimming Point site.

The GSC report provides three sections, the locations of which are shown on Fig. 4.5. All three were surveyed by echo-sounder mounted on a Zodiac. Horizontal control on the traverses is somewhat uncertain. The GSC report notes: "Markers parallaxed on each bank enabled accurate positioning of the boat across the channel. Horizontal distances were determined from air photos and maps." The meaning of these statements is somewhat unclear. Presumably the first means that the markers enabled the traverse to take place along an essentially straight line; and the second means that end points of the traverse were located on maps by reference to topography. It is not clear how accurate location of points along the traverse was obtained.

The three sections are shown in Fig. 4.12. The upstream section (A) appears to have been drawn with the right bank on the left side (i.e. looking upstream), in contrast to the other two.

The GSC report provides little interpetation of these sections other than to point out the existence of the large extent of nearshore shoal on all sections, and their importance in the development of bottomfast ice and protection of banks during spring breakup. The "ledge" on the right side of section C (about 90m wide and 6m beneath ice surface) was thought to represent a possible zone of deposition of sediment from Holmes Creek. However, there are similar ledges elsewhere in the reach (e.g. at borehole N74-501 in Fig. 4.4 on the left side) which should not be ignored.

The only comparison between the mid-70s profiles and those in 1991 that may be valid is for the section immediately downstream of Holmes Creek (GSC-C and Blench-SP5). The differences are quite remarkable. The 1974 profile (Fig. 4.11) is shallow (about 9m) with a slight mid-channel shoal and no ledge against the right bank. It shows poor correspondence with the 1975 bathymetry of Fig. 4.5. In contrast, the GSC echosounding shows an inner channel, offset slightly to the right of centre, extending to 14m depth, flanked on the right by the 7m deep ledge and a 1-m shallow nearshore platform.

4.6 Conclusions

Three main channel stability issues exist in this reach, all of which are interrelated:

1. How stable is the bed itself given the marked deepening of the thalweg between Swimming Point and Holmes Creek?
2. How stable is the outer right bank, both at the surface and, separated from the surface by a nearshore platform, at the edge of the inner channel?
3. How rapid is progradation of the left bank point bar towards the channel thalweg?

4.6.1 Bed stability

None of the data collected so far are sufficient to provide convincing answers to all questions of bed stability. GSC section B shows the thalweg at 17m, slightly less than the 20m noted in 1972 (Fig. 4.8), but given the uncertainty in vertical control and, more importantly, the apparent difference in location of the two sections, the comparison has little value. On the other hand, the apparent existence of a coarse gravel lag deposit under the left bank shoal and at the base of the scour hole near the right submerged bank should reduce further scour at the proposed section. The proposed location for the top of the pipeline was about 5.8m beneath the 1972 thalweg, corresponding to a depth below the September 1972 water level (Fig. 4.8) of 26 metres.

While it is beyond the terms of reference of this report to consider alternative locations for the East Channel crossing, the existence of gravel on the bed - at shallow depth - on the IWD section just downstream of Tununuk, raises the question as to whether this site might be a better location from the viewpoint of both design cost and channel stability.

4.6.2 Outer bank stability

The stability of the outer right bank relates in part to the makeup and origin of the submerged rightbank bench. Possible origins of the shallow nearshore ledges were discussed in the previous Channel Stability report (Carson, 1991a, p. 7, 10, 30) including wave action and hydrothermal erosion of ice-rich banktop sediments.

The exposed banktop of East Channel opposite Swimming Point is described as "undercut" in most reports implying that the submerged platform south east of the point is erosional. However, no sediment data seem to exist for this platform. Lapointe's (1986) map of bank erosion rates in the outer delta (Carson, 1991a, Fig. 3.6) is interesting in that it does not provide data for the Pleistocene sands of the outer bank downstream of GSC section A (Fig. 4.5) though this is precisely where the GSC air photograph is annotated with "eroding bluff" (Fig. 4.2). Moreover, aerial photographs taken in 1950 and 1972, shown in Fig. 4.13, examined by Blench (1973), seem to show little, if any, retreat of the bank top. Comparison with more recent photographs would be instructive.

In contrast, upstream, active bank erosion was indicated by Lapointe (1986) on both the outer left bank (0.3 m/yr upstream of Swimming Point to 3.0 m/yr along the island 4 km upstream) and the "inner" right bank (0.3 to 1.3 m/yr). In this reach immediately upstream of Swimming Point both banks are formed by modern alluvium rather than Pleistocene sediment. The distribution of banktop undercutting along East Channel, as indicated by Lapointe's data, seems to be unrelated to normal fluvial processes, and more likely controlled by wave action and thaw of ice-rich surface sediments.

Cooper and Hollingshead (1973) suggested that the stability of the submerged outer bank of the inner channel opposite Swimming Point may be due to the presence of permafrost under the submerged platform. However, there are still no permafrost data for this site. Further to the north (on Section 1), the nearshore borehole (N74-509) was permafrosted through the full depth, but N74-505 (on the bed at 2.2m below ice level) was unfrozen throughout 21 metres. The location of this borehole with respect to the edge of the shallow ledge is unclear. The possibility of a tough layer of peat on the surface of this submerged platform does not appear to have been considered.

The issue of the stability of the submerged right bank of the inner channel is as important as stability of the exposed undercut bank but the few borehole data in Area B (Fig. 4.3) do not provide any real answers. Blench (1973), on the assumption that "material in these (underwater) banks is moderately erodible and is in an unfrozen state" (p. 24), recommended that design allow for 200 ft (61m) of lateral erosion.

4.6.3 Point-bar stability

The available data also provide little information regarding progradation of the leftbank point bar. It is interesting, however, that the profile of Section B done by GSC in 1991 (Fig. 4.12) is essentially the same as that of Section I done in the mid-1970s (Fig. 4.9). However, the two sections were not done in the same place. The location for Section B, as supplied by GSC, shows it to correspond more with area A of Fig. 4.3, upstream of the pipeline crossing site, and therefore comparable with the section shown in Fig. 4.4. This latter section shows a distinct ledge at about 5m depth (site of boreholes N74-502 and -510) which no longer appears on the 1991 profile. This suggests substantial progradation of the point bar (about 60m), but this must be qualified by uncertainty in locations of the two cross-sections.

4.7 Future work

Unlike at Niglintgak and Taglu, little information exists on channel stability at Swimming Point because of the lack of repeated cross-section surveys. Theoretically, the GSC profiles could be compared with the CHS bathymetric map, but uncertainty in the horizontal and vertical control makes this questionable.

The CHS chart clearly shows a major scour hole, of uneven depth, developing in the right half of the channel off Swimming Point and continuing past Holmes Creek. The stability of this scour hole, in terms of both bed levels and outer bank scour, remains unclear. The apparent progradation on GSC Section B and apparent bed scour on GSC Section C need to be resolved.

Ultimately echosounding is the most efficient means of monitoring bed level changes in this reach, but the prime need is to establish the 1970s-1990s changes with more accuracy than is currently available. This requires (a) relocating the end markers of Blench's surveys or redefining them from field survey; and (b) resounding the sections with good horizontal and vertical control across the channel.

The best procedure for such work probably is to use soundings through winter ice. This could be done by IWD as part of any program to collect winter flow data on lower East Channel. By doing its next hydrometric measurements along SP-4 (and supplementing it with soundings (not current meter work) along SP-3 and SP-5, extremely important data in the vicinity of the proposed crossing area could be acquired without a great deal of extra effort.

This work is regarded as high-priority and it is recommended that IWD consider undertaking it in Year III of the current NOGAP program.

5. CONCLUSIONS

5.1 Nature of additional work needed

A great deal of work has already been done in acquiring data to assess channel stability in the three main areas of probable pipeline crossings in the Outer Delta. Ultimately, the adequacy of this information depends, to a large extent, on the degree of safety incorporated into the design of the pipeline crossings at the sites. Assessment of these designs is not, however, part of the terms of reference of this contract, and, in any case, preliminary designs have been seen for only one of the three areas, that of Swimming Point on East Channel.

The GSC resurvey of channel cross-sections on Kumak Channel indicates the marked instability of this channel but provides little assessment of the controls on this instability. Additional survey information is needed to fill in gaps to assist in such interpretation as described in Sections 2.9 and 2.10.

Changes in channel geometry since the 1970s in the Taglu area are generally much smaller, as would be expected from the much weaker flows. Channel stability in the future is likely to be controlled by changes at the bifurcation of Harry and Kuluarpak channels immediately south of the proposed plant site. Addi-tional information is needed here as outlined in Sections 3.11 and 3.12.

At Swimming Point there has been no assessment of longterm changes in channel morphology, except for air photograph comparison of the position of the right bank between 1950 and 1972. The GSC investigation did not include resurveys of old cross-sections. Information from repeat surveys is still clearly needed at this site, as outlined in Sections 4.6 and 4.7.

In all areas, channel stability will be affected by changes in flow partition at upstream channel bifurcations. This is something that needs to be borne in mind in developing a specific level of safety in the pipeline crossing design.

5.2 Involvement of IWD

The degree to which IWD should be involved in any such additional work will depend upon many factors, including availability of resources and the perception of its mandate. Specific recommendations for Year III of the current NOGAP program are summarized below.

The work described for **Kumak Channel** in Section 2.10 in paragraph (2) is important, is not excessively time-consuming, and could be done by IWD as part of its developing hydraulic and morphologic survey program in 1993. The work described in paragraph (3), while also of high-priority, relates more to stability of the dock area rather than proposed pipeline crossings, and is perhaps beyond IWD's mandate.

The lack of Kumak Channel profiles from Hardy (1977: KXS series) in the GSC report is puzzling, especially given that the lines were actually resurveyed by GSC. Some effort should be made to find these data. It would provide useful information to accompany the work noted above.

In the case of **Taglu**, though many questions remain regarding channel stability (Section 3.11), the proposed crossing sites seem to be relatively stable and the channels are much smaller than Kumak Channel. The interesting questions that remain unanswered (especially the stability of the Kuluarpak-Harry bifurcation) probably cannot be considered high-priority items for IWD work. No work is recommended for 1993.

At **Swimming Point**, comparison of the 1970s and 1990s data is ambiguous because of the lack of resurveys of old sections. These resurveys need to be done, notwithstanding the apparent stability of the section indicated by 1970s reports. As noted in Section 4.7, this work will require relocation of the endpoints of the surveys undertaken by Blench (1973, 1974a). Assuming that these resurveys could be done at a time when a winter-time gauging of Lower East Channel was already planned, the best approach to this work would be sounding through winter ice. It is recommended that IWD consider undertaking this work in 1993/94.

In summary, in providing this and the previous channel stability review, in making recommendations for further work in the Outer Delta, and in undertaking a limited amount of this work itself, it is believed that IWD will have provided the leadership in this matter expected of it as part of the NOGAP contract.

REFERENCES

Anderson, J.C and R.J. Anderson, 1974. Progress report on winter distribution of flow in the Mackenzie Delta, Northwest Territories. Hydrological Aspects of Northern Pipeline Development, Environmental-Social Committee, Northern Pipelines Report 74-12.

Anderson, J.C and D.K Mackay, 1973. Seasonal distribution of flow in the Mackenzie Delta, Northwest Territories. Hydrological Aspects of Northern Pipeline Development, Environmental-Social Committee, Northern Pipelines Report 73-3.

Are, F.E., 1977. The present state and problems of the investigation of permafrost shores of reservoirs. USA Cold Regions Research and Engineering Laboratory (CRREL) Draft Translation 714.

Blench, T. and Associates, 1973. River engineering aspects of the design of proposed pipeline crossings of the Mackenzie, Liard, Great Bear and Peel rivers. Report to Northern Engineering Services Ltd and Canadian Arctic Gas Study Limited, March 1973, prepared by R.H. Cooper.

Blench, T. and Associates, 1974a. 1974 river break-up and ice study. Mackenzie, Liard and Peel rivers. Data report. Report to Northern Engineering Services Ltd and Canadian Arctic Gas Study Limited, July, 1974, prepared by J.B. Nuttall.

Blench, T. and Associates, 1974b. 1974 river break-up and ice study. Mackenzie, Liard and Peel rivers. Engineering report. Report to Northern Engineering Services Ltd and Canadian Arctic Gas Study Limited, prepared by J.B. Nuttall and A.G. Mercer.

Blench, T. and Associates, 1975. Ice freeze-up study, Mackenzie Delta, 1974. Report to Northern Engineering Services Ltd and Canadian Arctic Gas Study Limited, April, 1975, prepared by J.B. Nuttall.

Brooker, E.W., 1972. Terrain data report. Vol 4. Cited by Hardy (1974b).

Carson, M.A., 1991a. Channel stability in the Mackenzie Delta, Northwest Territories: a review. Contract report to IWD, Environment Canada, Yellowknife.

Carson, M.A., 1991b. Proposals for hydraulic and morphologic surveys in the Mackenzie Delta, Northwest Territories. Contract report to IWD, Environment Canada, Yellowknife.

Carson, M.A., 1991c. Sedimentation measurements in the Mackenzie Delta, Northwest Territories: review and recommendations. Contract report to IWD, Environment Canada, Yellowknife.

Carson, M.A., 1991d. Applications of geomorphology for Inland Waters Directorate staff: Western and Northern Region. Contract report to IWD, Western and Northern region, Calgary.

Carson, M.A., 1993. Channel stability in the Mackenzie Delta, NWT: Information Reference Document. Proprietary report for IWD, Environment Canada, Yellowknife.

Cooper, R.H. and A.B. Hollingshead, 1973. Riverbank erosion in regions of permafrost. In "Fluvial Processes and Sedimentation", Proc. of Hydrology Symposium, IWD, Ottawa, 272-283.

Davies, K.F., 1975. Mackenzie River inputs to Beaufort Sea. Beaufort Sea Project Technical Report 15, Dept of Environment, Victoria, B.C.

Dallimore, S.R., 1992a. Undated letter to Jesse Jasper from S. R. Dallimore, in reply to letter of February 24, 1992.

Dallimore, S.R., 1992b. Terrain Sciences Division, Geological Survey of Canada: personal communication.

Deyell, M., 1991. Esso Resources Canada, Calgary: personal communication.

EBA, 1974. Preliminary Geotechnical Evaluation: Beaufort Gas Development, Richards Island, NWT. Report by EBA Engineering Consultants Ltd for Imperial Oil Ltd.

Hanright, J.A. and S.R. Dallimore (Editors), in prep. Geological, geotechnical and geophysical investigations of the Swimming Point pipeline crossing, East Channel, Mackenzie River. GSC Open File Report, draft copy.

Hardy, R.M. and Associates, 1973a. Reconnaissance of pipeline river crossings north of 60th parallel. Report prepared for Northern Engineering Services Ltd, June 1973.

Hardy, R.M. and Associates, 1973b. Geotechnical report. Major river crossings: proposed Arctic Gas pipeline route, Canadian section north of 60th parallel. Vol. 2. Report prepared for Northern Engineering Services Ltd, August 1973.

Hardy, R.M. and Associates, 1974a. Geotechnical report. Proposed Arctic Gas Pipeline, Cross Delta Alternative Route. Ground truth drilling program. Mackenzie Delta region. Report prepared for Northern Engineering Services Ltd, October 1974.

Hardy, R.M. and Associates, 1974b. Geotechnical data report. Proposed Arctic Gas pipeline. Major river crossings: drilling program. Prepared for Northern Engineering Services Company Ltd, June 1974.

Hardy, R.M. and Associates, 1977. Shell Niglintgak Gas Development: 1977 Geotechnical Program. Report prepared for CANEP - BROWN and ROOT, and Shell Canada Resources Ltd, Calgary, Alberta.

Hollingshead, G.W. and L.A. Rundquist, 1977. Morphology of Mackenzie Delta channels. Proc. 3rd National Hydrotechnical Conference, 309-326.

IWD, 1989. Historical streamflow summary: Yukon and Northwest Territories to 1988.

Jasper, J., 1991. 1991/92 IWD-NWT NOGAP workplan. IWD, Yellowknife, May 22, 1991.

Jenner and Hill, 1991. Sediment transport at the Mackenzie Delta - Beaufort Sea interface. In Proceedings of the Workshop on the Mackenzie Delta, 17-18 October 1989, Saskatoon, Saskatchewan, 39-52. Environment Canada.

Johnston, G.H. and R.J.E. Brown, 1965. Stratigraphy of the Mackenzie Delta, NWT. Bulletin of Geological Society of America, 76, 103-112.

Lapointe, M.F., 1986. Mackenzie Delta channel dynamics: miscellaneous data. NHRI, Inland Waters Directorate.

Lewis, C.P., 1988. Mackenzie Delta sedimentary environments and processes. Report to IWD, Environment Canada, Ottawa.

Mackay, J.R., 1963. The Mackenzie Delta area, NWT. Geographical Branch Memoir No. 8.

Neill, C.R., 1988. Northwest Hydraulic Consultants Limited, Edmonton, Alberta. Personal communication.

NESCL, 1975. Geotechnical data report. Proposed Arctic Gas pipeline. Cross Delta Alternative Route. Channel depth anomaly drilling and sampling program. Report for Canadian Arctic Gas Study Limited, January 1975.

NESCL, 1976. Channel geometry and flow distribution, Mackenzie River - Lower Delta, Summer 1975. Report by Northern Engineering Services Company Limited for Canadian Arctic Gas Study Limited.

Pemcan, 1972. Results of a pipeline crossing survey on the East Channel, Mackenzie River, in the vicinity of Swimming Point. Report cited by Blench (1973).

Rampton, V., 1972. Surficial geology and landforms, Mackenzie Delta (107C-W½). GSC Open File 96.

Sargeant, B., 1992. Canadian Hydrographic Service, Sidney, BC. Personal communication.

Slaney, F.F. and Company, 1974. 1972-74 environmental program, Mackenzie Delta, NWT. Report prepared for Imperial Oil Ltd., Gulf Oil Canada Ltd., Shell Canada Ltd., and Canadian Arctic Gas Study. Volume 2 - Hydrology.

Slaney, F.F. and Company, 1975. Report cited by Traynor and Dallimore (1992), title uncertain.

Slaney, F.F. and Company, 1976. Hydrology Survey (1975): Niglintgak, Mackenzie Delta, Northwest Territories. Report to Shell Canada Ltd, Calgary.

Traynor, S. and S.R. Dallimore, 1992. Channel stability at Taglu Island and Niglintgak Island, Richards Island, Mackenzie Delta. Terrain Sciences Division, GSC Open File 2552.

Wyder, J.E., 1974. Water bottom survey in the Mackenzie Delta area. Report for Northern Engineering Services Company Limited by Kenting Exploration Services Ltd, Calgary, Alberta.

Zrymiak, P. and Y. J. Durette, 1979. An investigation of the morphological processes occurring in the Squamish River estuary. Sediment Survey Section, Inland Waters Directorate, Ottawa.

List of Figures

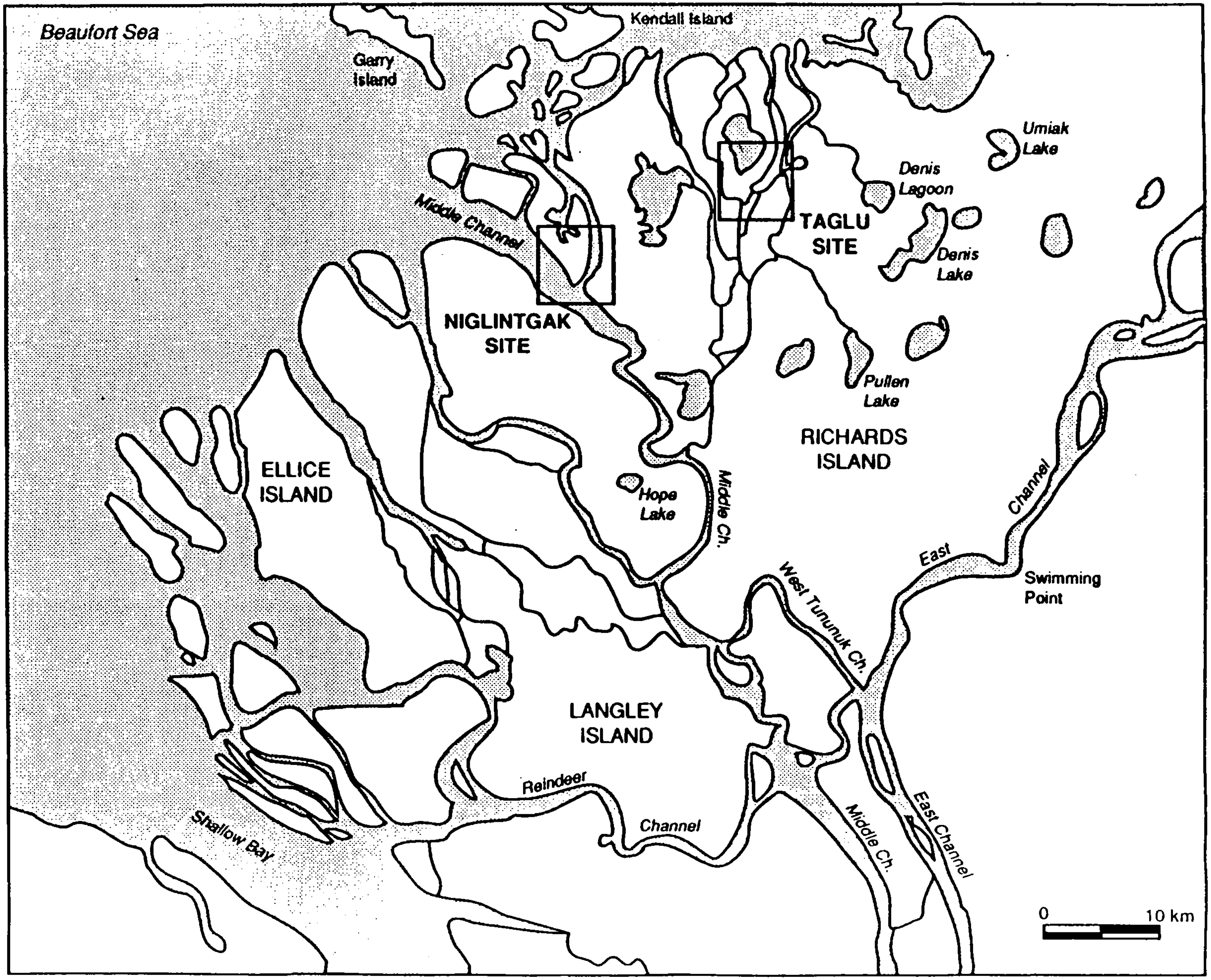


FIGURE 1.1 LOCATION MAP OF OUTER MACKENZIE DELTA
(from Traynor and Dallimore, 1992)

Downstream changes in trends of daily water level on the Mackenzie delta plain, summer and fall of 1973 (data for Mackenzie River above Arctic Red River and for East Channel at Inuvik courtesy Water Survey of Canada; for Harry Channel at Taglu G-33 from Slaney, 1974b, Fig. 2-2; and for the Beaufort Sea at Tuktoyaktuk from Canadian Hydrographic Service, 1975b).

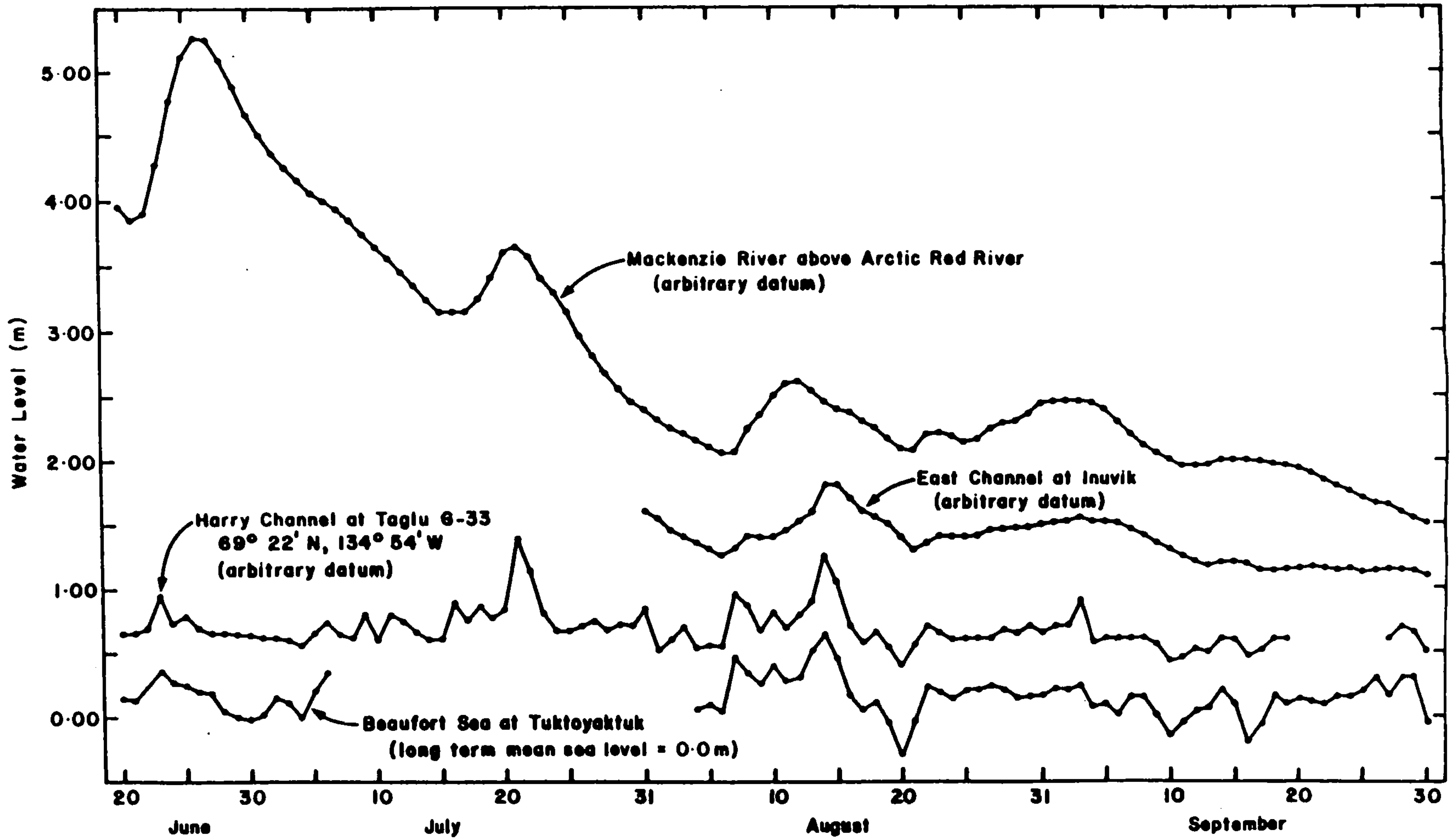


FIGURE 1.2

DOWNSTREAM CHANGE IN WATER LEVELS, MACKENZIE DELTA, 1973
(from C.P. Lewis, 1992, pers. comm.)

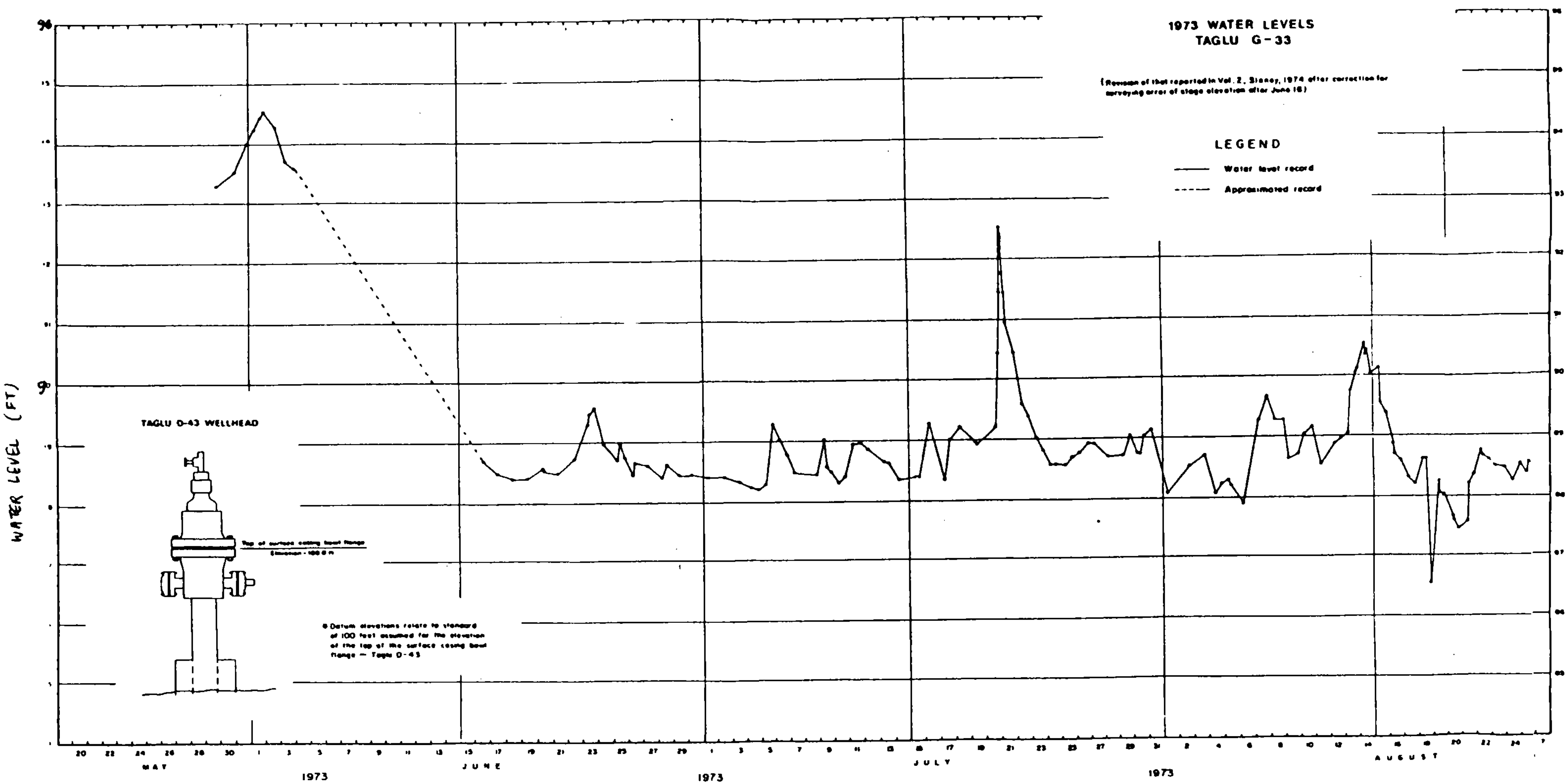


FIG. 1.3 WATER LEVELS AT TAGLU, 1973 (from Slaney, 1976)

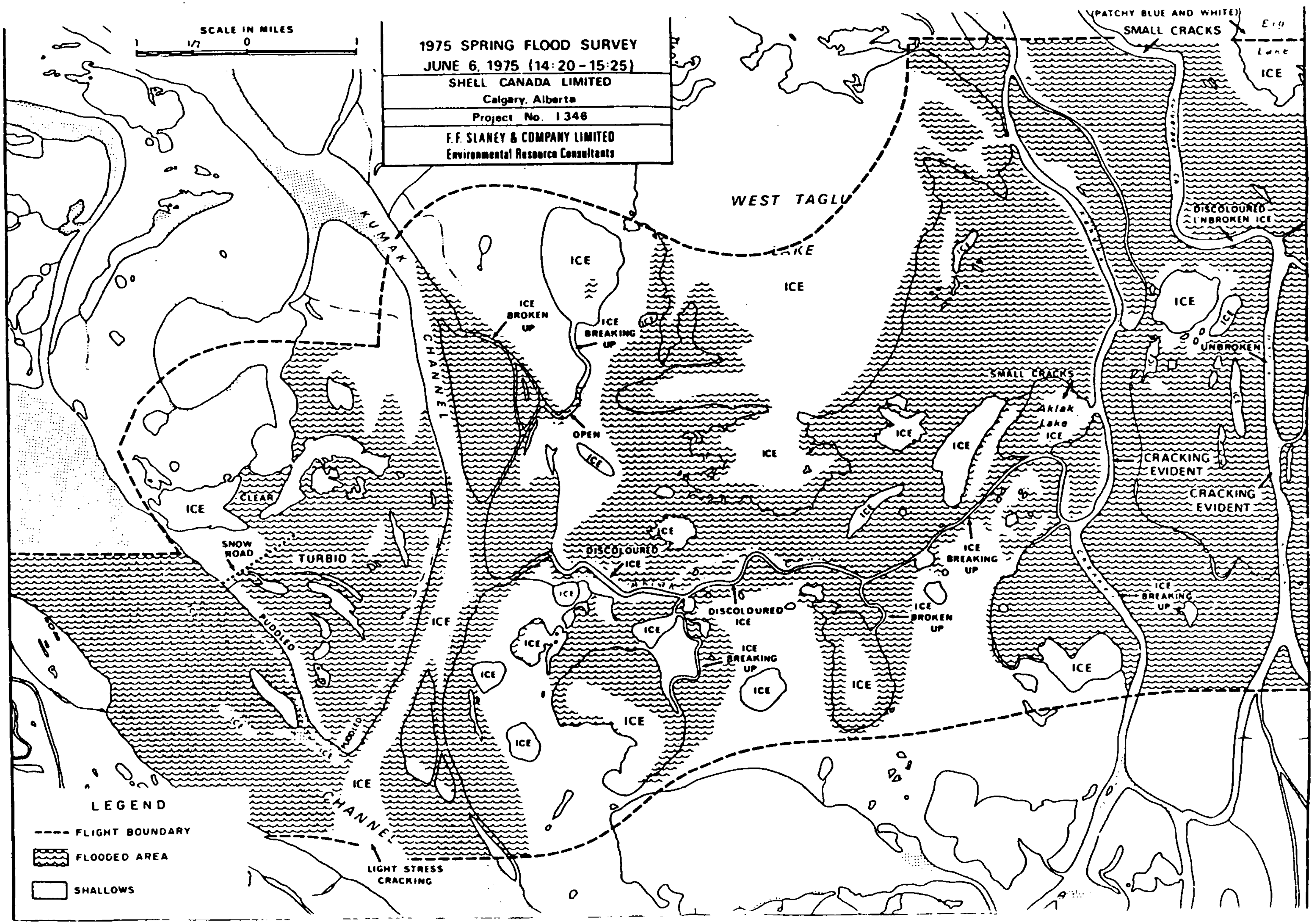
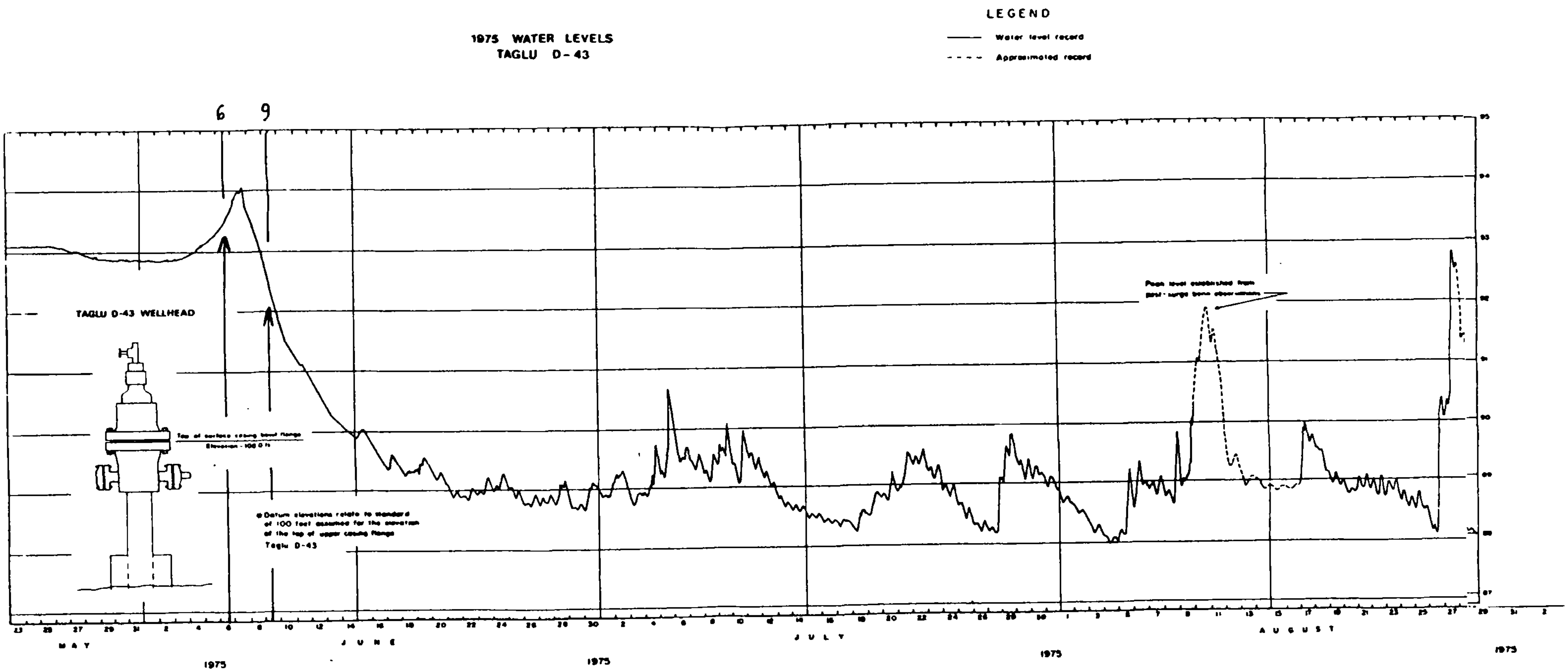


FIGURE 1.4 EXTENT OF FLOODING, NIGLINTGAK-TAGLU, JUNE 6 1975
(from Slaney, 1976)

FIGURE 1.5 WATER LEVELS AT TAGLU, 1975 (from Slaney, 1976)



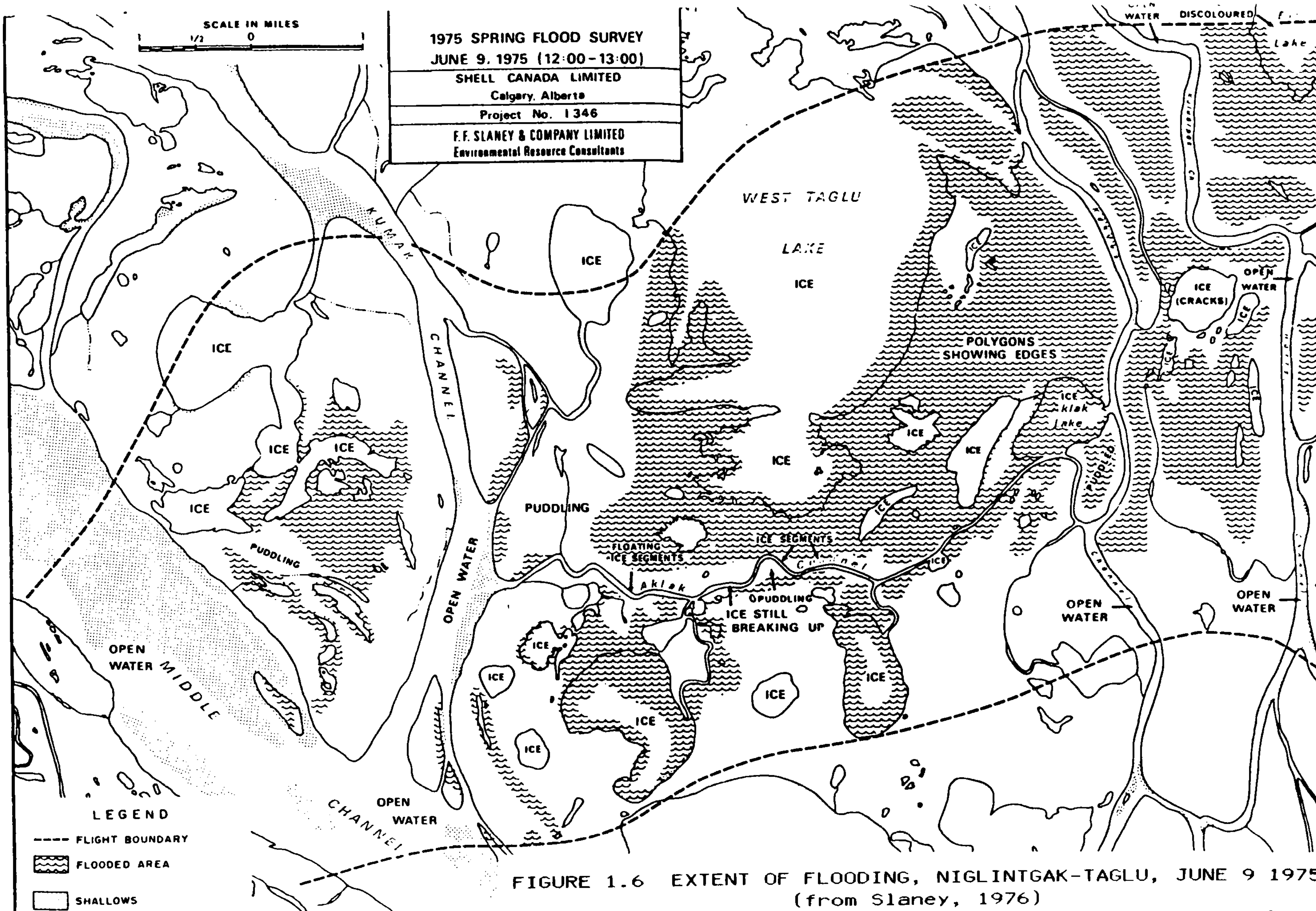


FIGURE 1.6 EXTENT OF FLOODING, NIGLINTGAK-TAGLU, JUNE 9 1975
(from Slaney, 1976)

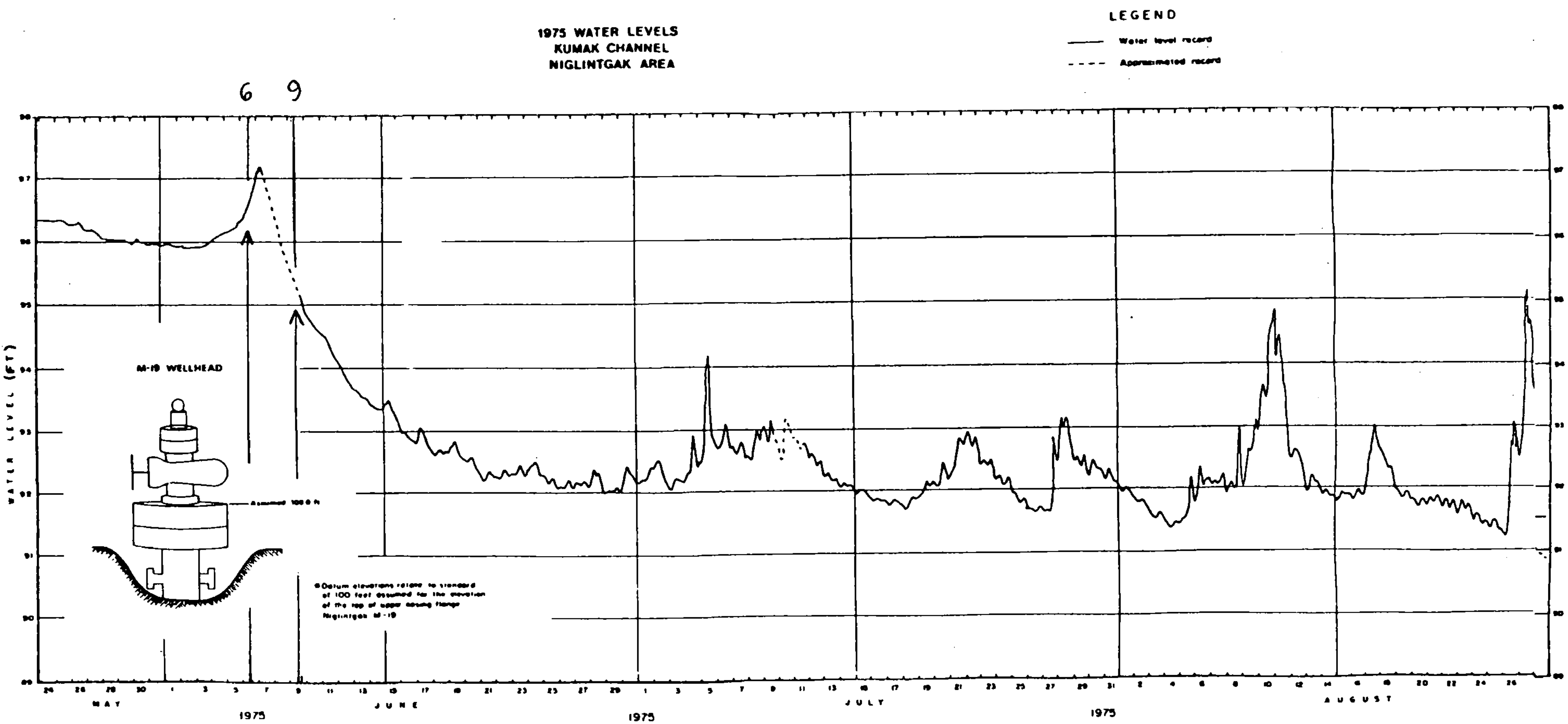


FIG. 1.7 WATER LEVELS IN KUMAK CHANNEL, 1975 (from Slaney, 1976)

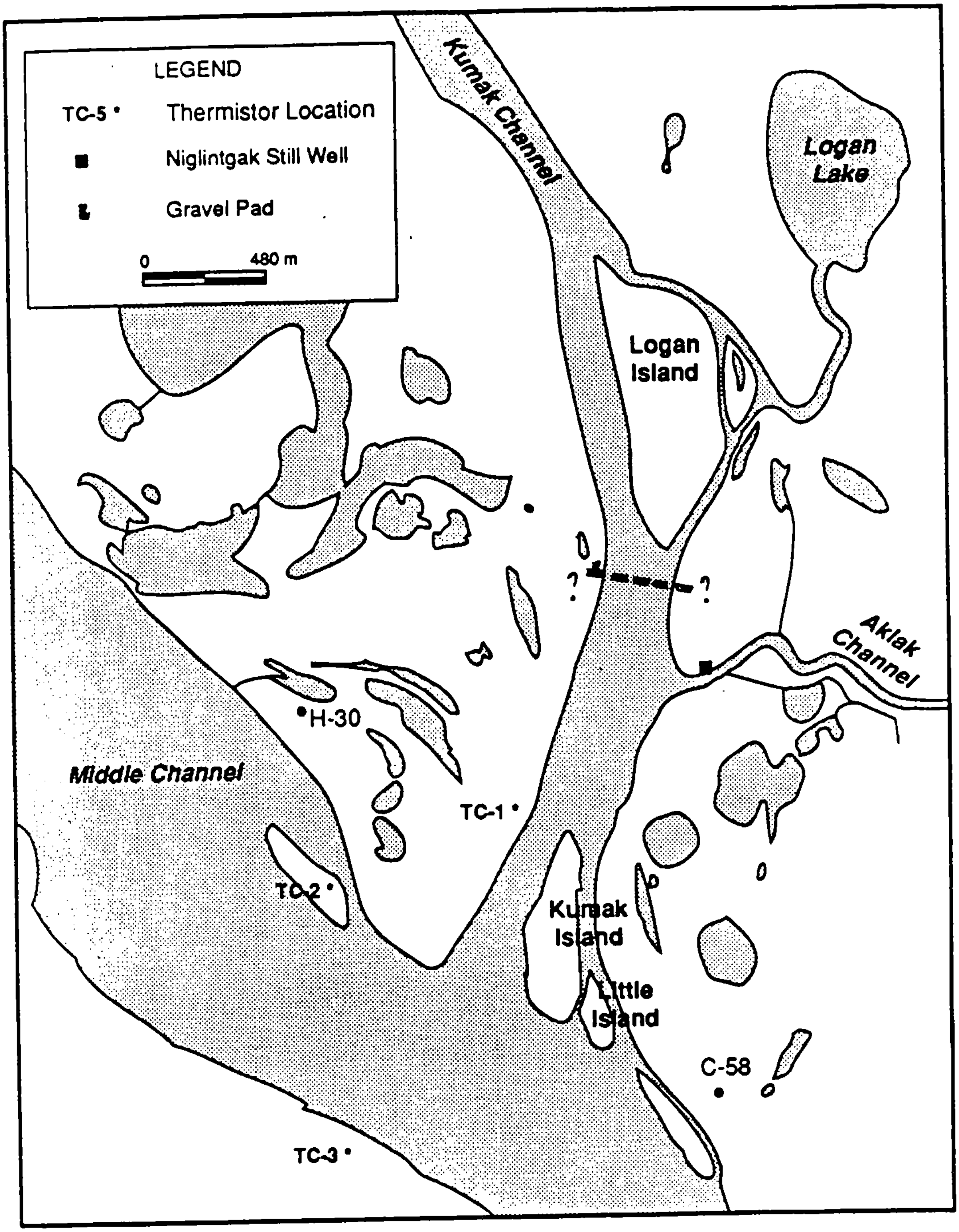


FIGURE 2.1

LOCATION MAP OF NIGLINTGAK AREA
(from Traynor and Dallimore, 1992)

? denotes possible pipeline crossing

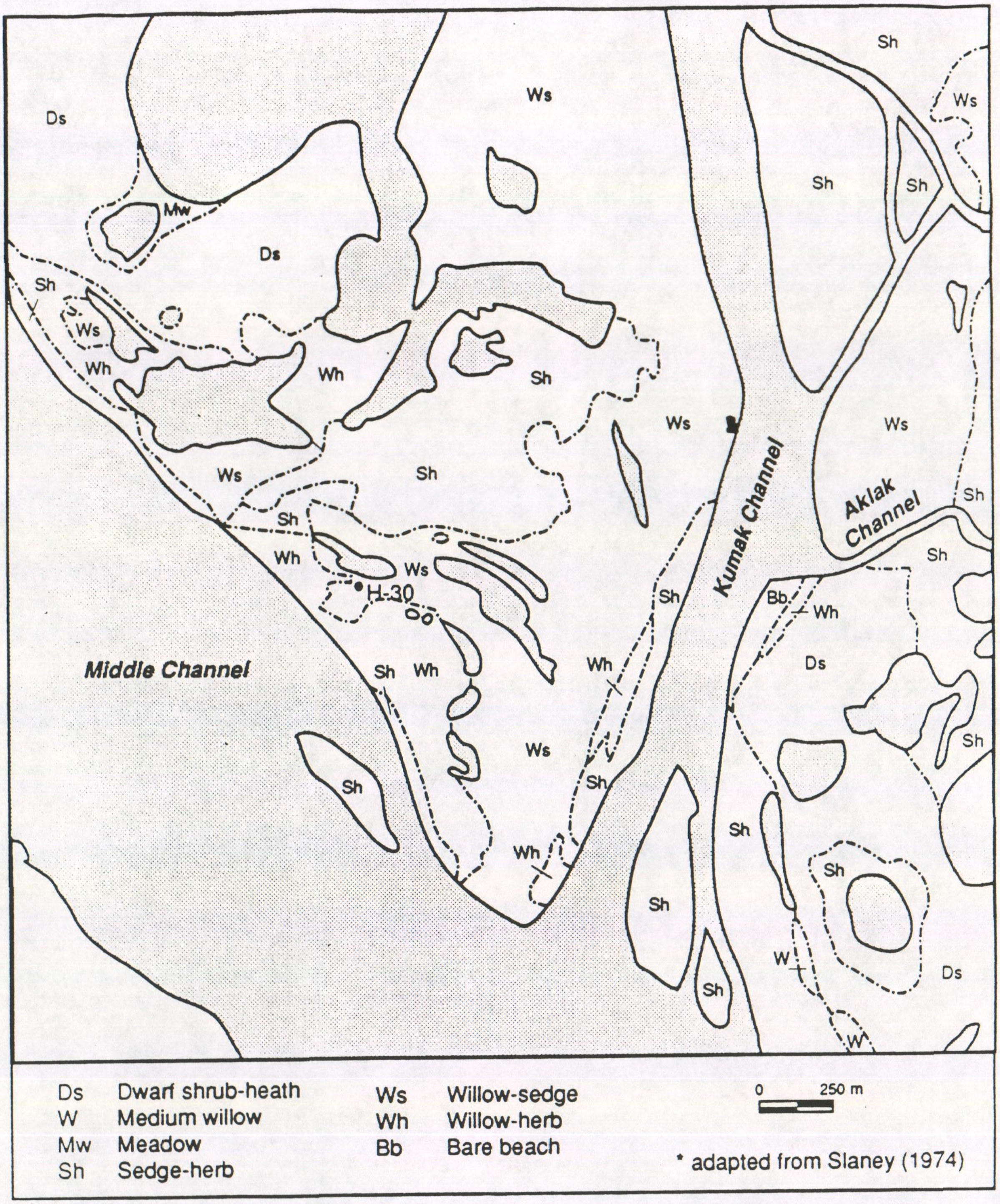
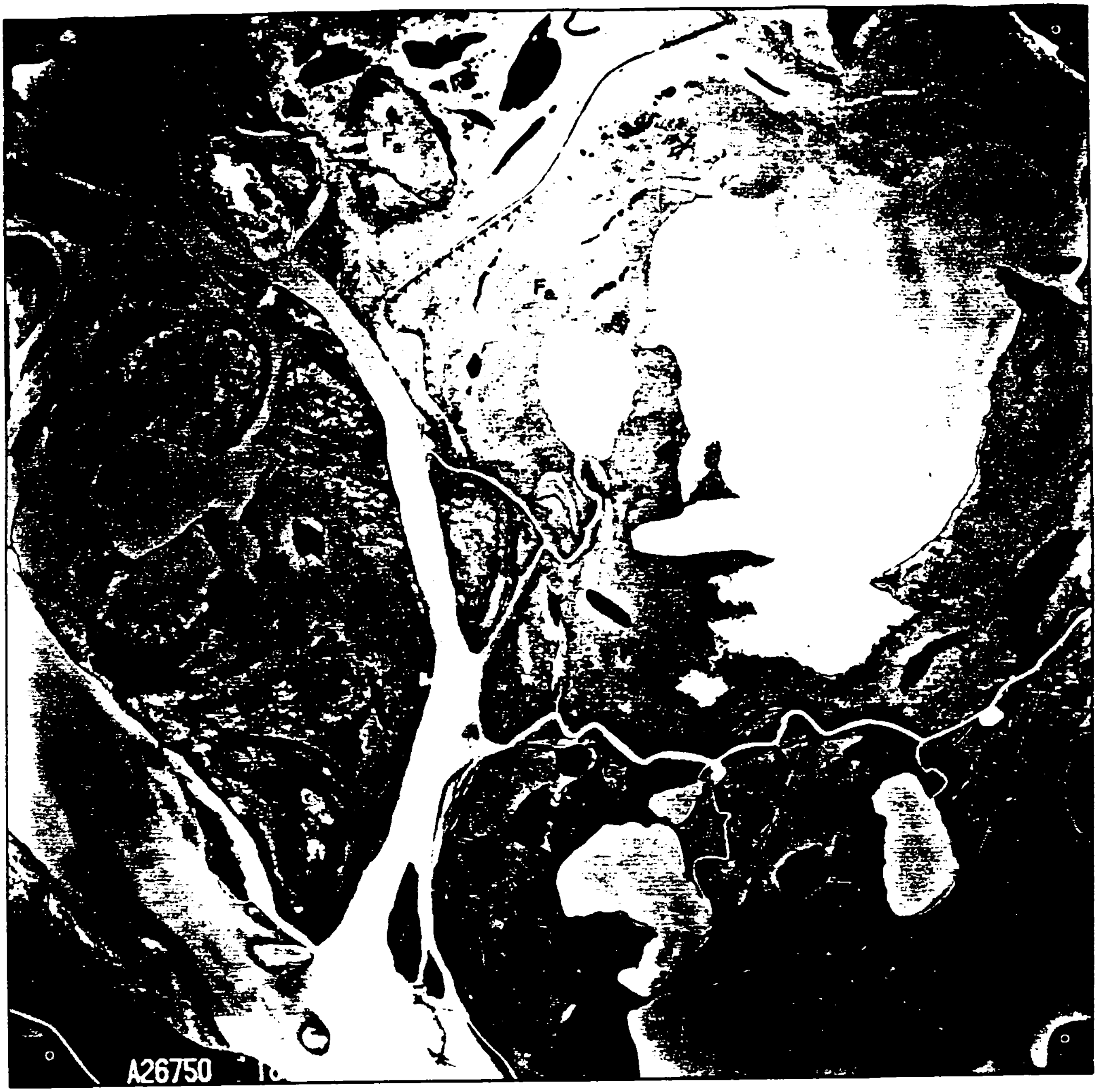


FIGURE 2.2

VEGETATION MAP OF NIGLINTGAK AREA
(from Traynor and Dallimore, 1992)



QUATERNARY
HOLOCENE

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

EARLY WISCONSINAN (?)

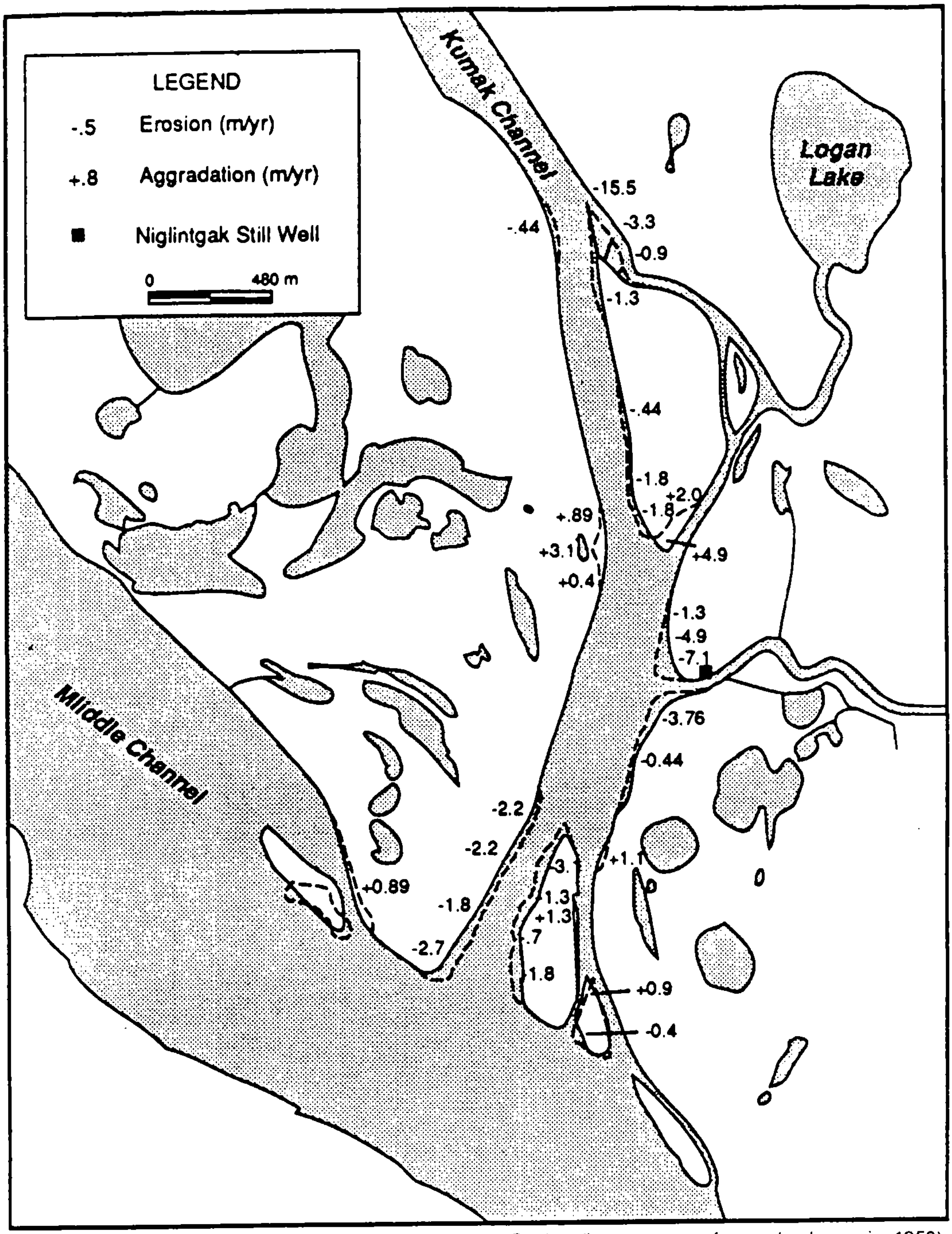
G_p	*Outwash plain*
M_m	*Rolling moraine*

Geological boundary . . .

Channel scars . . . .

FIGURE 2.3

SURFICIAL GEOLOGY OF NIGLINTGAK AREA
(from Traynor and Dallimore, 1992)



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

FIGURE 2.4

BANK STABILITY IN NIGLINTGAK AREA, 1950-1985
(from Traynor and Dallimore, 1992)

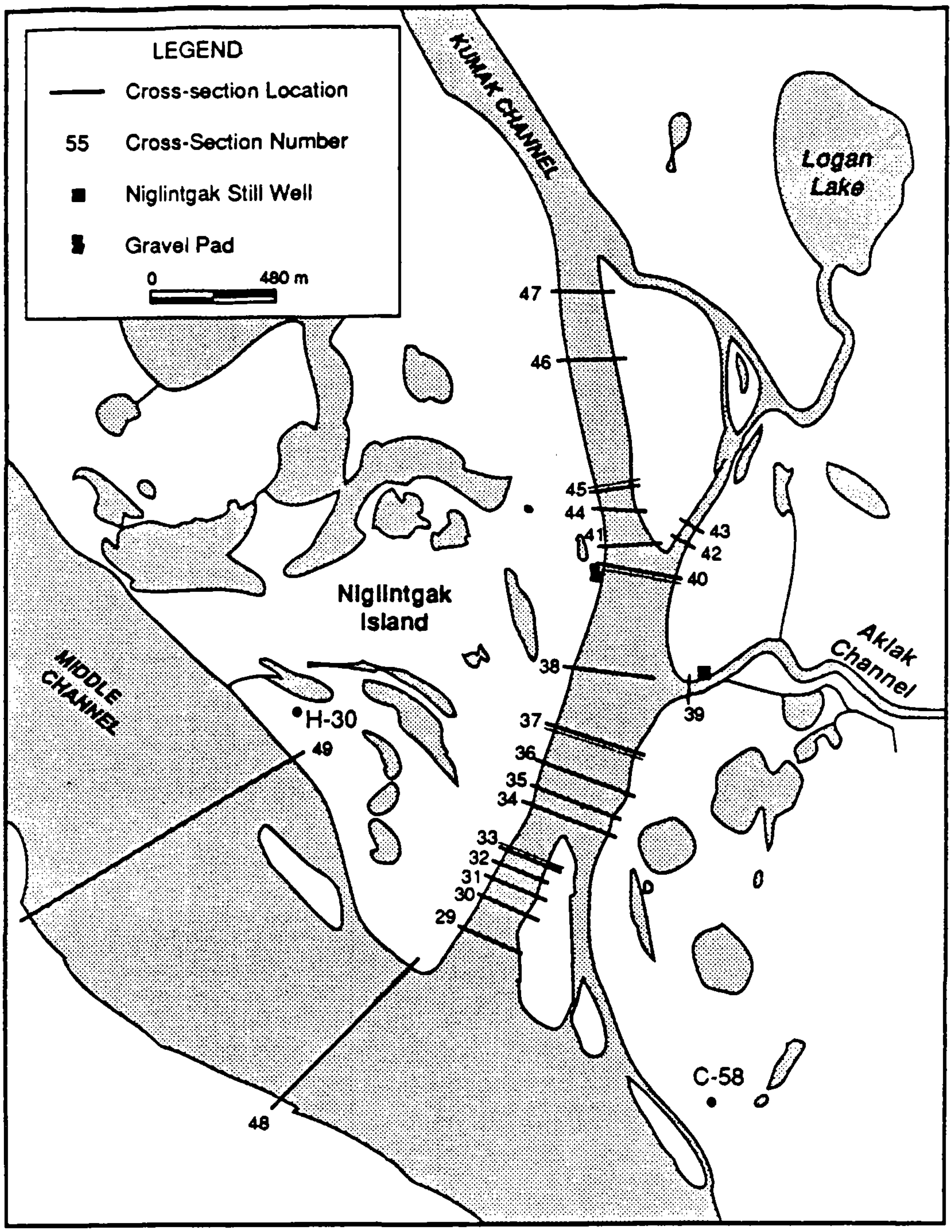


FIGURE 2.5

CROSS-SECTION LOCATIONS: NIGLINTGAK AREA
(from Traynor and Dallimore, 1992)

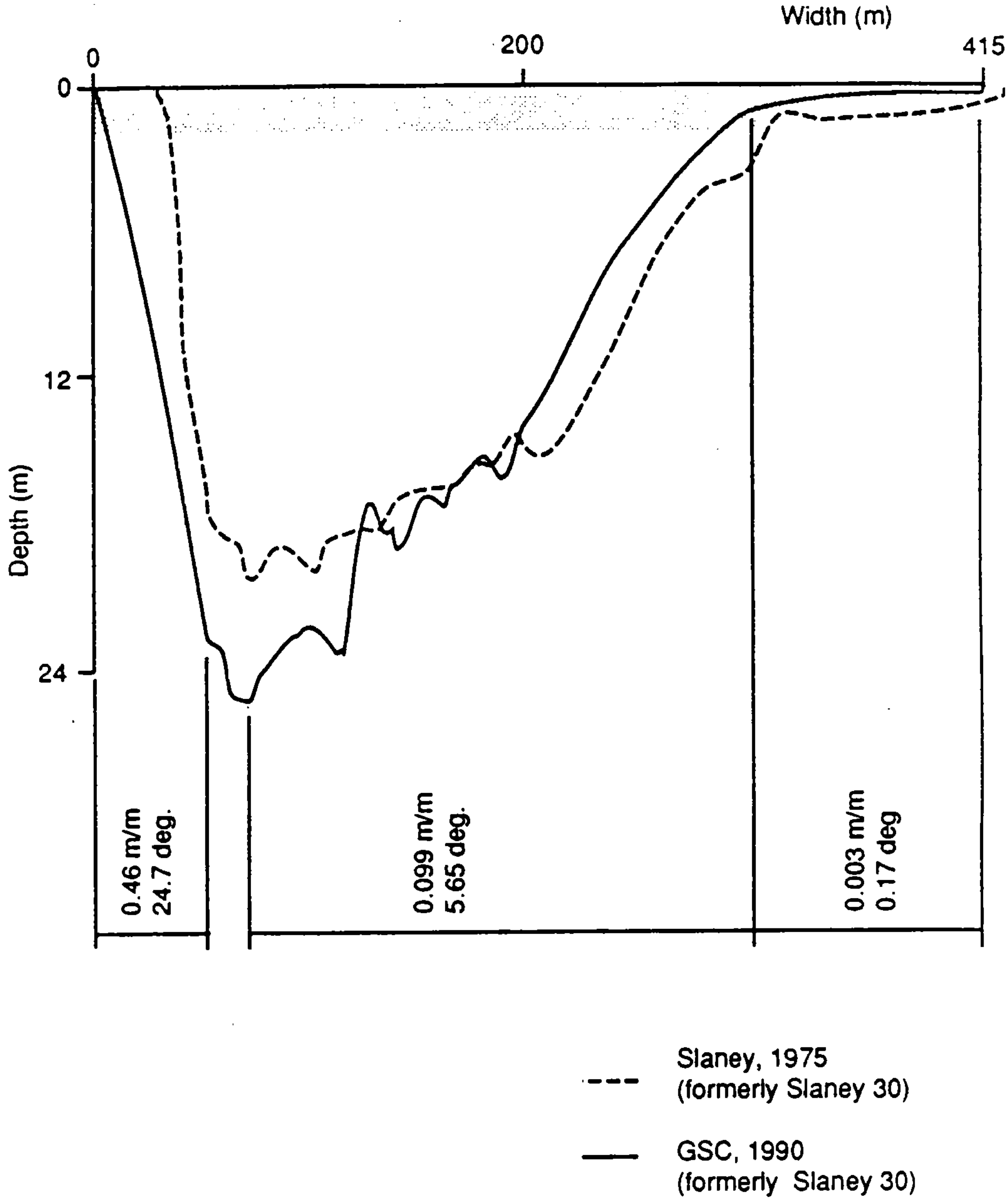


FIGURE 2.6

CROSS-SECTION 33 PROFILE CHANGES: KUMAK CHANNEL
(from Traynor and Dallimore, 1992)

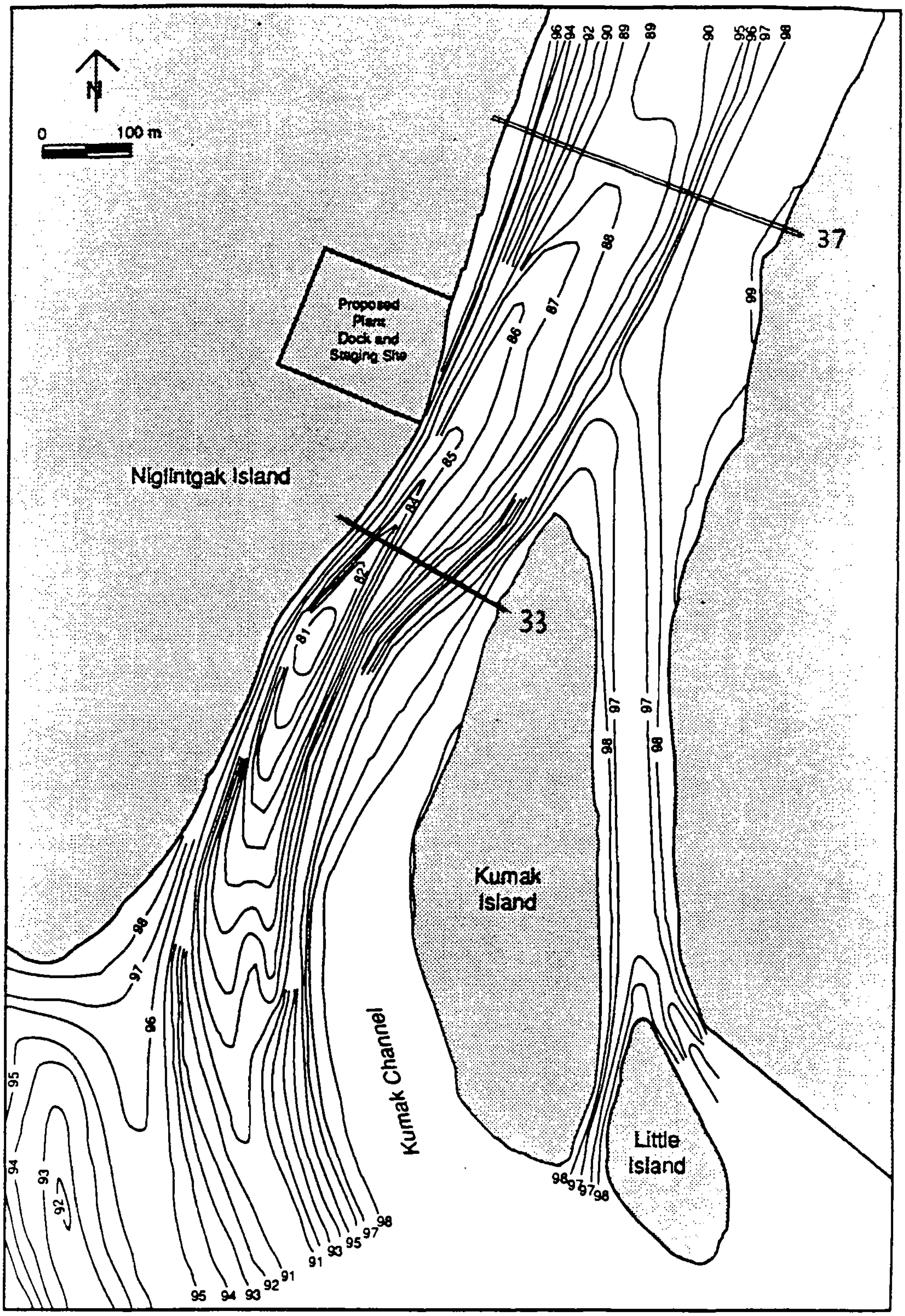


FIGURE 2.7

CHANNEL BATHYMETRY AT ENTRANCE TO KUMAK CHANNEL
(from Traynor and Dallimore, 1992)

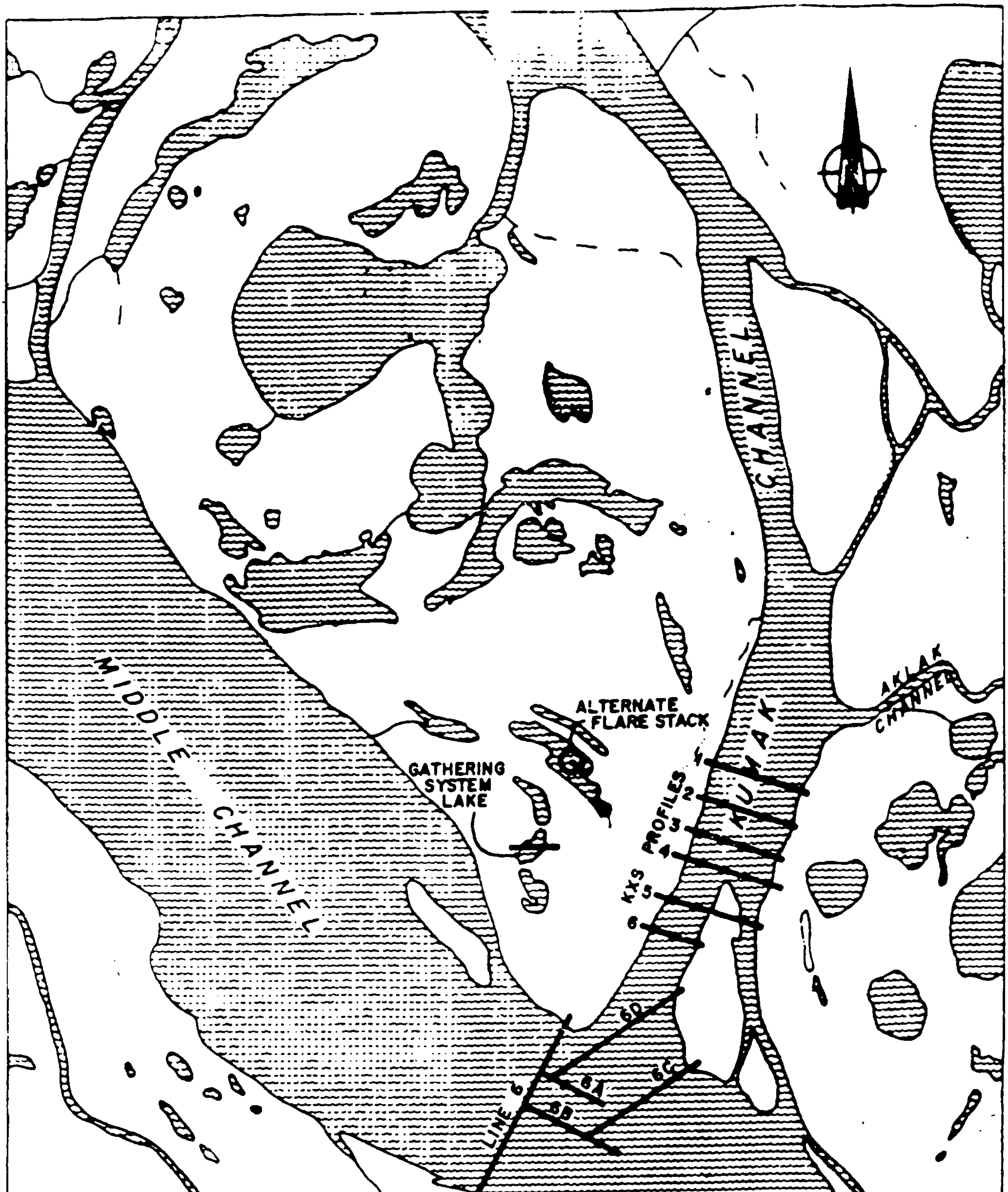
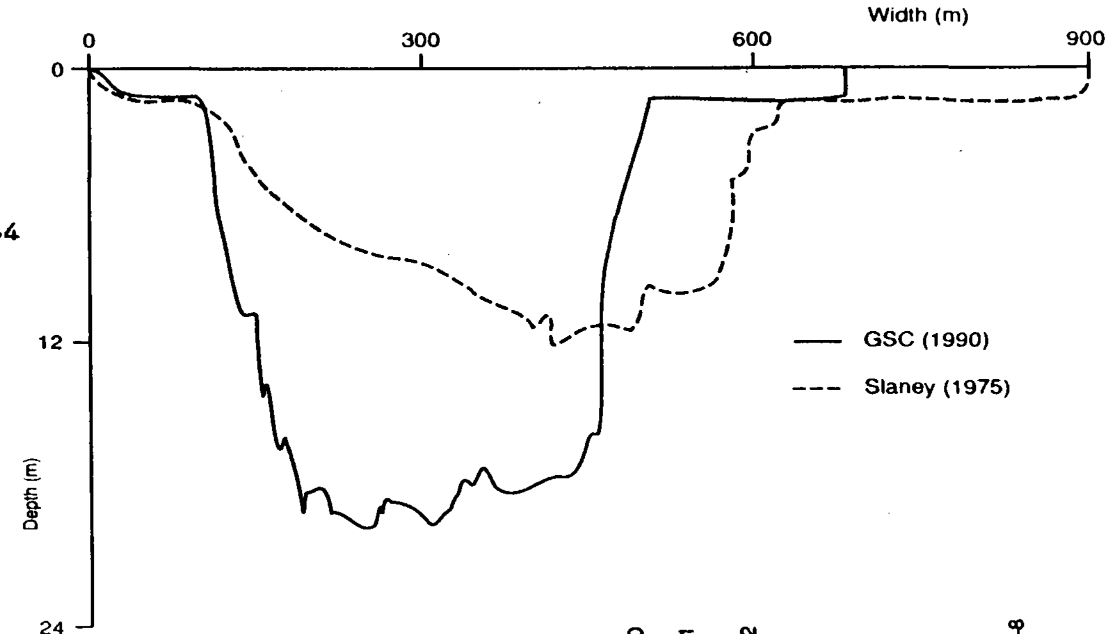


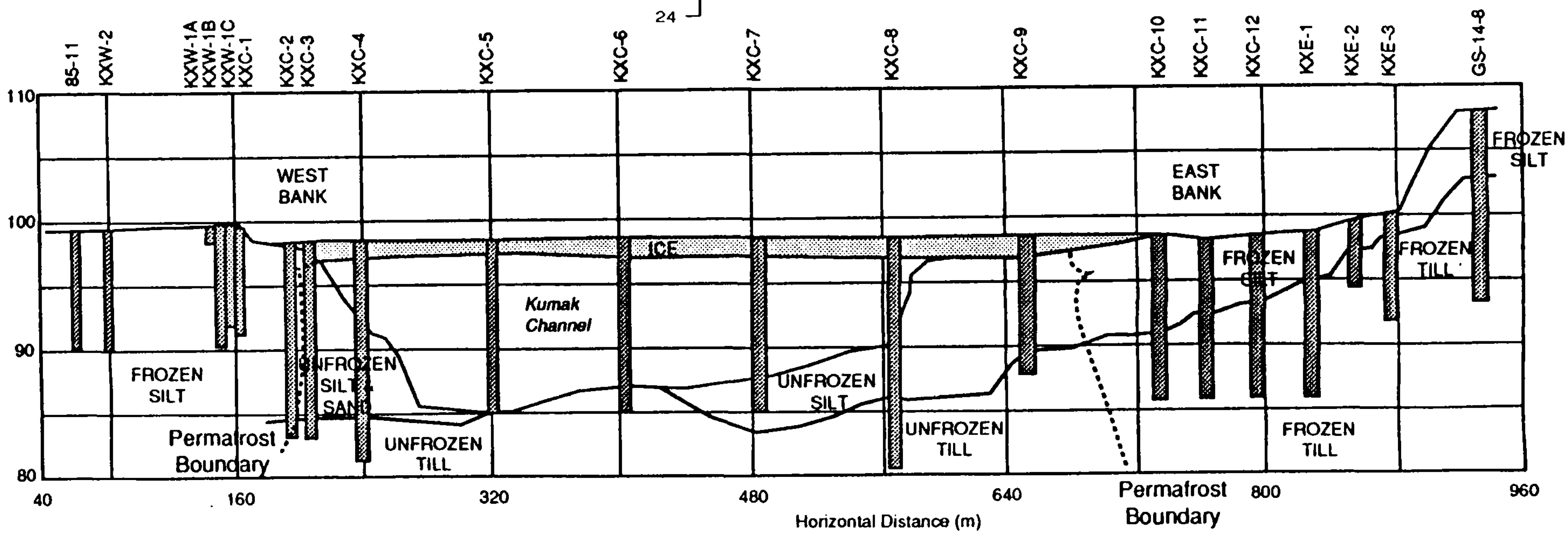
FIGURE 2.8

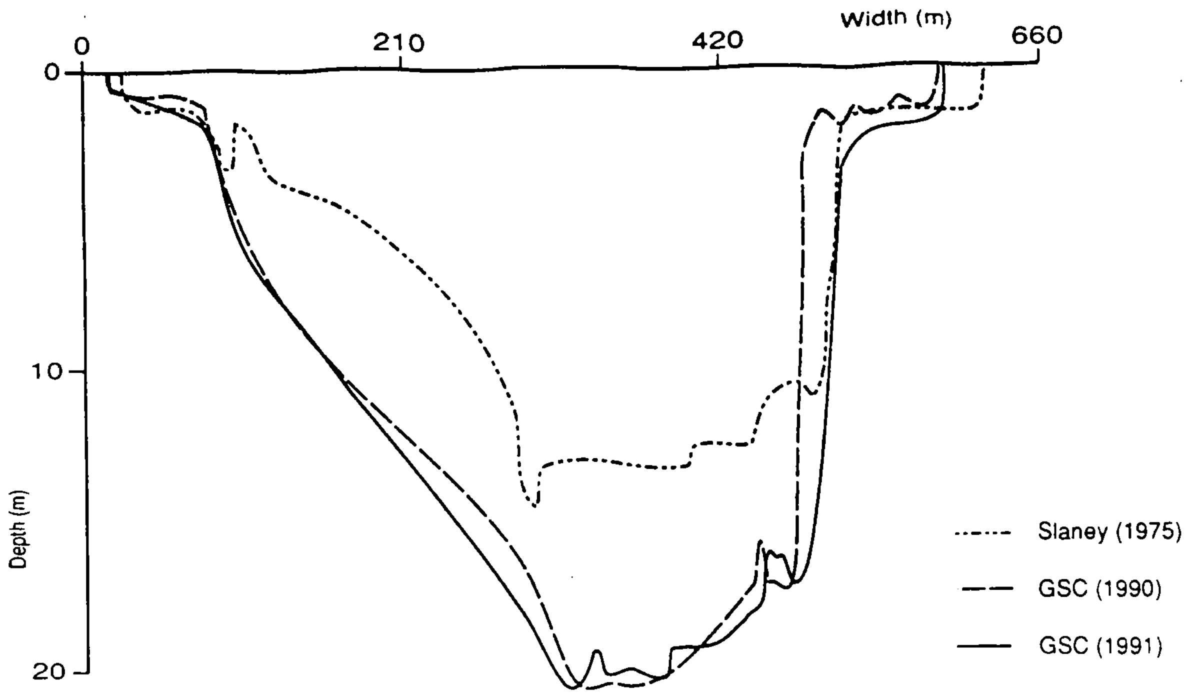
LOCATION OF SOUNDING PROFILES
(from Hardy, 1977)

FIGURE 2.9 KUMAK CHANNEL

TOP: CROSS-SECTION 37 PROFILE CHANGES
BOTTOM: GEOTECHNICAL BOREHOLES NEAR CS 34
(from Traynor and Dallimore, 1992)







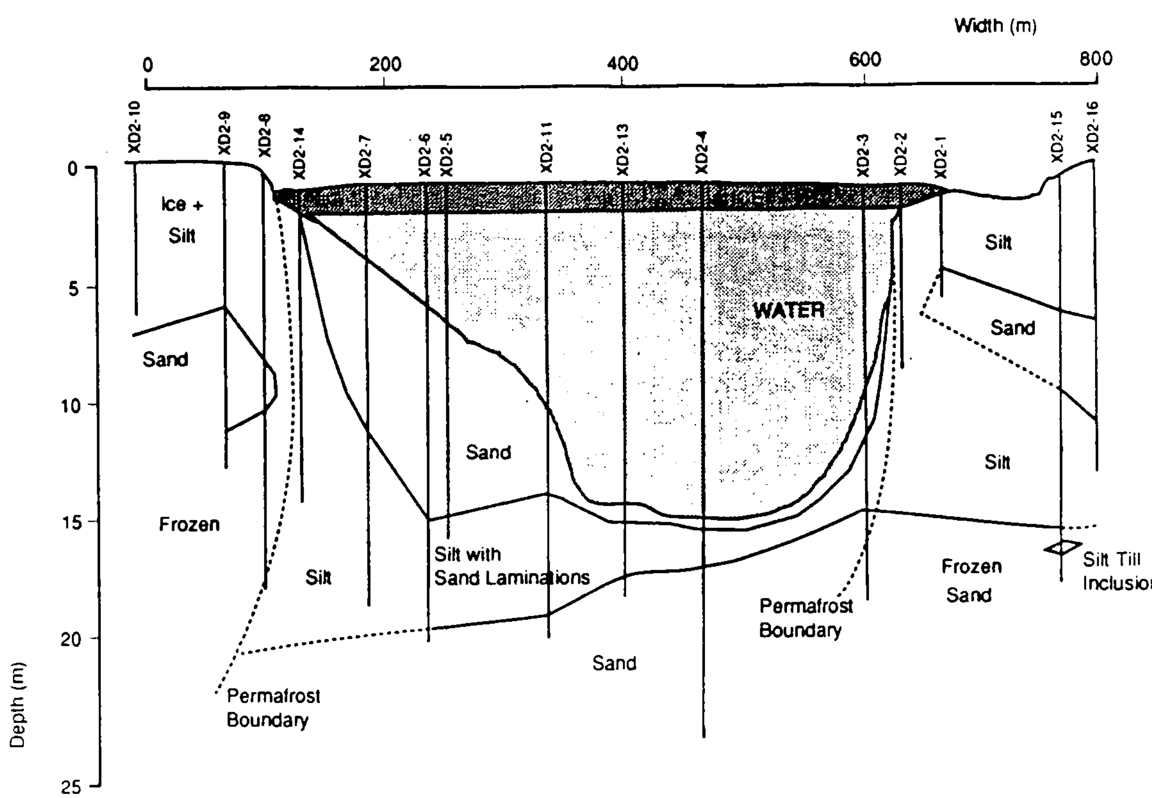


FIGURE 2.10 KUMAK CHANNEL

TOP: CROSS-SECTION 40 PROFILE CHANGES
BOTTOM: GEOTECHNICAL STRATIGRAPHY AT CS 40
(from Traynor and Dallimore, 1992)

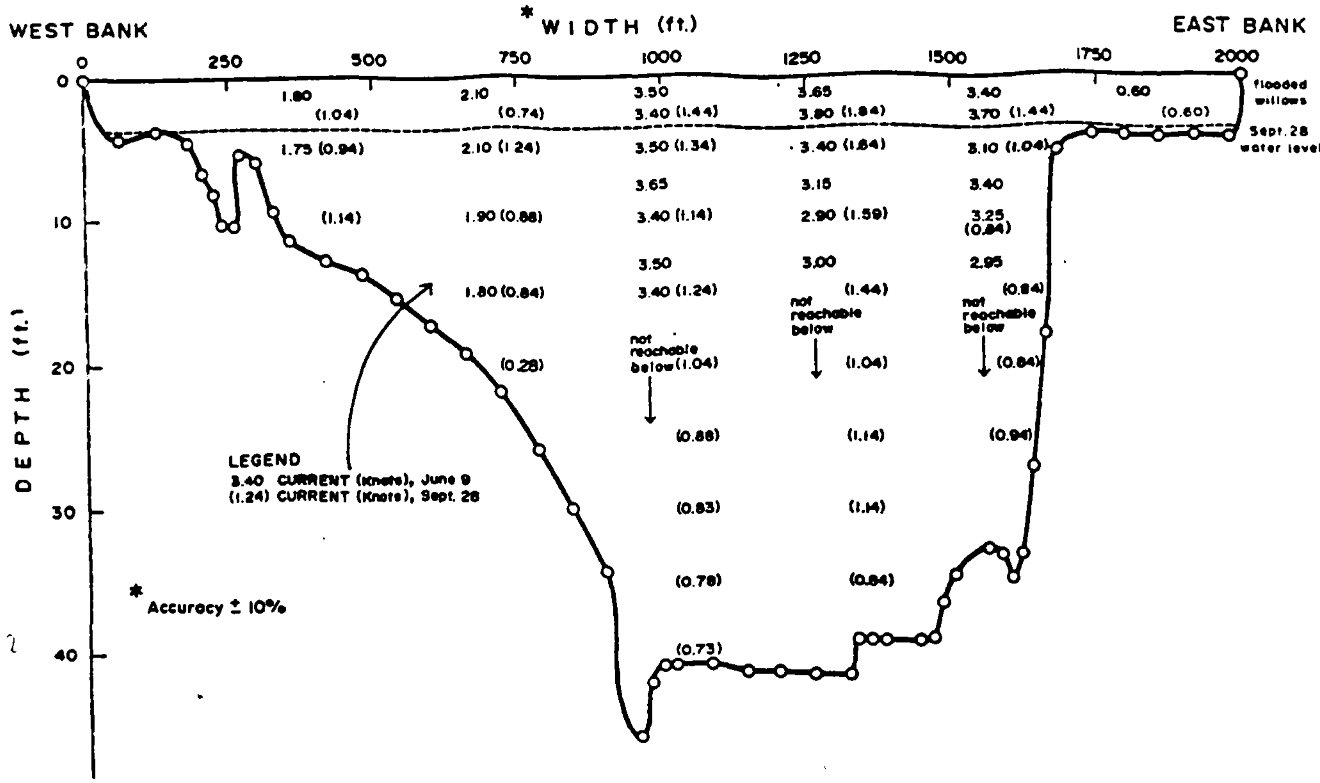
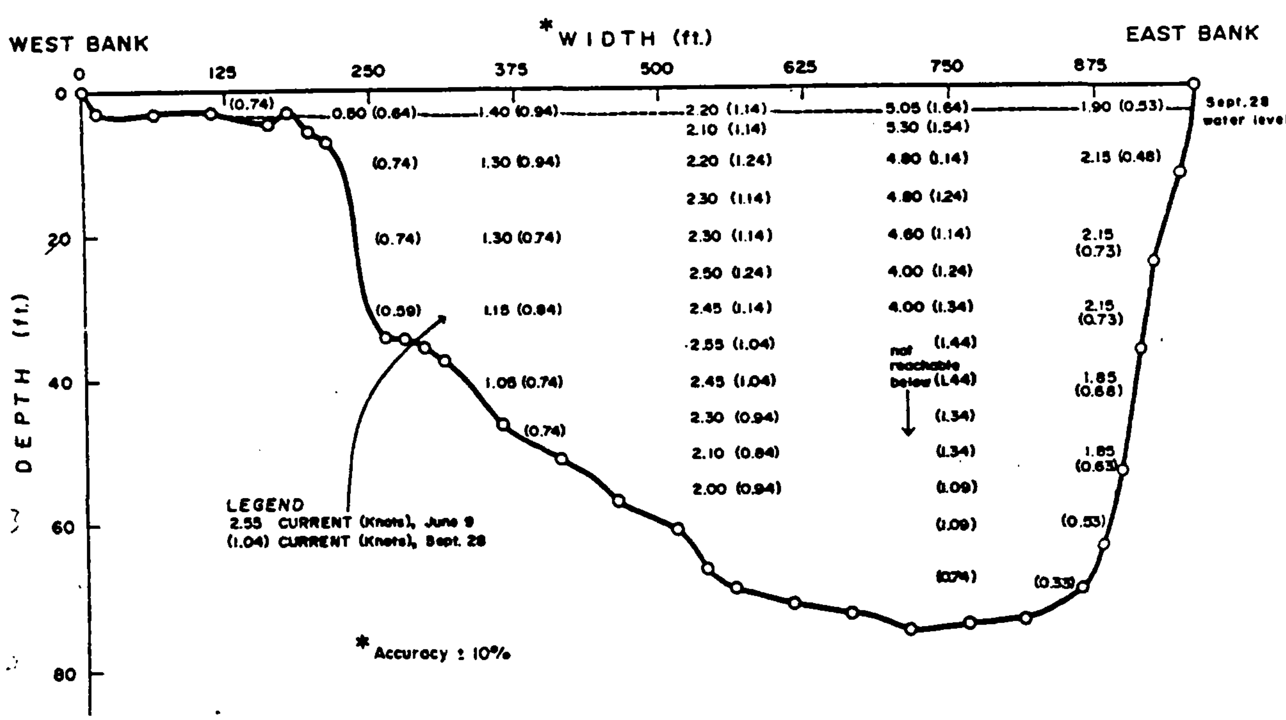
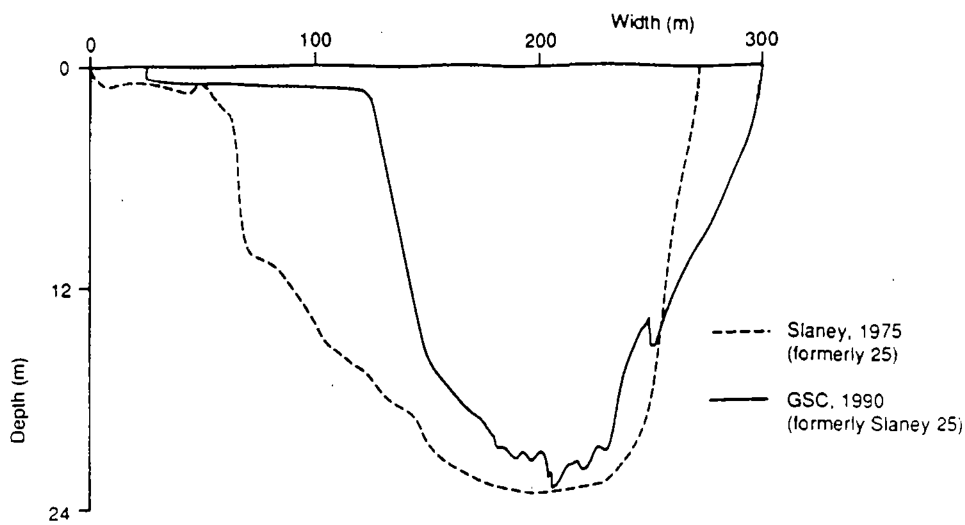


FIGURE 2.11

CROSS-SECTIONAL DISTRIBUTION OF CURRENT SPEED IN KUMAK CHANNEL:
TOP: CS 40; BOTTOM: CS 45
(from Slaney, 1976)





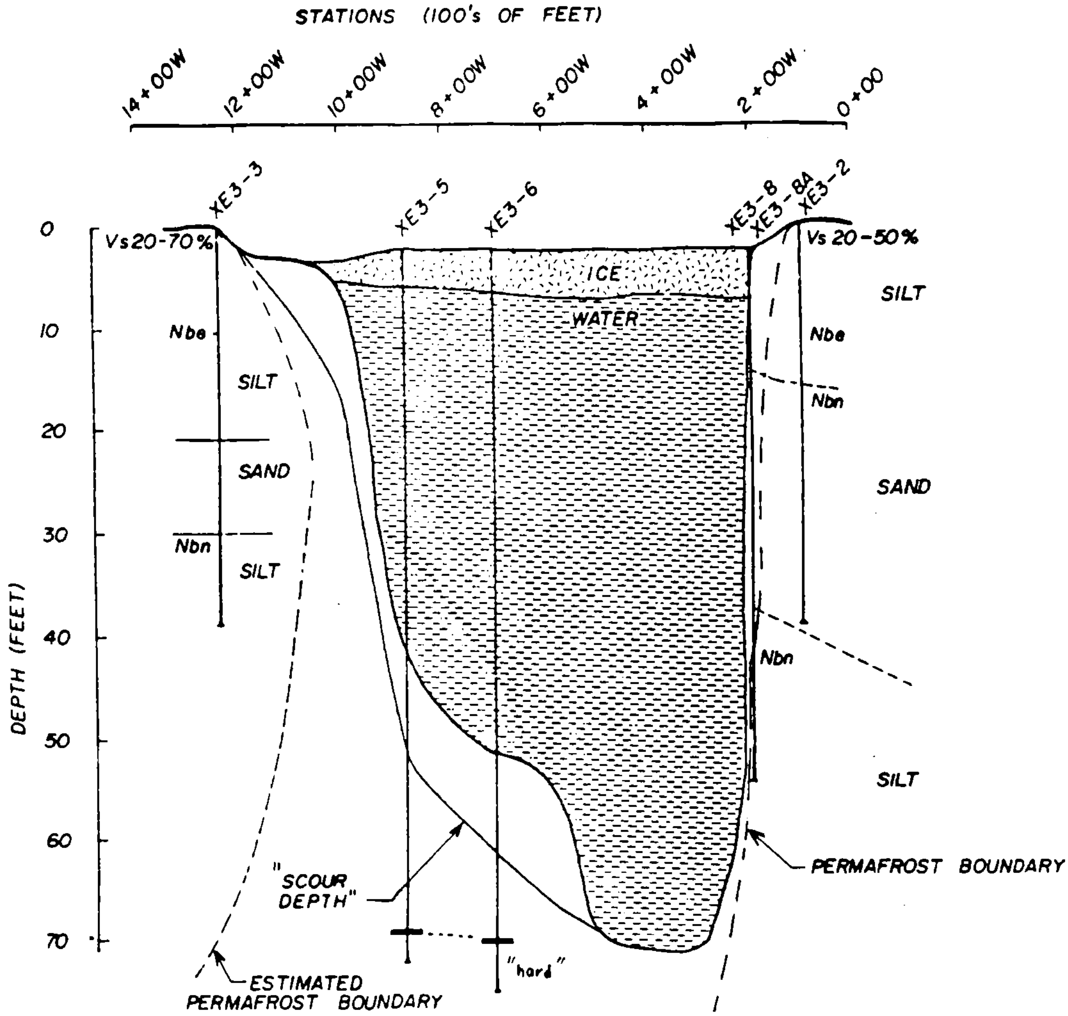


FIGURE 4-6 STRATIGRAPHIC SECTION CROSSING E-3

FIGURE 2.12 KUMAK CHANNEL

TOP: CS 45 PROFILE CHANGES (from Traynor and Dallimore, 1992)
BOTTOM: GEOTECHNICAL BOREHOLES NEAR CS 44 (from EBA, 1974)

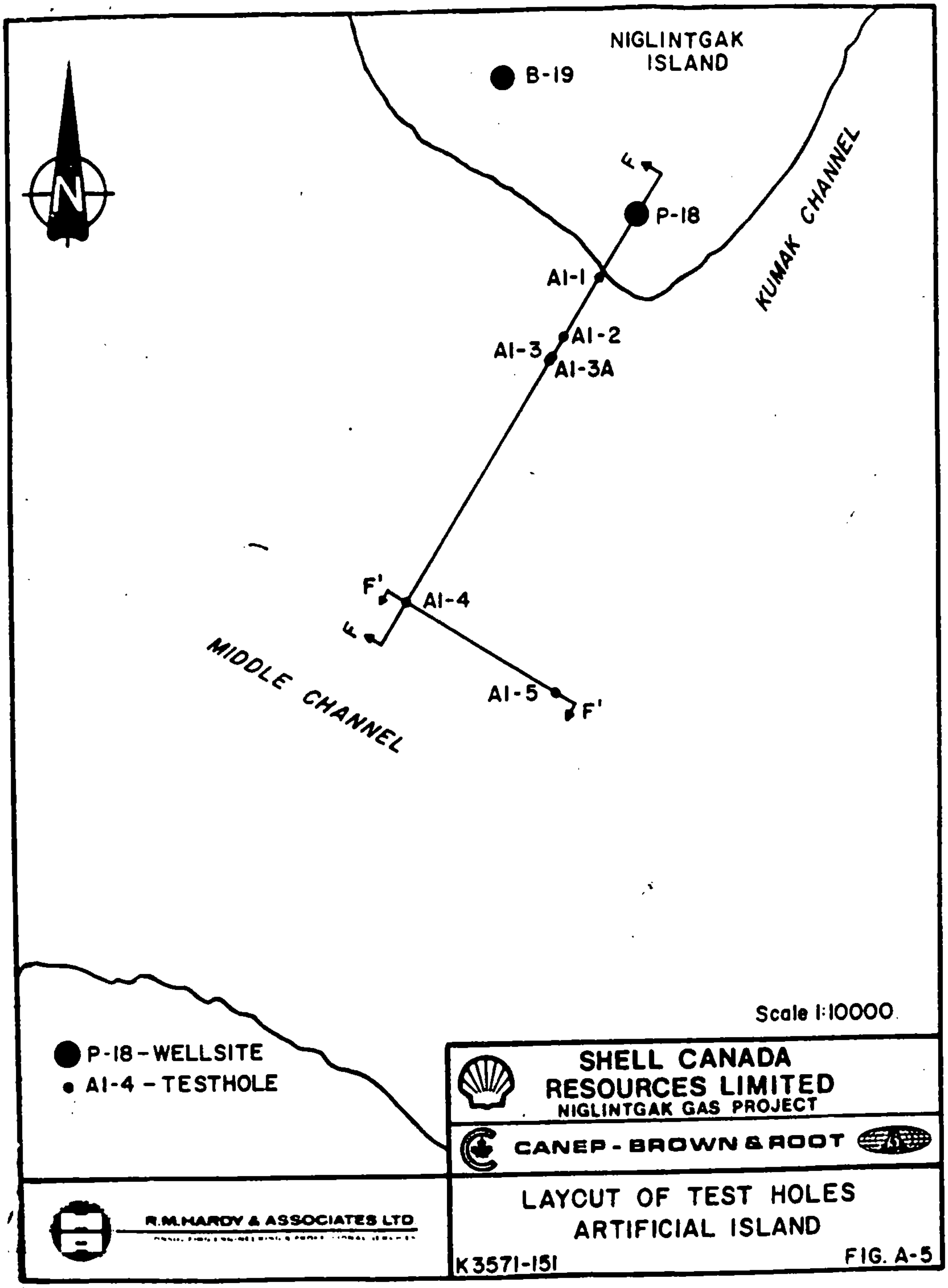


FIGURE 2.13

LOCATION OF HARDY SURVEY LINES IN MIDDLE CHANNEL OUTLET
(from Hardy, 1977)

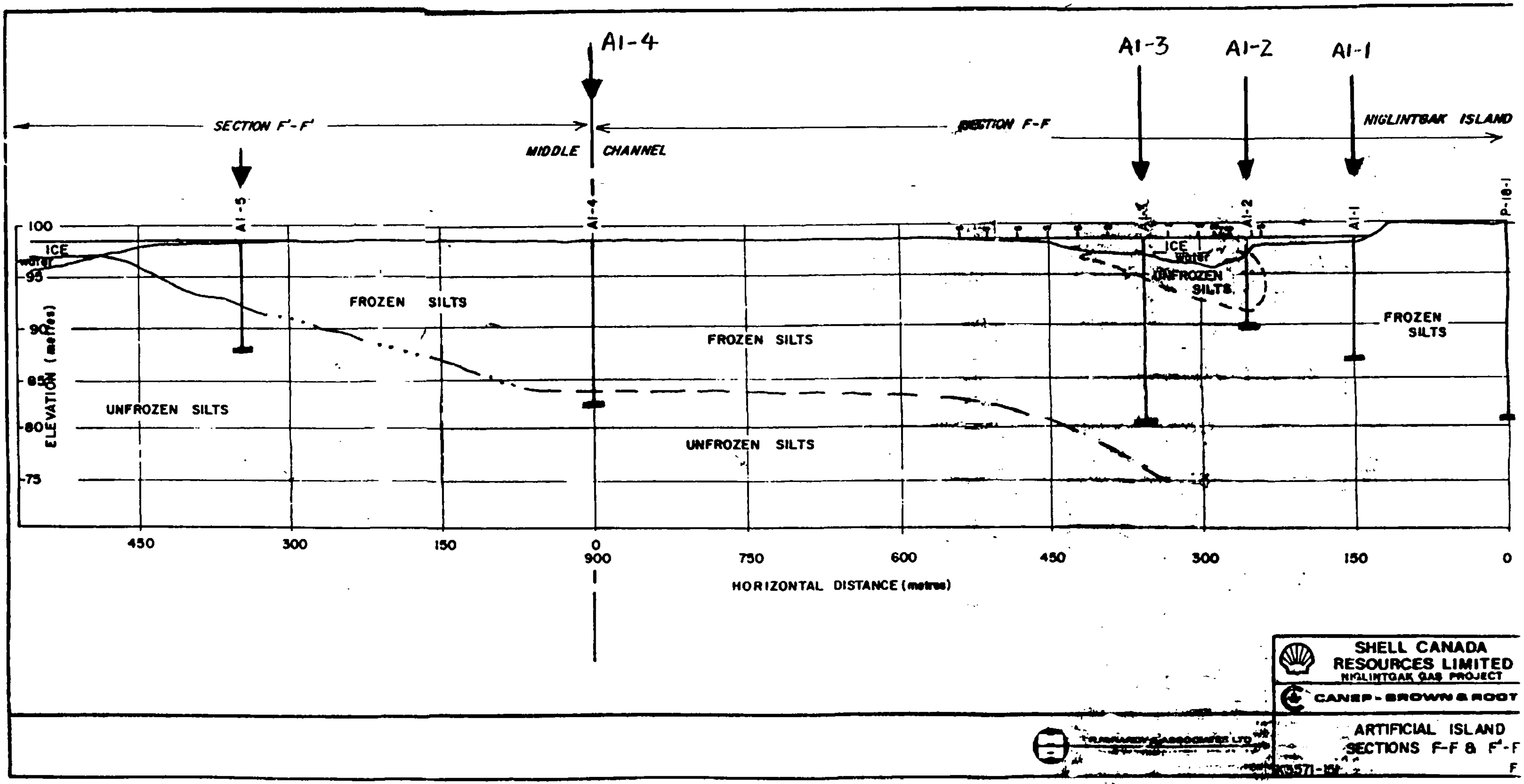


FIGURE 2.14 SEDIMENT CROSS-SECTION FOR MIDDLE CHANNEL OUTLET
(from Hardy, 1977: see Fig. 2.13 for borehole locations)

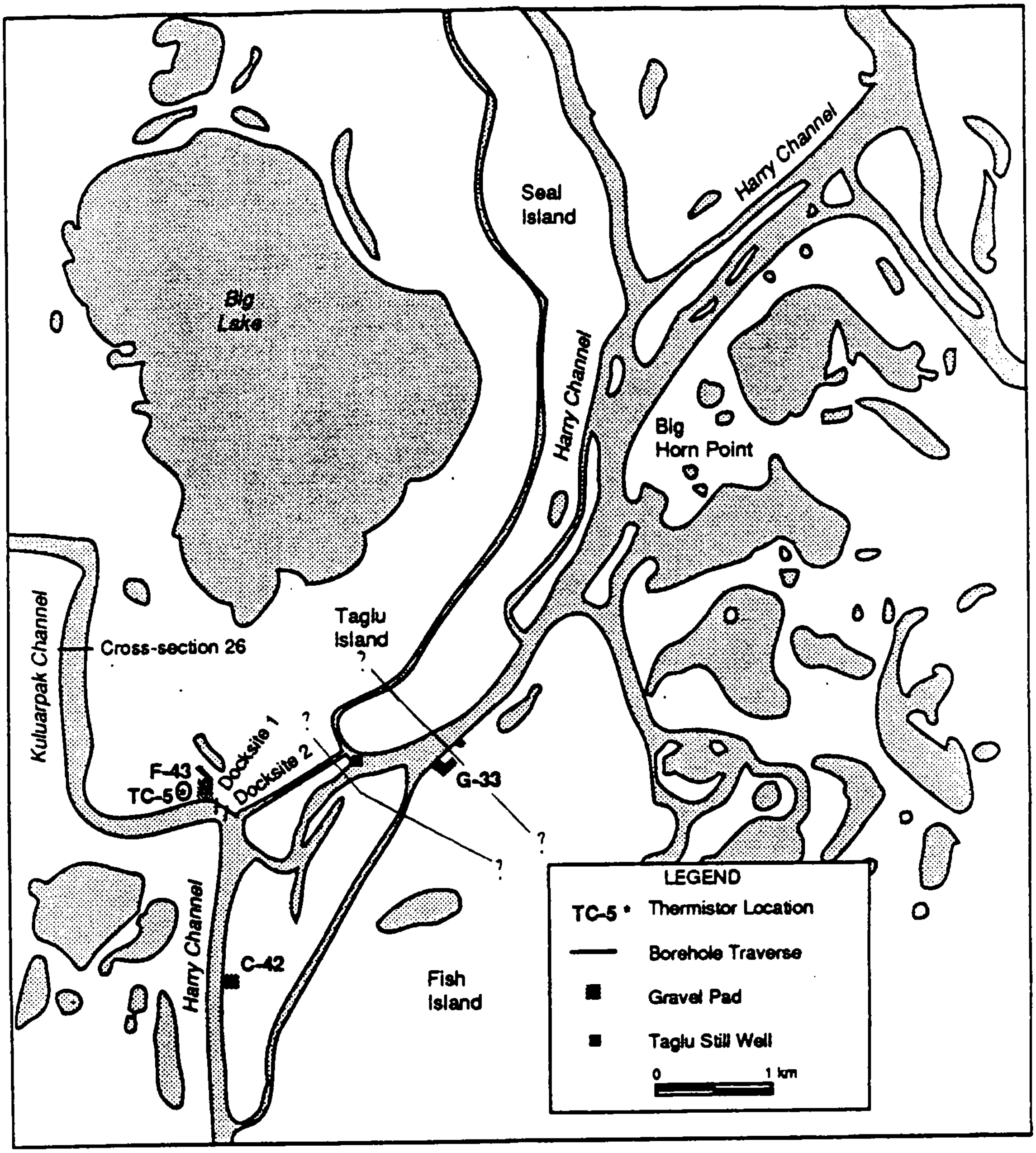


FIGURE 3.1

LOCATION MAP OF TAGLU AREA
? denotes possible pipeline crossing
(from Traynor and Dallimore, 1992)

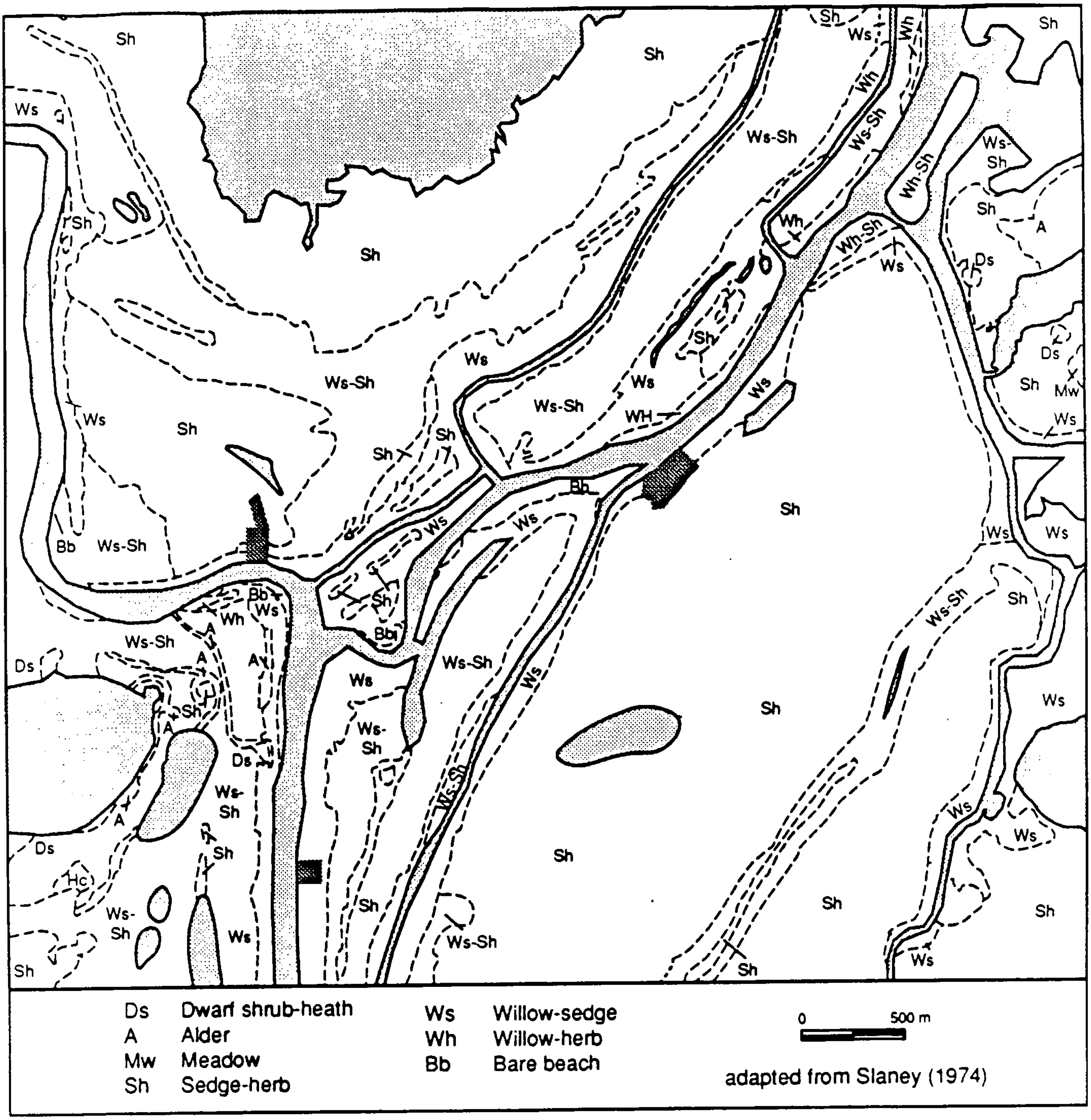


FIGURE 3.2

VEGETATION MAP OF TAGLU AREA
(from Traynor and Dallimore, 1992)

QUATERNARY
HOLOCENE

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

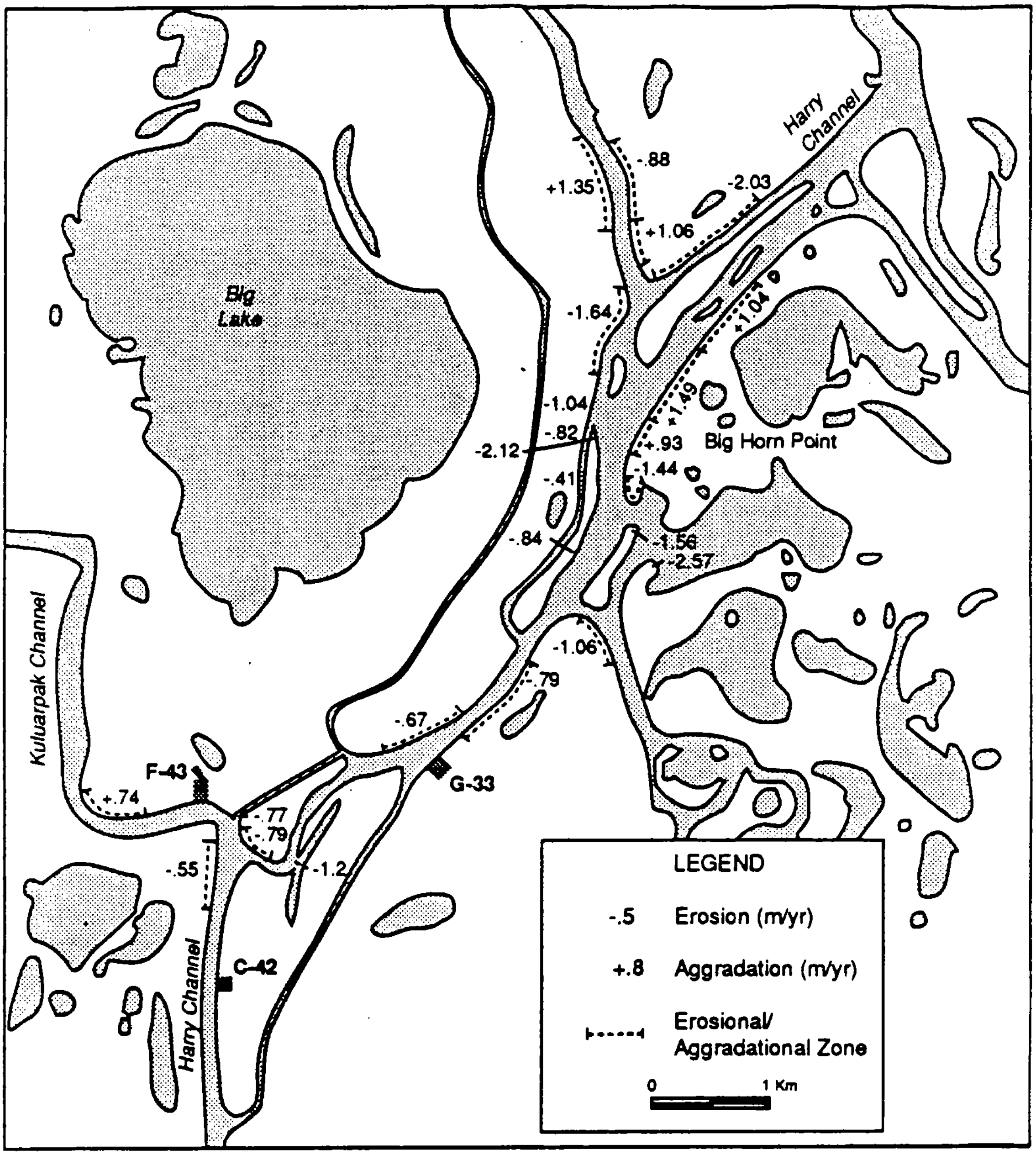
EARLY WISCONSINAN (?)

M_m	*Rolling moraine*

Geological boundary . . .
Channel scars . . . . . .
Pingo . . . .

FIGURE 3.3

SURFICIAL GEOLOGY OF TAGLU AREA
(from Traynor and Dallimore, 1992)



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

FIGURE 3.4

BANK STABILITY IN TAGLU AREA, 1950-1985
(from Traynor and Dallimore, 1992)

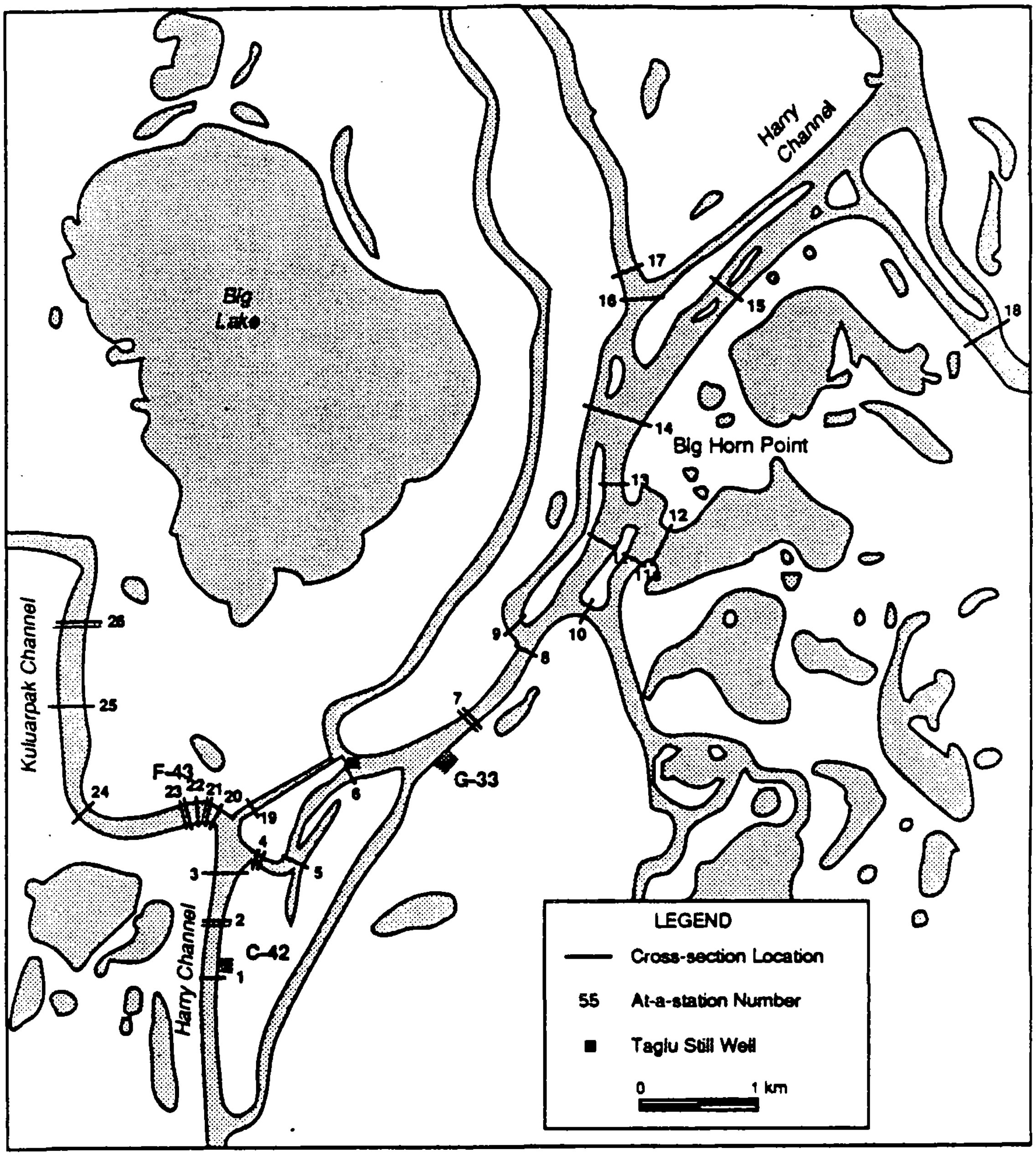
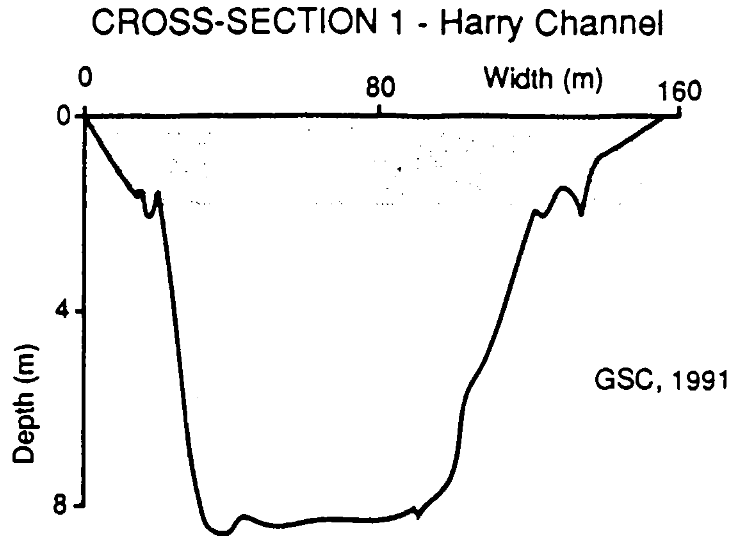
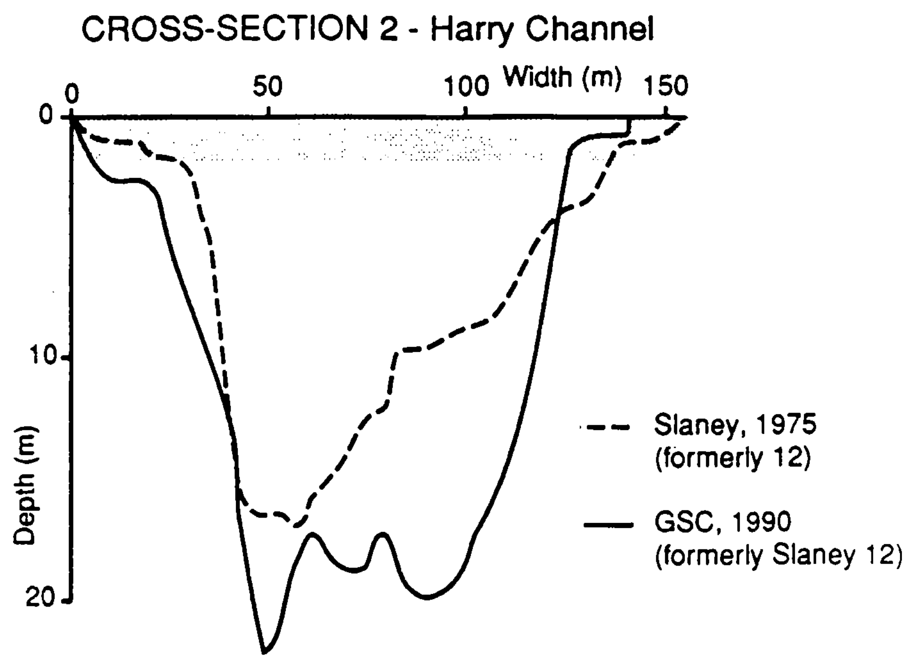


FIGURE 3.5

CROSS-SECTION LOCATIONS: TAGLU AREA
(from Traynor and Dallimore, 1992)





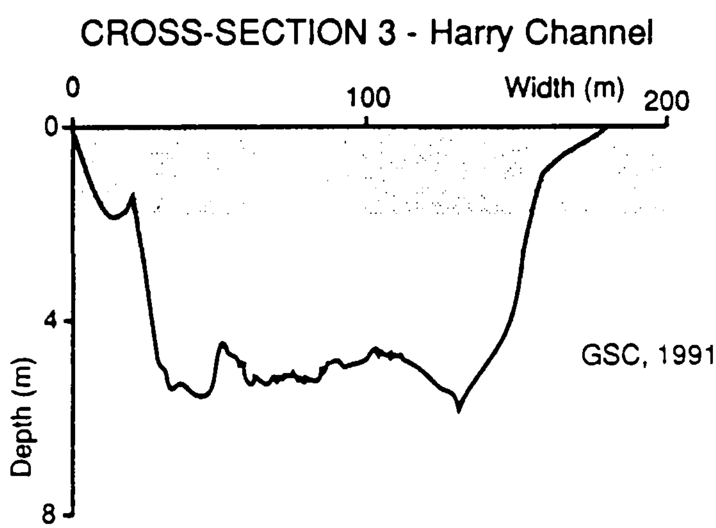
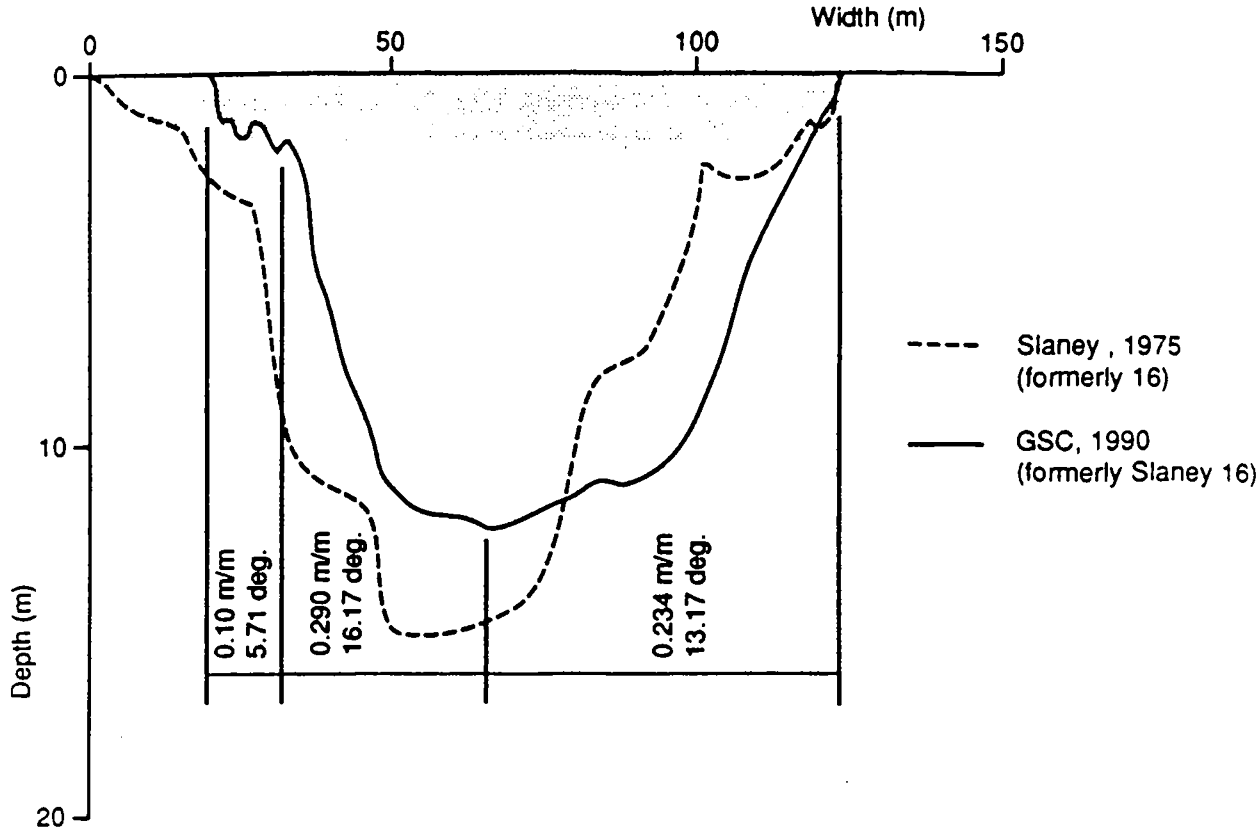


FIGURE 3.6

INCOMING HARRY CHANNEL: CS 1, 2 AND 3
(from Traynor and Dallimore, 1992)

CROSS-SECTION 21 - Kuluarpak Channel



CROSS-SECTION 23 - Kuluarpak Channel

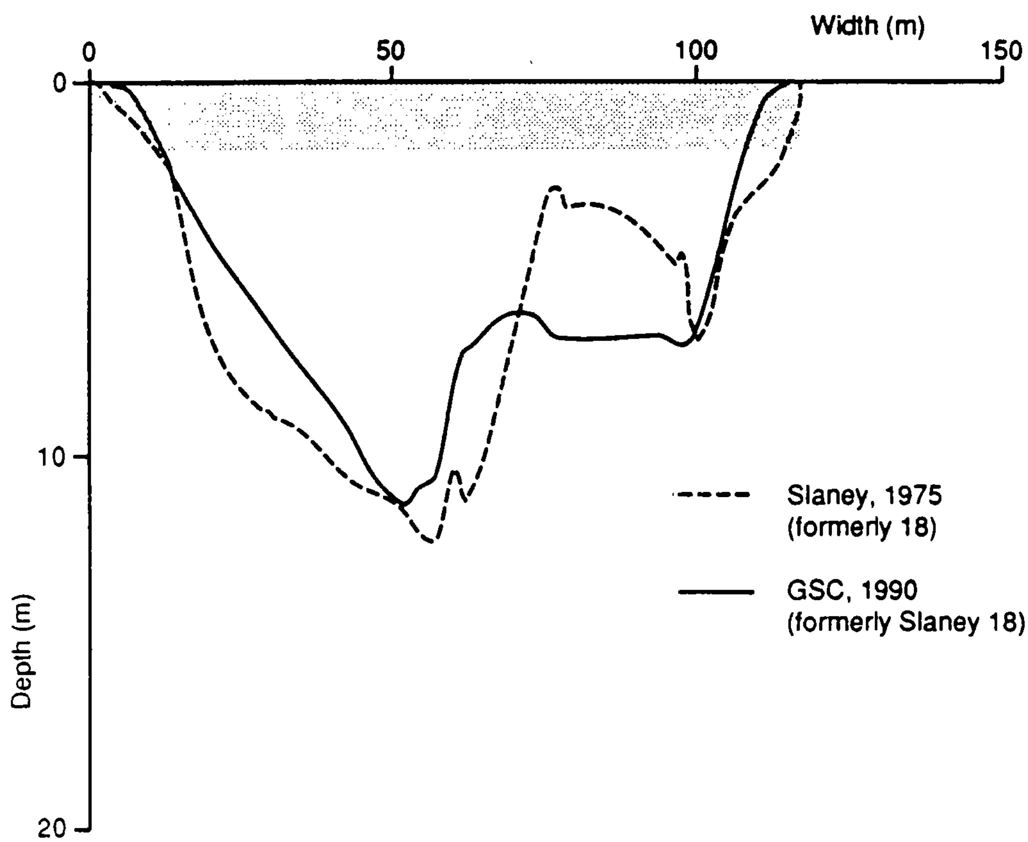


FIGURE 3.7

KULUARPAK CHANNEL ENTRANCE: CS 21 AND 23
(from Traynor and Dallimore, 1992)

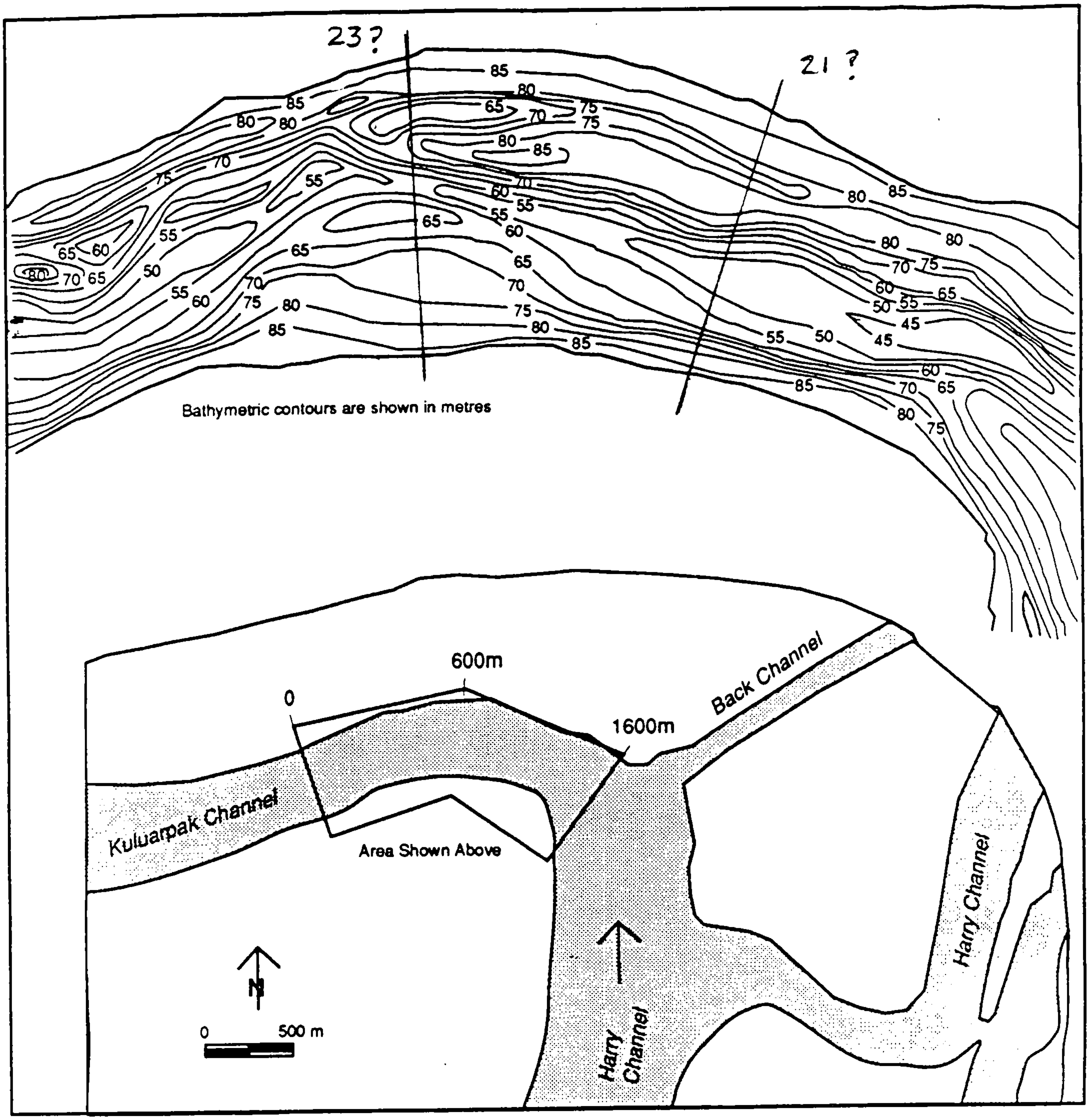
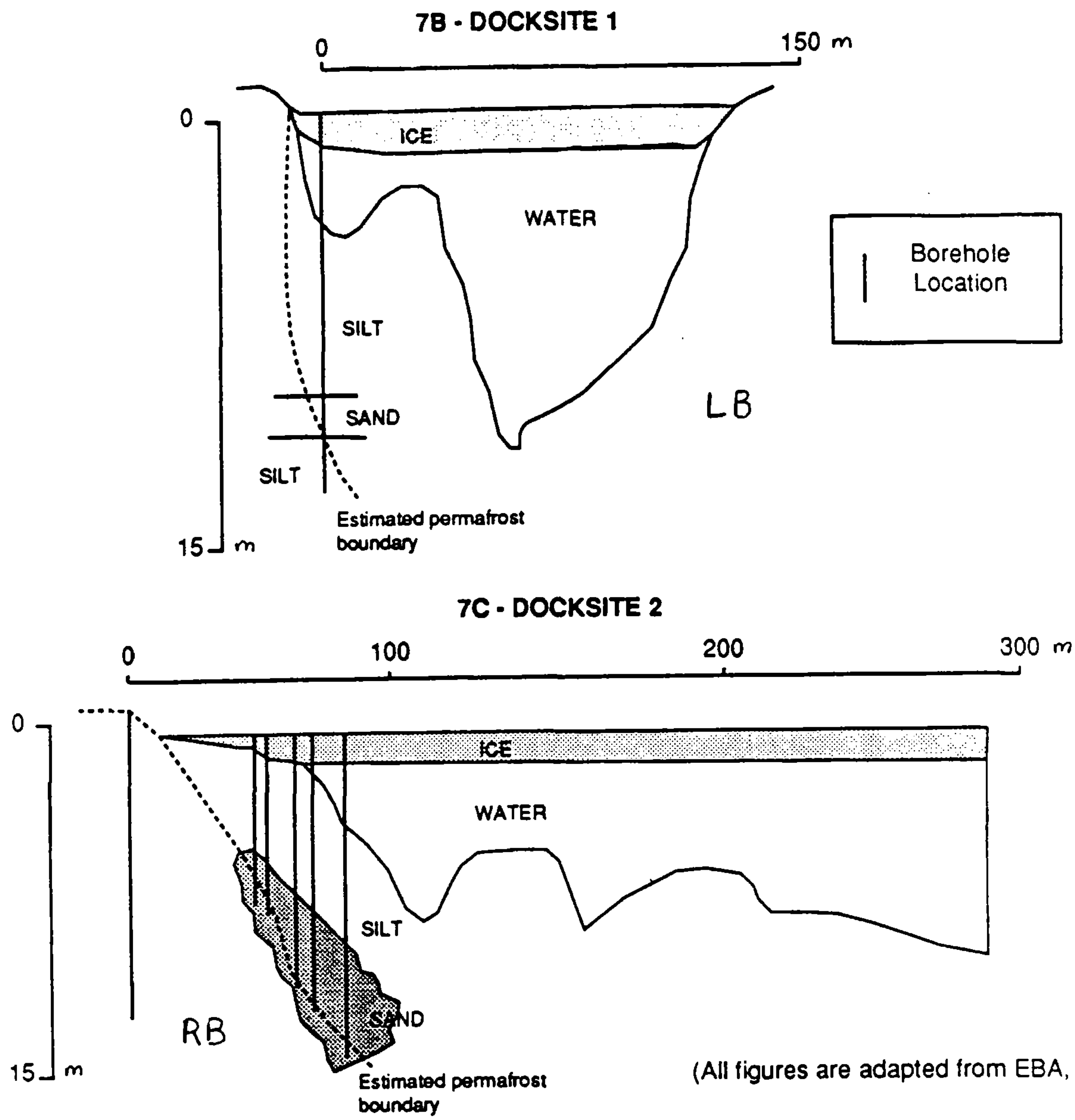


FIGURE 3.8

KULUARPAK CHANNEL ENTRANCE: 1977 BATHYMETRIC MAP
(from Traynor and Dallimore, 1992)

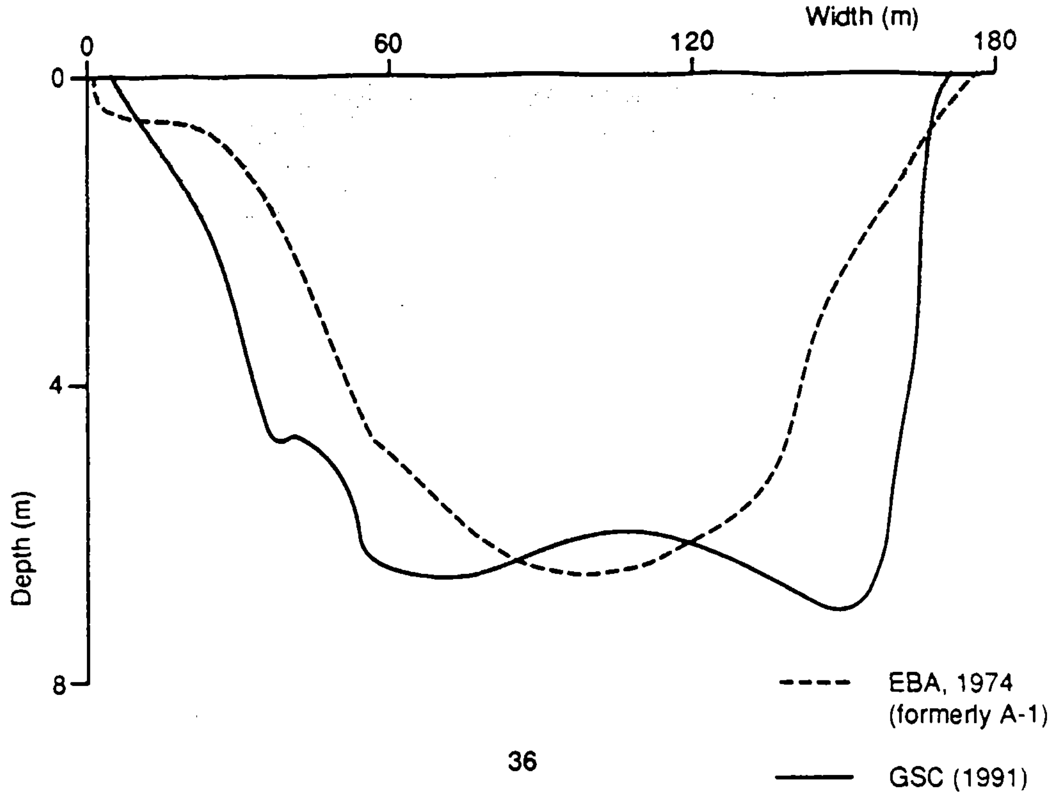


(All figures are adapted from EBA, 1974)

FIGURE 3.9

KULUARPAK CHANNEL ENTRANCE: GEOTECHNICAL PROFILES
(from Traynor and Dallimore, 1992)

CROSS-SECTION 26 - Kuluarpak Channel



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7A - CROSS-SECTION 26

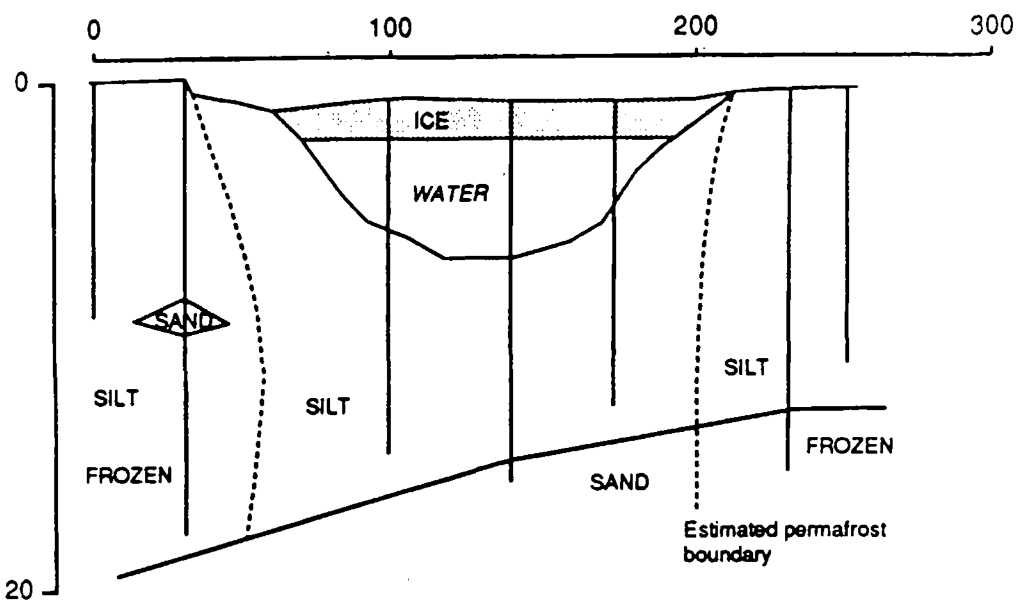
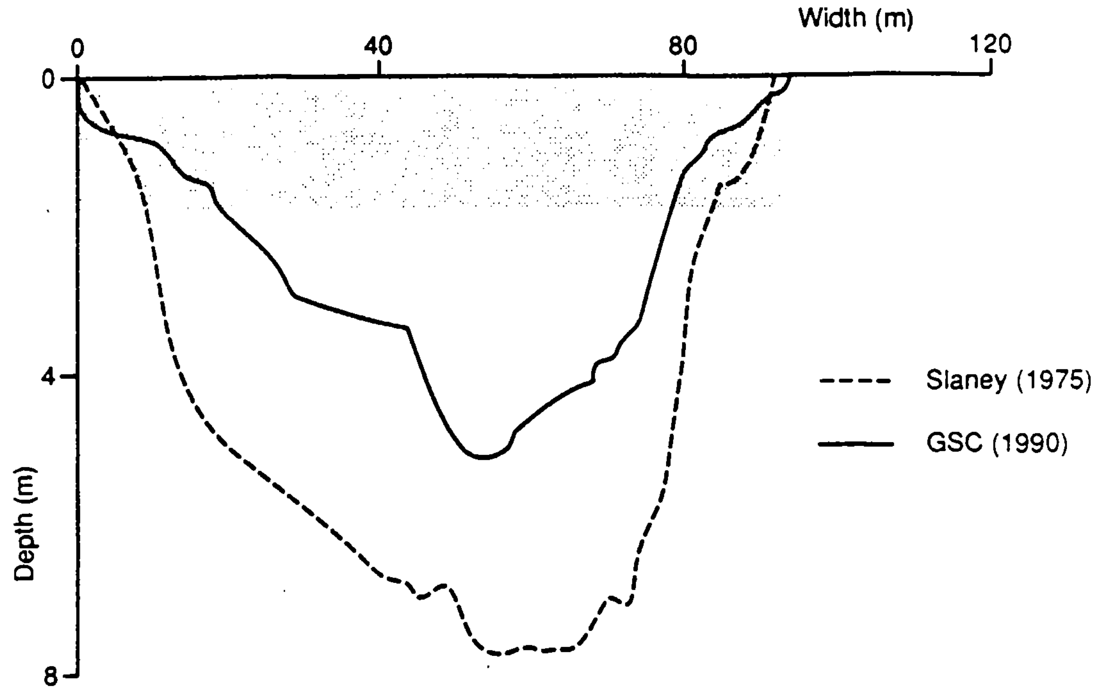


FIGURE 3.10 KULUARPAK CHANNEL CS 26
TOP: PROFILE CHANGES, 1974-1991 BOTTOM: GEOTECHNICAL PROFILE
(from Traynor and Dallimore, 1992)

CROSS-SECTION 4 - Harry Channel



CROSS-SECTION 5
Harry Channel

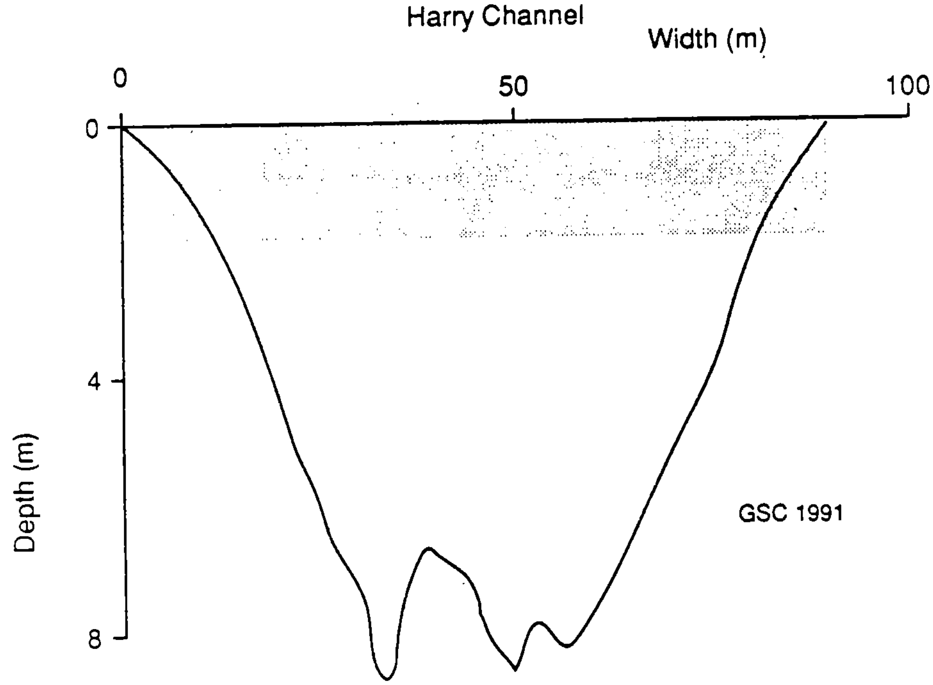
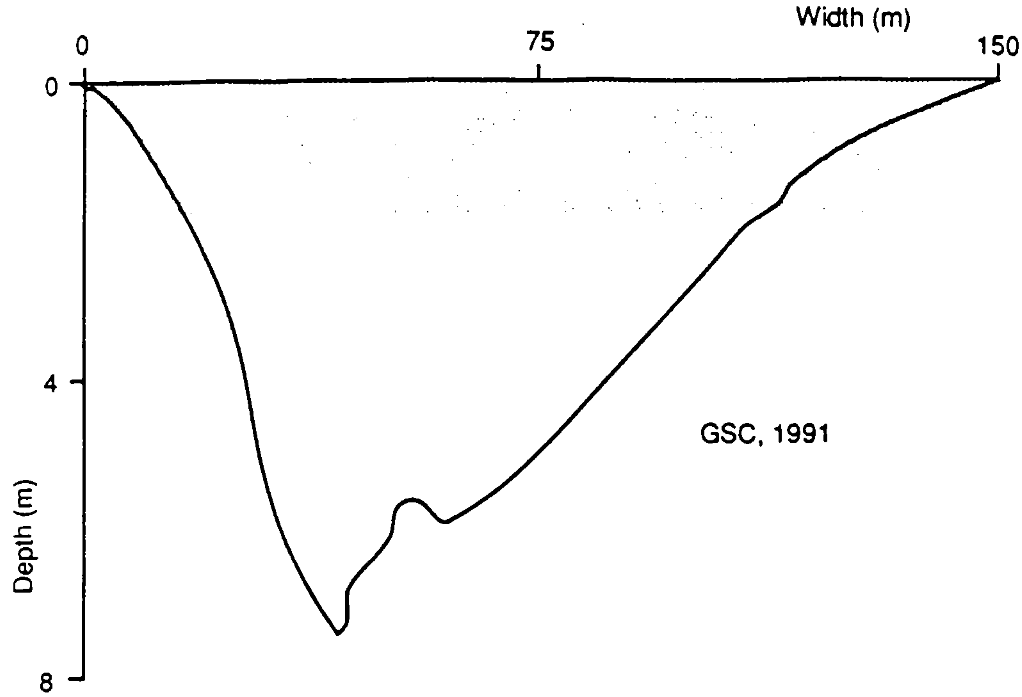


FIGURE 3.11

LOWER HARRY CHANNEL ENTRY REACH: CS 4 AND 5
(from Traynor and Dallimore, 1992)

CROSS-SECTION 6: Harry Channel



CROSS-SECTION 7 - Harry Channel

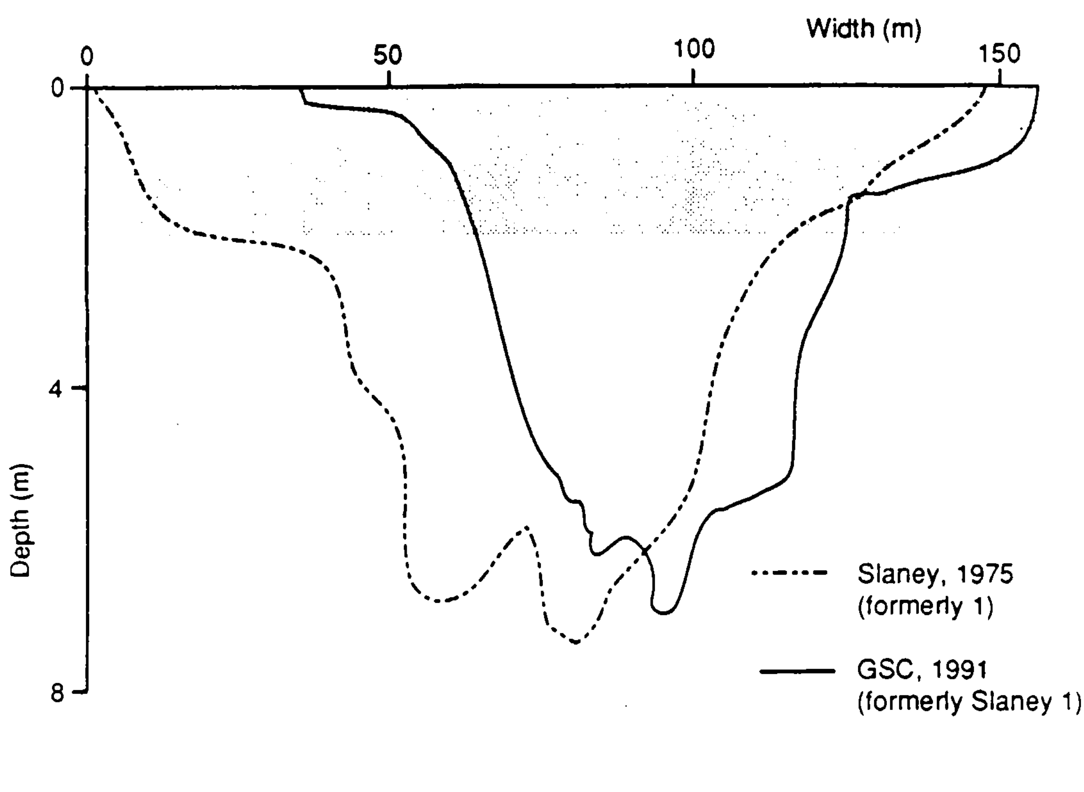
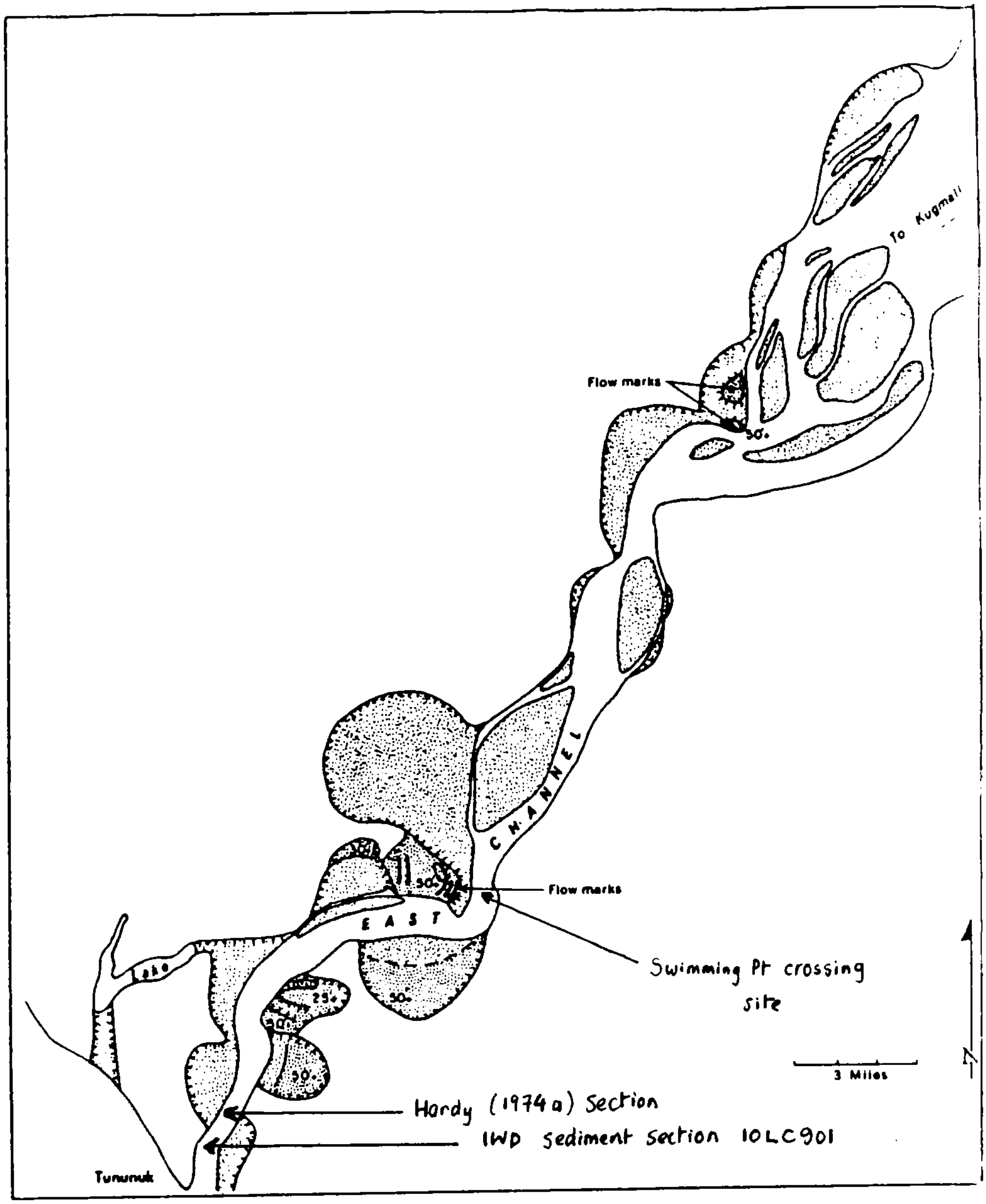


FIGURE 3.12

HARRY CHANNEL OPPOSITE SEAL ISLAND: CS 6 AND 7
(from Traynor and Dallimore, 1992)



East Channel between Tununuk and Kugmallit Bay. The high-level meander scars, in the dark stippled pattern, have smaller radii of curvature than the present channel.

FIGURE 4.1

MAP OF TERRACES AND FLOODPLAIN TRACTS IN LOWER EAST CHANNEL
(from Mackay, 1963)

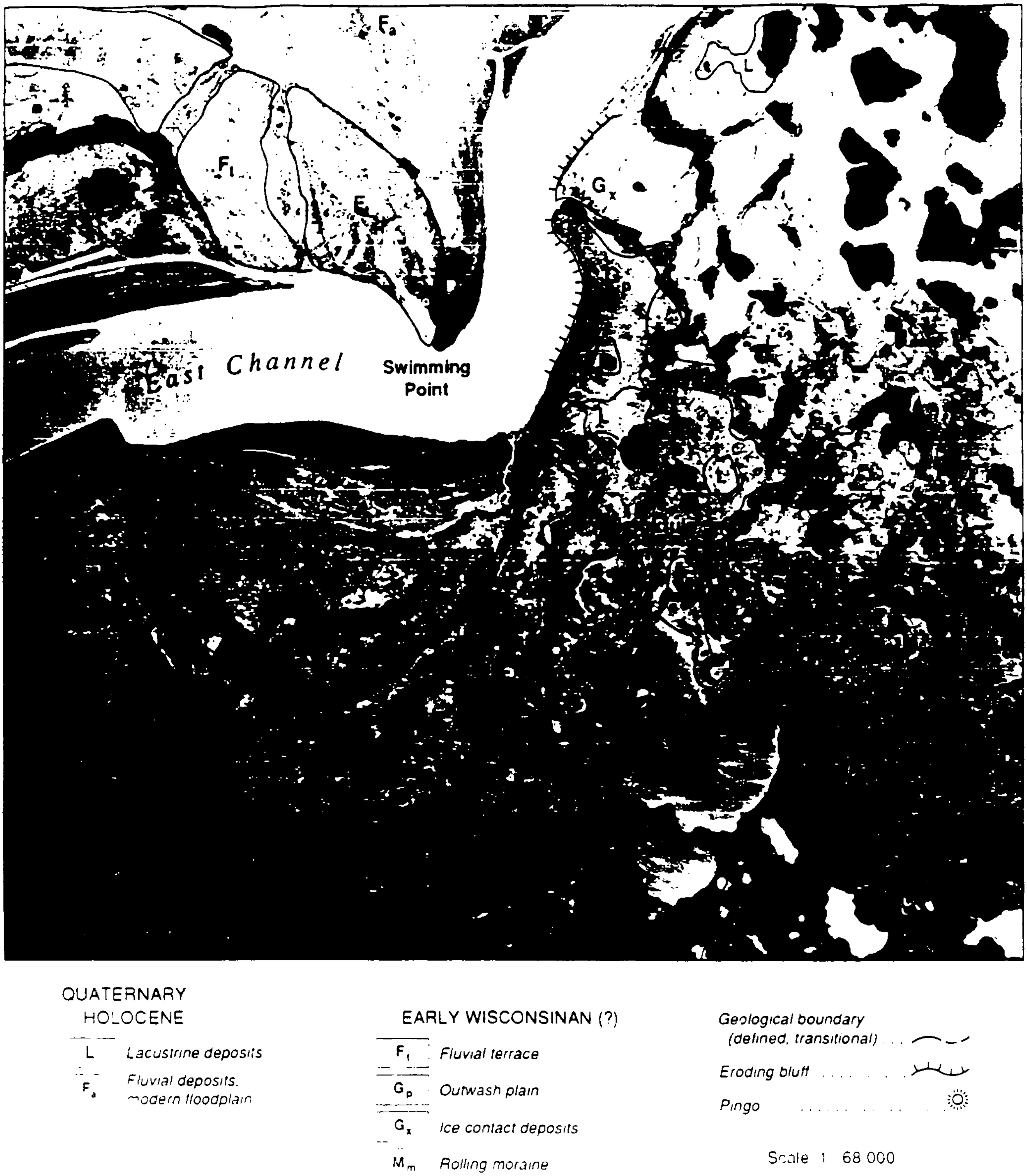


FIGURE 4.2

SURFICIAL DEPOSITS OF SWIMMING POINT AREA
(from Hanright and Dallimore, in prep.)

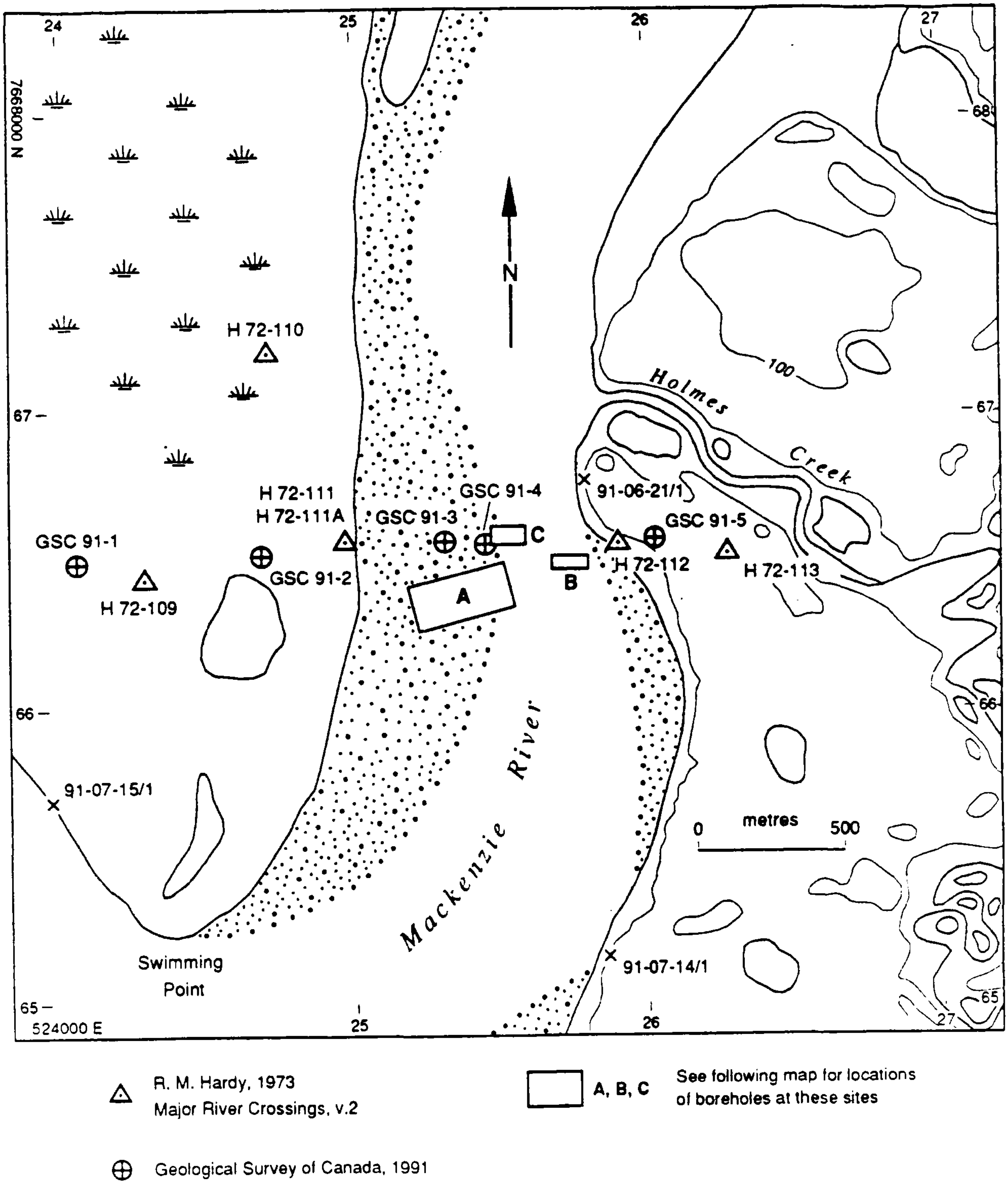


FIGURE 4.3

LOCATION OF HARDY AND GSC BOREHOLES IN SWIMMING POINT AREA
A,B = Hardy (1974b) See Appendix IV
(from Hanright and Dallimore, in prep.)

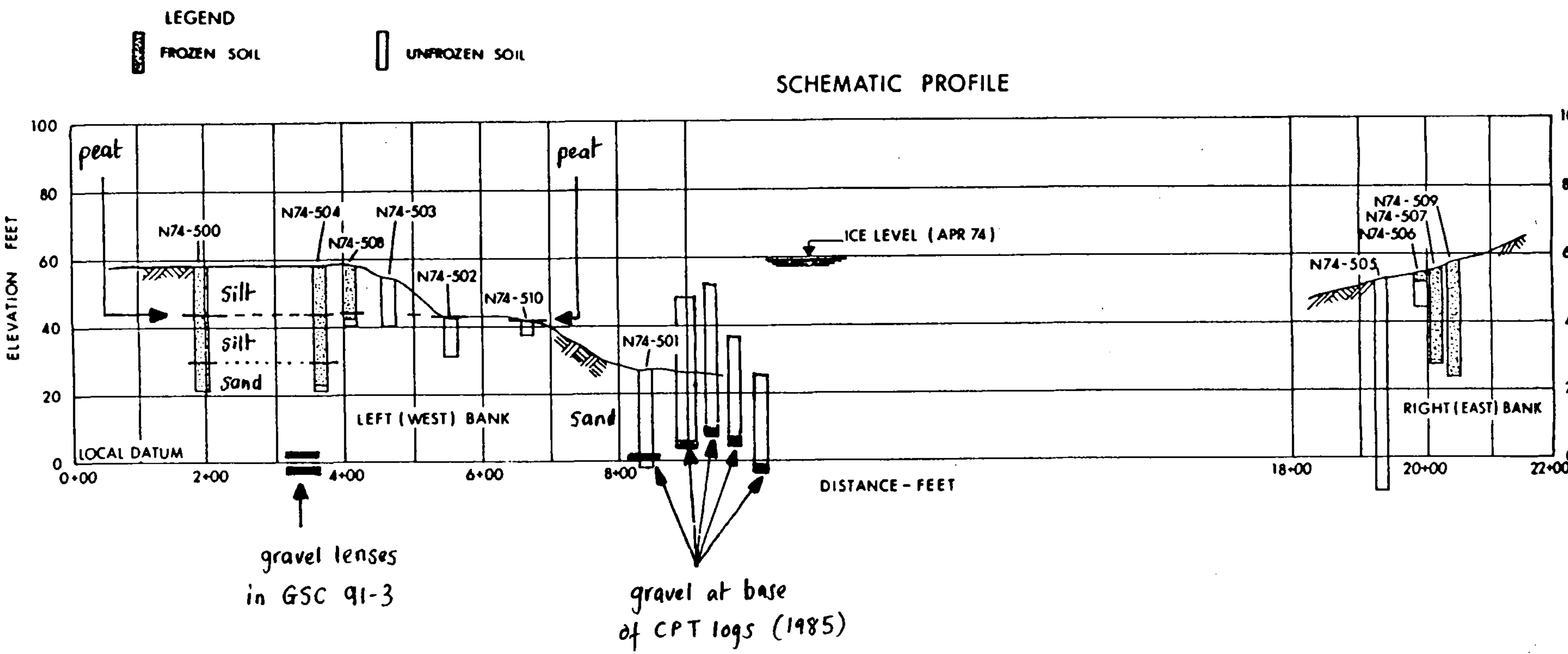


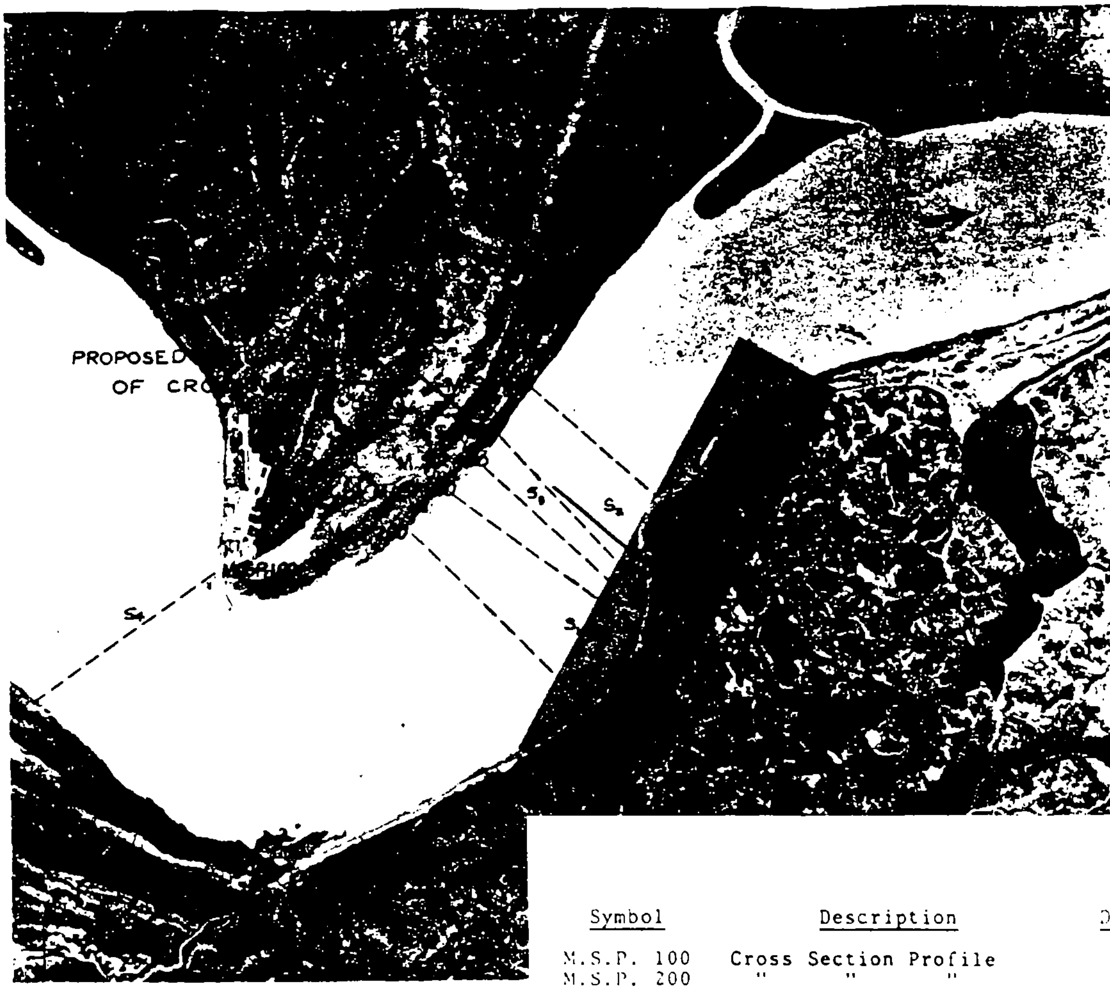
FIGURE 4.4

LITHOSTRATIGRAPHIC SECTION ACROSS EAST CHANNEL IN SWIMMING POINT AREA (partly from Hardy, 1974b)

FIGURE 4.5

BATHYMETRY OF SWIMMING POINT AREA AND LOCATION OF GSC PROFILES
(based on CHS Chart 6430, Canadian Hydrographic Service)

"I" is proposed pipeline cross-section line; marked as "SP-4" on Fig. 4.10



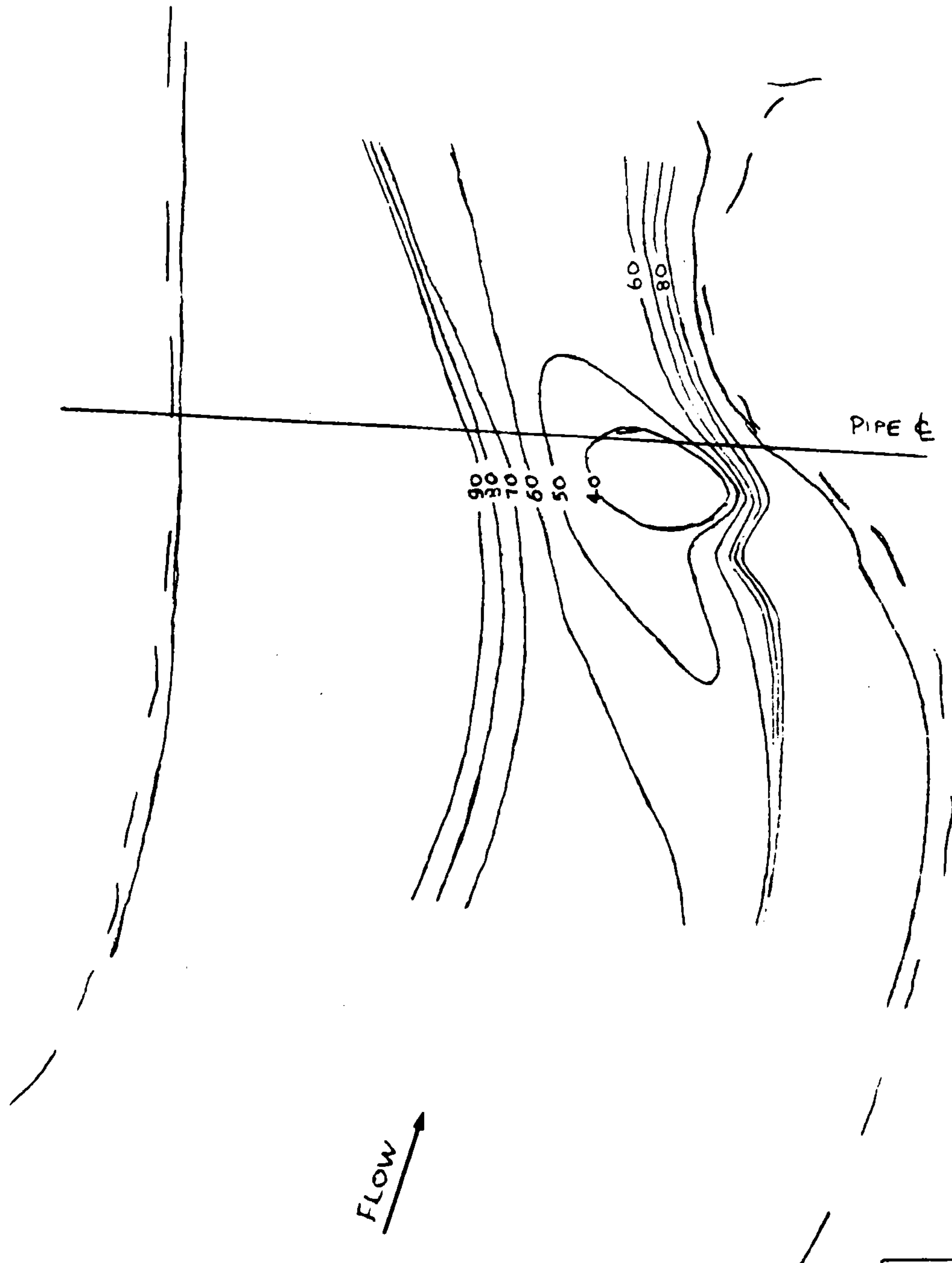
Symbol	Description	Dwg. No.
M.S.P. 100	Cross Section Profile	E6-1
M.S.P. 200	" " "	E6-1
M.S.P. 300	" " "	E6-1
M.S.P. 400	" " "	E6-2
M.S.P. 500	" " "	E6-2
M.S.P. 600	" " "	E6-2
S_1	Bed Sampling Location	E7
S_2	" " "	E7
S_3	" " "	E7
S_4	" " "	E7
	Comparative Air Photographs	E4

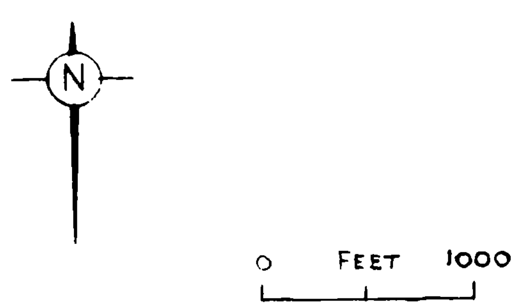
Date of Photograph 1972

Scale of Photograph 0 FEET 4000

FIGURE 4.6

LOCATION OF MID-SEVENTIES PROFILES
IN SWIMMING POINT AREA
(from Blench, 1973)





Note: (a) Riverbed contour lines are based on cross section profiles indexed on dwg. no. E3.

(b) Water level assumed 100.0' on date survey, September 23, 1972.

FIGURE 4.7

NORTHERN ENGINEERING SERV. LTD.

CANADIAN ARCTIC GAS STUDY LTD.

RIVERBED CONTOUR MAP - MACKENZIE
AT SWIMMING POINT

T. BLENCH AND ASSOCIATES LTD.
EDMONTON. ALBERTA

Drawn:	Date:	Dwg. E 5

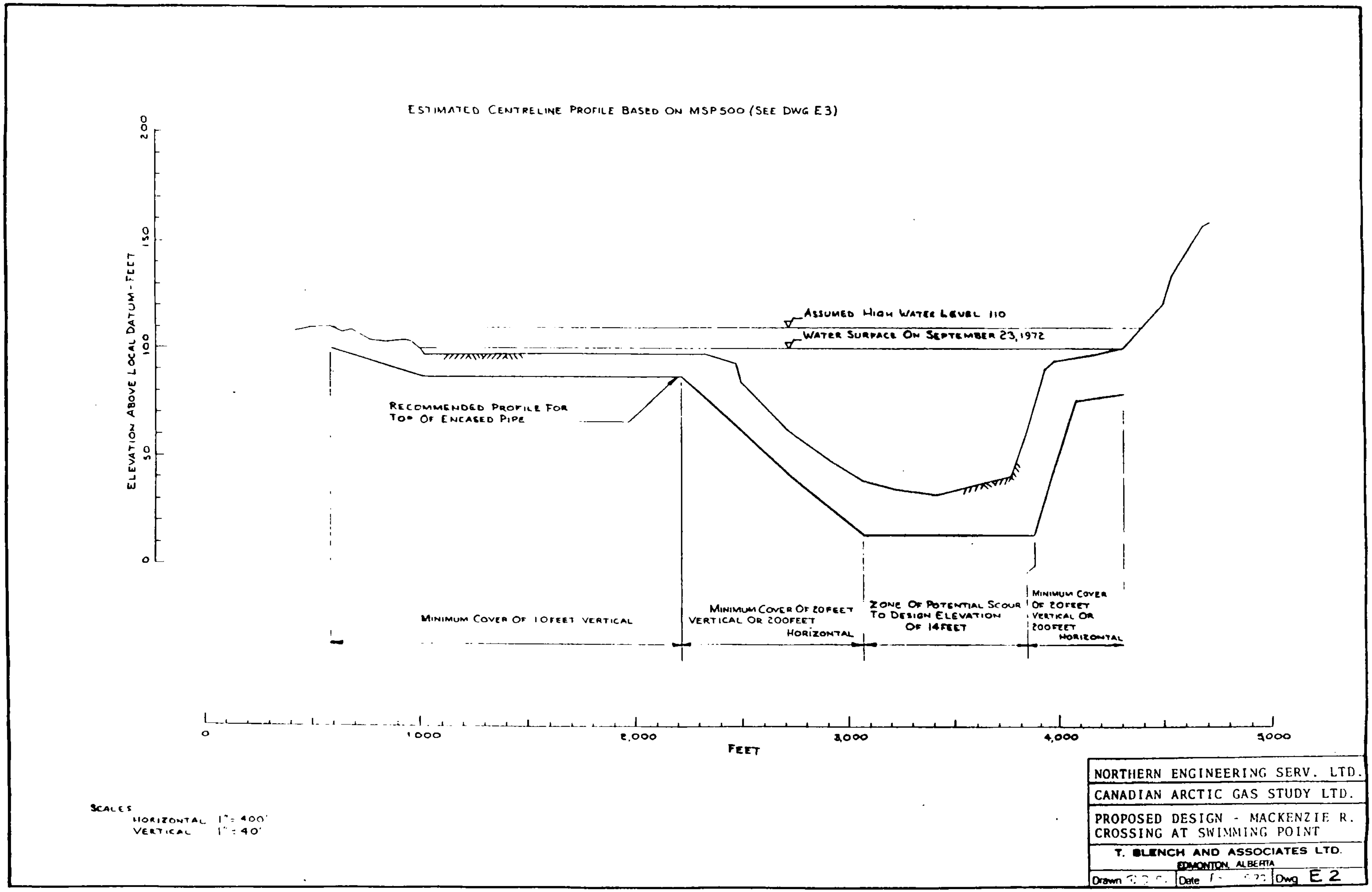


FIG. 4.8 PROPOSED DESIGN OF CROSSING AT SWIMMING POINT
(from Blench, 1973)

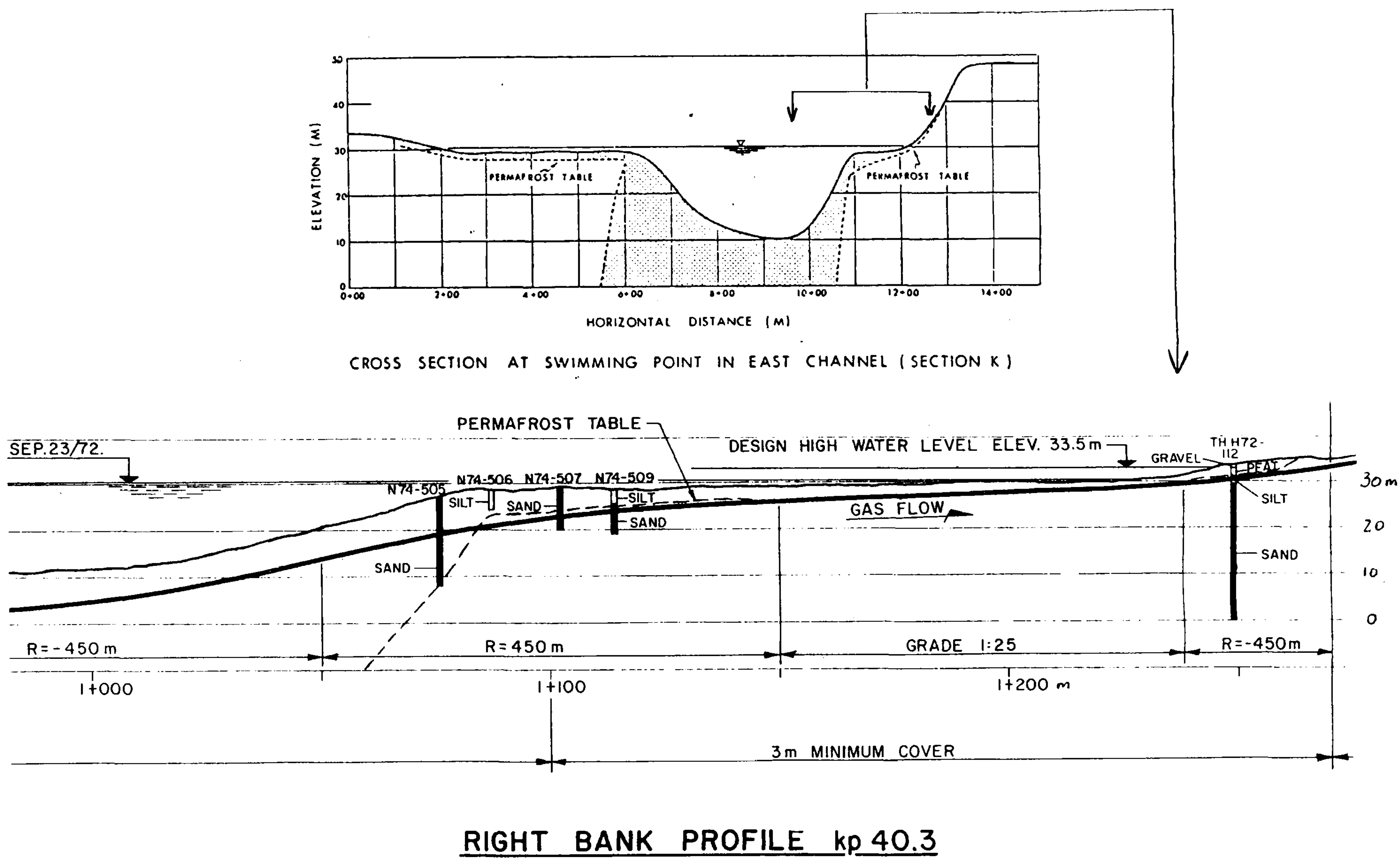


FIGURE 4.9

SWIMMING POINT: DETAILS OF CROSSING DESIGN AT RIGHT BANK
(from Cooper and Hollingshead, 1973, and Kaustinen, 1987)

NOTES

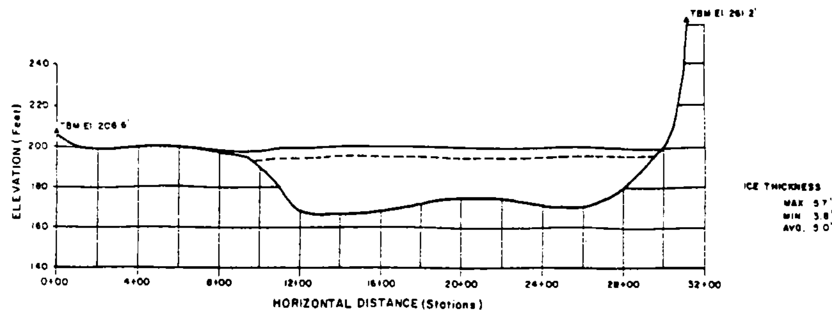
1. DATE OF AERIAL PHOTOGRAPHY: JUNE 30, 1972
2. SCALE OF PHOTOGRAPHY: 1 inch = 2000 ft
3. DATE OF RIVER SURVEY: APRIL 14 - 19, 1974
4. FOR DETAILED DESCRIPTIONS OF TBM's SEE PLATES II-8a THRU II-8b
5. FOR PLOTTED PROFILES OF SURVEYED CROSS SECTIONS SEE PLATES II-6a THRU II-6h

LEGEND

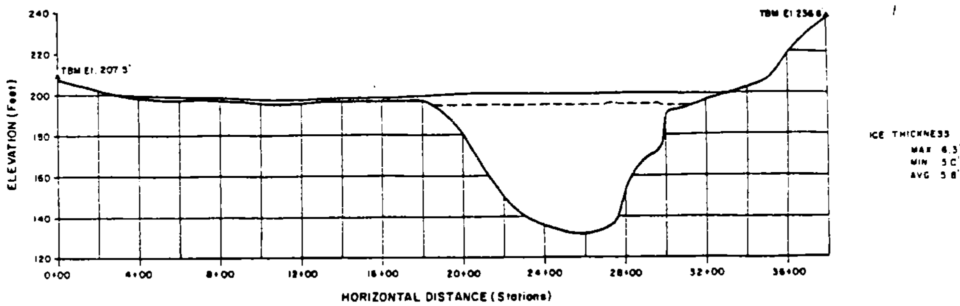
SP-2 - CROSS SECTION NUMBER
▼ — CROSS SECTION TEMPORARY BENCH MARK (TBM)

FIGURE 4.10

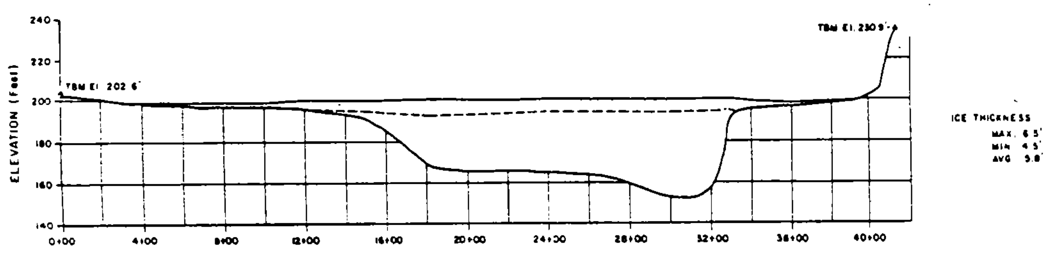
LOCATIONS OF CROSS-SECTIONS IN SWIMMING POINT AREA
(from Blench, 1974a)



CROSS SECTION SP-5



CROSS SECTION SP-4



CROSS SECTION SP-3

FIGURE 4.11

SECTIONS NEAR SWIMMING POINT CROSSING SITE, 1973
(from Blench, 1974a)

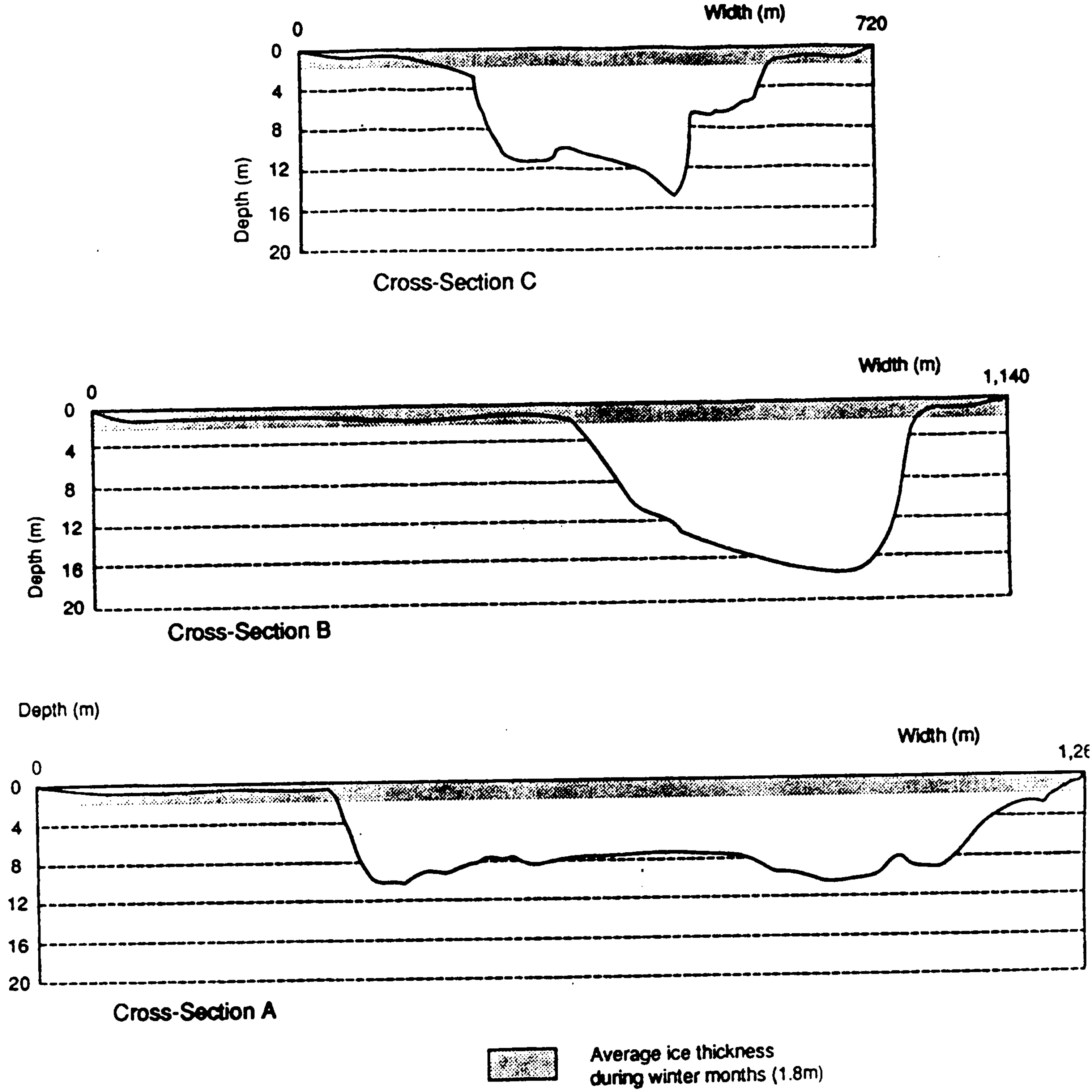


FIGURE 4.12

SECTIONS NEAR SWIMMING POINT CROSSING SITE: 1991
(from Hanright and Dallimore, in prep.)

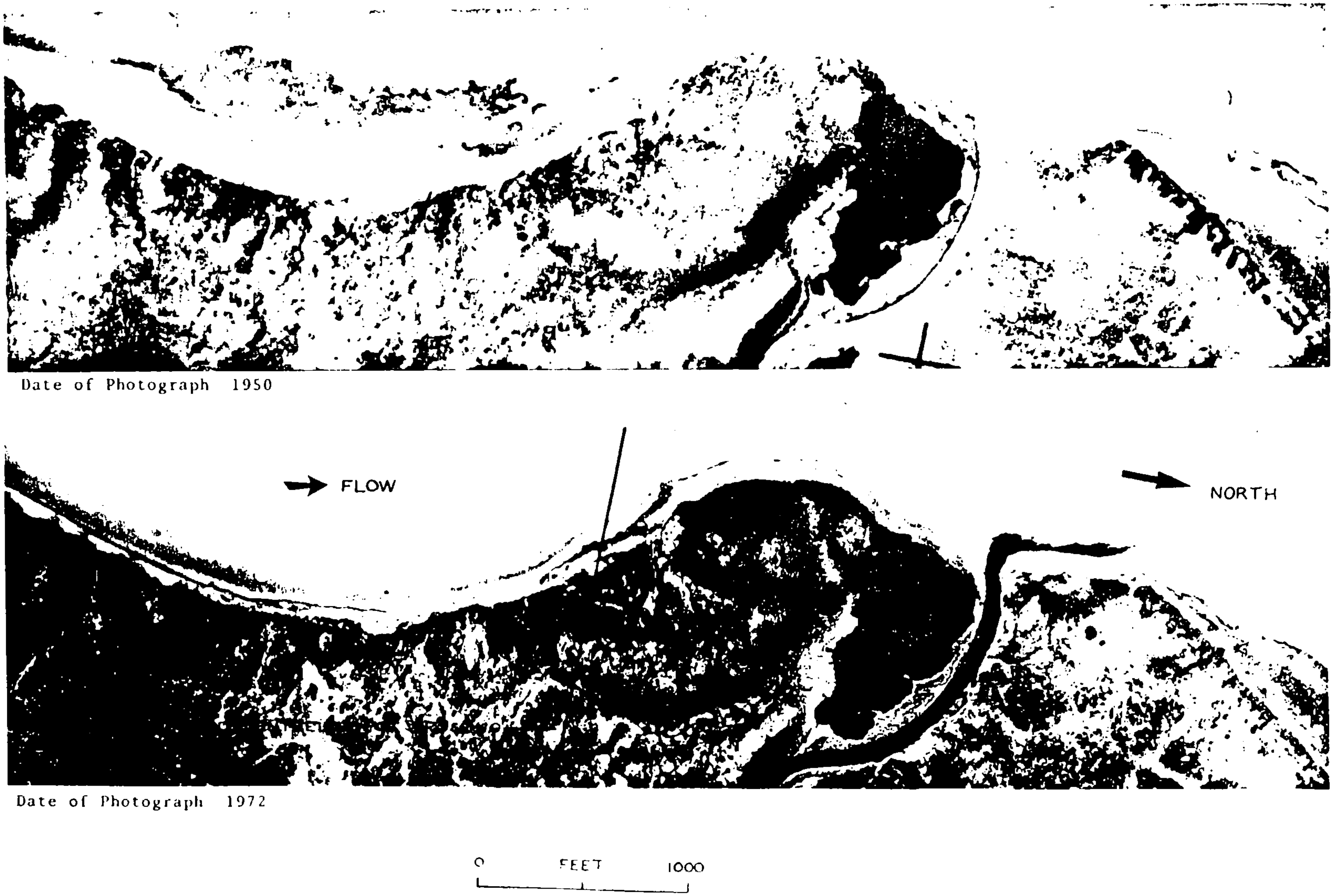


FIG. 4.13 SWIMMING POINT CROSSING SITE: AIR PHOTOGRAPHY COMPARISON OF RIGHT BANK AREA, 1950-1972 (from Blench, 1973)