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IVVAVIK NATIONAL PARK COASTAL EROSION STUDY

S.M. Solomon

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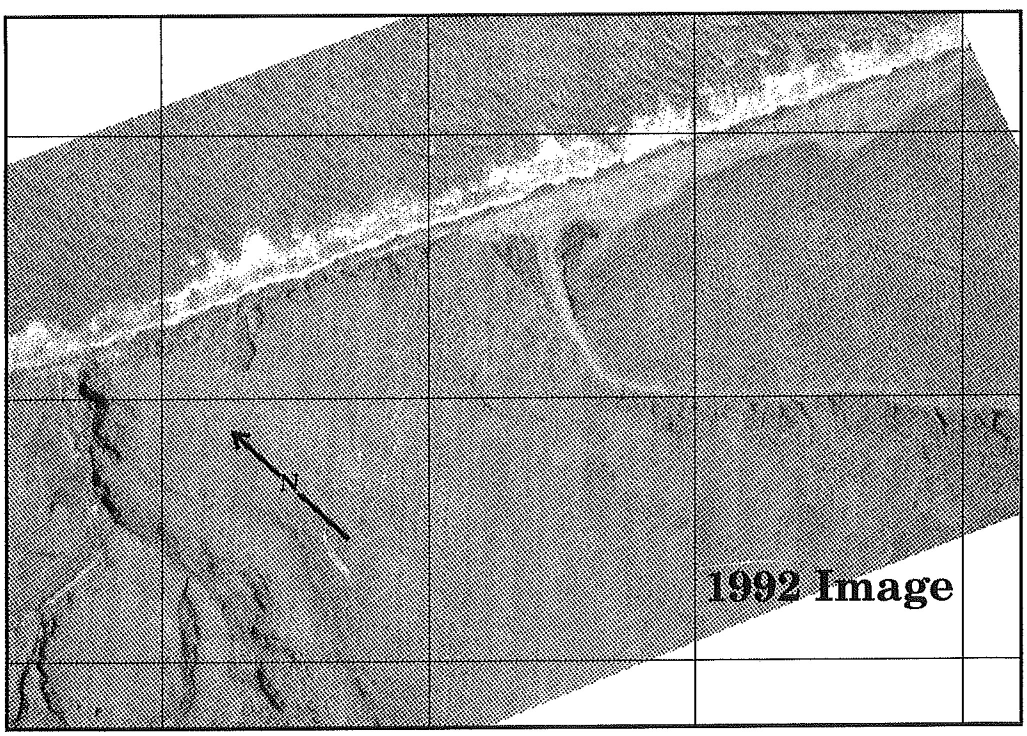

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by: S.M. Solomon, Geological Survey of Canada

Introduction

This report describes field work and air photo studies performed by the Geological Survey of Canada and TekMap Consulting on behalf of Ivvavik National Park (Heritage Canada). The purpose of the study was to evaluate the stability of the coastline at five archaeological sites in the park. The sites are Catton Point, Nunaluk Spit, Clarence Lagoon, Stokes Point and Niakolik Point (**Figure** 1).

The stability analysis implemented is a two-phase process. Phase one consists of an assessment of past coastal changes based on historical air photography collected by the National Air Photo Library (NAPL) and the Geological Survey of Canada (GSC). This approach provides a general indication of how the coast has behaved under the range of climatic and oceanographic conditions which prevailed during the time intervals encompassed by the air photographs. This analysis was performed by TekMap Consulting and their report is included as Appendix A.

While the historical behaviour of the coast is a useful indicator of its future behaviour, this approach does not take into account variability of coastal geology and conditions which lie outside the range of past conditions which the coast has experienced. It is therefore very important to make an attempt to analyze the processes responsible for the past behaviour and relate those processes to present and future behaviour. The collection of data for this analysis was initiated as phase 2 of the Ivvavik Park study. Detailed geological and morphological data were collected at each site in order to characterize the variability of the coast as input into process-based descriptive and numerical models of coastal development. As part of the morphological data collection, sites were established to permit monitoring of coastal changes on an ongoing basis.

The bulk of this report describes the data collected and provides a preliminary assessment of the relative stability of the five sites. Weather conditions and time constraints did not permit a comprehensive suite of data to be collected at all sites. It is hoped that the additional data required to complete the analysis can be collected during the 1996 field season.

Previous Work

The Beaufort Sea coast of Ivvavik National Park consists in large part of low tundra cliffs developed in unconsolidated but ice-bonded Quaternary deposits (Rampton (1982). Ground ice is exposed in the coastal bluffs in the form of massive ice and ice wedges. Sediments derived from erosion of these cliffs, from rivers, and from onshore transport of shoreface materials accumulate in large coastal barriers such as those found in front of the Malcom and Firth Rivers and at Stokes Point (MacDonald and Lewis, 1973; Lewis and Forbes, 1975; Forbes and Frobel, 1985).

The coastal areas of the Beaufort Sea are ice-covered for 8 to 9 months of the year. Freeze-up typically begins in October and break-up in June. During the open water seasons, ice remains within several hundred km of the coast and, in heavy ice years, will stay within 20-50 km. Spring breakup along the Yukon coast occurs several weeks later than it does along the Mackenzie Delta front and in some years ice remains hard-ashore west of Herschel Island

Sea-ice is often frozen to the seabed in water depths less than 2 m. Floating landfast ice extends offshore to a shear zone at the edge of the mobile polar ice pack. Pressure ridges, which develop in the shear zone, cause widespread scouring of the seabed in water depths greater than 8 m. The landfast ice zone is most extensive in the Mackenzie Delta region but quite narrow west of Herschel Island which means that intensive scour can develop quite close to the coastline.

Winter ice conditions play a significant role in sediment transport and coastal morphological development along the Alaskan Beaufort Sea (Reimnitz et al., 1990). According to Reimnitz et al. (1990), ice pile-up and ice ride-up occur primarily during the fall and early winter as freezeup takes place. Sheets of ice are pushed shoreward either remaining intact (ice ride-up) or breaking up into small plates on or near the beach (pile-up). Sediment can be pushed or deposited onto the beach and backshore areas as a result of this process and in some locations, this process represents a significant sediment source (e.g. parts of the Alaskan Beaufort Sea). It has been suggested that the barrier islands along the western Yukon coast (e.g. Nunaluk Spit) receive most of their sediment through this mechanism (Harper, 1990).

During the 4 month open water season, ice-free fetches of more than 100 km are common. Storm winds, which become increasingly frequent in late August and September, come predominantly out of the west and northwest, with a secondary mode from the east. Winds blowing over open coastal waters generate significant wave heights of 4 m or more with peak periods up to 10 s (Pinchin et al., 1985).

The range of astronomical spring tides is no more than 0.5 m, but winds can generate positive and negative storm surges (Henry, 1975). Maximum storm surge limits found in the vicinity of Tuktoyaktuk (as deduced from driftwood log-line elevations) are about 2.5 to 3 m above mean water level (Forbes and Frobel, 1985; Harper et al., 1988). Maximum reliable storm surge indicators found within Ivvavik Park are about 2 m (Forbes and Frobel, 1985) and during a severe storm in September, 1970, the water level at Herschel Island was estimated to be about 1.3 m (Dept. of Public Works, 1971). Marine gravels found at 4.2 m elevation at Komakuk (Forbes and Frobel, 1985) and on top of nearby 6 m cliffs (MacDonald and Lewis, 1975) are likely the result of other mechanisms such as wave run-up and ice-push (Forbes and Frobel, 1985; Forbes and Taylor, 1994).

Despite the short open-water season and the attendant ice-related wave restrictions, many parts of the coast are retreating rapidly. Cliff retreat rates of more than 2 m a^{-1} are common and much higher rates have been reported (Forbes and Frobel, 1985; Harper et al. 1985; MacKay, 1986; and Solomon et al. 1993). Rapid rates of coastal change result in part from thermal instability of the ice-rich coastal bluffs. Manifestations of this instability come in the form of retrogressive thaw failures, block-collapse caused by niching and failure along ice-wedge polygons, and thaw consolidation through melting of ice-rich sediments in the nearshore. Sediment entrainment by frazil-ice and associated erosion processes are proposed by Reimnitz and Barnes (1987) to be a major factor in coastal retreat in northern Alaska. Their role in erosion along the Yukon coast has yet to be determined. As mentioned above, ice pile-up and ride-up are additional factors in Alaskan coastal development (Reimnitz et al. 1990) which may play a role along the Yukon coast (Forbes and Taylor, 1994).

Conditions during the field season

Winds

Observations of temperature, wind speed and wind direction for Tuktoyaktuk were acquired from the Atmospheric Environment Service in Edmonton for the period June 1, 1995 to October 31,

1995. This period encompasses the open water time interval during which sufficient fetch is available for the generation of wind-driven waves. The observations were made at the Tuktoyaktuk airport hourly from 0800 h MST to 2300 h MST. The 1995 open water season was characterized by relatively benign conditions; wind velocity exceeded 37 km h^{-1} only 18 times in 2409 observations (< 1%). The average wind speed for the period was 15 km h^{-1} and the average temperature about 6°C. Thirty seven km h^{-1} was the minimum criterion for storm identification in a study of cliff erosion along the Beaufort Sea coast by Solomon et al. (1993) (cf. Carter and Stone 1989). The most damaging storms in the Tuktoyaktuk area are associated with storm-driven high water levels caused by northwesterly winds. Approximately 30% of the winds recorded at Tuktoyaktuk were from the northwest quadrant. However, storm winds (as defined above) were present for < 0.5% of the observations. Severe storms are characterized by winds in excess of 70 km h^{-1} for periods of 10 to 48 hours or more (cf. Eid and Cardone, 1992: Solomon et al., 1993; Solomon and Covill, 1995).

The Ivvavik surveys took place between August 1-12. This period of time was dominated by 10-20 km h^{-1} easterly and northerly winds at Tuktoyaktuk (**Figure** 2). The average wind speed during this period was 11.6 km h^{-1}. Casual observations of wind speed and direction made at Catton Point agreed with the Tuktoyaktuk observations. Moderate northeasterlies blew on August 3, 5-6, 9-11 (Julian days 215, 217-218, 221-223); more than half of the time.

Water Level

Water level measurements are available only from the tide gauge installed at the Hamlet of Tuktoyaktuk. According to the Department of Fisheries and Oceans (DFO) tide tables for 1995, the secondary ports of Kay Point and Herschel Island lag the Tuktoyaktuk tides by 64 minutes and 76 minutes respectively. Tides at the secondary ports are predicted to be within 10 cm of those at Tuktoyaktuk. Experience has shown however, that differences in water levels caused by winds can exceed the tidal range by a factor of 4-5 at Tuktoyaktuk (Henry, 1975).

Water levels measured at Tuktoyaktuk for the period of the field surveys were obtained from DFO at the Institute of Ocean Sciences (Sydney, BC). The records show a typical pattern of semi-diurnal (twice daily) tides superimposed on a longer frequency oscillation with a period of several days to a week (**Figure** 3). These oscillations are caused by the natural neap and spring (lunar) tidal cycles in combination with wind-induced storm surges which are positive when the winds blow from the west and northwest and negative when they come from the northeast, east and south. For example, northerly winds during the period July 25-27 caused a 20 cm elevation of the high tide and a 10 cm elevation of the low tide above the predicted values (cf. DFO tide charts). Water level fluctuations during the field surveys (August 1 to August 11) were generally small and within normal tidal variations with the exception of an extremely low low tide (30 cm below the predicted tide) on August 9. This was probably related to the strong easterly winds blowing that day.

Ice

Ice is usually present in the study area from mid-October until mid-July (Niakolik) to early August (Clarence Lagoon) (Dickins et al. 1987). There is a distinct delay in break-up from east to west with distance from the MacKenzie River. These dates represent medians of a relatively small dataset. Actual breakup and freeze up dates may vary by a month or more.

According to weekly ice charts supplied by Environment Canada, ice along the Yukon coast began to break up during the last week in June. By July 18 only a few strips of ice remained west of Herschel Island and by August 1, the entire Canadian Beaufort Sea coast was clear of ice. Ice free fetch was about 200 km to the north and west and virtually unlimited to the east. Ice continued to limit westerly fetch until the end of August when it withdrew completely from the western edge of the map area. Significant concentrations of pack ice limited northerly fetch to about 200 km for the entire open water season. Freeze-up occurred along the Yukon coast during the week of October 10-17 and progressed to complete ice cover by October 30.

Waves
Significant deep water wave height (H_s) and period (T_s) were estimated for the north and northeasterly events which occurred during August 1-12 using the U.S. Army Corps of Engineers (1977) nomographs based on the SMB relation. Wind speeds from Tuktoyaktuk were used as input into the graph and since they were not corrected to an open water wind speed, they underestimate the wave conditions. Typical events during 1995 produced predicted significant wave heights and periods of about 1 m and 4-5 s respectively. The largest storms on record produce deep water waves of 3.5 m (H_s) and 10 s (T_s) (Eid and Cardone, 1992).

Methods

Surveys were performed using a Wild T2 theodolite and a 3 m stadia rod with bubble level. Echo-sounding was performed with a Knudsen 320M hydrographic sounder and a 200khz transducer mounted on an inflatable rubber boat. The echosounding lines were navigated using a Garmin differential GPS system operating in real-time via radio-modems. Soundings and DGPS positions were logged onto a laptop computer at a rate of once per second. Average horizontal positional accuracies for the DGPS are 12-17 m, but differences between successive logged navigation points suggest that accuracies were much better. Where the DGPS failed, accuracies varied from 60 m to more than 100 m.

Echo-sounding profiles are plotted as depth below local water level versus cumulative distance along the observed mean bearing line of the survey. Where survey elevations are available for a benchmark reference, the surveys were corrected to that elevation. Small changes in attitude due to steering, current and DGPS inaccuracies are projected back onto the mean bearing line geometrically by calculating the difference between the mean bearing and the bearing between any two successive positions. Thus actual depths measured off the line are assumed to be representative of the depth on the line. This is probably a reasonable assumption in water depths below wave base, but may result in some errors close to shore. Care must be taken in comparing these profiles with future profiles and a comparison in the map view of the actual positions will provide some assistance in assessing the validity of the comparisons.

Water temperature was logged offshore from Catton Point in 3.5 m water depth from August 3-10, 1995. A submersible temperature logger (Minilog™) was programmed to record the water temperature within 15 cm of the bottom once every hour.

Stokes Point (Site No. 30Y57 Borden No. NiVi-5)
Survey date: August 4, 1995; JD 216

Description
The Stokes Point site is at the northwestern end of a lagoon which is almost entirely enclosed by a barrier spit (**Figure** 4). The coastline in the area is oriented northwest/southeast and the morphology of the spit indicates that sediment transport is dominantly to the east. This has lead to the formation of a large prograded system of beach ridges at the southeastern end of the lagoon. Highly polygonized tundra of probable drained lake origin characterizes most of the site with one

profile extending across a section of lower elevation marsh at the edge of the lagoon (within range of storm tides). West of the study site the land surface continues to rise and becomes less polygonized - a zone of upland tundra. Active thermokarst is present in the upland tundra immediately to the northwest of the profile sites The whole area can be characterized as being ice-rich (cf. Harper et al. 1985). Also in the zone of upland tundra, within 350 m of the profiles, there is a small drainage network extending several km landward from the coast.

Three profiles were established within the drained lake tundra and marsh zones surrounding the gravesites (**Figure** 4). In this area, ice wedge polygons in various stages of degradation are ubiquitous and form incipient drainage networks. The edge of the coastal bluff is actively eroding with blocks of tundra falling over the bank. The sediments comprising the bluff are dark grey organic mud with abundant fragments of wood. Grasses and sedges (e.g. cotton grass) dominate the vegetation. The bluff is fronted by a narrow (10-15 m wide) pebbly sand beach with a driftwood line at the base of the bluffs and a gravel berm at the high tide line. The spit line is backed by a low marsh which shows evidence of flooding during storms. There is a fresh driftwood line seaward of the beach crest and weathered driftwood scattered landward of the crest and up to the edges of the marsh.

Gravesites are scattered over the surface of the drained lake tundra bluff at an approximate elevation of 4-5 m overlooking the lagoon. The graves consist of weathered timbers and a few scattered human bones including what appears to be a fragment of a child's skull. The graves are located 3-10 m from the cliff edge along the Stokes West line.

Sediment Samples

Four samples were taken along the Stokes BM line. Stokes001 is a drained lake peat retrieved from the coastal bluff. It is a dark grey mud with an organic content of 6.4% by weight. Stokes002 was taken at the base of the bluffs on the beach and is composed of well sorted medium sand with abundant moss fragments. Stokes003 is comprised of sandy cobbles from the crest of the beach and Stokes004, taken at the waterline is mostly coarse sand and granules.

Retreat measurements

Measurements of coastal retreat range from 0 m at the drainage network to 5.3 m at the coastal marsh based on 1954 to 1970 air photography (Harper et al. 1985). MacDonald and Lewis (1973) report 20 m of retreat at the site between 1952 and 1970. More recent measurements indicate retreat rates of less than 0.25 ma^{-1} at the gravesites and more than 2 ma^{-1} in the thermokarst slump (Appendix A). Comparison of air photos taken in 1970 and 1992 show a marked increase in thermokarst activity and ice wedge degradation despite a relatively stable bluff position. The 1985 air photo illustrates that the thermokarst activity was initiated prior to that year and may have been caused by severe storms which impacted the coast in the early 1980's (Solomon et al., 1993).

Surveys

Three profiles were surveyed at Stokes Point: Stokes East, Stokes BM145 and Stokes West (**Figures** 4 and 5, **Table** 1). Distances between survey lines are: 36 m from BM145 to Stokes West and 56.6. m from BM145 to Stokes East. An echosounding survey to illustrate the nearshore profile was performed at each profile (**Figure** 6). Stokes East characterizes the spit which fronts the Stokes lagoon (**Figure** 5). Elevations are relative to the water level at the time of the surveys. The maximum elevation of the spit was 1.48 m. Stokes BM145 and Stokes West profiles are located on the low bluffs composed of ice-wedge-rich drained-lake tundra. Elevations are 4 to 5 m with a steep active bluff edge (**Figures** 5 and 6). The beach slope at all three profiles is similar: 5-6° (gradient of 1:10 to 1:12). A small bench is present just below the water line at Stokes East and West, but not at the BM145 line. A prominent nearshore bar is present within about 50 m of the shoreline and at a depth of about 1 m on all three lines, however the bar is significantly farther from the waterline and somewhat more subdued at the BM145 line than at the other two lines (**Figure** 6). In all three cases, the nearshore profiles seaward of the bar are slightly concave upward, with mean slopes ranging from 0.56° to 0.75° (1:100 to 1:75).

Stokes West is located such that it crosses one gravesite (**Figure** 4). The seaward timbers of the grave are within several metres of the cliff edge. This suggests that the bluff edge has retreated substantially (as much as 10-15 m) since the 1992 airphoto. It is possible that the severe storm and the accompanying surge which occurred in 1993 (Solomon, 1995) could have been responsible for a dramatic alteration of retreat rate. It will be necessary to re-survey the area in detail (especially the graves themselves) to tie the surveys to air photo retreat measurements. An additional air photography mission would be very helpful in quantifying the changes since 1992.

Table 1: Stokes Point Surveys Summary
Distances (m) are measured from the rear pegs

From	to front peg	to cliff edge	to beach crest
BM145	16.7	27.2	
StokesWest(rear peg)	11.4	21.4	
StokesEast(rear peg)	25.1	na	38.5

Nunaluk Spit (Site No. 30Y94 Borden No. NjVk-1)
Survey date: August 2, 1995; JD 214)
Description
Nunaluk Spit is a long (25 km), narrow barrier island complex oriented east-west, located west of Herschel Island and in front of the Firth and Malcolm River deltas (**Figure** 7). The study site is a remnant of tundra which has become a part of the barrier complex and is being eroded as the barrier moves landward with rising sea level. It is dome-shaped, with a steep seaward face and a gentle slope towards the lagoon of the Firth River delta. A Geodetic Surveys Division benchmark (number A56) is located within 1 m of the cliff edge at an elevation of 5.1 m. At the time of the last Geodetic Survey visit (October, 1993) the BM was 5 m south of the bluff edge.

The remains of a cabin and numerous tent sites are found on the top of the remnant (Inuvialuit whale hunting camp - Neufeld and Adams, 1993). The seaward bluff is steep and actively eroding, however there is no ice visible in the cliff face. The bluff is composed of mud with scattered pebbles and occasional cobbles. The beach fronting the eroding bluff is narrow and composed of sand and pebbles. Several higher water level swash lines are present. The base of the bluff is composed of lobate, hardened mudflows with a veneer of sand and gravel deposited on their surfaces by storm waves. A narrow, sparse band of driftwood is present at the toe of the bluffs; it is continuous with a driftwood line on the spit to either side of the tundra remnant. The crest of the spit is higher than the driftwood line. The lagoon side of the spit is very shallow (< 0.3 m deep within about 30 m of the spit).

Sediment Samples
No samples were obtained at Nunaluk.

Retreat measurements
According to Harper et al. (1985), there was virtually no change in the position of the spit between

1951 and 1972. More recent measurements made for this report (Appendix A) indicate average retreat rates of 1-2 ma^{-1} at the cliff edge at the island for the periods 1952 to 1970 and 1970 to 1976. Distance to the cliff edge from the benchmark was noted to be 5 m in 1993 and only 1 m in 1995 suggesting a continuation at the same retreat rate of about 2 ma^{-1}. Differences between the measurements made by Harper et al. (1985) and for this study may be the result of differences in techniques used for the respective studies. Due to the changing nature of the delta front it is very difficult to pick accurate points as references to register air photos and for scale. However, changes in the overall island shape between 1952 and subsequent photos does indicate substantial changes took place. MacDonald and Lewis (1973) report that the spit downdrift of the island extended eastward by 690 m between 1952 and 1970.

Attempts to measure erosion of the beach/spit complex is frustrated by a lack of information on water levels at the time of the air photos. An oblique photograph taken by D. M. Welch in summer, 1988 (National Park documents) shows a fairly wide beach with a distinctive fresh driftwood line well below the present edge of the coastal bluffs. An older driftwood line can be seen scattered on the lower portions of the tundra surface. The lower line was not present in 1995, possibly removed during the severe storm and high water levels recorded at Tuktoyaktuk in September, 1993 (Solomon and Covill, 1995).

Surveys
Four profiles were surveyed on August 2, 1995. The lines are called: BM line, 30W(est), 80W(est), and 30E(ast) (**Figure** 8). The numerals and directions represent offsets from the benchmark line.The BM line uses the old GSC benchmark (BMA56) as a foresight peg; a new GSC benchmark (BM143) was installed at the rear stake of the BM line. The lines are marked with 1"x 2" stakes with orange tops as foresites and backsites. Lines are oriented 073° true.

Maximum elevations relative to the local water level at the time of the surveys were about 5 m. Using the elevation at the BMA56, as a reference, the maximum elevation measured in the surveys was 5.6 m which means that water levels were about 0.6 m above mean sea-level (asl). The crest of the spit at line 80W was 3 m asl. The slope of the beach (from the top of the driftwood line to the edge of the drop-off was 5° to 6°.

Table 2 Nunaluk surveys summary

From	to cliff edge
30E(rear peg)	21.5 m
BM143	22.5 m
30W(rear peg)	22.7 m
80W(rear peg)	40.8 m

An attempt was made to perform bathymetry surveys offshore from the profile lines, however, we were not able to receive the differential GPS corrections from Catton Point. A single, uncontrolled survey line was run along the BM line extension. It reveals an almost flat seabed in water depths of 5-6 m with a rapid shoaling to 3 m and then a more gentle slope to 2 m water depth. There is a narrow trough at the base of the beach in 2.5 m of water then a steep slope rising up to join the subaerial beach. This profile differs somewhat from one which was performed at approximately the same site in 1972 (MacDonald and Lewis, 1973). The earlier profile is uniformly concave up with a suggestion of a subtle bar at 4 m water depth, whereas the 1995 profile is convex upward between 2-4 m water depth with a prominent bar and trough at the base of the beach (1 -2 m water depth). Interestingly, both profiles were performed two years after large storm events (1970 and 1993), thus the response of the seabed to the storms (subsequent reworking) appears to be quite different.

Niakolik Point (Site No. 30Y48 Borden No. NhVh-5)
Survey date: August 7-8, 1995; JD 219-220)

Description
Niakolik Point is a peninsula on the west side of the Babbage River Delta within the confines of Phillips Bay (**Figure** 1). It is protected from easterly and northerly winds by Kay Point and from westerlies by the NW orientation of the shoreline along that reach of coast. Fetch is relatively unrestricted only from the NNW. Spit orientations on the north side of the peninsula (**Figure** 9) indicate that sediment transport is towards the east (cf. Forbes, 1981). The Phillips Bay area was the site of intensive research during the 1970s (MacDonald and Lewis, 1973; Forbes, 1981; Lewis, 1975; Carson et al. 1975; and Forbes, 1975). Much of this work was directed towards quantifying the fluvial inputs and developing a sediment budget for the estuary (Forbes 1981). Echosounding in the Babbage delta channels identified a hard reflector within 1 m of the channel bottoms which was tentatively identified as the frost table. This surprising result suggests that even relatively deep channels freeze to the bottom, either by infilling with sediments or by transmission of sub-zero temperatures through unfrozen brines concentrated within closed channels during the winter. Water depths within the estuary are predominantly less than 2 m (Forbes, 1975) indicating that most of the inner estuary and delta channels are sealed off by bottom-fast ice at some point during the winter.

The peninsula itself consists of an upland tundra area 20-30 m in elevation surrounded by a fringe of low lying, marshy ground. The low lying area can be further subdivided into three zones:

zone 1: a relatively well-drained central area above all but the highest storm and flood waters (2-2.5 m). This zone is occupied by the remains of a log cabin (Inuvialuit habitation, village and graves - Neufeld and Adams, 1993).

zone 2: a zone to the south of the cabin which is heavily dissected by degrading, low, rectangular ice-wedge polygons. These are melting into extensive ponds and marsh oozes. The host sediments are largely peats and this area is likely the remains of a drained lake. The elevations are less than 1 m (relative to water level at the time of the survey) so this area is inundated frequently. Driftwood logs are scattered over the surface of this zone; they are concentrated into lines at higher elevations. There is no beach at the water's edge; the peat shore slopes steeply down into the water.

zone 3: this area consists of lowlying sands and driftwood which have been transported by wind-driven waves and currents. The source of the sands lie to the west where the higher upland tundra cliffs are characterized by retrogressive thaw failures and block failures. The stratigraphy of the cliffs to the west is 0-3 m peat at the top, underlain by 1-3 m of silt and sand which is underlain in turn by 1-5 m of till or sand and gravel (MacDonald and Lewis, 1973). This zone is relatively complex and contains beaches, spits, small ponds and driftwood-filled lowlands. Ice wedge polygons are forming on the surface of the vegetated backshore; these polygons are larger than those in zone 2 and have more than 4 sides. This suggests a different substrate than that of zone 2. Peaty material is present below a sand/gravel lag immediately offshore from this zone. The seaward edge of this zone is characterized by a sandy bluff 1.5 to 2 m high with a thin (10 cm) veneer of peat. A narrow sand beach is present with abundant organic debris (fine wood and peat) in the swash zone.

Sediment Samples
Four samples were taken in order to characterize the sediment sources and sinks. Niak001 represents the low sand bluffs on the north side of zone 3. It consists of medium sorted fine to coarse sand and scattered pebbles with abundant coal, wood and vegetation fragments (2% organic carbon). Niak002 is taken from the beach in front of the bluff and consists of similar material with fewer organics (0.5% organic carbon). Niak003 was obtained from 0.5 m water depth underlying a lag of gravel and sand. It is comprised predominantly of organic material (5% by weight - considerably more by volume). Niak004 was obtained from the bluffs which comprise the south edge of zone 2. It is also highly organic (22% by weight).

Retreat measurements
Erosion of 1.15 m was measured along the shoreline in zone 1 (Harper et al. 1985) between 1954 and 1972 whereas there was virtually no change in the shoreline west of zone 3 (no measurements were made in zone 3 (Harper et al. 1985). Measurements made for this study (Appendix A) show dramatic changes in zone 3 between 1952 and 1992, with the greatest changes occurring between 1974 and 1985. Overall, the rate has been close to 2 m a^{-1} along the north edge of zone 3. Little change was noted in the higher tundra cliffs to the west of zone 3 (consistent with the results of the earlier work) and steady retreat of about 1 ma^{-1} continues to occur in zone 2. There has been very little change in the position of the tundra cliff tops or bases in the 40 years covered by the air photos.

Surveys
Five survey lines were established: three lines in zone 3 and two lines in zone 2. The zone 3 lines are referenced to a GSC benchmark (BM140) set at the NE corner of the log cabin. Each of the three lines are marked with a 1 m tall, 1"x 2" rear stake painted orange . Foresites on the centre and eastern lines are 0.5 m tall 1"x 2" stakes; on the western line, the foresight is a piece of driftwood marked with black electrical tape. The baseline is oriented at 095° MN and the lines are oriented at 005° MN. The centre line is also aligned with the BM140. The centre line is 75 m from the western line and 141 m from the eastern line.

Along the southern shoreline of zone 2, two lines were established along a baseline bearing 205° MN with the lines oriented at 120° MN. The lines are 100 m apart.

Table 3 Summary of Niakolik Surveys

Line	rear peg to foresite	rear peg to cliff edge
BM140	32.2	45.1
Zone3-east	30.1	34.6
Zone3-west	50	91.2
zone2-east	7.7	12.5
Zone2-west	18.2	22.1

Of the three surveys in zone 3, only the BM140 survey extended below the waterline (**Figure** 10). The slope of the beach in front of the coastal bluffs increases from 5° in the east to 20° in the west. The zone 3-west line extended over a dense mat of driftwood which has been trapped in a low area. It may restrict the sediment supply to the beach causing it to steepen. The section below the waterline at BM140 is concave up just below the beach (slope=1.5°) for about 20 m and then drops off steeply (slope = 7°) from 0.55 m to 1.05 m. Thaw depths increased from 40-60 cm over the tundra surface to a maximum of slightly more than 1 m at the cliff and waterline. Depths decreased slightly (81-89 cm) offshore, but within 10 m of the waterline.

Along the southern edge of zone 2, the coastal bluff drops steeply (slope=12-13°) to about 0.4 m below the waterline at the time of the survey then flattens (slope=1.5°) (**Figure** 11). Thaw depths increase from 44 cm on the drained lake tundra surface to a maximum at the waterline (79 cm) and decrease slightly further offshore (56 cm).

Clarence Lagoon (Site No. 30Y96 Borden No. NjVo-5)
Survey date: August 6, 7, 10,1995; JD 218, 219, 222)

Description
Clarence Lagoon is located 6 km east of the Canada-U.S. border (**Figure** 1). The lagoon is almost completely enclosed by a spit which is probably sourced from the eroding cliffs predominantly from the west with some contribution from the east. However, the dominant sediment transport direction is not entirely clear based on coastal morphology. The lagoon is fed by the Clarence River, Craig Creek and several other unnamed rivers. A Hudson Bay Company trading post was located on its shores and the buildings are still standing. The study location is at the western end of the lagoon on a peninsula oriented approximately east-west (**Figure** 12).

A collapsed radio tower and an Inuvialuit or Western Thule grave are listed as cultural resources in the immediate vicinity (Neufeld and Adams, 1993).

There is a small inlet at the west end of the barrier fronting the lagoon. A large ebb shoal lies just seaward of the inlet and several small islands are located inside the lagoon and appear to be associated with the inlet (**Figure** 12). On August 6 (Julian Day 218), a strong current was running out of the lagoon creating a very confused sea where the current met the sea waves over the ebb shoal. Though the weather was calm at the time of the survey the winds had been blowing at about 20 km h^{-1} for the previous 24 hours. Navigation through the inlet would have been impossible at that time. According to a local source (Mervin Joe - Park Warden), the inlet was navigable in 1992, but closed up during a storm during that summer. Historical air photos show the inlet was closed in 1972 and open in 1976. In 1972 another inlet had opened at the east end of the barrier. The need to discharge water building up from river discharges into the lagoon means that complete closure of the inlets for long periods of time in the summer are highly unlikely. During the course of the survey period, two distinct sets of sea swells were approaching from the NW and NE. Breaker heights occasionally exceeded 1 m as a result of constructive interference, with run-up overtopping the highest storm berm.

The coastal bluffs ascend gradually to the west from the barrier. As they rise, the bluff face becomes wetter suggesting an increase in the ice content. The upper surface of the bluffs is characterised by sedges and grasses and is dissected by networks of ice-wedge polygons. The polygons become more prominent from east to west. Bluff slopes are actively eroding with many small thaw failures which are centred on ice wedges. In fact, the planform of the coastal bluffs appears to be controlled by the ice wedge configuration with promontories forming between the wedges. The mudflows at the bluff bases are generally solid enough to walk upon. Muddy diamicts with boulders reaching more than 1 m in diameter (typically 30-50 cm) form the bluff sediments. The upper beach sediments consist of well-sorted gravel with scattered driftwood and boulders. The coarsest gravel is found on top of the upper beach storm berm; the sediments become finer seaward. MacDonald and Lewis (1973) report a mantle of 30 cm of gravel at the tops of cliffs in the area in 1972; this gravel mantle was not present in 1995.

Sediment Samples
Samples were taken along the BM141 line in order to characterize the sediment sources and sinks. CL001 represents a veneer of sand overlying gravel in the swash zone at the water line @1700 h. Sample CL002 is the underlying gravel layer. CL003 is a sample of the clayey diamict which comprises the coastal bluff. It is difficult to obtain a representative sample due to the large variation in grain size in the bluffs. Based on a visual estimate, the boulder content in the bluffs is fairly small (< 5%).

Retreat measurements
Based on air photos from 1951 and 1976, cliff erosion rates of 0.4 ma^{-1} at the barrier and at the easternmost end of the tundra were measured by Harper et al. (1985). These rates increase to about 2 ma^{-1} to the west (higher elevations and increased ice content). Retreat rates of 0.5 ma^{-1} between 1976 and 1992 were measured at the eastern end of the tundra cliff as part of this study (Appendix A).

Surveys
Three beach profile surveys were performed at Clarence Lagoon on August 6, 1995. The lines are called BM141, CLW(est) and CLE(ast) (**Figure** 13). The lines are oriented orthogonal to the coast at an orientation of 049° MN. BM141 is identified by a GSC benchmark #141 at the landward end of the line. The other two landward markers are located to the east and west of the BM marker on a baseline oriented at 239° MN. The CLE line is located 51.5 m east of the BM141 line and the CLW line is located at 51.3 m to the west. Survey monuments marked by both Canada and the U.S. Coast Guard are located about 300 m west of the BM141 line (**Table** 4).

Table 4 Summary of Clarence Lagoon Surveys
Canada BM1 and BM2 refer to benchmarks installed to the west of the study site by the Canadian Geodetic Survey and the U.S. Coast Guard

Line	rear peg to foresite	rear peg to cliff edge
BM141	12.2	19.2
CLE	9.6	12.5
CLW	14.2	23.4
Canada BM1	na	10.4
Canada BM2	15.7 (pipe w/o cap)	18

Elevations descend from about 6 m at the cliff edge on line CLW to 4.5 m at the BM141 line and to 3.2 m at line CLE (**Figure** 13). The mean slope of the beach profile from the base of the water line is roughly the same on all three lines: 6-6.5°. However, the bluff profile is much steeper on the two westerly lines than on line CLE.

A thaw profile was measured along the BM141 line using a frost probe. On the tundra surfaces depth to ice-bonding varied from 60 to 75 cm. On the cliff face and at the cliff base it increased to 100 cm and 105 cm respectively. Gravel on the beach made it impossible to measure thaw depths seaward of the bluff.

Catton Point (Site No. 30Y61 Borden No. NiVj-2)
Survey date: August 3, 1995; JD 215)

Description
Catton Point is located southeast of Herschel Island in Ptarmigan Bay. The study site is in the vicinity of a dome-shaped tundra remnant anchoring a long, thin sand and gravel spit covered in abundant driftwood (**Figure** 14). A cabin owned by Danny and Annie Gordon of Aklavik is located on the southeastern edge of the tundra remnant with several smokehouses and wind shelters on the spit in the immediate vicinity. Inuvialuit gravesites are scattered over the tundra surface, especially on the northwest end. Ground squirrel tunnels honeycomb the tundra and there is abundant evidence of grizzly bear excavations as well.

The tundra is fronted by a wide beach with several driftwood lines and storm berms (**Figure** 15). At the base of the vegetated tundra bluff, an older partially buried and well-rotted litter of driftwood may mark the former position of the beach prior to development of the spit. The spit is about 30-50 m wide with a distinctive crest (**Figure** 16). The lagoonward face of the spit is punctuated by washover lobes which drop steeply into the lagoon. Towards its proximal end, the spit elevation decreases with more frequent washover channels extending across the spit and into the lagoon. The distal end of the spit consists of a series of prograding recurves. The ends of the recurves and several small spits on the inside of the lagoon at the Catton Point spit (**Figure** 14) show evidence of transport to the southeast (opposite from the direction outside of the spit). Transport in this direction is driven by winds from the northwest through Workboat Passage (between Herschel Island and the mainland) and the limitations imposed on southeast fetch by the mainland.

Based on the overall spit orientation, sediment transport on the seaward side is mostly from the southeast. This is largely due to the sheltering effects of Herschel Island. Spits on the east side of Herschel are oriented towards the south, indicating sediment transport from the north, with a confluence in the vicinity of Catton Point.

The lagoon (**Figure** 14) appears to be a significant sink for organic material; both locally derived and allochthonous. The local material is peat which is eroded (along with muddy diamict) from the low tundra bluffs along the mainland. The rebedded peat forms thick (at least 0.5 m) deposits along the bluffs and toward the head of the lagoon. The deposits are visible in the intertidal zone, but their extent below the waterline is unknown. Gravel derived from the erosion of the bluffs is also scattered on the intertidal flats. Driftwood is commonly scattered along the base of the bluffs and is concentrated at the head of the lagoon in a low embayment (**Figure** 14). Here the driftwood is stacked at 1-2 m high on the landward side of the proximal end of the spit. The likely sources of the driftwood are the Babbage River to the east and the Firth and Malcom Rivers to the west, though some is probably derived from the Mackenzie as well.

The beach in the vicinity of the tundra remnant consists of a series of storm berms at various elevations comprised of gravel with some sand. Higher elevation berms are associated with distinctive driftwood lines. During the 8 days we were camped on the island, the swash zone exhibited moderate variability in both form and texture. In general, small cusps (5-10 m wavelength) characterized the swash zone. Gravel up to several cm in diameter was moved by swash and backwash over a coarse sand and granule surface. Small berms were formed during intervals of higher water (caused either by tide or small storm surges). Observations of waves were made during one period of strong NE winds (estimated 30 km h^{-1}) on August 10 (JD 222; wind 15-30 km h^{-1} at Tuktoyaktuk). There were 2-3 tiers of waves breaking simultaneously by surging within about 50 m of the beach. At the step (base of the beach) the breakers plunged directly on to the beach, removing pebbles and gravel from the surface leaving a smooth veneer of sand 2-3 cm thick. During the course of the wind storm (nearly 48 hours), the beach slope appeared to flatten without producing a storm berm. No washover occurred during the storm, which is consistent with the relatively lower water levels normally associated with easterly winds.

Three pits were dug on the beach (along the tundra line) to evaluate the vertical distribution of sediment texture. Pit A was situated on the seaward edge of a recent storm berm within 0.5 m of the water elevation at that time (surface slope=25°). The upper 20 cm consists of gravel (1-2 cm diameter) overlying 1-2 cm of gravel with abundant finely disseminated organic debris (peat fragments). Below the organic zone was a well sorted coarse sand with occasional granules. Pit B was located at the landward edge of the storm berm at a slightly higher elevation (surface slope=2-3°). This site was characterised by a 5 cm surface gravel lag overlying 2-3 cm of coarse sand and an additional 10 cm of sandy gravel with abundant organic debris as described above. From 18 cm below the surface to the base of the pit (about 50 cm), medium to coarse sand predominated with scattered pebbles. Pit C was located at an older high water swash line landward of the storm berm (surface slope=8°). The stratigraphy consisted of a surface layer (5 cm thick) of imbricated 1-3 cm oblate pebbles with abundant organic debris overlying 2 cm of coarse sand with a few pebbles. Sandy gravel with a lens of pea gravel comprises the next 25 cm layer, which is underlain by three 4 cm thick sequences of sand which coarsen upwards to gravel.

Sediment Samples
Seven samples were retrieved in the Catton Point area. Two samples (Cat001 and Cat002) were taken from the shoreface in 3 -3.5 m water depth. They consisted of fine muddy sand. Cat003 represents surficial beach gravels taken from the water line. Samples Cat 004-007 came from Pit B and represent the various sediment facies described above.

Retreat measurements
No measurements of cliff retreat were made by Harper et al (1985) at the Catton Point site, however, they did measure retreat inside the lagoon of as much as 3.4 m (1954-1972). Immediately updrift of Catton Point (at the proximal end of the spit), they measured retreat at < 0.10 ma^{-1}) for the same time period. Measurements performed for this study (Appendix A) show that the Catton tundra remnant and the immediately adjoining spit has remained relatively stable between 1953 and 1976. The most actively eroding section is on the lagoon side of the tundra remnant, on the south side. This area is presently the site of active thermokarst development, some of which is related to the presence of an old dug-out ice house. Unfortunately there is no air photography more recent than 1976.

Surveys
A base station was set up for GPS navigation on the highest point of the Catton tundra remnant ("Catbase"). A 10 hour GPS average position was used for the base station coordinates. The GPS elevation at the site was 14 m. The location is marked with GSC BM147. A second GSC benchmark (BM148) was installed on the spit east of BM147 and east of a large wind shelter as well. The distance between the two benchmarks is 426 m. Two cliff and beach profile lines were measured along lines which included the two benchmarks; Catton Tundra and Catton Spit (**Figures** 15 and 16). The Catton tundra line was oriented 038° MN and the Catton spit line was oriented 045° MN. Both lines display similar morphologies on the seaward sides with an older storm berm 1-1.5 m asl about 15 m from the water line and a fairly steep profile (6-7°) based on the distance from a more recent and lower elevation berm. The spit is 76 m from waterline to waterline and its crest lies at the centre (35 m from the lagoon) at a maximum elevation of 1.3 m relative to the water level at the Beaufort sea side. On the lagoon side of the spit line, there is a narrow berm and driftwood line with an elevation of 1 m. The slope on the lagoon side is 7°.

The morphology of the tundra line is similar to the spit line with a few significant differences. In general, the crestal elevations are about 0.5 m higher on the tundra line, and there is less distance between the seaward storm berm and the central crest. This is consistent with a trend of decreasing elevation in a proximal direction delineated by increased numbers of washovers in that direction. At the landward edge of the tundra line, relatively recent gravels overlie darker, lichen covered gravels exposed in troughs between what appear to be washover lobes. The darker (and older?) gravels are associated with an overgrown, well-rotted driftwood line which is exposed at the base of the tundra bluffs. While the more recent, fresher driftwood lines are continuous with driftwood lines on the spit, this older driftwood is not. It is likely that this association of gravel and rotted driftwood represents a beach which was present prior to the tundra remnant being incorporated into the spit.

The two beach profiles were initially surveyed on August 3 and re-surveyed on August 10 after a period of exposure to a relatively strong NE blow and a somewhat windy week (**Figure** 17 and 18). Similar changes occurred on both lines. Previously formed subtle storm berms at < 0.5 m above the local water level were removed. The beach slope within 15 m of the waterline decreased at the tundra line, but remained constant on the spit line.

Echo sounding surveys were used to extend the beach profiles into deeper water. Two lines were surveyed, one off each profile. Profiles were very similar, exhibiting concave up morphologies and a rapid shoaling from 2.3 m to the beach (**Figure** 19). The gradient beyond 2.3 m water depth is 0.10° on the tundra line and 0.14° on the spit line. Inshore of 2.3 m, the slope increases to 2.1° on the tundra line and 2.8° on the spit. No bars are present on either line. The slightly higher gradient on the spit line reflects a more general shoaling trend towards the NW which can be seen on the hydrographic chart of the area.

Water Temperature
Water temperature of the nearshore has been identified as a critical factor in determining the erosion rate of frozen beach and coastal bluff sediments (Baird and Associates, 1995). Limited historical water temperature and salinity data are available in the vicinity of Phillips Bay and the Babbage River estuary (Forbes, 1981; Bond and Erickson, 1989). These data illustrate the dependence of salinity and water temperature on wind direction. Easterly winds drive surface waters offshore causing upwellings of colder, more saline Beaufort Sea waters (Bond and Erickson, 1989). The data collected off Catton Point (**Table** 5) corroborates the dependence of temperature on wind direction and speed (**Figure** 20). On August 5, 1995 (day 217) a strong easterly wind was observed at Tuktoyaktuk. Water level at the Tuktoyaktuk tide gauge dropped in association with a wind-induced negative surge. Within one day of the start of the blow, water temperatures at Catton Point decreased dramatically from 9°C to 1.6-3°C. The winds at Catton Point were blowing out of the northeast on August 5 and turned towards the west during the night. This suggests that the negative surge caused movement of surface waters offshore and resulted in an upwelling of colder bottom waters. However, a similar wind and water level event on day 221 (August 9, 1995) did not result in a decrease in water temperature at Catton Point. The difference may be related to event duration and/or the details of the wind speeds and directions throughout the event.

Table 5 Water temperature

Mean	6.6°C
Median	6.6°C
Mode	6.5°C
Standard Deviation	1.8°C
Range	8.2°C
Minimum	1.6°C
Maximum	9.8°C
# of observations	184

Discussion

With the exception of Niakolik Point, the sites are quite similar morphologically. They consist of a tundra-backed beach composed of gravel and sand, which is associated with a barrier or spit of some kind. The beach slopes are invariably steep (5-7°) and are similar to other Beaufort Sea sites to the east (**Table** 6). The retreat rate varies (**Table** 7), as does subaerial morphology, tundra bluff height, composition and inferred ice content (**Table** 8). Niakolik is unique in that it consists predominantly of modern sands and peats, with no obvious older tundra exposed at the study site. The general elevation is also considerably lower than the other sites.

All five locations have been ranked according to the rate of bluff retreat as measured in air photos and their degree of exposure. The period of time over which the rate of retreat has been calculated varies depending on the available photography (**Table** 7). However, patterns do emerge over the period of record. The degree of exposure ranking is based on examination of the terrain-influenced fetch limitations in eight 45° quadrants, assuming no variation in fetch due to ice.

Of the 4 similar sites, bluff retreat rates are lowest at Catton Point and highest at Nunaluk and Stokes. The contrast in retreat rates at these sites is likely a function of the sheltering of Catton Point from the effects of NW storms (those associated with storm surges) by Herschel Island. The abundant supply of sediment at Catton Point from sources to the east, probably contributes to its relative stability as well. A dependence on updrift sediment supply renders the Catton Point site vulnerable to disruptions of sediment pathways caused by natural breaching of the spit. A 1976 air photo (**Figure** 14) illustrates a breach in the spit downdrift (northwest) of the Catton Point site with a plume showing influx of sediment into the bay. While this is scenario is likely to occur during a severe storm, such a breach is also likely to heal naturally (as occurred in the case of the downdrift breach sometime between 1976 and the present).

Although Stokes Point is ranked second to Nunaluk in bluff retreat amongst the tundra-backed locations, in fact, the two sites exhibit similar magnitudes of retreat. The ranking may have reversed in more recent years given the evidence that Nunaluk has retreated 2 m a^{-1} over the past several years compared with the possibility of retreat at Stokes of 4-6 m a^{-1} (based on the location

Table 6: Beach and Nearshore slope

Location	Beach slope	Nearshore slope
Stokes Pt.	5-6°	2.5° (0-2 m inside bar)
		0.6-0.8° (2-8 m outside bar)
Nunaluk	5-6°	na
Niakolik zone 3	5-20°	1.5-7° (within 30 m of WL)
Niakolik zone 2	12-13°	1.5° (within 10 m of WL)
Clarence Lagoon	6-6.5°	na
Catton Pt.	6-7°	0.1-0.15° (>2.3 m wd)
		2.5° (<2.3 m wd)
Tuktoyaktuk	7°	2.2° (<1.2 m wd)
		0.8° (<3.3 m > 1.2 m)
		0.14° (> 3.3 m)
North Head	5.7°	1.1° (outside bar)
		0.09° (to 3.5 m)
Tibjak	5.7°	0.95° (across bar)
		2.9° (outside bar)
		0.45 m (> 2 m to 5 m)
King Pt.	3-4° (at proximal ends of barrier)	6-8° (< 2 wd)
	1-1.5° (in centre of barrier)	0.5-0.6° (2-7 m)

Table 7: Bluff retreat (m a^{-1})
Different retreat rates for a given time period at each site refer to different profile locations.

Location	**1952,53-70**	**1970-76**	**1976-92**
Catton Point	0.84, 0.27, 0.24	0.86, 0.32, 0.32	na
Nunaluk	1.2, 0.94, 2.48	1.38,1.9, 2.47	na
Clarence Lagoon	na	na	0.53, 0.57
Location	**1952,54-70**	**1970-85**	**1985-92**
Niakolik zone2	1.26, 0.94	0.27, 0.19	0.9, 0.34
Niakolik zone3	1.07, 1.74	2.18, 2.83	2.37, 2.07
Stokes	0,0	2.4, 0.21	2.23, 0.45

Table 8 Retreat ranking and characteristics summary

Location	**retreat rank**	**exposure rank**	**bluff height (m)** **composition** **ice content**	**nrsh->offsh slope** **morphology**	**median # of wks of open water***
Niakolik (Z3)	1	4	2 organic sand ice poor	1.5->7° no bar(?)	12
Nunaluk	2	3	5 diamict ice poor	na bar	8-10
Stokes Pt.	3	2	4-5 organic mud ice rich	2.5->0.6° bar	12
Niakolik (Z2)	4	5	<1 peat ice rich	1.5°->na no bar (?)	12
Clarence Lagoon	5	1	3-6 diamict ice rich	na (?)	6-8
Catton Point	6	3	14 diamict ice poor	0.1->2.5° no bar	12

*Source: Dickens et al, 1987

of graves relative to the 1995 cliff edge). While these estimates of recent erosion need to be confirmed by more detailed mapping, they indicate that caution must be exercised in basing predictions of erosion on past performance. The ice-rich nature of sediments at Stokes Point may contribute to a more episodic form of retreat, whereas Nunaluk may be more likely to behave in a uniform fashion.

It is interesting to note that Clarence Lagoon, despite its ranking as the most exposed location on the basis of terrain, has experienced relatively little bluff retreat. The most obvious explanation is that the open water season at this location is shorter than at other sites. Freeze-up occurs at about the same time as the other sites (second to third week of October - Dickens et al. 1987), but ice was present until the last week in July (several weeks later than Stokes, Catton and Niakolik). Not having acquired nearshore morphology data, it is not possible to rule out a morphological factor as well. It is possible that ice push and/or ride-up play a role in nourishing the beaches at Clarence Lagoon (Forbes and Frobel, 1985). It is the only one of the locations which is likely to experience significant ice movements during the winter. The other locations tend to be protected by wide expanses of landfast ice (Dickens et al. 1987).

Conclusions and Recommendations

At this stage of the project, it is possible to rank the five sites in terms of the short-term vulnerability to destruction by erosion. Nunaluk and Stokes are at the highest risk; Niakolik, followed by Catton are lower risk localities. The presence of grave timbers within 3-4 m of the cliff edge at Stokes suggests that the next large storm will likely see the destruction of cultural artifacts. We were unable to identify the locations of archaeological remains at Clarence Lagoon, so the level of risk is difficult to assess. At present, its erosion rate is relatively low. Prediction of future risks depends largely on the ice distribution and storminess likely to occur in the future. Dramatic increases in the duration of open water seasons (which may accompany global climate warming) probably herald a rapid increase in erosion rate (cf. Solomon et al. 1993). If ice nourishment plays a role in beach processes at Clarence Lagoon, erosion rates there could increase more quickly than at other locations.

At the present time, we recommend maintenance of a “watching brief” on the sites. Acquisition of high resolution air photography at all sites will be extremely helpful in elucidating the effects of the 1993 storm (at sites where we have 1992 photography) and improving our database of baseline information (at sites where we have no recent photography). It will also be necessary to finish collecting baseline characterization data (nearshore morphology, sediment samples, thaw profiles) at sites which have incomplete datasets (Nunaluk, Niakolik, and Clarence Lagoon). Repetitive onshore and offshore surveys will quantify the temporal variability in morphology. Nearshore temperatures were logged for a brief period off Catton Point. Longer term water temperature data is needed as input for numerical models of erosion which are currently under development.

Methodologies for application of a combined thermal-hydrodynamic erosion model (Baird and Associates, 1995) to long-term shoreface profile development and cliff retreat will be available by March 31, 1996. Despite a lack of calibration, the application of the model will permit an analysis of relative stability between sites under altered climatic regimes. Completion of the basic characterization data collection is required to provide input data for the model.

A comprehensive list of data requirements is provided in **Table** 9. Recent advances in precise differential GPS for cm-level surveying now permit rapid topographic mapping. GSCA has been evaluating this equipment as a replacement for conventional optical surveying for beach surveys. It would be very useful for mapping all of the study sites as a basis for monitoring and modelling.

Another very useful GPS product would be the collection of data for 2-3 days at each benchmark location. Using precise ephemeris data available from the Geodetic Survey of Canada, improved horizontal and vertical positions could be calculated. In general, benchmarks and monuments along the Beaufort Sea are of dubious quality and some thought should be given by the Park to the development of their own network of monuments (both for coastal and inland work).

Table 9: List of data requirements
•Air photo needed at Catton Point and Nunaluk at a minimum; all sites if possible (to assess 1993 storm impacts).
•Thaw profiles in the nearshore (0-1 m water depth) at all sites.
•Nearshore profiles at Niakolik, Nunaluk and Clarence Lagoon*; repeat profiles at other sites if time permits.
•Offshore samples at all sites except Catton Point (beach and bluff samples at Nunaluk)*.
•Detailed survey of graves at Stokes Point and cabins at Niakolik and Nunaluk for air photo scale.
•Repeat beach surveys at as many of the sites as possible (to assess annual variability).
•Nearshore water temperature monitoring.
•Use DGPS and Precise ephemeris from Geomatics Canada to survey in Benchmarks for future use (needed for all of Beaufort).

NB *Nearshore profiling and sampling can be accomplished in the spring by augering through the ice at predetermined intervals and measuring the ice thickness and water depth and taking Livingston core or grab samples. Water temperature and salinity measurements will also be of interest. The identification of ice pile-up, ice ride-up and pressure-ridge development will be useful for assessing the role of ice-related processes. Data collection of benchmark position data can also be performed at any time , but is probably best accomplished when the weather warms up so that battery life is less critical.*

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Figures

larger scale 1970 air photo. The lagoon behind the spit is a major sink for organic matter eroded from peat cliffs and for driftwood. Sediment transport is to the north on the outside of the spit and to the south on the inside. The break in the spit to the north of the tundra remnant has healed since the photo was taken.

Figure 15 Oblique photo of Catton tundra cliff with the beach profile superimposed. Driftwood log lines and storm berms mark previous high water lines. Driftwood shelters, drying teepees and a small hunter's cabin can be seen on the beach and the adjacent tundra. Some thermokarst activity is taking place at the cliff edge below the cabin. It is probably related to the disturbance created by the building of an ice cellar.

Figure 16 Oblique photo of Catton spit with the beach profile superimposed. The survey begins in the lagoon at the edge of a washover lobe. Driftwood log lines and storm berms mark previous high water lines. Driftwood shelters, drying teepees and a small hunter's cabin can be seen on the spit and the adjacent tundra. Some thermokarst activity is taking place at the cliff edge below the cabin. It is probably related to the disturbance created by the building of an ice cellar.

Figure 17 Beach profiles on the Catton tundra line measured on August 3 and August 10, 1995. A small amount of erosion has taken place at the water line, caused by a series of moderate northerly and easterly wind storms.

Figure 18 Beach profiles on the Catton spit line measured on August 3 and August 10, 1995. A small amount of erosion has taken place at the water line, caused by a series of moderate northerly and easterly wind storms.

Figure 19 Beach and nearshore profiles measured on Catton Spit tundra remnant. The tundra line is slightly lower gradient than the spit line, which is consistent with the presence of a large sediment sink immediately to the north and west of the spit.

Figure 20 Water temperatures at Catton Point between August 3 to August 10, 1995. Relatively strong easterly winds at Tuktoyaktuk (northeast backing to west at Catton Point) appear to be responsible for the drop in temperature on August 6-7.

Tables

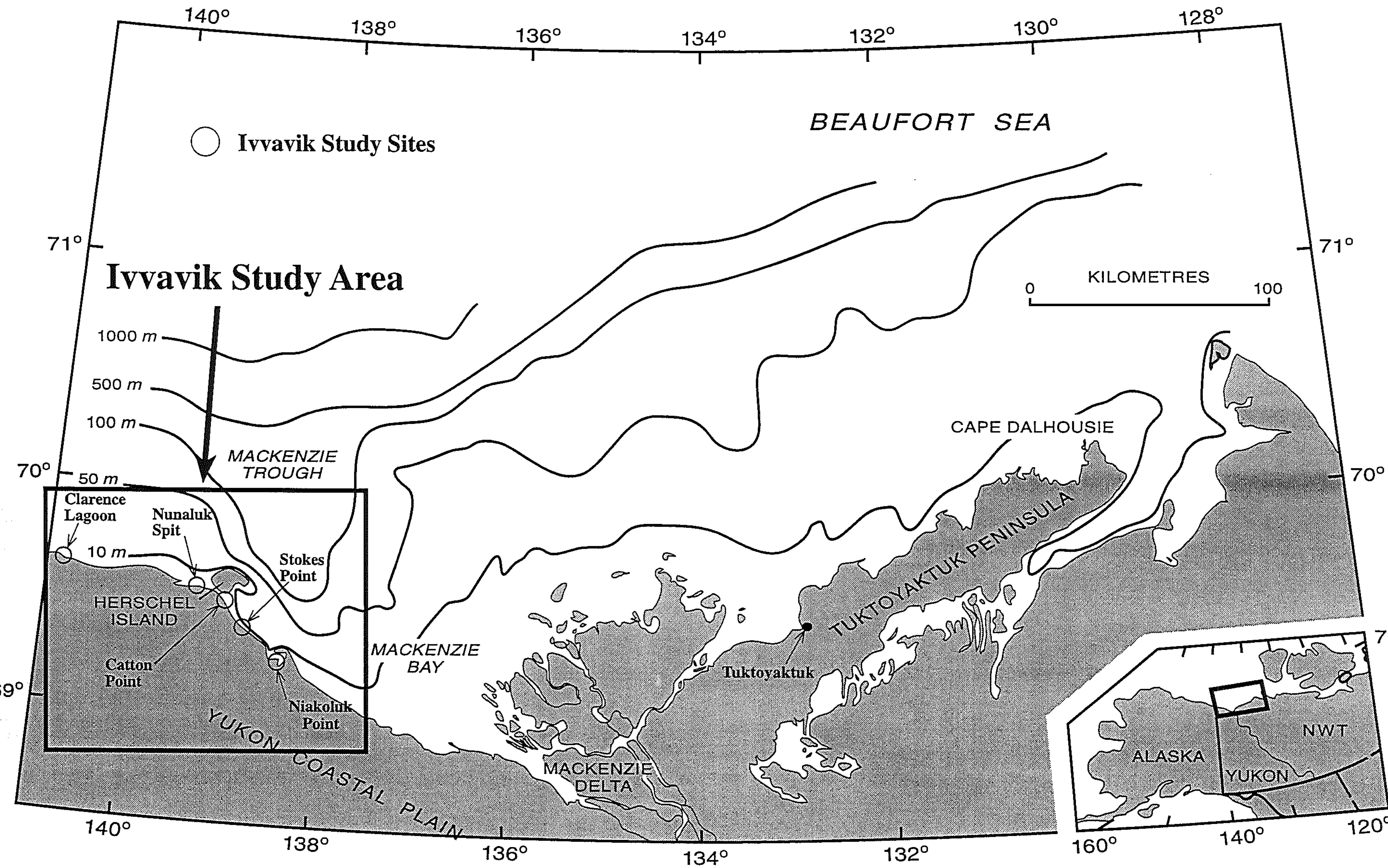


Figure 1 Map of the Canadian Beaufort Sea showing the location of the 5 field sites.

Figure 2 Tuktoyaktuk wind speed and direction Aug 1-12,1995

Graph of wind speed and direction at the Tuktoyaktuk airport during the field surveys. The graph is based on hourly observations (no observations were made between 2300h and 0800h).

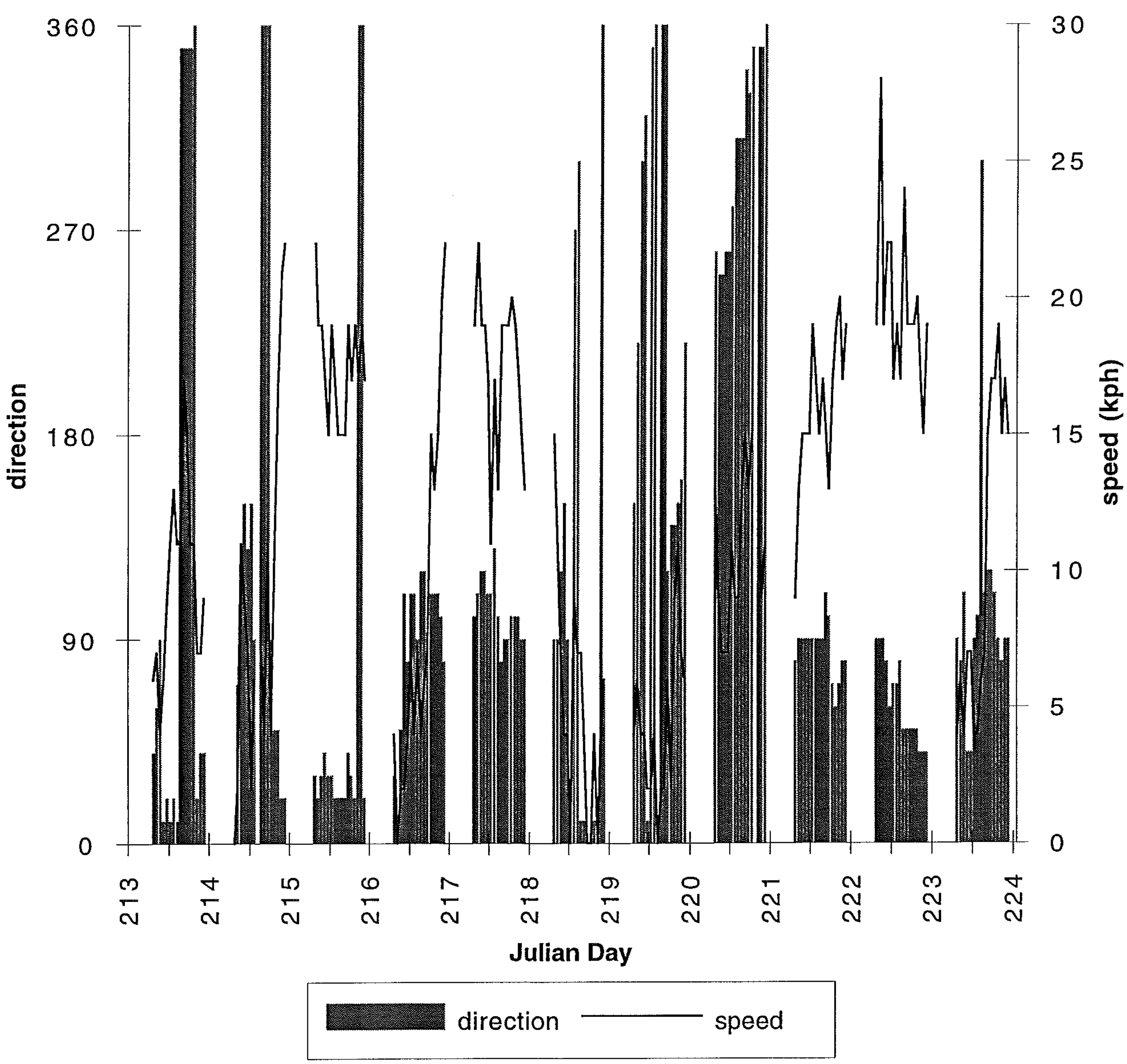


Figure 3 Graph of water levels at Tuktoyaktuk during the field surveys (August 1-12, 1995)

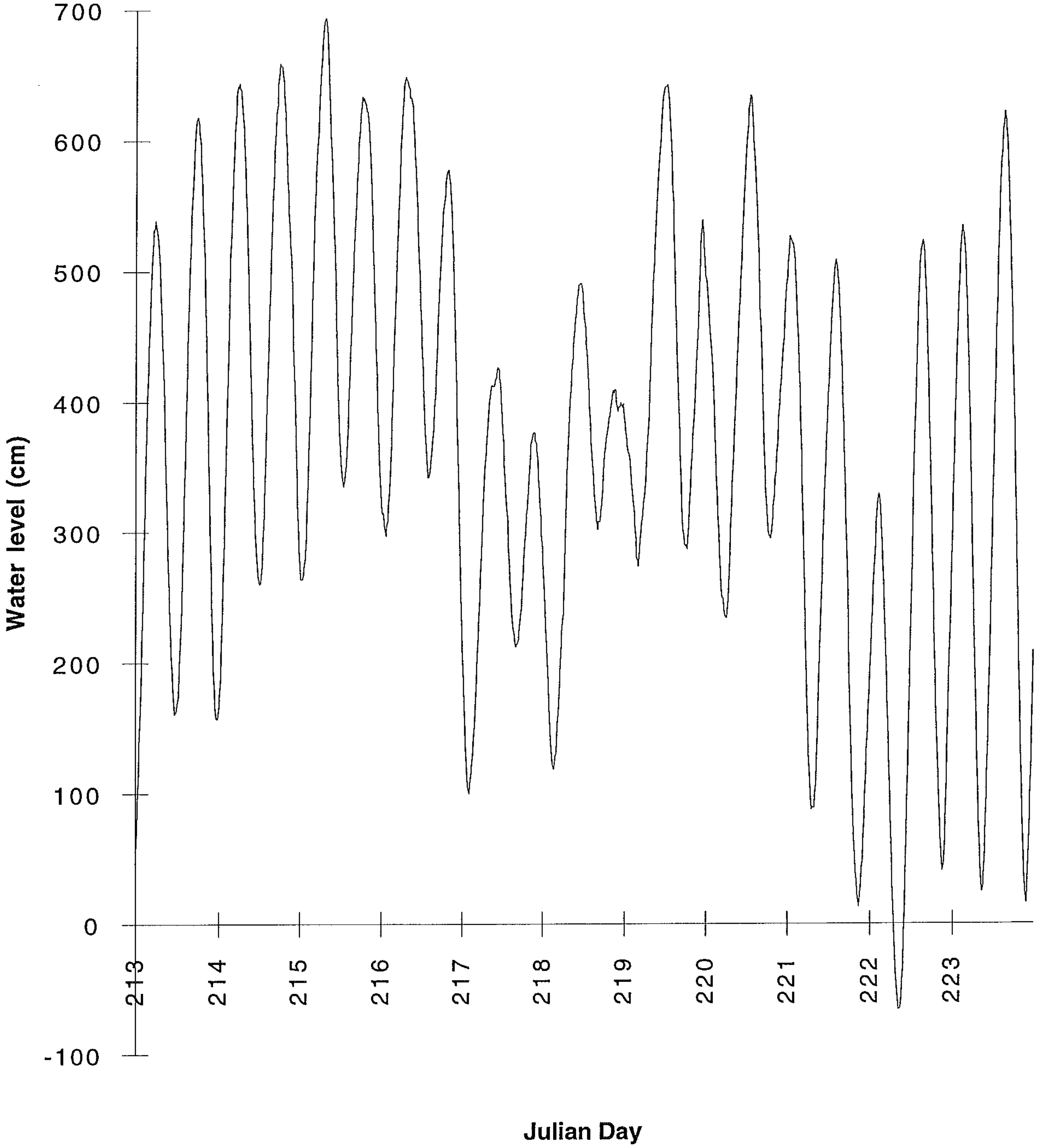


Figure 4 Stokes Point 1970 air photograph showing the 1995 survey lines, the position of the 1992 cliff edge, information on coastal types, and the location of archaeological sites. The position of the 1995 cliff edge relative to the gravesites suggests that 10-15 m of erosion may have occurred since 1992.

Figure 5   Stokes Point beach profiles.

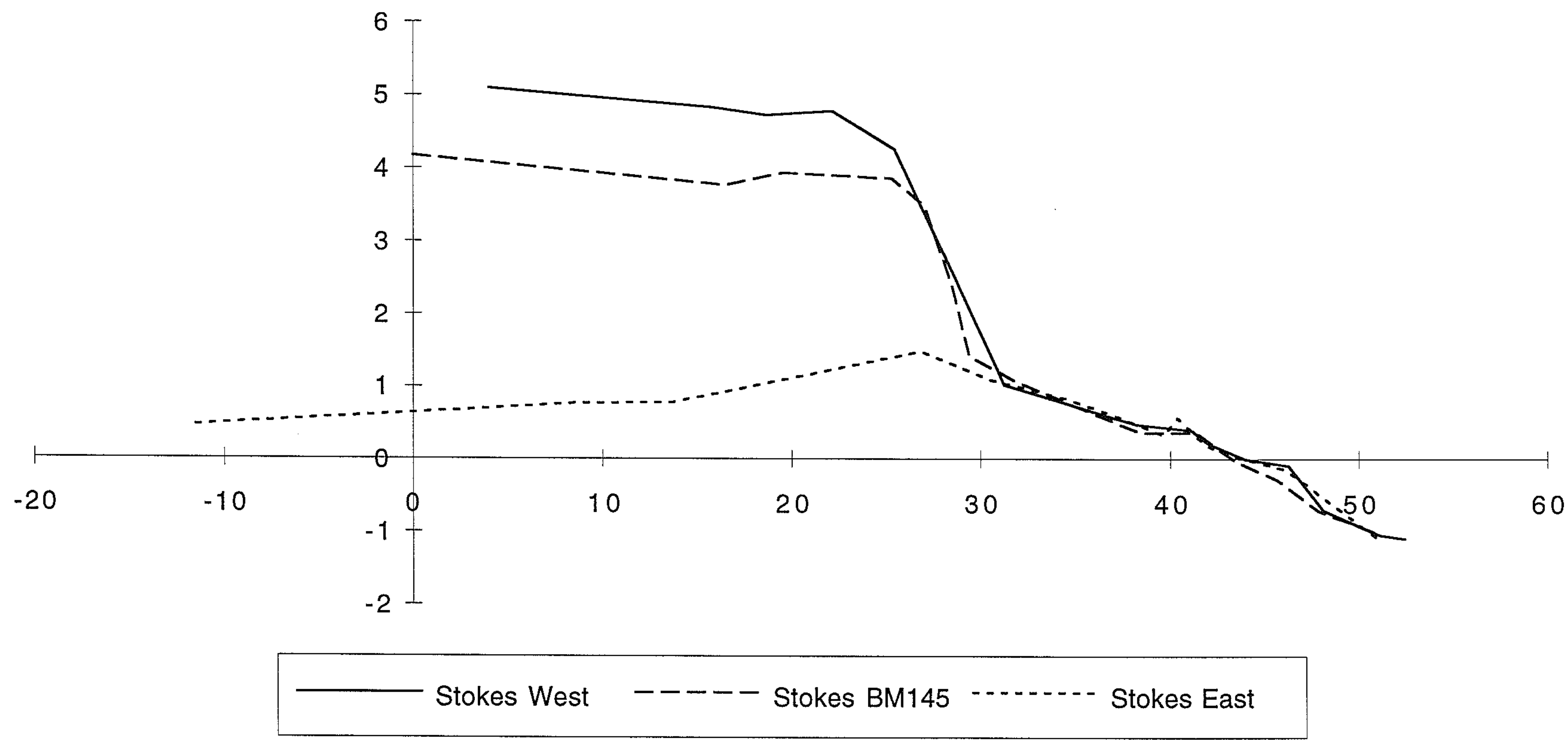
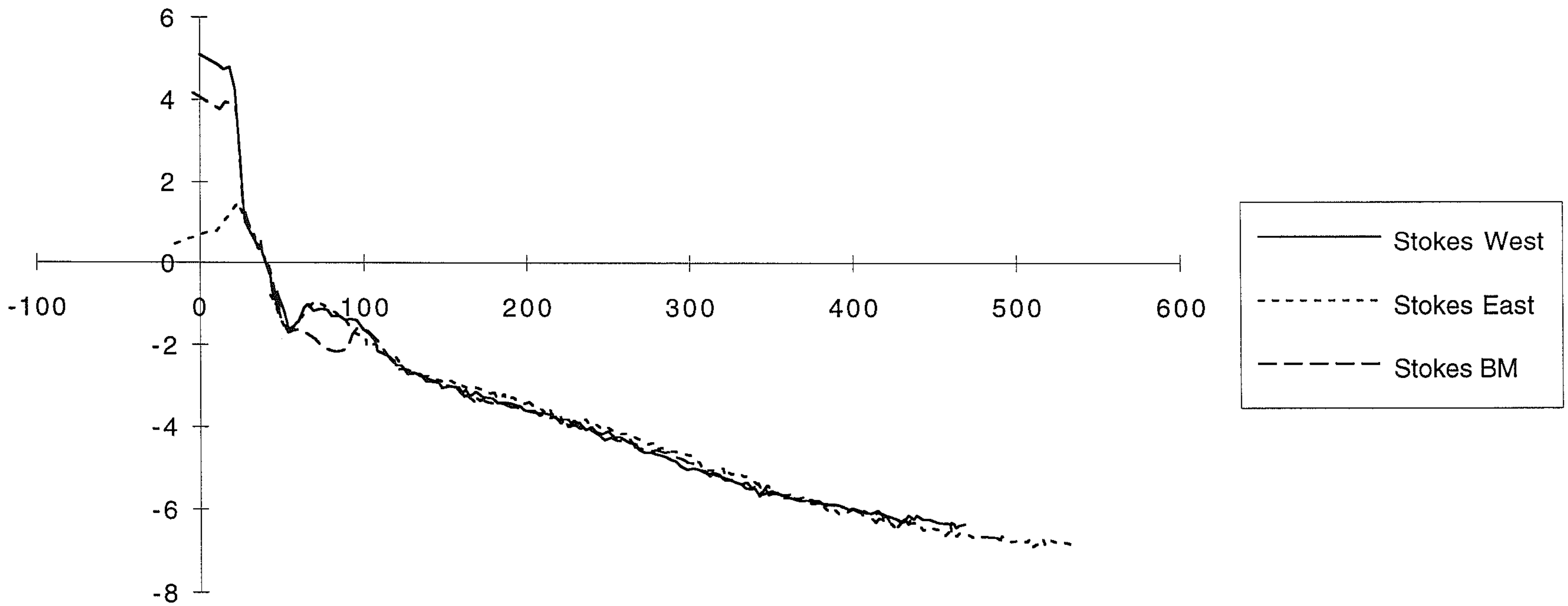
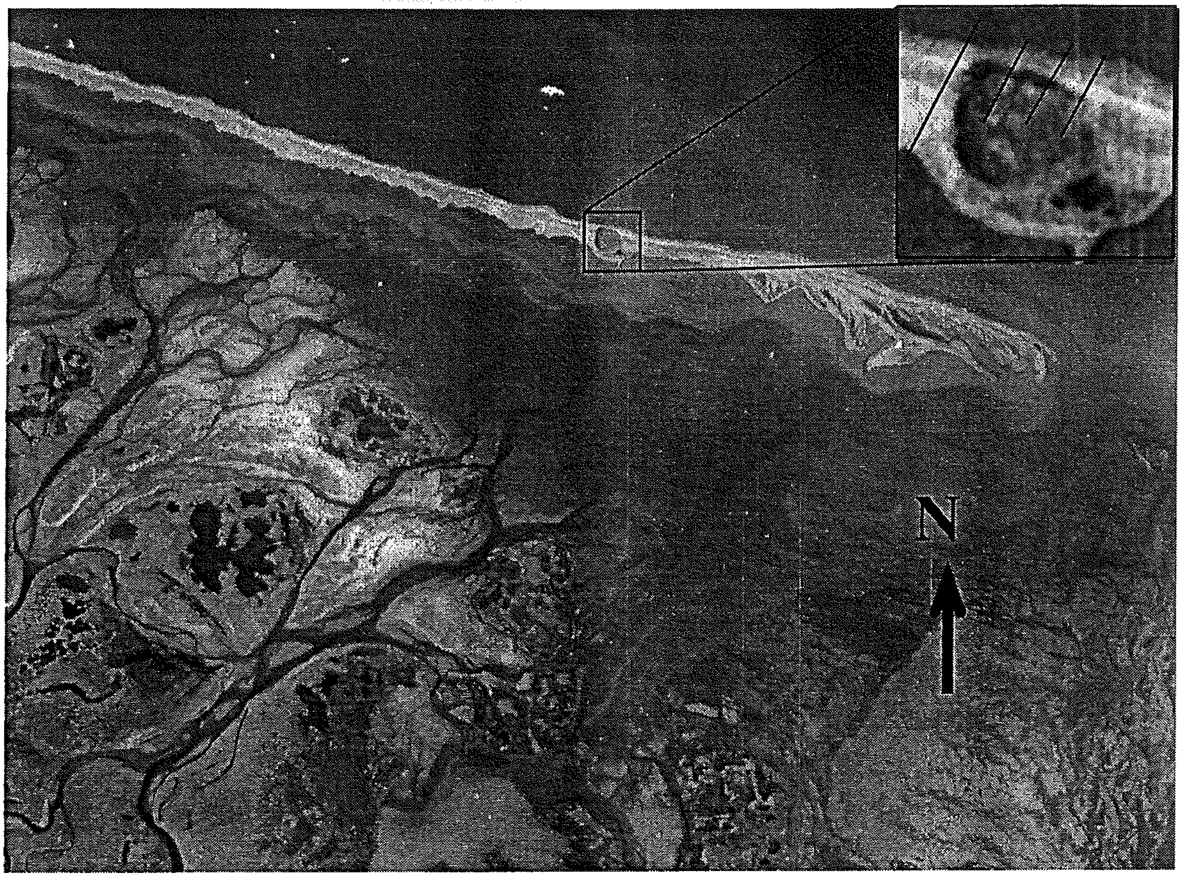


Figure 6 Stokes Point beach and nearshore profiles. Note the seaward displacement of the bar on the BM line.





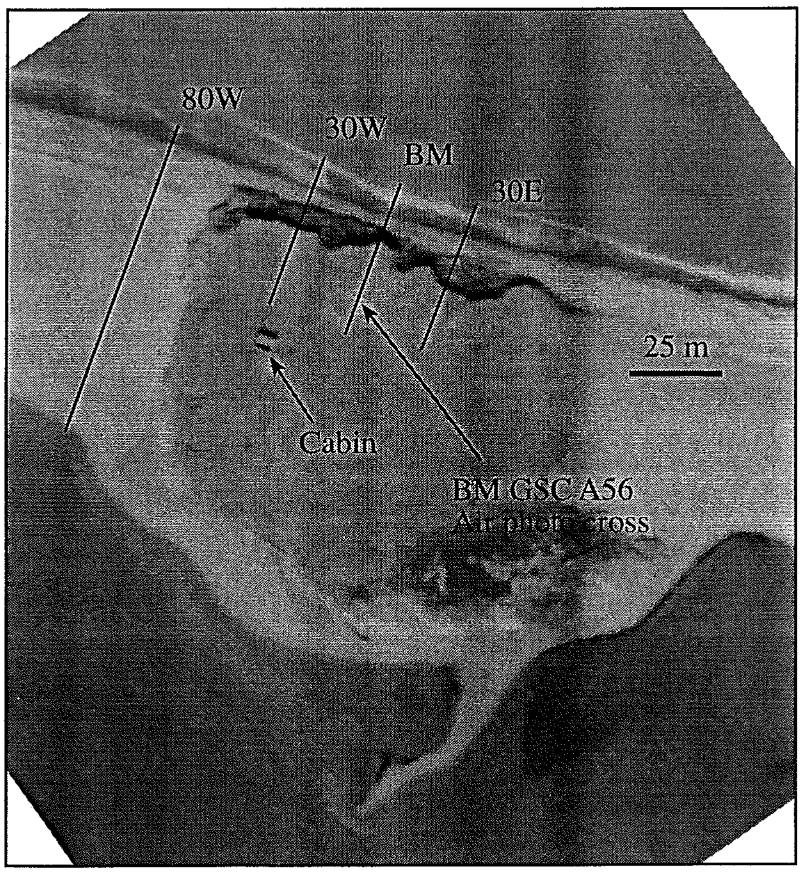
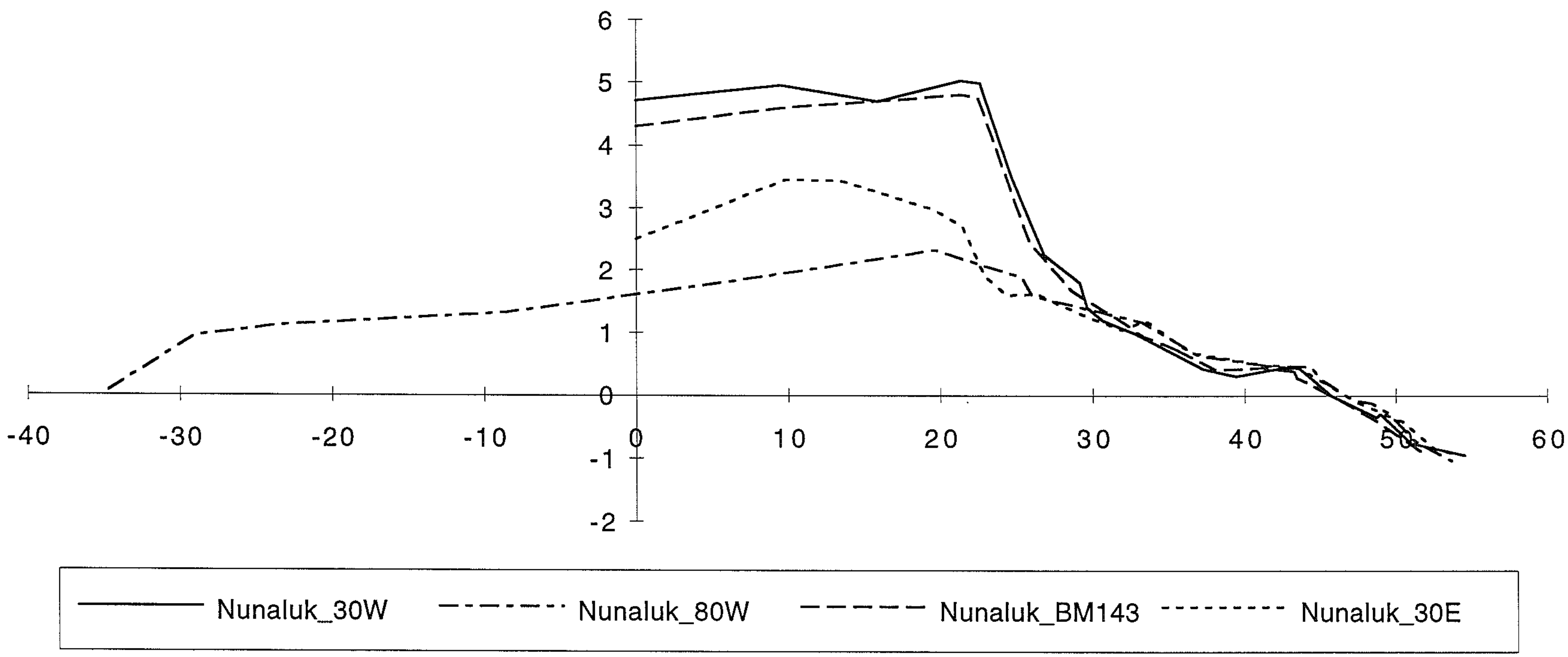


Figure 7 Nunaluk survey site; upper photo was taken in 1976, the lower photo in 1970. The 1976 photo illustrates the shallow lagoon and distributary channels of the Firth River. A cabin and an air photo marker can be seen in 1970 photo along with the 1995 survey lines.

Figure 8 Nunaluk profiles - note the similarity between profiles across the beach (below 1 m elevation).



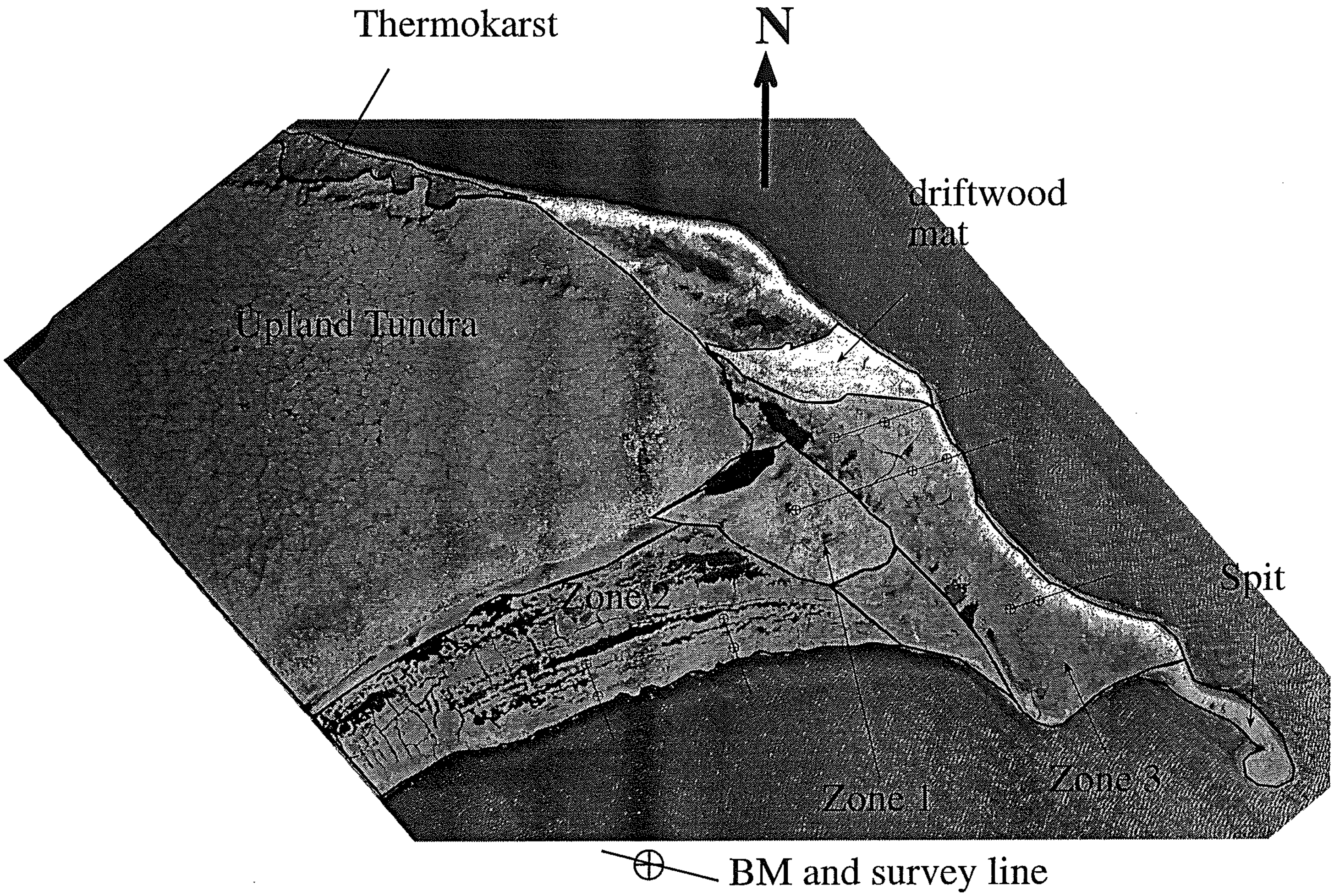


Figure 9 Niakolik 1992 air photo illustrating the coastal zonation and the 1995 survey sites. Cultural and archaeological artifacts are located in zone 1 and on the upland tundra. Zone 1 is slightly higher than zones 2 and 3. Zone 2 is primarily peat and degrading ice wedge polygons. Zone 3 is mostly sand and gravel.

Figure 10 Niakolik zone 3 (north) profiles. There is a bench immediately below the waterline and a drop-off about 20 m from shore on the BM140 line.

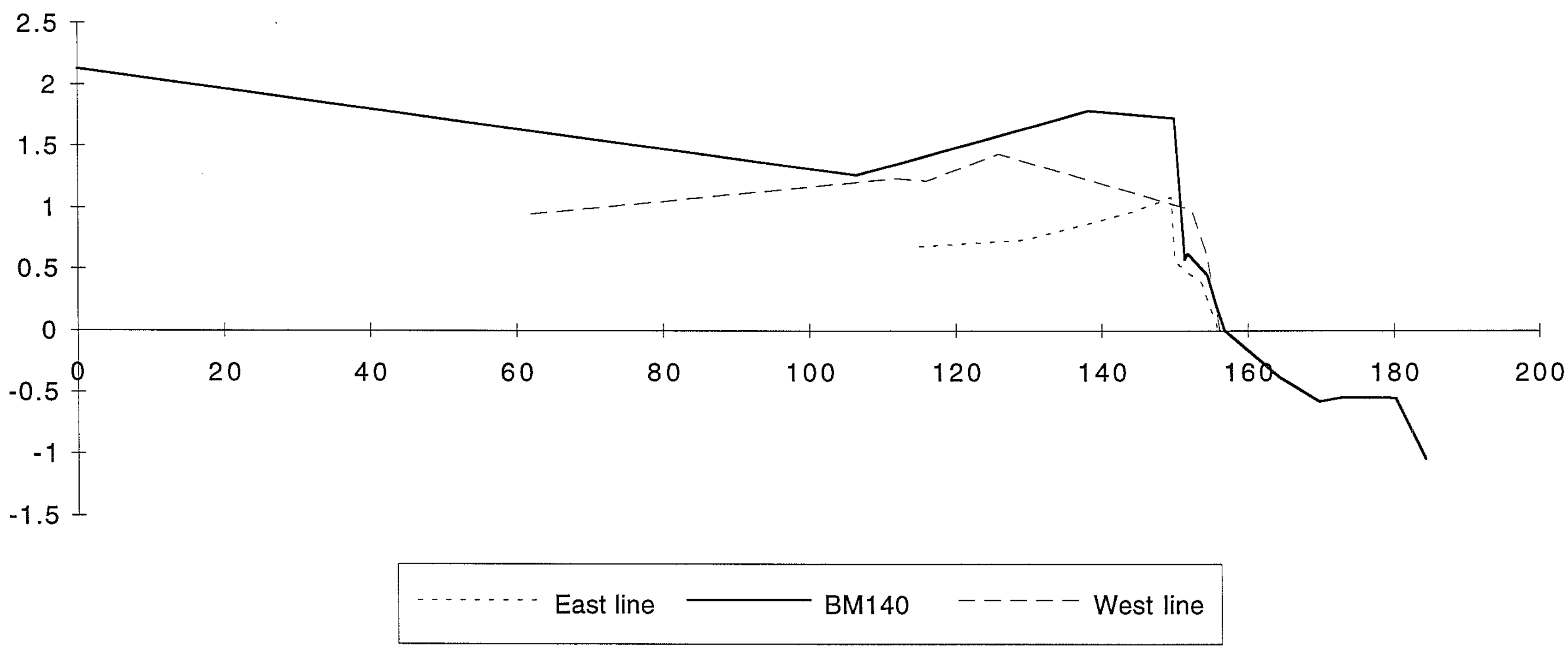
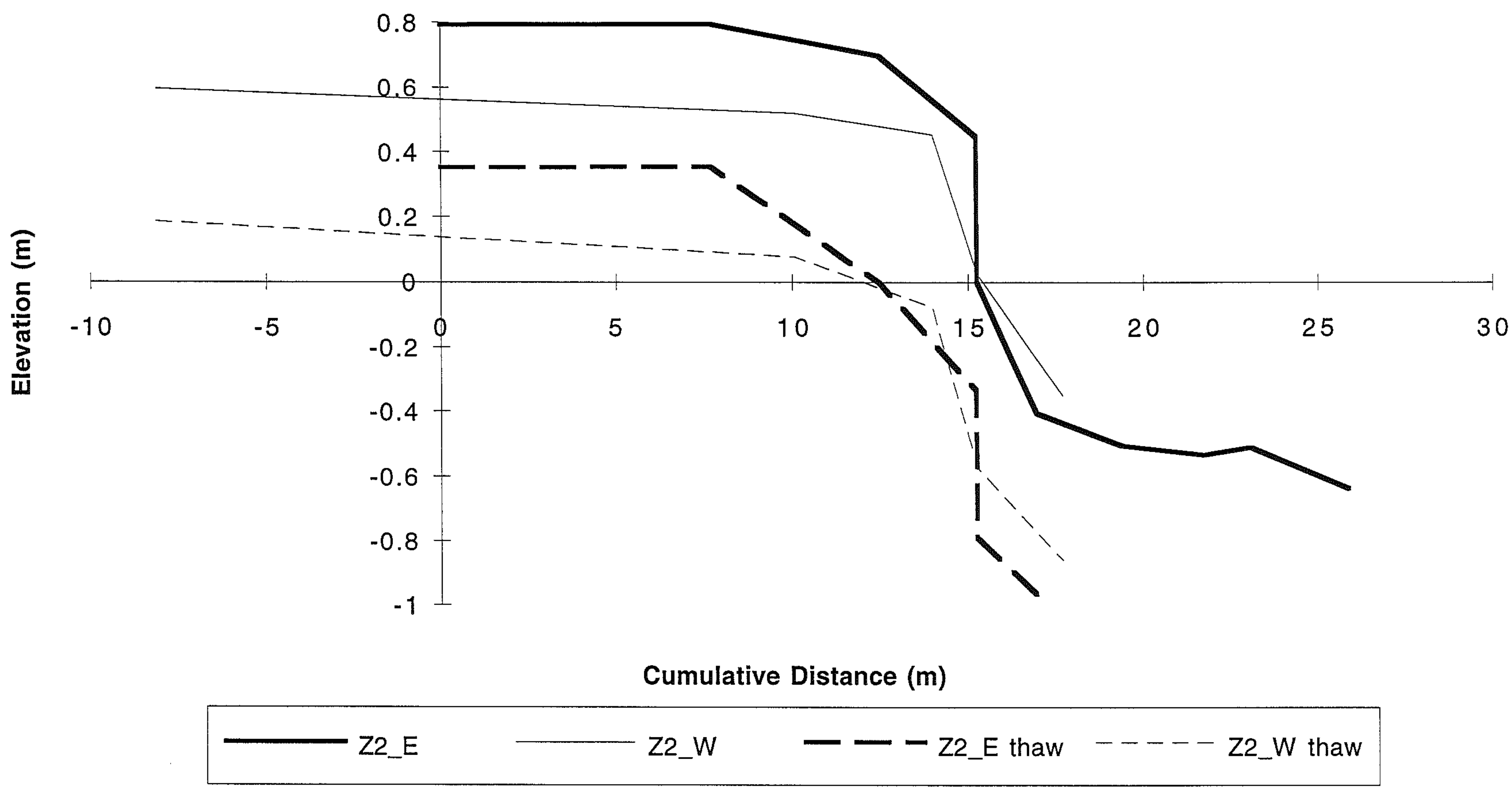


Figure 11 Niakolik zone 2 (south) profiles (including a thaw profile). The east line (Z2_E) is slightly higher than the west line. Active layer thickness on both lines is similar on both lines.



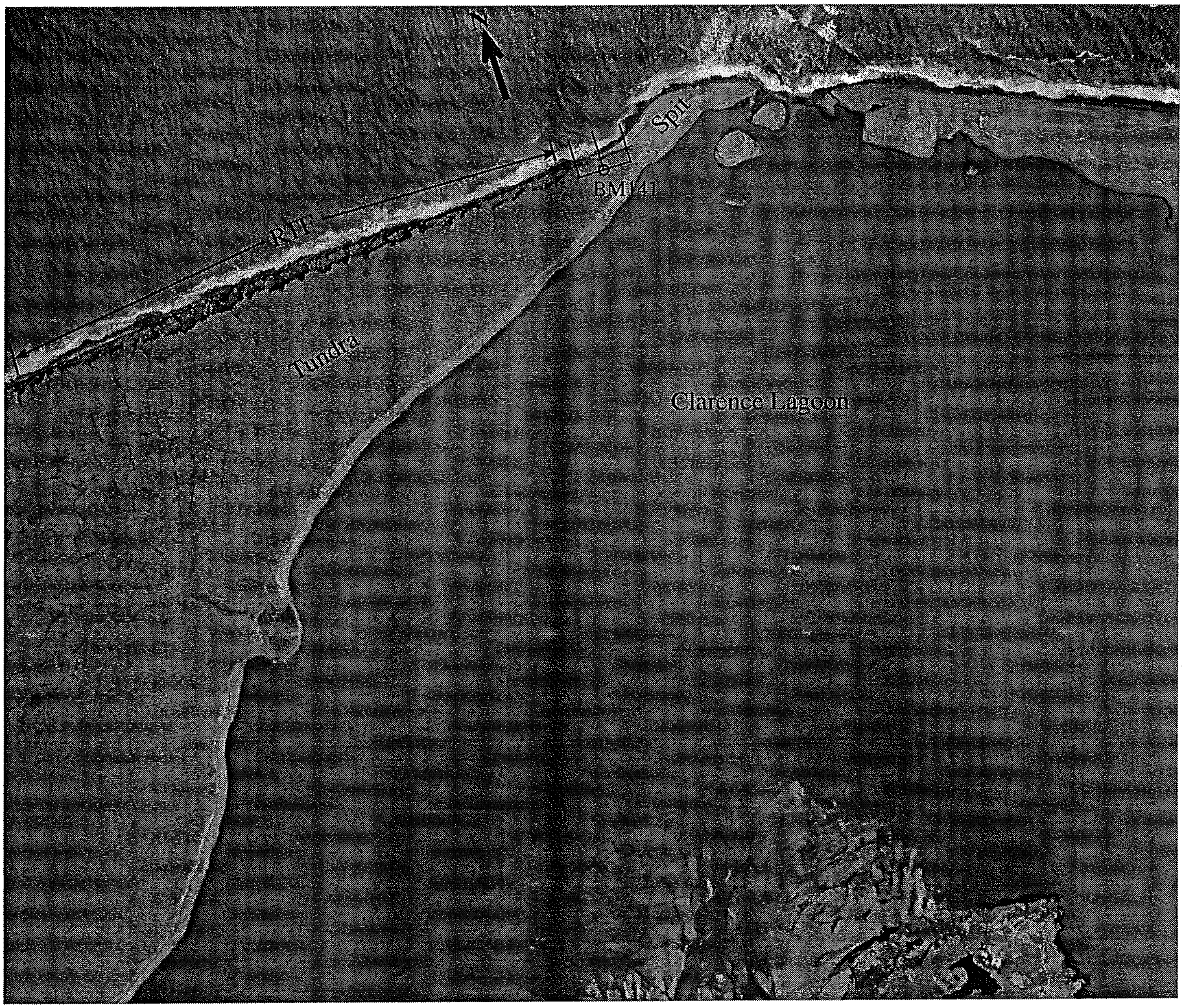
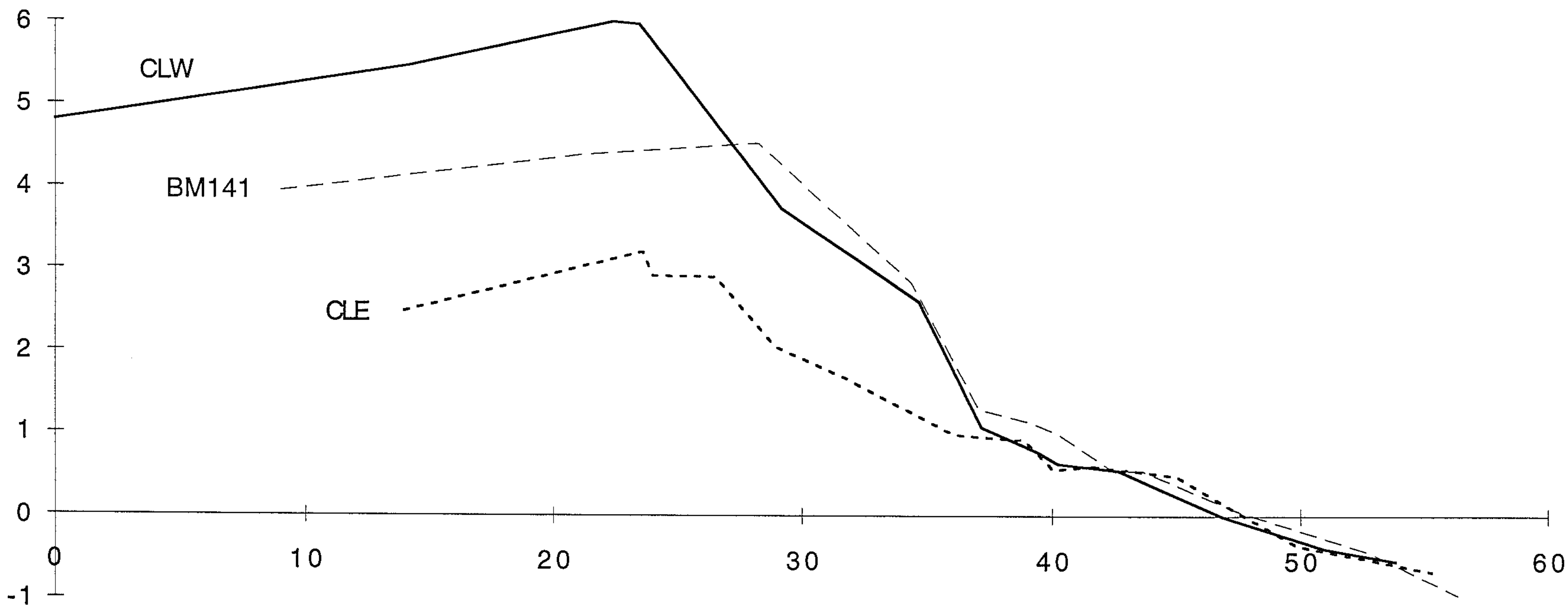


Figure 12 Clarence Lagoon 1992 air photo depicting the 1995 survey locations. The breach in the spit is navigable only during calm weather; a significant current runs out of the lagoon. Most of the cliff-line is ice-rich and is affected to some degree by thermokarst and retrogressive thaw failures (RTF). Ice wedges become more pronounced towards the west.

Figure 13 Clarence Lagoon profiles. The cliffs rise rapidly and steepen towards the west, but the beach slope is consistent on each profile.



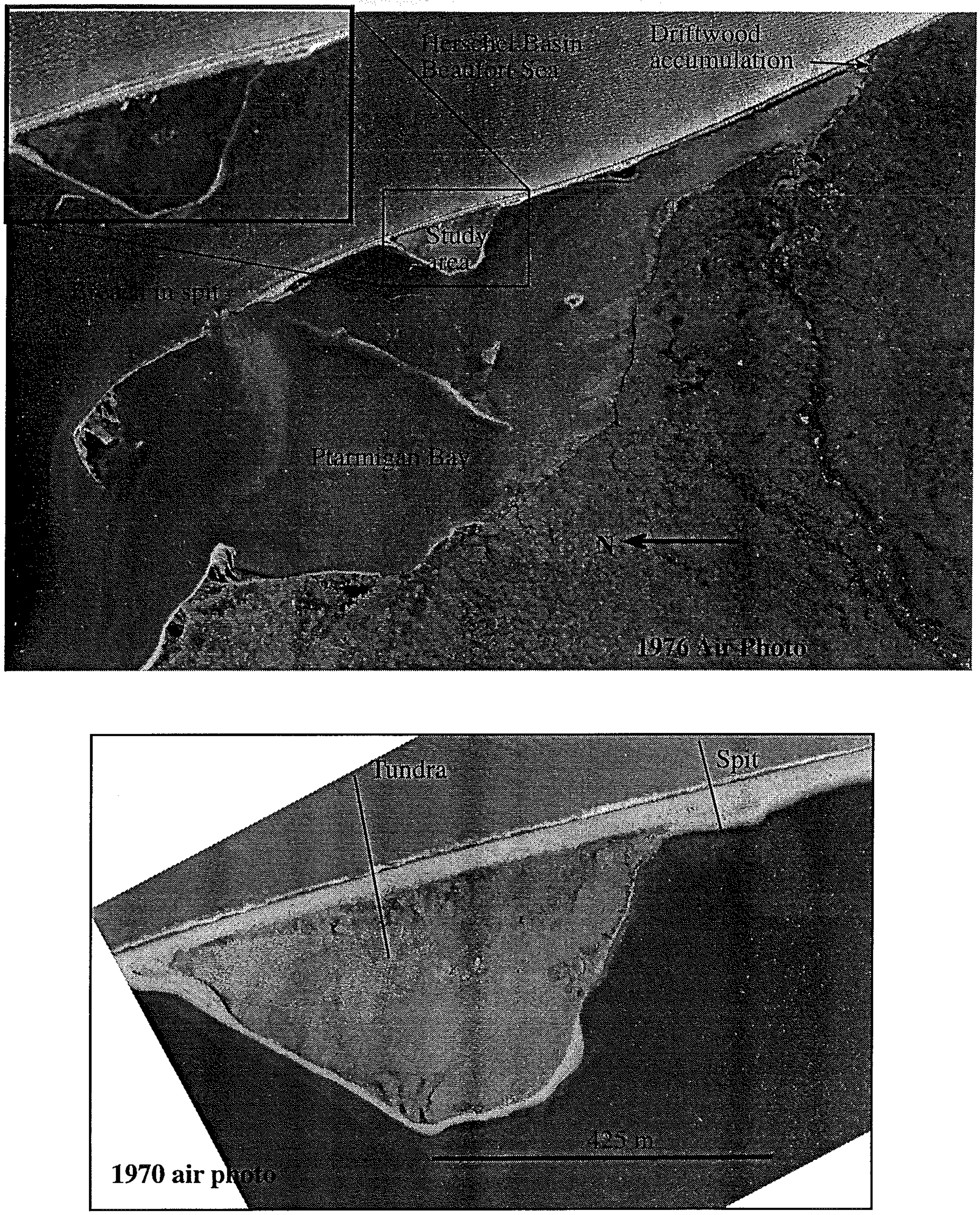


Figure 14 Catton Point survey site. The upper image is based on a 1976 air photo; the study area is the large tundra remnant anchoring the spit. The lower image is based on a larger scale 1970 air photo. The lagoon behind the spit is a major sink for organic matter eroded from peat cliffs and for driftwood. Sediment transport is to the north on the outside of the spit and to the south on the inside. The break in the spit to the north of the tundra remnant has healed since the photo was taken.

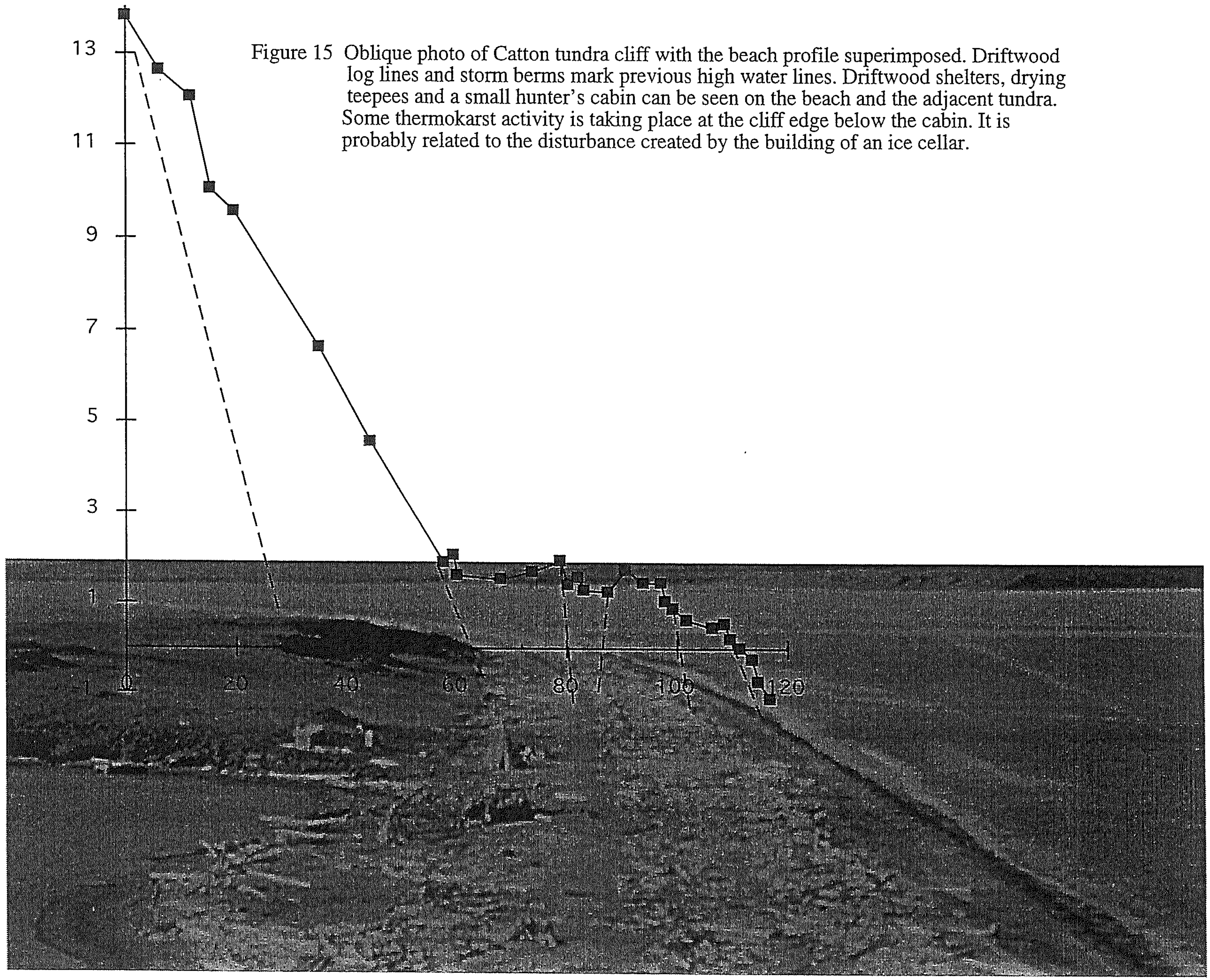


Figure 15 Oblique photo of Catton tundra cliff with the beach profile superimposed. Driftwood log lines and storm berms mark previous high water lines. Driftwood shelters, drying teepees and a small hunter's cabin can be seen on the beach and the adjacent tundra. Some thermokarst activity is taking place at the cliff edge below the cabin. It is probably related to the disturbance created by the building of an ice cellar.

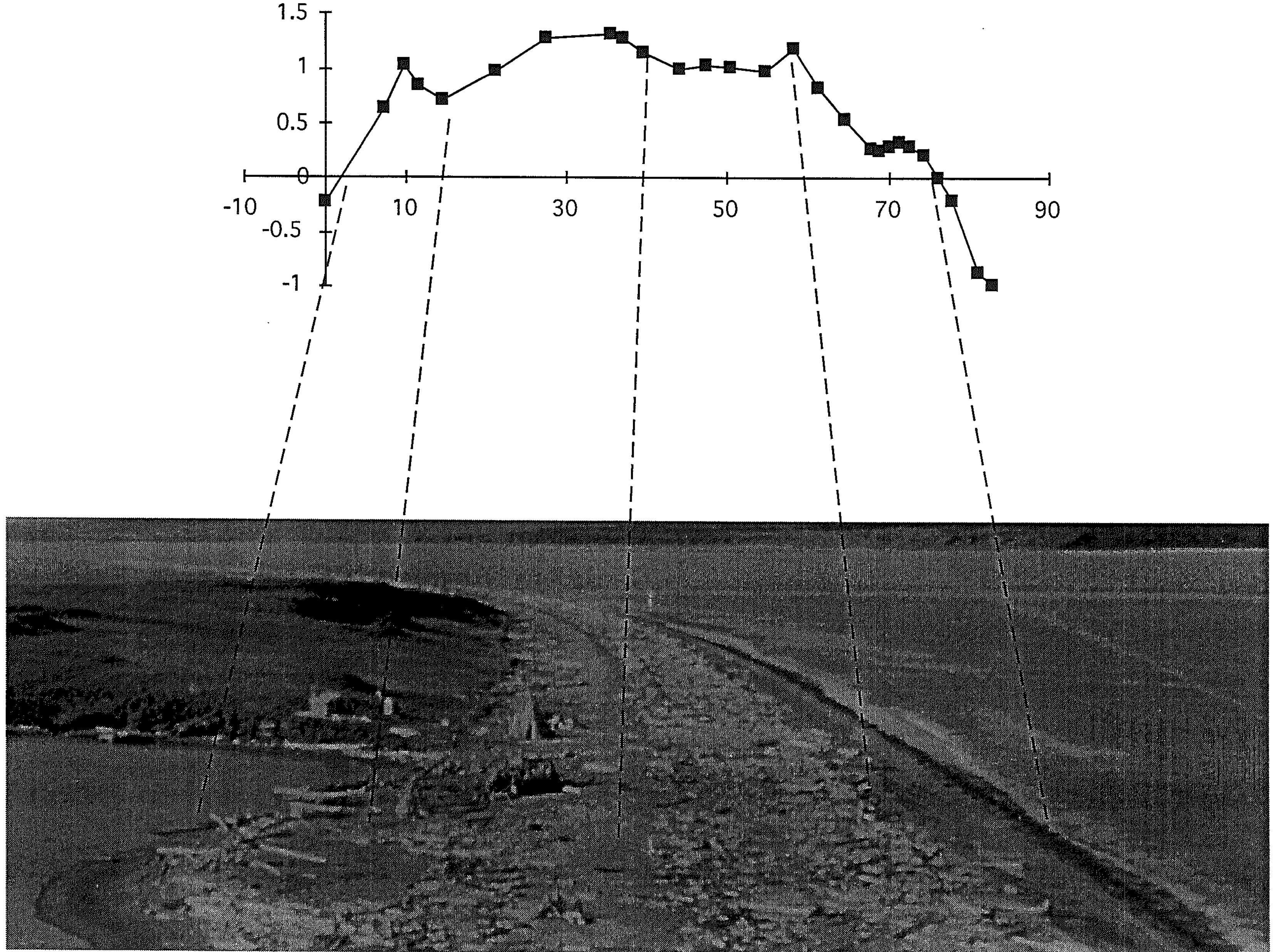


Figure 16 Oblique photo of Catton spit with the beach profile superimposed. The survey begins in the lagoon at the edge of a washover lobe. Driftwood log lines and storm berms mark previous high water lines. Driftwood shelters, drying teepees and a small hunter's cabin can be seen on the spit and the adjacent tundra. Some thermokarst activity is taking place at the cliff edge below the cabin. It is probably related to the disturbance created by the building of an ice cellar.

Figure 17 Beach profiles on the Catton tundra line measured on Aug. 3 and Aug. 10, 1995. A small amount of erosion has taken place at the water line, caused by a series of moderate wind storms.

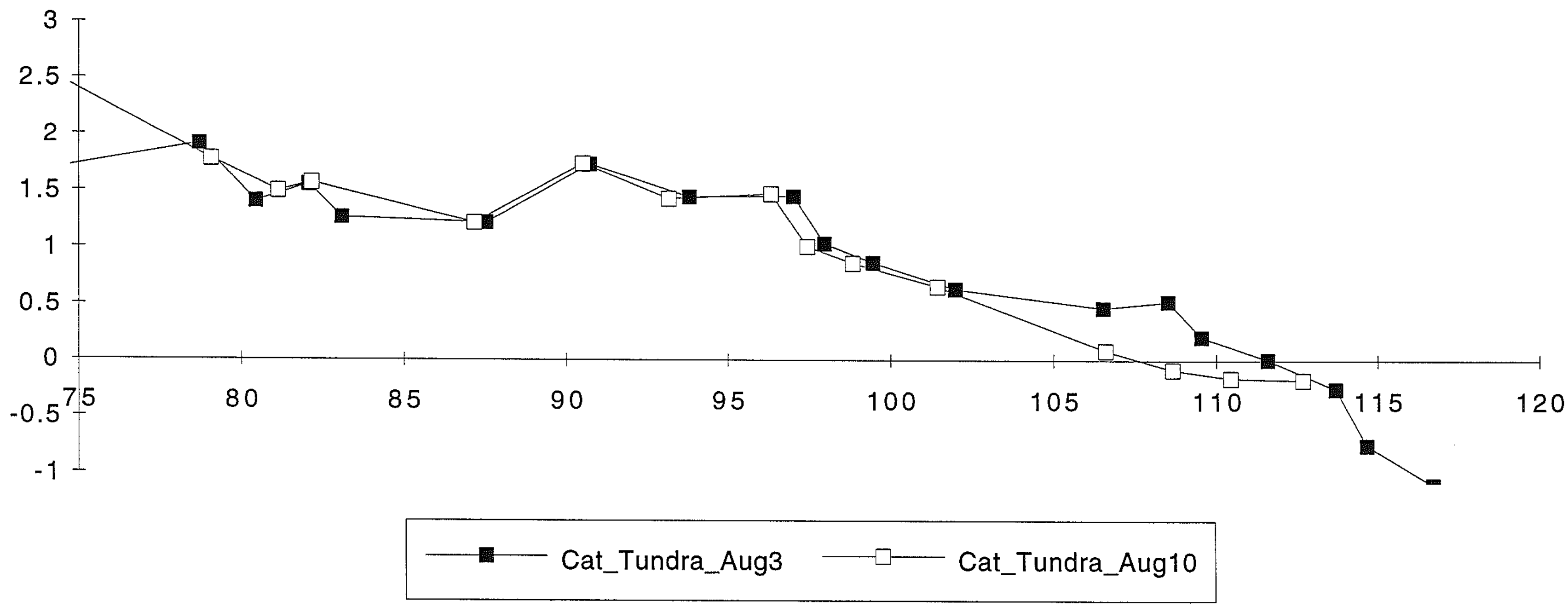


Figure 18 Beach profiles on the Catton spit line measured on Aug. 3 and Aug. 10, 1995. A small amount of erosion has taken place at the water line, caused by a series of moderate wind storms.

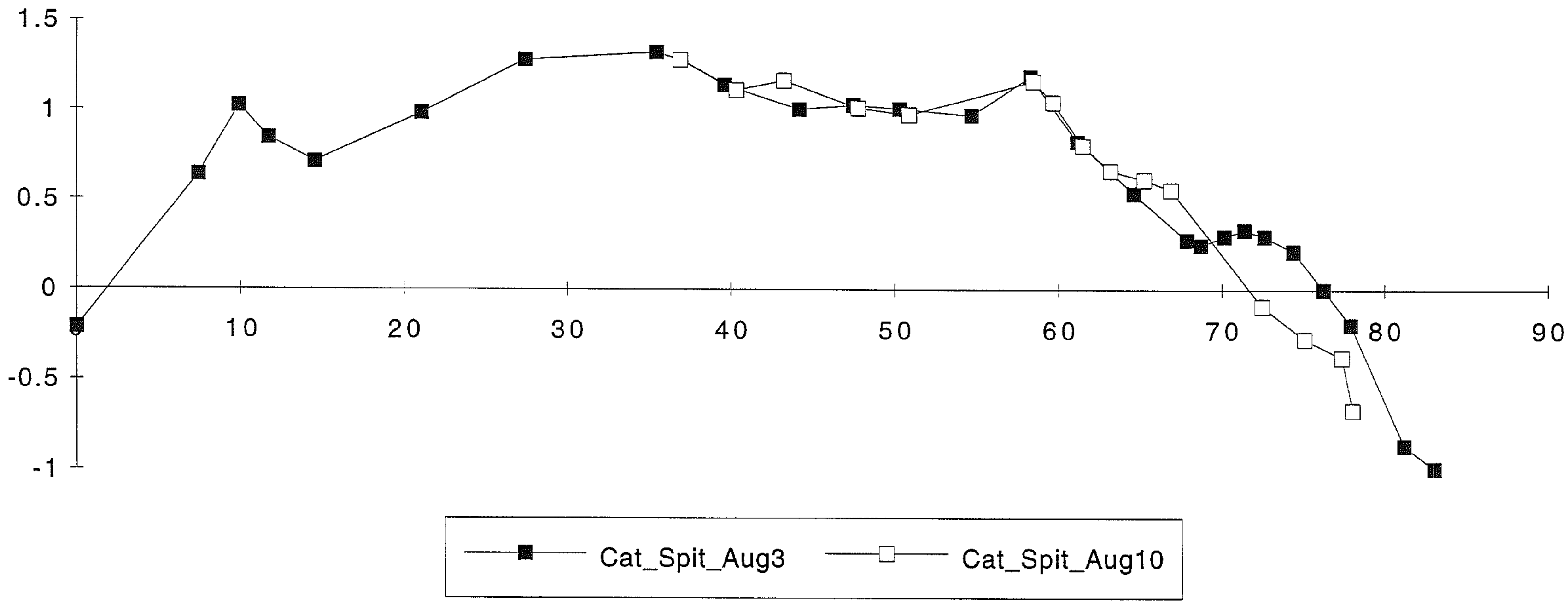


Figure 19 Beach and nearshore profiles measured on Catton Spit tundra remnant. The tundra line is slightly lower gradient than the spit line, which is consistent with the presence of a large sediment sink immediately to the north and west of the spit.

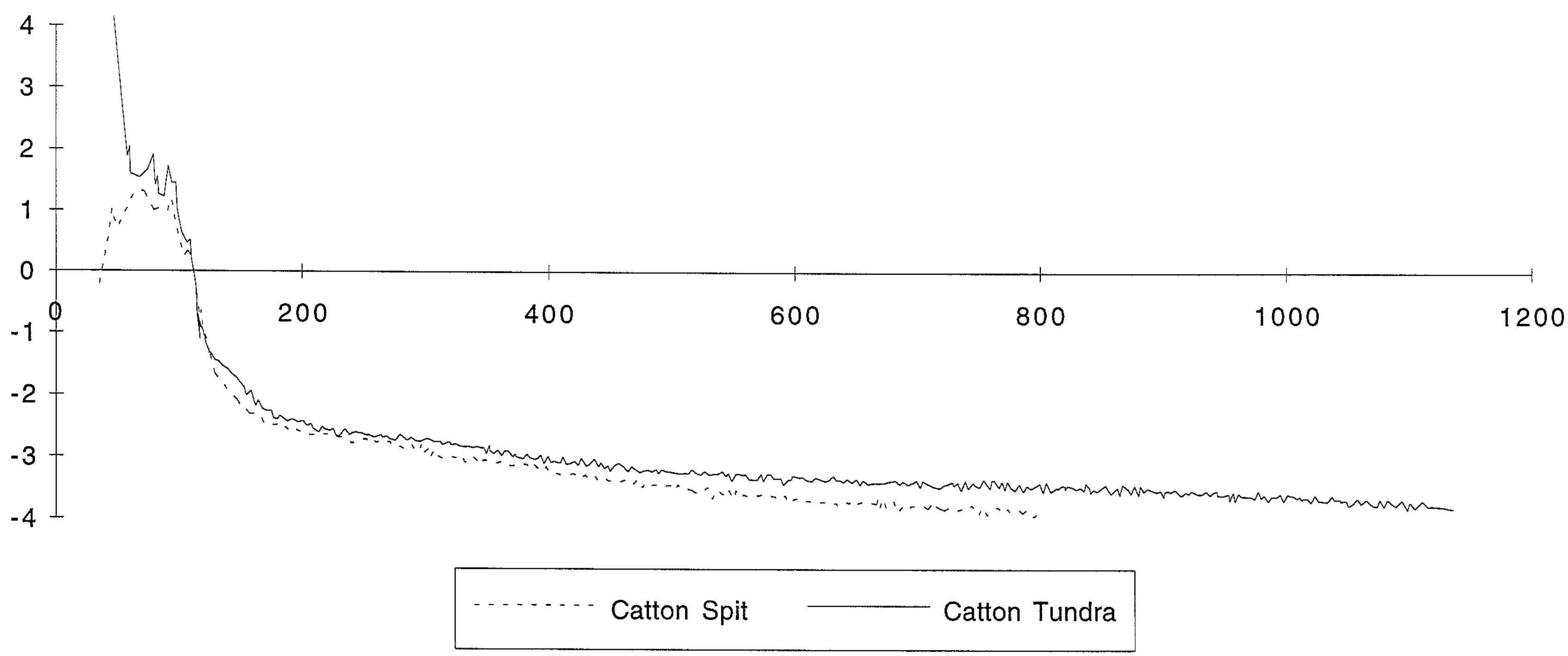
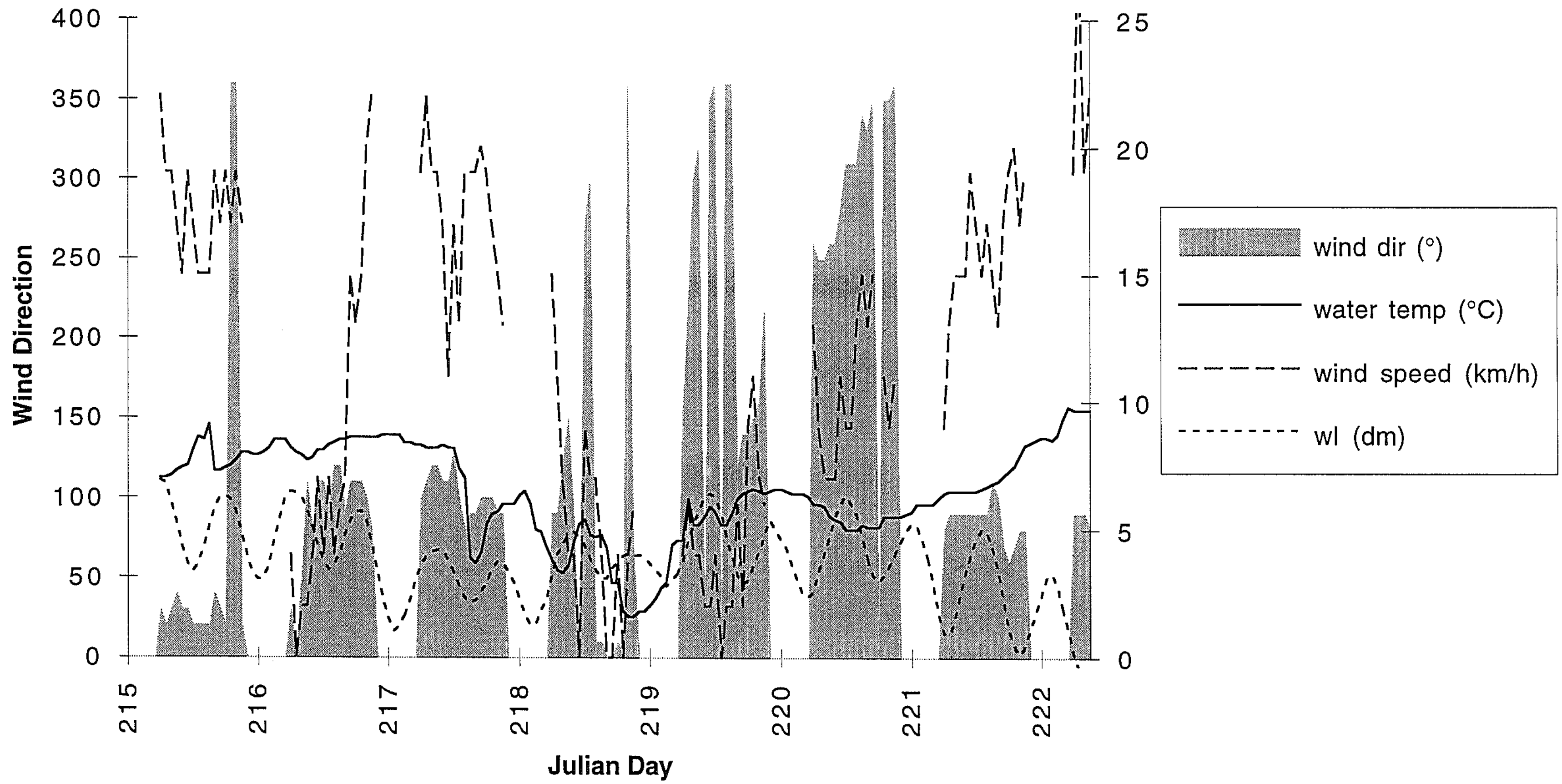


Figure 20 Water temperatures at Catton Point between Aug. 3 to Aug. 10, 1995. Relatively strong easterly winds at Tuktoyaktuk (northeast backing to west at Catton Point) appear to be responsible for the drop in temperature on August 6-7 (JD218-219).



Appendix A : Report on historical coastal erosion at five sites in Ivvavik National Park

Prepared by: Bob Covill
TekMap Consulting
P.O. Box 11166
Windsor Junction, NS
(902) 860-1062

Nunaluk

Photos scanned:	1952	600 DPI
	1970	400 DPI
	1976	600 DPI

- all images were rectified to the 1970 image.
- due to the low resolution of the 1952 and 1976 photos, plus the lack of stable ground control points along Nunaluk spit, it was difficult to accurately choose ortho-rectification points for these images.
- a scale correction factor of 0.76 was obtained from comparative measurements made on the 1970 image.
- the cliff line of the tundra island was digitized using the edge of vegetation as the boundary, with the exception of the NE cliff face where the active cliff edge (ie. break in slope) was used. - The coast line was digitized using the bright white high water line as a guide. Portions of the spit at either end of the tundra island were included.
- Due to poor resolution of the 1952 and 1976 photos it is difficult to accurately distinguish the high water line (particularly on the ocean side). Therefore apparent coast line changes may be in part attributable to changes in water level. This is particularly evident in the 1976 image where the apparent coastal retreat is 3+ metres per year !!
- the SW end of the tundra island and the coast line directly behind it have remained relatively stable as has a portion of the spit to the SE.
- the total area of the spit was measured for each year.

Nunaluk Measurements

Location	Interval (year) 52 to 70	52 to 70 retreat (m/a	70 to 76	70 to 76 retreat (m/a
Cliff Line				
NE end (1)	24.09	1.02	10.88	1.38
NE end (2)	22.25	0.94	15.02	1.90
SE end (1)	58.67	2.48	19.53	2.47
Coast line				
(1)	36.77	1.55	26.91	3.41
(2)	26.91	1.14	25.46	3.22

Year	1952	1970	1976
Meas. area	30822.10	18227.78	15675.55
Area (sq. m.)	17802.84	10528.37	9054.20
Area Change (sq. m.)		7274.48	1474.17

Clarence Lagoon

Photos scanned:	1976	600 DPI
	1992	400 DPI (2)

- all images were rectified to a mosaic of the 1992 images.
- a scale correction factor of 0.39 was obtained from comparative measurements made on the 1992 image (mosaic).
- the coast line was digitized using the bright white high water line. A portion of the spit to the NE was also digitized.
- In the 1992 image(s) the high water line has noticeably decreased along the N side from its 1976 position. In some areas in the 1992 image the high water line is almost at the base of the cliff. Without other photography (from other intermediate years) it is difficult to determine if the apparent "beach retreat" is a factor of changing water levels.
- in the 1976 image a portion of the high water line along the N side is obscured by ice. That same portion is obscured in the 1992 image by debris eroded from cliff face (see photo).
- The portion of the spit directly to the NE shows a counter clockwise rotation between 1976 and 1992, moving some 16 metres to the N.
- the cliff base was digitized using the edge of vegetation as a marker on the low lying S side, and the foot of the cliff as a marker along the N side of the study area.
- the cliff top was digitized along the N side, using the active break in slope as the marker.
- the highest retreat rate of the cliff line was observed at the NE end of the study area.
- it should be noted that for the NW end of the study area, the high water line and the cliff base show marked retreat, while the cliff top remained relatively stable.
- the S side of the study area showed minimal retreats ranging between 0.18 and 0.38 m/a for the high water line and cliff base.
- the boundary between areas with high polygon concentration were digitized on the 1992 image(s).

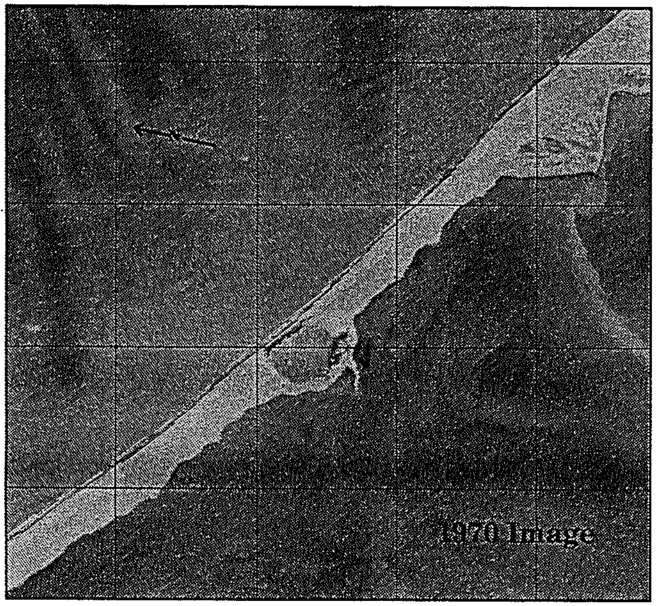
Clarence Lagoon Measurements

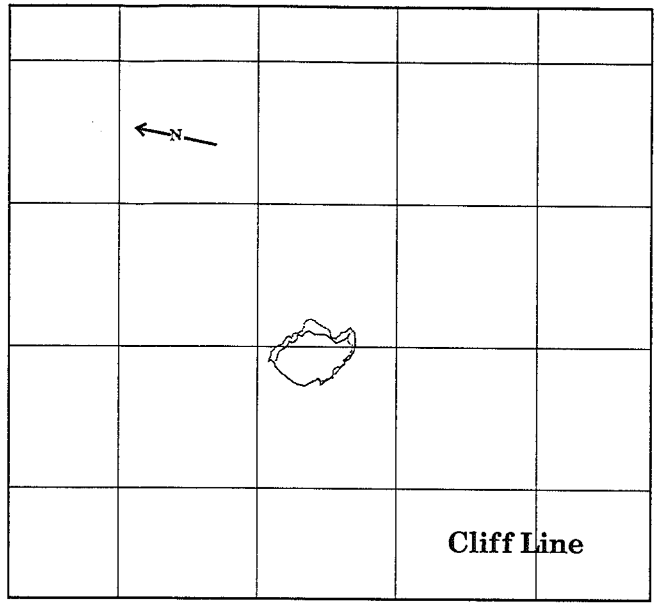
Location	Interval	
	76 to 92	76 to 92 retreat (m/a)
Cliff Top		
N - central (1) *	21.86	0.53
NE (2)	23.58	0.57
Cliff Base		
NW (1)	13.78	0.34
N - central (2)	21.09	0.51
NE (3)	29.94	0.73
SE (4)	13.78	0.34
S - central (5)	16.18	0.39
Water Line		
NW (1)	45.11	1.10
NW (2)	36.69	0.89
NE (3)	66.37	1.62
NE - spit (4) #	-40.92	-1.00
SE (5)	10.81	0.26
SE (6)	7.41	0.18

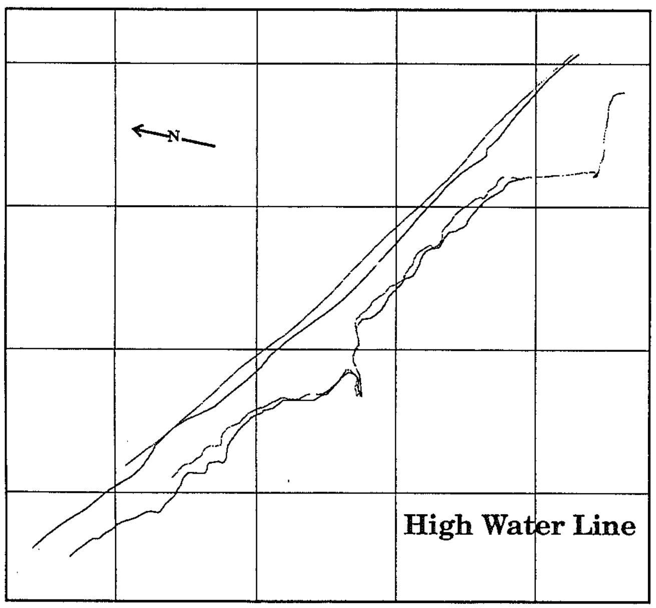
** "central" indicates the approximate position along the vector line (eg. halfway between a NW and NE position)*

 # the negative retreat on the spit indicates deposition.

NUNALUK







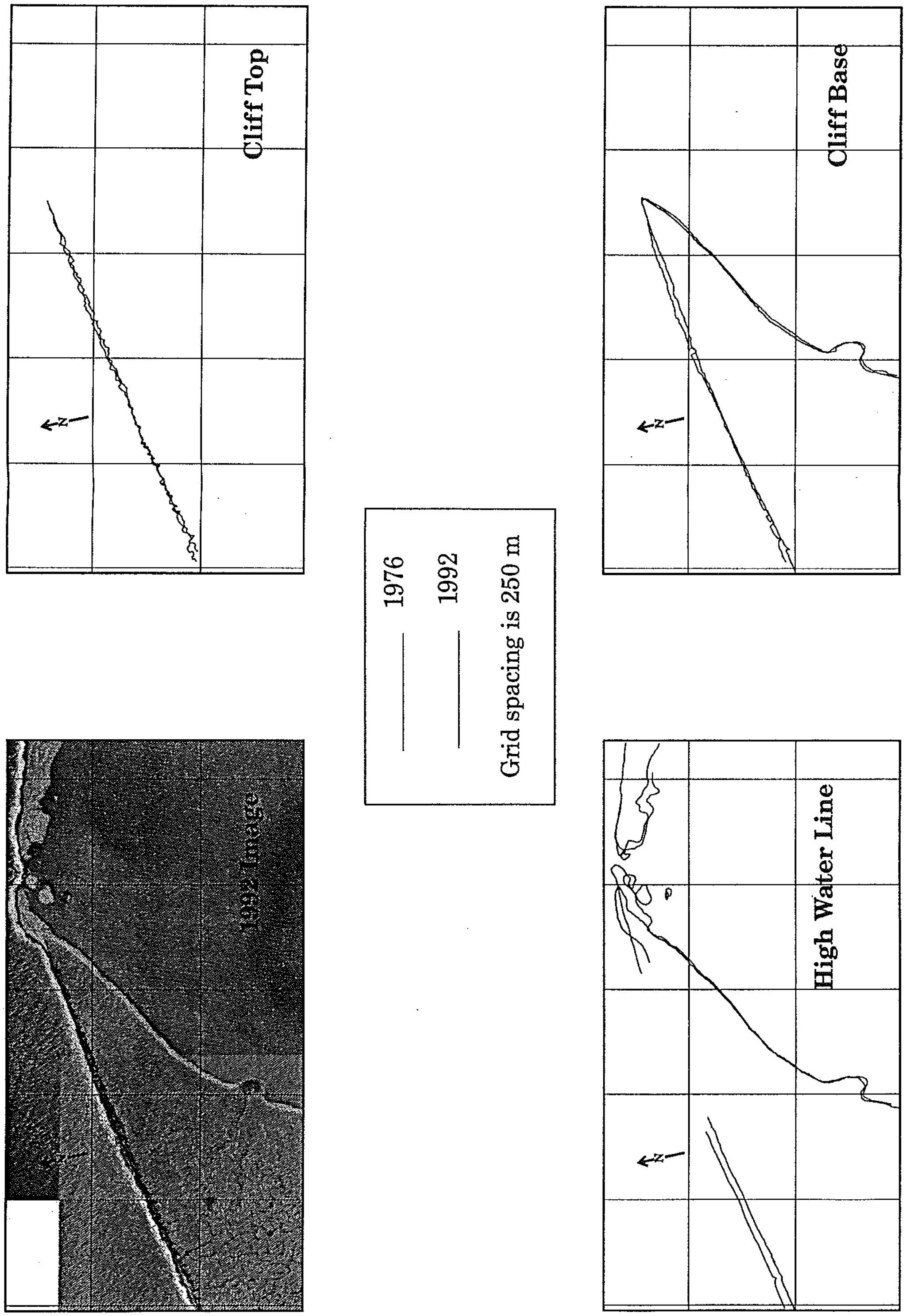
1952

1970

1976

Grid spacing is 250 m

CLARENCE LAGOON



Niakolik

Photos scanned:	1944	600 DPI
	1952	600 DPI
	1970	400 DPI
	1974	600 DPI
	1985	600 DPI
	1992	400 DPI

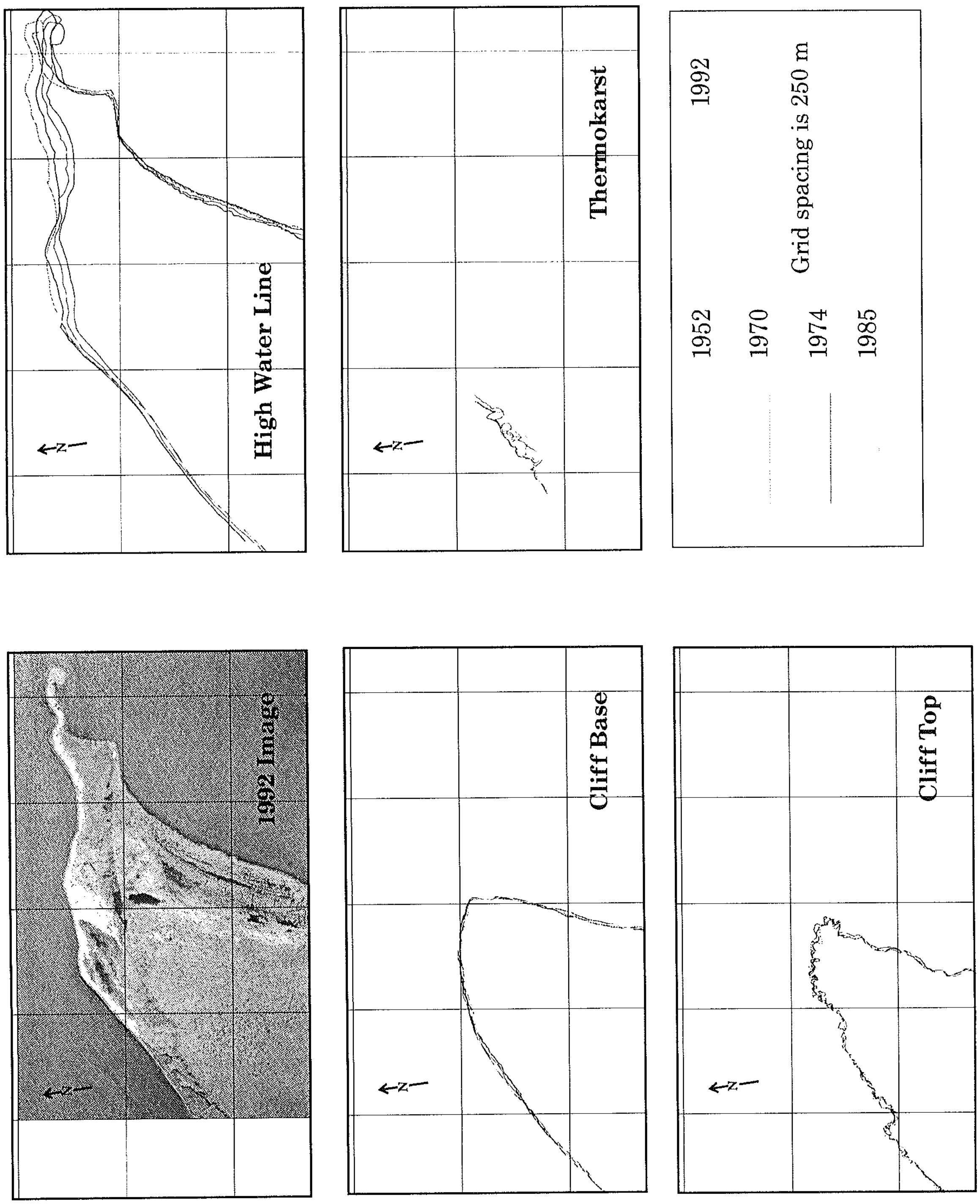
- all images were rectified to the 1992 image.
- a scale conversion factor of 0.375 was obtained from comparative measurements made on the 1970 and 1992 images.
- The cliff edge was digitized and is distinguished by the break in slope. The N edge of the cliff is easily distinguished because of a sharp change in slope. The cliff edge to NE and S is more difficult to distinguish due to a much lower cliff slope (there is no active erosion visible on these slopes).
- in areas with low cliff slope, the edge was picked using concentration of polygons. A source of error in picking this edge is estimated at plus/minus 5 m.
- the cliff base was digitized and is easily distinguished as the edge of vegetation at the toe of the slope.
- the coastline was digitized using high water line (ie. bright white line).
- the highest coastal retreat is observed at the N tip of Niakolik, in the large area below cliff level. This area shows high retreat rates (up to 2.8 m/a) after 1970.
- due to poor resolution, of the 1952, 1974, and 1985 photography it is difficult to accurately distinguish the high water line. Therefore, observed coastal changes that include these years, may be attributable to changes in water level.
- the thermokarst seen on the active NW cliff face was digitized for all years.
- the extent of low lying drained lakes on the SE side was digitized for each year. The limit of the drained lakes is again difficult to accurately pick, particularly on the low resolution photography. Therefore no useful measurements can be made. Qualitatively the extent of the drained lakes has remained stable.

Niakolik Measurements

	Interval (year)					
Location	**52 to 70**	**52 to 70 retreat (m/a)**	**70 to 85**	**70 to 85 retreat (m/a)**	**85 to 92**	**85 to 92 retreat (m/a)**
Coast vector						
SE side (1)	60.49	1.26	10.79	0.27	16.76	0.90
SE side (2)	45.31	0.94	7.63	0.19	6.43	0.34
Coast vector						
N side (1)	51.29	1.07	87.32	2.18	44.30	2.37
N side (2)	83.31	1.74	113.37	2.83	38.69	2.07
Cliff base						
active side(NW)	23.23	0.48	-8.13	-0.20	n/a	0.00
active side(NW)	27.45	0.57	-15.78	-0.39	4.11	0.22
Cliff edge						
active side(NW)	n/a	0.00	13.01	0.33	n/a	0.00
active side(NW)	n/a	0.00	18.08	0.45	n/a	0.00

* n/a indicates that retreat is negligible

NIAKOLIK



High Water Line
Thermokarst
1952
1970
1974
1985
1992
Grid spacing is 250 m
1992 Image
Cliff Base
Cliff Top
N

Catton Point

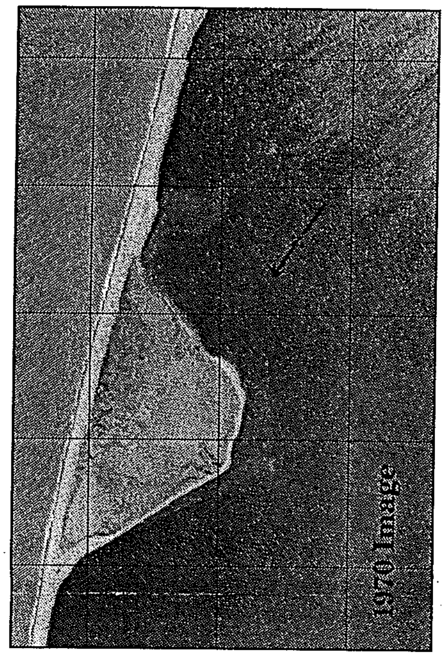
Photos scanned:	1953	600 DPI
	1970	400 DPI (2)
	1976	600 DPI

- all images were rectified to the 1970 image(s)
- two images from 1970 were patched together in a mosaic
- a scale correction factor of 0.76 was obtained from comparative measurements made on the 1970 image.
- the coastline was digitized using the bright white high water line as a guide. Portions of the spit at either end of the tundra island were included.
- the cliff base was digitized using the distinct vegetation boundary visible at the toe of the cliff.
- In general the tundra island has remained relatively stable with exception of the S edge (ie. inside the spit) of the island where rates up to 90 cm/a were measured.
- The spit in the areas directly adjacent to the island have also remained relatively stable.

Catton Point Measurements

	Interval (year)			
Location	53 to 70	53 to 70 retreat (m/a)	70 to 76	70 to 76 retreat (m/a)
Coast vector				
S edge (1)	18.81	0.84	6.80	0.86
S edge (2)	6.11	0.27	2.53	0.32
SE edge (3)	5.36	0.24	2.53	0.32
Cliff vector				
S edge (1)	20.36	0.91	7.19	0.91
S edge (2)	5.31	0.24	5.33	0.68

CATTON POINT

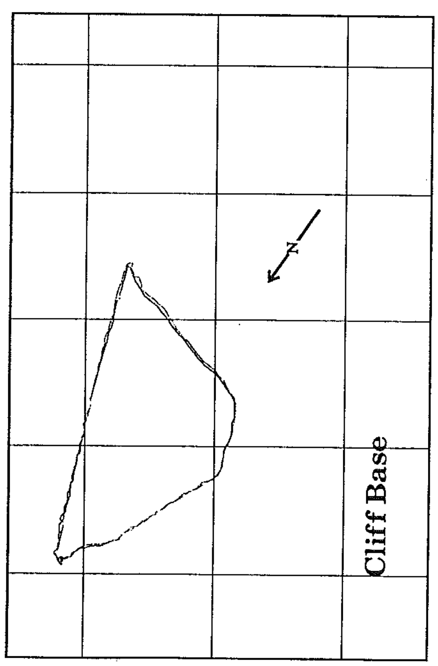


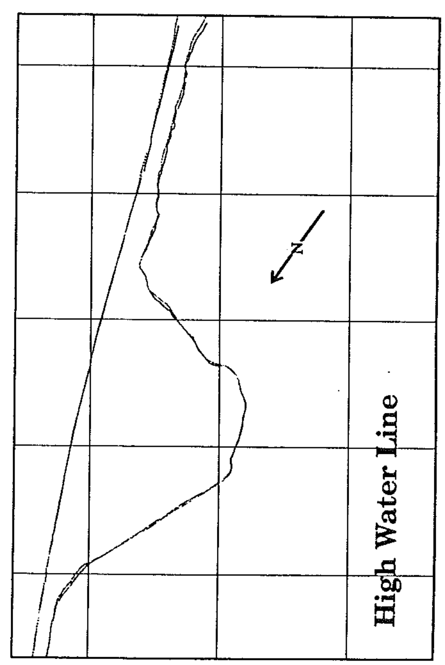
1953

1970

1976

Grid spacing is 250 m





Stokes Point

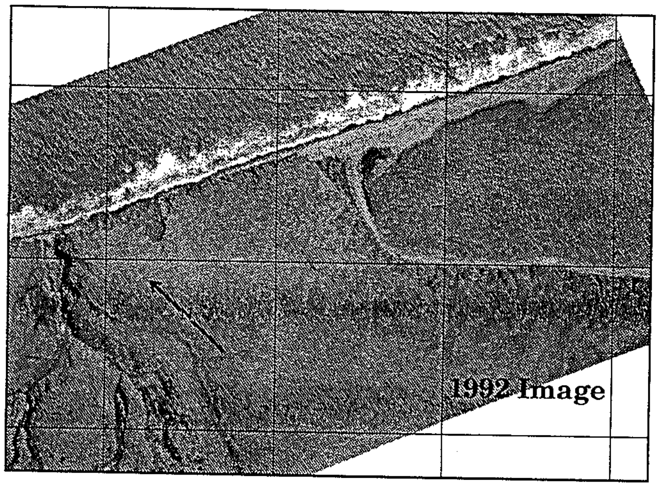
Photos scanned:	1954	600 DPI
	1970	400 DPI
	1985	600 DPI
	1992	400 DPI

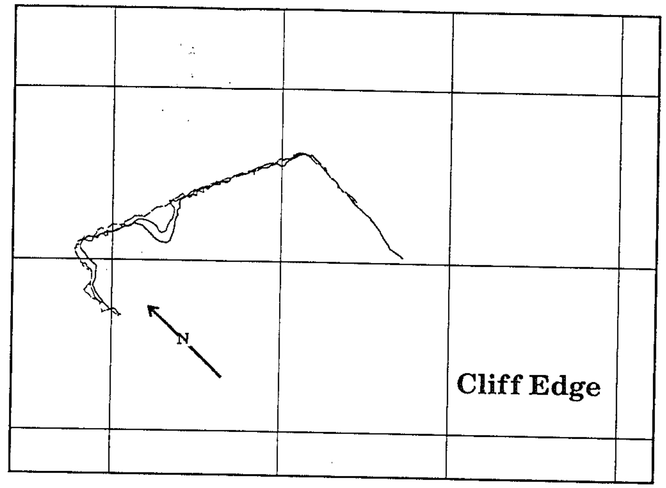
- all images were rectified to the 1970 image.
- a scale correction factor of 0.78 was obtained from comparative measurements made on the 1992 and 1970 images.
- cliff edge was digitized and is distinguished by the break in slope.
- the coastline was digitized using the high water line (ie. bright white), including a portion of the spit.
- due to poor resolution of the 1954 image, it is difficult to accurately distinguish the high water line. Therefore, the apparent coastal change observed between 1954 and 1970 may simply be due to water level change ??
- the high water line at the NW end of the study area is defined by the base of the cliff.
- in the 1970 image, the base of the cliff is obscured by shadows.
- the thermal karst was digitized for 1992, 1985, and 1970. No thermal karst is evident in the 1954 image.
- the upland area was digitized from the 1992 image and is defined by the concentration of polygons.
- retreat of the coastal vector in 1992 does <u>not</u> appear to be a rectification problem, as other features do not appear rotated. A post 1992 image would be useful to clarify this.

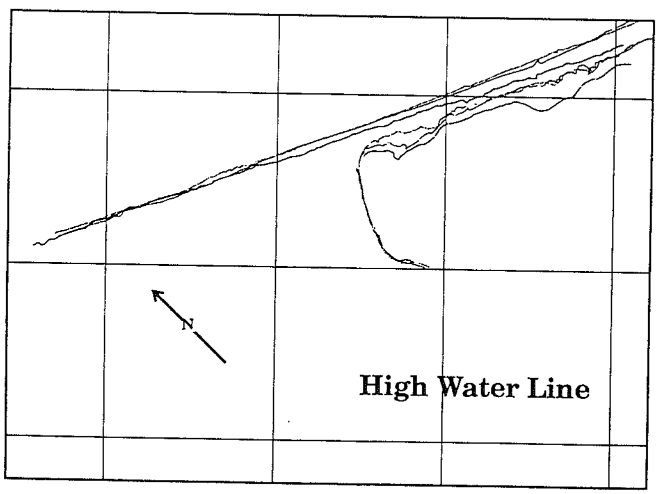
Stokes Point Measurements

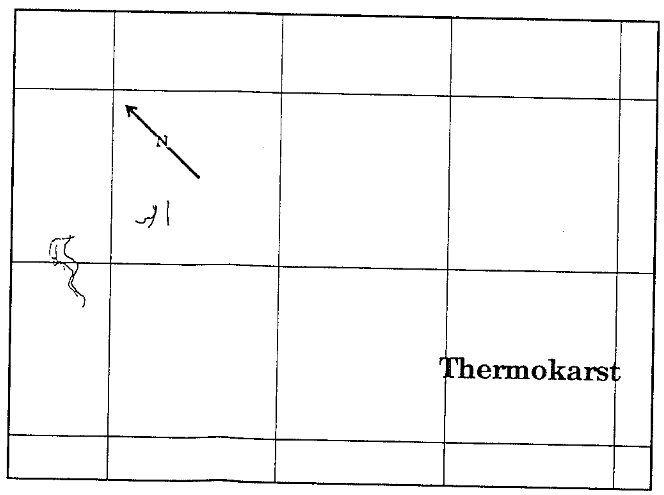
Location	Interval (year)					
	54 to 70	54 to 70 retreat (m/a	70 to 85	70 to 85 retreat (m/a	85 to 92	85 to 92 retreat (m/a
Cliff edge						
1 (slump)	0.00	0.00	46.23	2.40	19.99	2.23
2 (near corner)	0.00	0.00	4.03	0.21	4.03	0.45
Coast vector						
1 (near corner)	9.23	0.45	0.00	0.00	14.05	1.57
2 (on spit)	5.72	0.28	6.40	0.33	17.78	1.98
3 (below cliff)	6.09	0.30	7.88	0.41	0.00	0.00

STOKES POINT









1954
1970
1985
1992
Grid spacing is 250 m

Appendix B Benchmark Positions (NAD27 UTM Zone 7)

Location	GSC BM#	Easting (m)	Northing(m)	Latitude	Longitude
Clarence Lagoon	BM141	506366	7724593	140.83611	69.63139
Catton Point	BM147	575219	7709101	139.07639	69.48194
Catton Point (base)	BM148	575009	7709473	139.08194	69.48528
Nunaluk	BM143	555899	7717364	139.56556	69.56083
Nunaluk	GSC A56	555905	7717384	139.56528	69.56083
Stokes Point	BM145	586480	7696166	138.80056	69.3625
Niakolik	BM140	599085	7684011	138.49278	69.24944