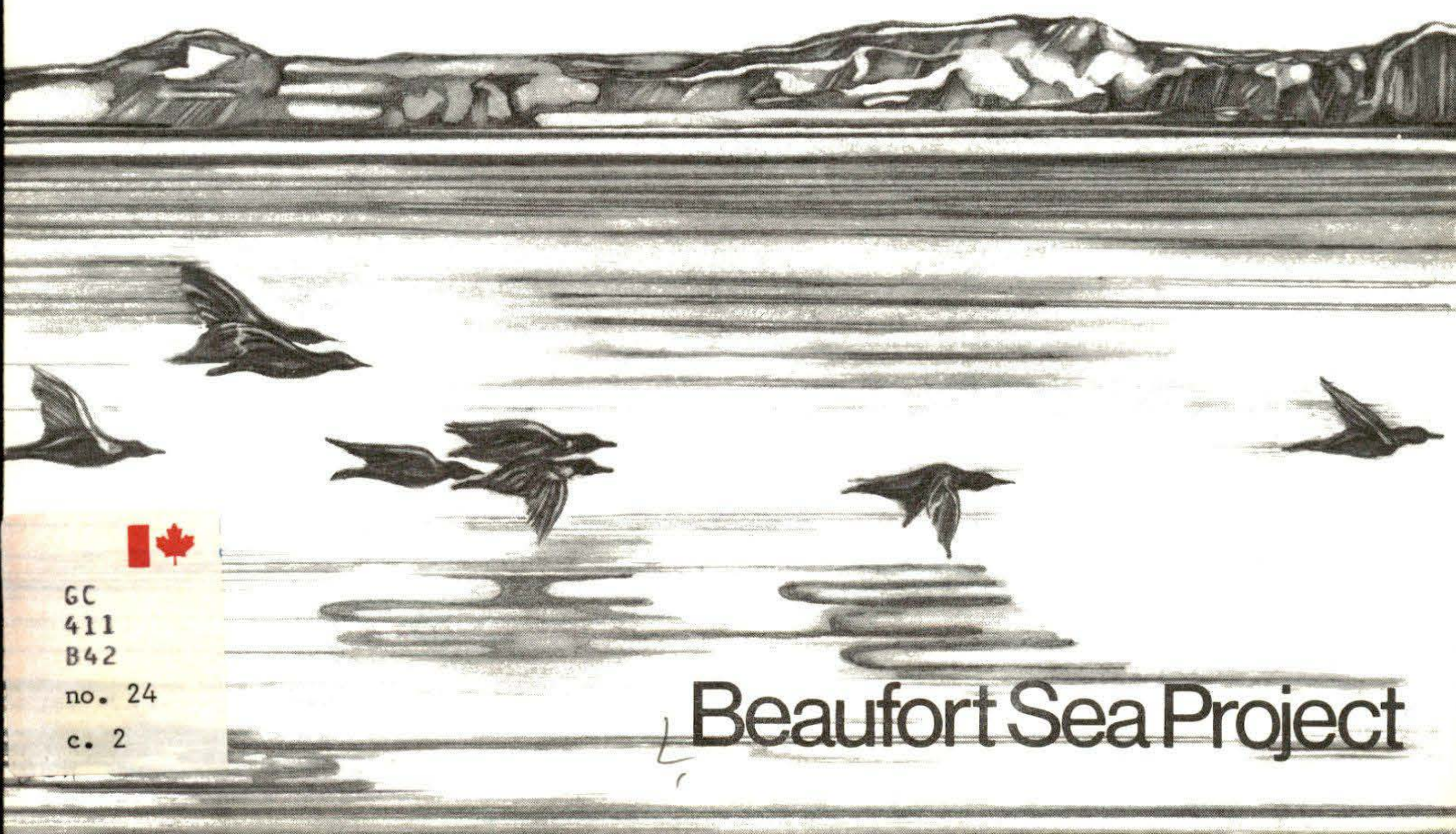
Coastal Sedimentary Processes and Sediments, Southern Beaufort Sea

C.P. LEWIS and D.L. FORBES

Technical Report No. 24



Beaufort Sea Project

COASTAL SEDIMENTARY PROCESSES AND SEDIMENTS, SOUTHERN CANADIAN BEAUFORT SEA

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Beaufort Sea Technical Report #24

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1. SUMMARY

1.1 Objectives of the Study

This technical report is based primarily on fieldwork conducted during the summer of 1974 into the geometry, composition, origin and stability of coastal landforms bordering the Beaufort Sea from the Alaska-Yukon boundary east to the Mackenzie Delta. The 1974 study followed general reconnaissance investigations of the northwest coast of the Tuktoyaktuk Peninsula in 1973 and of the Yukon coast in 1972 (McDonald and Lewis, 1973). The results of these earlier studies have been incorporated here to extend coverage as far east as Cape Dalhousie at the eastern end of the Tuktoyaktuk Peninsula. As well, prepared testimony by the senior author, presented to the Mackenzie Valley Pipeline Inquiry on February 13, 1976, is included in this report as an appendix. The reader is referred to this appendix for a more general overview of physical aspects of the Beaufort Sea coast, discussion of the implications of offshore hydrocarbon resource development on the coastal zone, and for additional detailed information on the modern Mackenzie delta plain.

The purposes of the 1974 fieldwork were twofold:

1. The general reconnaissance studies in 1972 and 1973 raised many questions about the detailed nature, magnitude and frequency of processes and responses in this arctic coastal zone, questions which could best be answered by a longer term instrumented study at a representative sample location. Kay Point, Y.T. (Figure 1) was chosen as the sample site because it offers a wide range of coastal features in a small area. Concentrated fieldwork at this location will continue through the summer of 1977 with occasional visits thereafter. Scientific studies include (see Figure 1, inset, for locations):

    a. Erosion of and sediment transport from the coastal cliffs southeast of the point;
    b. Growth, migration and short period changes in Kay spit;
    c. Morphology, sedimentology and hydraulics of the Babbage River delta, an estuarine delta of the Mackenzie type; and
    d. Sediment transport and deposition in Phillips Bay, a nearshore sediment sink.

2. The second objective of 1974 fieldwork was to examine the geological aspects of coastal susceptibility to oil spills, a part of the joint industry - government Beaufort Sea study of the potential environmental hazards of proposed exploratory offshore drilling. In this context, the intentions of this study were to:

    a. Identify and determine the extent of those areas of the coastal zone most susceptible to inundation by sea water;
    b. Determine the present geometry, nature of sediments and vegetation of these areas;
    c. Examine patterns of sediment erosion, transportation and deposition; and
    d. Identify and discuss conditions peculiar to an arctic coastal environment relating to potential damage from an oil spill.

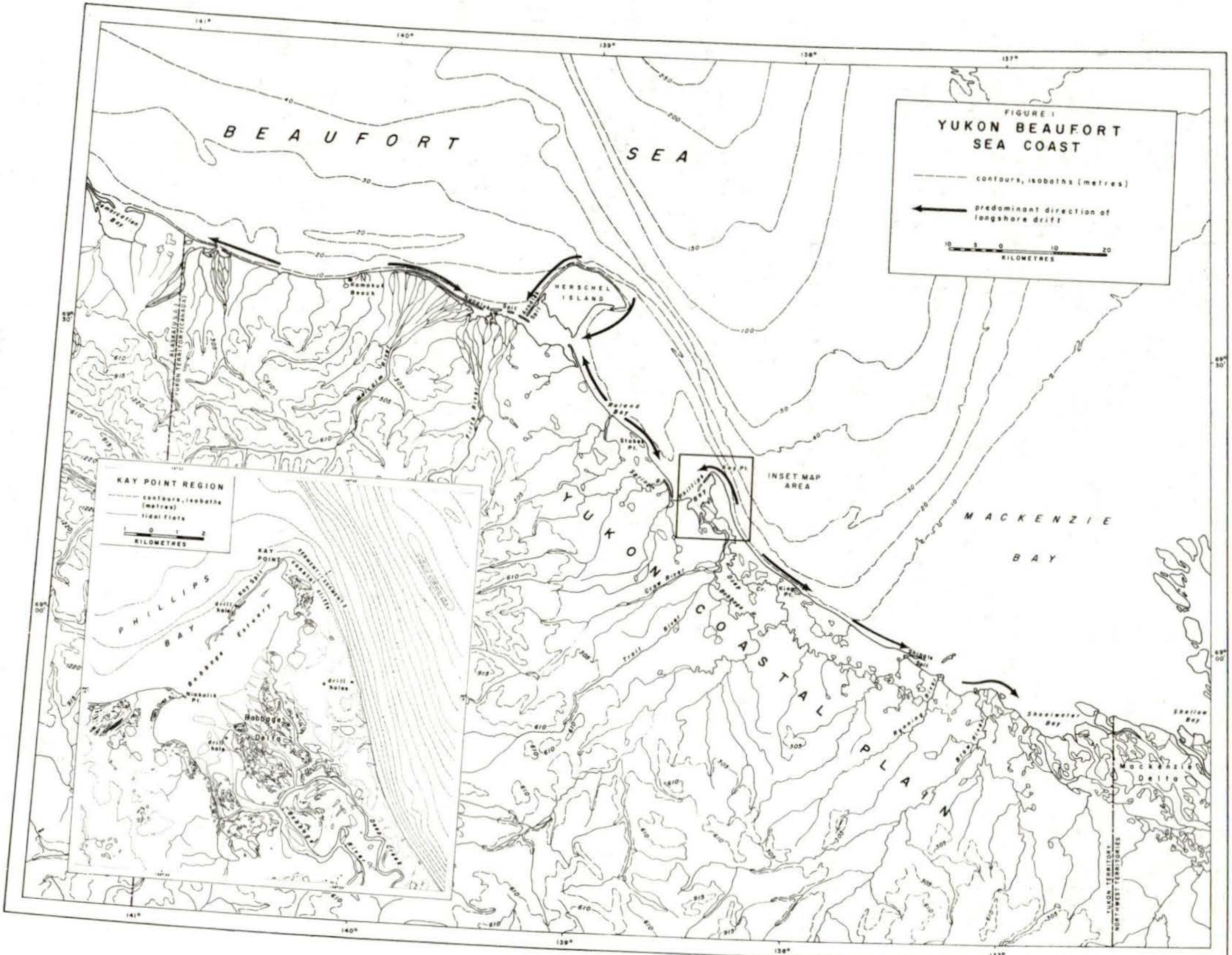


FIGURE I
YUKON BEAUFORT SEA COAST
contours, isobaths (metres)
predominant direction of longshore drift
KILOMETRES
BEAUFORT SEA
HERSCHEL ISLAND
INSET MAP AREA
MACKENZIE BAY
YUKON COASTAL PLAIN
Kay Pt.
Mackenzie Delta
YUKON TERRITORY
NORTHWEST TERRITORIES
KAY POINT REGION
contours, isobaths (metres)
tidal flats
KILOMETRES
KAY POINT
PHILLIPS BAY
Babbage Delta
drill holes

During the summer of 1974, fieldwork was carried out on the major spits at Shingle and Kay Points, on Nunaluk spit in the Firth River region, on the Blow and Babbage River deltas and, as examples of sediment source areas, on cliff segments at Shingle Point and Kay Point (Figure 1).

1.2 Scientific Conclusions

The main scientific conclusions resulting from this study are:

1. The major geomorphologic features of the Yukon Beaufort Sea coast are: (a) steep coastal cliffs, often containing significant amounts of ground ice, and fronted by narrow beaches; (b) spits and barriers up to 10 or more kilometres in exposed length and several hundred metres wide; and (c) deltas of coastal plain rivers with vegetated or partially vegetated exposed delta plains up to 50 $km.^2$ in area.

2. Cliff sediments range from gravel to icy clay. The fine material is moved off shore and beaches, spits and barriers are usually composed of remnant gravels and sands. Coastal plain rivers have gravel beds but this gravel does not reach the lower delta plains where sediments are primarily organic-rich silts and fine sands.

3. Cliff retreat of up to 90 m. in 16-18 years has occurred, largely through undercutting and subsequent block slumping, gulleying, and mud flow associated with ground ice slumps. Sediment derived from this retreat is moved along shore and has led to hundreds of metres of spit and barrier extension over the same period.

4. Significant sediment transport events are associated with spring break-up and storm floods on the rivers and with meteorological tides and wave activity during these storms along the coast. Berm elevations of over 1.5 m. on spits and driftwood lines more than 2 m. above normal high tide on exposed delta plains attest to the rise in sea level and inundation of coastal depositional features during these storms, most commonly in the summer and fall but occasionally during winter.

5. First flow in rivers, deltas and estuaries occurs well before sea ice break-up and is commonly over bottomfast winter ice. This ice inhibits bed scour during early flooding. Following spring break-up, river discharge declines except for brief rises during storm events.

6. The direct effects of sea ice on the stability of coastal features appear to be small. Only minor examples of the movement of beach sediment by ice push and scour of the nearshore seabed by ice have been observed, this latter phenomenon apparently ceasing shoreward of the 10 m. isobath. Indirect effects, particularly the influence of the amount and location of ice on storm surges and associated wave activity, are much more important.

7. Offshore gradients can be quite steep off many portions of the Yukon coast, most commonly where the shoreline is cliffed. Profiles are generally concave upward and few nearshore bars exist. Off river deltas, though, depths are very shallow, seldom exceeding 2 m. a kilometre or more from shore. Shallow depths in the Babbage estuary prevent the development of significant vertical variations in water temperature and salinity.

8. Rapid coastal retreat, shallow water depths and low water temperatures have enabled the preservation or formation of permanently frozen ground beneath estuary and nearshore areas.

9. Unlike the Yukon coast, the northwest coast of the Tuktoyaktuk Peninsula is deeply embayed along its length, its shape reflecting the breaching of thermokarst lakes which cover large portions of the coastal plain. Major spits and long barrier bar sequences have formed because of the much lower offshore gradient than off the Yukon coast. Sediments in coastal depositional features are mixed gravels and sands west of the settlement of Tuktoyaktuk and, most commonly, pure sand east of Tuktoyaktuk. Like the Yukon coast, the shoreline of the Tuktoyaktuk Peninsula is retreating, with most of the derived sediment being moved northeast toward Liverpool Bay.

1.3 Implications and Recommendations

1.3.1 General Scientific

In an average year, the southern Beaufort Sea coast, particularly east of Herschel Island, has a relatively long open water season and cannot be considered true arctic in nature. Normal marine processes dominate for about three months of the year. During this time period, the arctic environment influences these processes only through the increased relative importance of extreme storm events, the occasional movement of sea ice near shore during these events and, as was so well demonstrated during the summer of 1974, through the major year to year variations in climate and sea ice conditions which may occur.

The response of coastal materials to summer marine processes, however, is conditioned by the arctic environment. Frozen ground plays an important role in the coastal zone, most importantly through its influence on rates of coastal retreat and, along the Tuktoyaktuk Peninsula, through the control by thermokarst lakes of coastal configuration.

1.3.2 Matters Relevant to Development

Development is considered here primarily with respect to the potential effects on the Beaufort Sea coastal zone of an oil spill during exploratory offshore drilling. Consideration is given as well, however, to the possible use of the coast for staging areas or other shore installations associated with petroleum exploration and development.

The details of coastal processes and responses, particularly for short-period events, are not yet well understood in the Beaufort Sea area. The studies undertaken at Kay Point will go far toward remedying this situation. The discussion which follows, however, precedes the completion of these studies and its value must be considered in the context of this lack of knowledge.

1. The coastal zone is a dynamic one, particularly so in this part of the Arctic where shore materials are unconsolidated and often contain significant quantities of ground ice. Its instability must be taken into account in considerations of both oil spills and coastline development.

2. The largest areas subject to frequent inundation by sea water and thus, potentially, by oil in that water are the river deltas, particularly the Mackenzie itself and, along the Yukon coast, the Blow and Babbage deltas. These deltas have a high silt content and their sediments are frozen to considerable depths. Thermal disturbance through vegetation damage could lead to compaction of thawed sediments. Because the delta plains are major wildfowl nesting areas, oil must be prevented from reaching them.

3. Oil is most likely to reach the coast during summer and fall but open water and wave activity are possible even during winter. The sea ice was broken up off Kay Point and the Babbage estuary flooded during a severe storm in early January 1974 (R. Mackenzie, pers. comm.).

4. Shoreline materials are constantly in motion during the open water season and, with the continuous possibility of storm surges, oil from a spill could cover depositional coastal features at any time, be buried by subsequent sediment accumulation, exposed again, transported along the shore, re-buried, and so on.

5. In the event of an oil spill approaching the coastline, it may be possible to use lagoons behind spits and bars or, along the Tuktoyaktuk Peninsula, breached thermokarst lakes to contain it. The resultant potential for destruction of fish and wildlife is critical to this suggestion but, if other methods of containment are less reliable or cause even greater destruction, use of natural features may become viable.

6. Shore installations must be carefully located so as to avoid areas where large amounts of ground ice are present. Disturbance of the ground thermal regime will only serve to further increase already rapid rates of coastal retreat. Construction off shore must take into account the likely presence of and, because of low sea water temperatures, the possible growth of sub-bottom frozen ground.

7. Beach material is primarily local in origin, its maximum travel defined by the distance to the outer boundary of the feeder area of the nearshore sediment sink toward which it is moving. Removal of material or blockage of longshore drift for construction purposes will have effects both up- and down-drift. Because many natural features are important nesting areas and because disturbance at one construction site may affect conditions at another, final selection of sites should be made only after the detailed nature of sediment supply in the area is known.

2. INTRODUCTION

2.1 General Nature and Scope of Study

This technical report is based primarily on fieldwork conducted during the summer of 1974 into the geometry, composition, origin and stability of coastal landforms bordering the Beaufort Sea from the Alaska-Yukon boundary east to the Mackenzie Delta. The 1974 study followed the general reconnaissance investigations of the northwest coast of the Tuktoyaktuk Peninsula in 1973 and of the Yukon coast in 1972 (McDonald and Lewis, 1973). The results of these earlier studies have been incorporated here to extend coverage as far east as Cape Dalhousie at the eastern end of Tuktoyaktuk Peninsula. As well, prepared testimony by the senior author, presented to the Mackenzie Valley Pipeline Inquiry on February 13, 1976, is included in this report as an appendix. The reader is referred to this appendix for a more general overview of physical aspects of the Beaufort Sea coast, discussion of the implications of offshore hydrocarbon resource development on the coastal zone, and for additional detailed information on the modern Mackenzie delta plain.

The purposes of 1974 fieldwork were twofold:

1. The general reconnaissance studies in 1972 and 1973 raised many questions about the detailed nature, magnitude and frequency of processes and responses in this arctic coastal zone, questions which could best be answered by a longer term instrumented study at a representative sample location. Kay Point, Y.T. (Figure 1) was chosen as the sample site because it offers a wide range of coastal features in a small area. Concentrated fieldwork at this location was begun in 1974, continued in 1975 and will be completed in 1977.

2. The second objective of 1974 fieldwork was to examine the geological aspects of coastal susceptibility to oil spills, a part of the joint industry - government Beaufort Sea study of the potential environmental hazards of proposed exploratory offshore drilling. In this context, the intention was to examine those coastal features most susceptible to inundation by sea water. Because of extremely poor weather and sea ice conditions during the summer of 1974, work was confined to the Yukon coast.

2.2 Specific Objectives

Specific objectives can conveniently be divided into two parts: those concerned with the Kay Point process-response study and those concerned with coastal susceptibility to oil spills.

2.2.1 Kay Point

Work at Kay Point is focussed on the nature, magnitude and frequency of stresses exerted on a variety of coastal sedimentary environments and on the response of these environments to the imposed stresses. The emphasis is on system responses to storms or floods but seasonal and longer term changes are being examined as well. In all cases, greatest attention is given to those characteristics which differ from coasts in more temperate locations and which might make an arctic coast a special case from a development point of view.

Specific studies include (see Figure 1, inset, for locations):

1. Erosion of and sediment transport from the coastal cliffs southeast of the point;
2. Growth, migration and short-period changes in Kay spit;
3. Morphology, sedimentology and hydraulics of the Babbage River delta, an estuarine delta of the Mackenzie type; and
4. Sediment transport and deposition in Phillips Bay, a nearshore sediment sink.

2.2.2 Coastal Susceptibility to Oil Spills

The degree and duration of damage to the coastal zone resulting from an offshore oil spill are dependent primarily on: (a) whether or not the oil reaches the coastline, (b) the frequency and duration of inundation of coastal features by sea water containing oil, and (c) the reaction between the oil, once present, and the sediments, vegetation and wildlife existing within the coastal zone.

In this context, the intentions of this study are to:

1. Identify and determine the extent of those areas of the coastal zone most susceptible to inundation by sea water;
2. Determine the present geometry, nature of sediments and vegetation of these areas;
3. Examine patterns of sediment erosion, transportation and deposition; and
4. Identify and discuss conditions peculiar to an arctic coastal environment relating to potential damage from an oil spill.

During the summer of 1974, fieldwork was carried out on the major spits at Shingle and Kay points, on Nunaluk spit in the Firth River region, on the Blow and Babbage River deltas and, as examples of sediment source areas, on cliff segments at Shingle Point and Kay Point (Figure 1).

2.3 Relevance to Development Problems

The coastal zone is one of the most complex and dynamic environments with which development must contend. Because of the importance of the Beaufort Sea for transportation, harbours, staging areas and perhaps pipelines will accompany the development and movement of resources on land. This study is intended to provide both reconnaissance-level and detailed process-response information relevant to construction at the coast.

The development of resources at sea will also affect the coastal zone, both through the need for support facilities on land and because of the dangers of and need to protect the coast against pollution associated with offshore development. An oil spill during offshore drilling could reach the coastline and have serious detrimental effects on vegetation, wildlife and man. It is the intention of this study to provide background information relevant to an evaluation of the nature, magnitude and duration of potential damage and of methods of minimizing this damage.

2.4 Acknowledgments

The authors are indebted to many people for co-operation in the field during 1974. Assistance at Kay Point was provided by B. Hawley, M. Krastman, S. Nichols, and A. Pinsonnault. G.R. Bernyk led the sub-party investigating coastal susceptibility to oil spills and was assisted by B. Gamble, D. Hunter, R. Jurchuk and P. Smale. Dr. J.A.M. Hunter of the Geological Survey provided advice and support for shallow water seismic studies at Kay Point carried out by J. Carson and S. Carson. Electrical resistivity sounding and profiling on coastal spits done by L.E. Stannard was helped greatly by advice and support from Dr. W.J. Scott of the Geological Survey. Vegetation studies in all areas were carried out by J.M. Teversham of the University of British Columbia. Dr. R. Gilbert of the Queen's University supervised the March 1974 drilling program at Kay Point. Logistic support offered by the Inuvik Research Laboratory and by the Polar Continental Shelf Project is also gratefully acknowledged.

Thanks are due also to H. Kerfoot and L. Lightstone for assistance in preparations for the field season, to G.R. Bernyk for help in the reduction of field data and to D.J. Egan and the Geological Survey Cartography and photography sections for assistance in illustrating this report.

3. CURRENT STATE OF KNOWLEDGE

Geomorphic and sedimentologic studies of the Yukon coast are few. Rampton (1974a) has mapped surficial materials at and landward of the coast. Hughes (1970) discussed the history and features of glaciation and Mackay, Rampton and Fyles (1972) reported on coastal exposures indicative of glacially-deformed relic Pleistocene permafrost. Mackay (1960, 1963) commented on the nature of small boat harbours and noted evidence of shoreline retreat along the Yukon coast. Walker and McCloy (1969) and McCloy (1970) examined the morphology and hydrology of the Blow River delta with emphasis on the role played by the arctic environment in morphologic change. McDonald and Lewis (1973) discussed the distribution and variety of marine sediment types along the coast, inferred from coastal depositional features the broad patterns of nearshore sediment movement and storage, and produced several maps showing photogrammetric measurements of coastal change and typical stratigraphic sections of segments of coast.

The types of knowledge of the Yukon coast which presently exist, therefore, are primarily stratigraphic, very localized or reconnaissance-level in nature. Detailed mapping of coastal depositional features has not been attempted and the characteristics of shore and nearshore processes and responses can only be inferred by extrapolation from the Alaskan portion of the Beaufort Sea coast (eg. Wiseman et al, 1973; Walker, 1974).

4. STUDY AREA

The nature of the Yukon Beaufort Sea coastal zone has been conditioned primarily by erosion and redistribution of the unconsolidated Quaternary sediments of the Yukon coastal plain. These deposits are greater than 30 m. thick and consist mainly of: lacustrine silty-clay; alluvial fan sands and gravels; plus, east of the Firth River (Figure 1), marine, estuarine and fluvial silt, sand and gravel, commonly glacially-contorted and capped by till; and glaciofluvial gravel and sand (Rampton, 1974b).

Coastal plain rivers also supply significant amounts of sediment to the coastal zone. Of these, the largest are the Firth, the Babbage and the Blow (Table 1). No estimates of annual sediment load are available for these rivers but differences in this together with contrasting physiographic settings, history and coastal current conditions must account for the great dissimilarity of their deltas.

In addition to the deltas, two other major coastal types can be distinguished: steep cliffs fronted by narrow beaches and large spits and barriers. Erosion of the cliffs has been rapid in recent years, particularly where the sediments contain considerable pore, wedge or massive ice. Material derived from this erosion and from the coastal plain rivers is dispersed by well developed longshore currents to four main sediment sinks: (a) Demarcation Bay, (b) between Herschel Island and the mainland, (c) Phillips Bay and (d) Shoalwater Bay (Figure 1). Photogrammetric data indicate recent extension of the spits and barriers, evidence of this longshore movement of sediment (McDonald and Lewis, 1973).

TABLE I

Yukon Coastal Plain Rivers[a]

	Firth	Babbage	Blow
Basin area ($km.^2$)	6200	5000	3700
Maximum probable flood area ($m.^3/sec.$)	1000	1130	710
Delta type	fan	estuarine	arcuate
Delta plain area ($km.^2$)	-	25	50

[a]After McDonald and Lewis, 1973 and Church, 1971.

5. SOURCES, METHODS AND RATIONALE OF DATA COLLECTION

The purpose of this section of the report is to detail the specific types of information collected, the methods by which this information was obtained, and the uses to which it has been put.

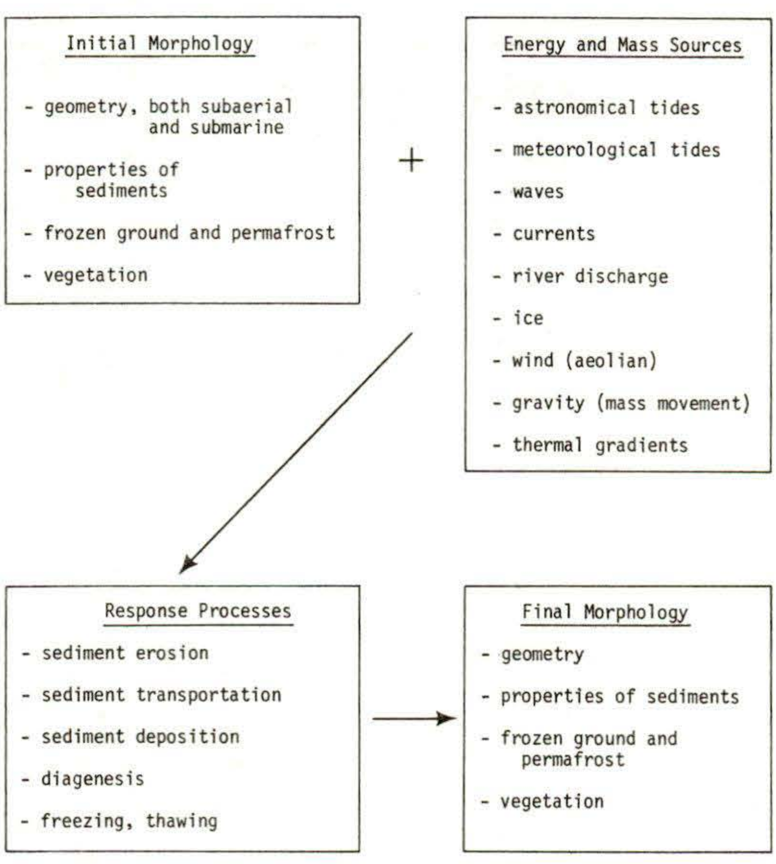
5.1 Kay Point

The evolution of a coastal landscape can be examined in the context of any of several different time scales. As has been mentioned previously, the scale of most concern in the various components of the Kay Point study is that of the storm event - changes over several hours to several days. The seasonal scale - changes over weeks and months - is also of great importance, however, because of its relevance to the question of the role played by the arctic environment in coastal processes and responses. Of lesser interest to this study but still essential to it are changes which have occurred over periods of years. These can only be determined indirectly but, if reliable evidence is available, attest to the sum effect of shorter period events.

The framework for data collection in each component of the Kay Point study is detailed in the process-response model shown in Figure 2.

FIGURE 2

Generalized Process - Response Model



In a practical sense, measurement to the necessary accuracy of all variables relevant to a particular event at any of the time scales of interest is not possible. The model is idealized and will indicate the weaknesses of specific studies as well as their strengths.

Initial investigations in the Kay Point region were oriented primarily toward establishing a grid network for data collection and obtaining the detailed background information necessary for future studies - ie. the initial morphology. In addition to qualitative observations of coastal morphology and processes, the following data were collected in 1974:

1. Meteorological information, most importantly continuous recording of atmospheric pressure and wind speed and direction to relate to waves, currents and meteorological tides;
2. Continuous tide gauge data (through the co-operation of the Marine Sciences Directorate, Department of the Environment);
3. Continuous recordings of water levels on the Babbage River and Deep Creek above their junction to define water inputs to the Babbage delta;
4. Spot measurements of water transmissivity, salinity, conductivity and temperature in the Babbage estuary and delta channels;
5. Survey profiles both along and across Kay spit, the cliffs and the Babbage delta and across the delta channels;
6. Establishment of detailed study zones with permanently marked profiles at 500 m. intervals along Kay spit to enable morphologic change during storm and seasonal time periods to be monitored;
7. Echo sounding (Raytheon DE-719-B with 200 kHz. narrowbeam transducer) and side scan sonar profiles up the largest Babbage delta distributary and along 1000 m. grid lines in the Babbage estuary and in the nearshore zones (out to a maximum of 10 m. water depth) off Kay spit and the coastal cliffs;
8. Seismic refraction profiles along the above grid lines to locate the upper boundary of sub-bottom frozen ground;
9. Surface sediment samples of the Babbage delta and estuary on a 1000 x 500 m. grid, supplemented by more detailed sampling at selected sites including channel cross-sections;
10. Drilling (up to 60 m. depth) on the cliffs, the spit and the delta to define stratigraphy and sediment properties and to permit installation of ground temperature cables; data from these and future cables together with surface temperature, drill log and seismic refraction information will be used in the development and testing of a model of the perturbation in the ground temperature field caused by the presence and migration of the coastal cliff and spit; and
11. Vegetation mapping on the Babbage delta plain, the spit and the cliffs.

Data collection was continued during the summer of 1975 and full analysis awaits completion of the field program in 1977.

5.2 Coastal Susceptibility to Oil Spills

Fieldwork for this portion of the project was designed to augment the 1972 reconnaissance study (McDonald and Lewis, 1973) in the particular context of the goals discussed previously. The research design used in the Kay Point process-response study so that comparisons and, perhaps, extrapolations could most easily be made.

The approach taken was spatially hierarchical in nature with progressively more detailed work being done with each step down in the hierarchy. The highest level, the region, was defined as the segment of coastline providing sediment to each of the nearshore sediment sinks discussed earlier (Figure 1). Within each region studied, areas - ie. coastal types such as cliff segments, major spits and bars, deltas, etc. - were selected and examined in more detail. Intensive fieldwork was carried out in two to four 80 m. wide zones in an area, each zone extending, if practical, from the offshore-nearshore boundary (10 m. isobath) well into the backshore (beyond the limit of marine activity).

The geomorphologic data collected in a zone include the following:

1. Sketch map and photographs - of general topography, major geomorphic features, abrupt changes in sediment properties, etc.;
2. Definition of subaerial stratum boundaries - between portions of the zone which appear homogeneous with respect to type or gradient of processes, eg. foreshore, backshore and subdivisions of each;
3. Subaerial profile surveys - three to five, oriented normal to the trend of the shoreline;
4. Subaerial sediment samples - five surface samples in each stratum, positioned systematically within strata along the zonal centre-line;
5. Active layer thicknesses - mean of five probings at each sediment sample site;
6. Bathymetric profiles - high frequency echo sounding and side scan sonar along the extension of the zoneal centre-line to the offshore-nearshore boundary;
7. Submarine stratum boundaries - as for subaerial, subdivisions of the nearshore; and
8. Submarine grab samples - as for subaerial.

This data will be used to produce a topographic map of each zone, to estimate mean grain size and grain size gradient for the zone and for each stratum within it and, when data for all zones in an area are combined, to infer areal gradients and the type and nature of active processes.

In addition to the geomorphologic studies, botanical work was carried out in connection with surveyed profiles in the Shingle Point and Kay Point regions and on Nunaluk spit. Collections of all vascular plants and representative bryophytes were made for all areas studied. The distribution of the vegetation was examined in relation to the varied geomorphic units within each study zone using a quadrat method for continuous vegetated areas and by a line transect method for discontinuous areas. The collections are presently being identified and, when completed, plant communities present will be described and discussed in terms of their geomorphic significance (J.M. Teversham, pers. comm.).

As well, electrical resistivity sounding and profiling were completed on Shingle, Kay, Spring River (Figure 1) and Nunaluk spits. The aim of this experiment was to test the usefulness of this geophysical method in distinguishing the top and bottom of permafrost and the thickness of gravel in coastal spits.

Finally, general observations on river and sea ice break-up and on the morphology of portions of each region not included in the study areas were made, the surface area of coastal features subject to frequent inundation by sea water measured, and spot surveys taken of the elevation of high water driftwood lines.

Figure 3. View east over the Babbage delta during spring break-up; note the floating channel ice. (8 June 1972; GSC 202717-J)

6. RESULTS

6.1 Kay Point, 1974 Fieldwork

6.1.1 Babbage Delta and Estuary

The estuarine Babbage delta (Figure 3) receives discharge and sediment directly from both the Babbage River and from its tributary, Deep Creek. These streams drain a 5000 $km.^2$ catchment on the Barn and British mountains and the Yukon coastal plain. Data on total water and sediment discharge from the drainage basin are lacking, but indirect estimates (Church, 1971) suggest maximum probable floods of 910 $m.^3$/sec. for the Babbage above Deep Creek and 220 $m.^3$/sec. for Deep Creek. Total annual precipitation averages 200 mm. (Shingle Point, 1962-1971) and four months (June through September) have mean temperatures over 0^oC. Most sediment movement probably occurs during spring break-up in late May and June and during summer and fall storm floods. The delta plain may also be flooded by storm tides, most commonly in the summer and fall but occasionally during winter (R. Mackenzie, pers. comm.). As a result, some marine sediment, including a large amount of driftwood, is also incorporated in the delta.

Morphology and sediments

A generalized surface facies map of the Kay Point area is given in Figure 4. The subaerial Babbage delta comprises by far the largest land area below the highest driftwood line, the upper limit of the storm surge flooding (2-3 m. above mean high tide). On two sides, the delta and its estuary are bounded by upland glacial, marine and lacustrine sediments of the Yukon coastal plain. Alluvial surfaces in the valley above the highest storm line are associated with a variety of sediments: from channel gravels of the braided Crow River on the south to fine-grained overbank deposits of Deep Creek on the north (Figure 1). Polygonal ice-wedge structures are common on this facies and winter or spring accumulation of aeolian sediment, apparently derived from channel bars, was noted along some banks.

The delta plain, as mapped here, includes all deltaic surfaces above normal high tide which are subject to storm surge flooding. The lower floodplain, generally less than 1 m. above mean high tide, comprises vegetated levees and interlevee flats and partially vegetated shallow flood basins, interspersed with numerous tidal ponds and connecting channels. Levees, except along minor channels have negligible relief: vegetation mapping (J. Teversham, pers. comm.) revealed little consistent contrast between levee and interlevee flora and a complex distribution of the few species present over the floodplain. Included in the delta plain facies are scattered higher surfaces, inactive levees flanking abandoned channels and a major abandoned channel at the head of the delta, all subject to driftwood accumulation under occasional storm flooding.

Little is known of the stratigraphy of the delta plain. Channel banks expose stratified silt and organic detritus including occasional large driftwood logs. A borehole at the delta front (Figure 4, drill hole # 4) drilled in March, 1974 was logged as follows:

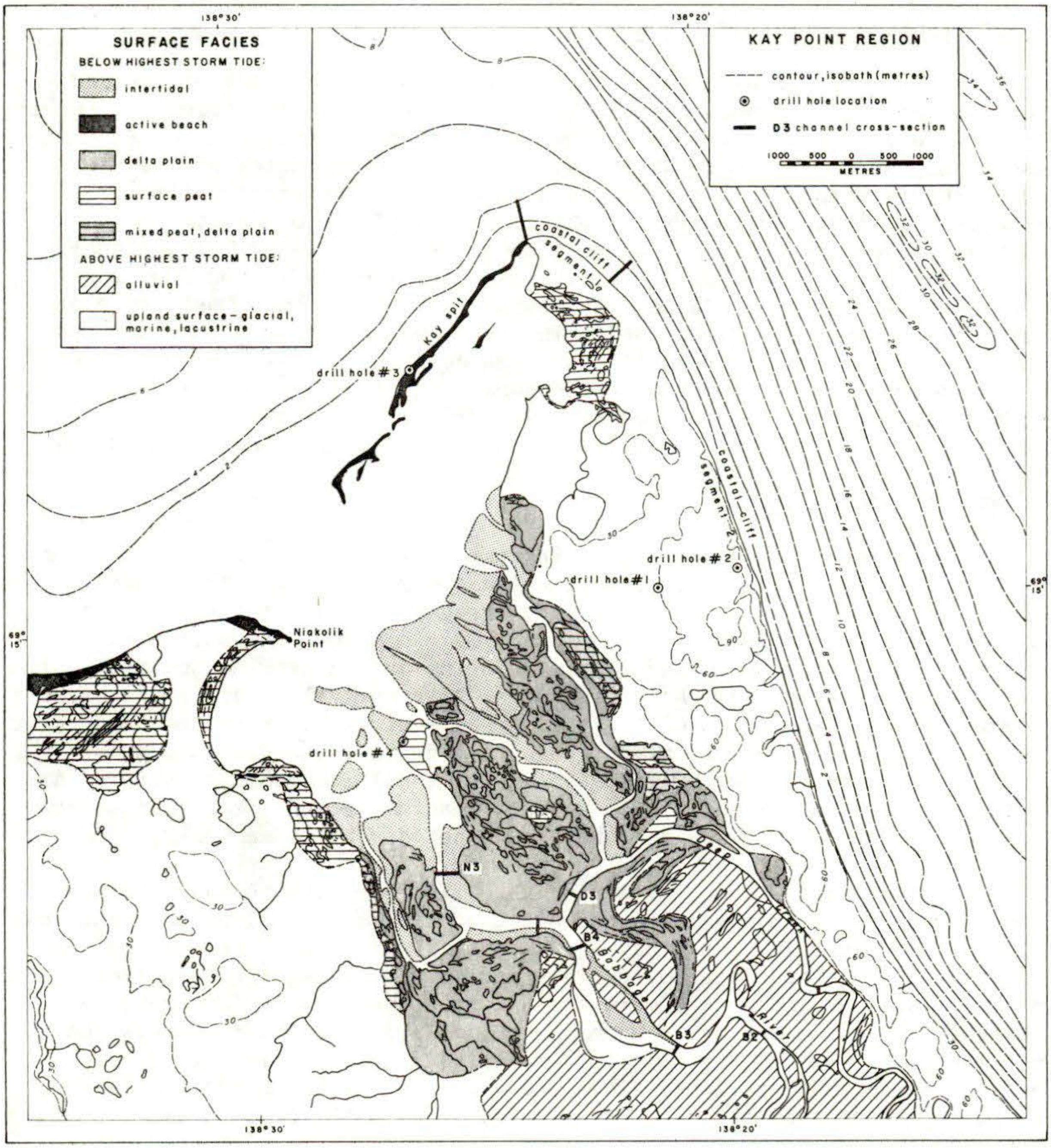


Figure 4. Kay Point Region: Generalized Surface Facies.

0-2.6 m.	peat, medium sand with 30-40% ice by volume
2.6-6.1 m.	90-100% ice by volume
6.1-22.9 m.	medium gravel with less than 20% ice by volume
22.9 m.	abundant salt water encountered

The gravel may derive from the Babbage River but is more probably fluvio-glacial valley fill associated with late-Wisconsin ice at King Point (Figure 1.).

Sediments in the several major distributary channels which cross the delta are predominantly sand. Gravel, present in both the Babbage and Deep Creek above the delta, is absent from delta channels. The main distributary was sounded in August 1974 and scour holes up to 7.5 m. deep were encountered. It is probable that frozen ground underlies the delta channels. Hand probing at section N3 (Figure 4) revealed frozen substrate 0.5-2.0 m. beneath the channel bottom at least out to 3 m. water depth and possibly continuing beneath the thalweg at 5.5 m. McDonald and Lewis (1973) interpreted as frozen ground a prominent reflector observed in July 1972 echograms from Babbage delta channels.

Surface peat (Figure 4) occurs extensively at or near sea level around the estuary and as relic patches on the modern delta plain. It also occurs beneath silts in cut-bank exposures in and above the delta. In several places (Figure 4) peat and delta plain facies are mixed. The age or ages of the peat exposures is unknown at this time.

Intertidal surfaces are essentially unvegetated (Figure 7). Sediments of this facies range from silt to sand, with rare ice-rafted gravel, little driftwood, and occasional clasts of peat. Bedforms exposed at low water attest to upstream sand movement on channel bars under low-stage flood-tide conditions. Initial impressions suggest that the intertidal areas may be expanding in places at the expense of the delta plain.

The Babbage estuary between the delta and Kay spit is both very shallow and flat; except near shore, water depths are consistently in the 1-2 m. range and only one bar, 500 m. behind the spit and parallel to it, was found. Bottom surface sediments are largely well sorted fine sands and coarse silts. Neither echo sounding nor side scan data showed any evidence of ice or strudel* scour (Reimnitz et al, 1974), although the estuary probably freezes to the bottom in many places in winter and a strudel vortex was observed near the distal end of Kay spit in June 1972 (McDonald and Lewis, 1973). Seismic refraction data indicate sub-bottom frozen ground within the estuary (Carson et al, 1975).

Seasonal flow characteristics

A break-up and summer flow sequence similar to that reported for Alaskan rivers (Barnes and Reimnitz, 1972; Walker, 1974) was observed on rivers of the Yukon north slope in 1974. Three phases were distinguished: (a) pre-break-up flooding over winter ice, (b) break-up accompanied and followed by snowmelt flooding with pronounced diurnal fluctuation, and (c) general summer flow recession interrupted by brief storm floods.

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* bottom marks left by water draining through holes in ice.

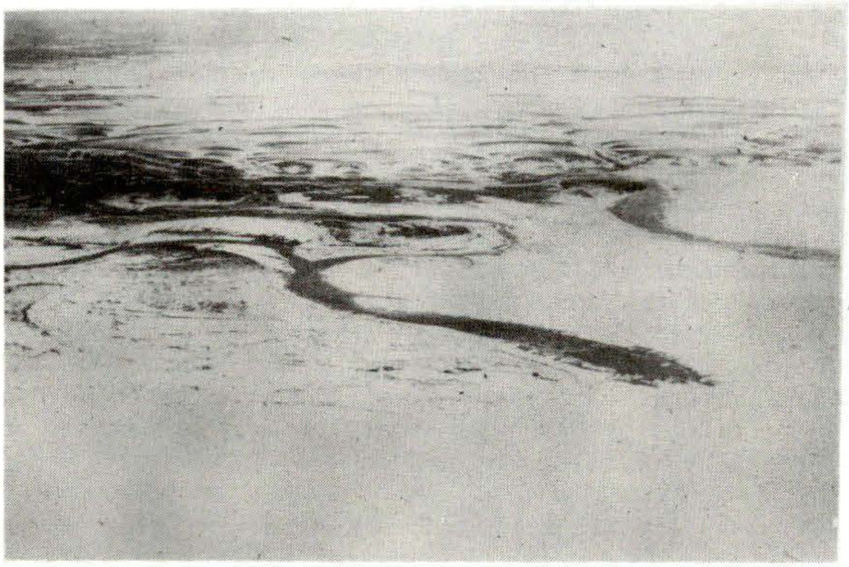


Figure 5. Blow River delta: pre-break-up flooding over winter ice.
(20 May 1974; GSC 202717-0)

Figure 6. Babbage River estuary: pre-break-up flooding over winter ice; Kay spit at extreme left centre, Niakolik Point at right centre.
(20 May 1974; GSC 202717-D)

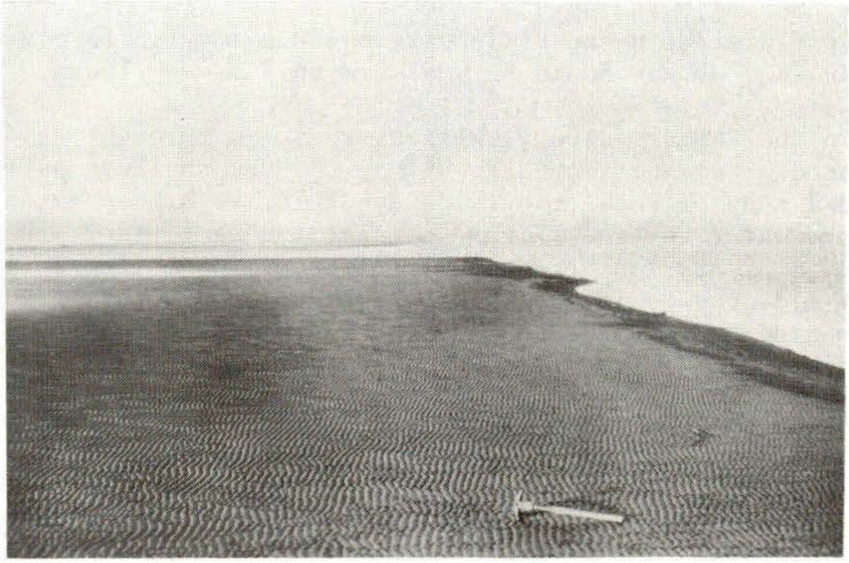


Figure 7. Unvegetated intertidal flat at the mouth of the main distributary of the Babbage delta.
(10 July 1972; GSC 202717-C)

Figure 8. Sediment covered winter ice with thermo-erosional bedforms which has risen to the surface in the Babbage estuary.
(12 June 1972; GSC 202717-B)

Pre-break-up flooding began at the head of the Babbage delta on May 16, 1974. Flow in the Firth River had already advanced over ice to Nunaluk spit (Figure 1), but other rivers along the coast, including the Malcolm, Spring, Running and Blow, showed no evidence of flow. Pre-break-up flooding in the Blow Delta began by May 18 (Figure 5) and was well advanced by May 30 in the Malcolm and Spring rivers.

On the Babbage, the flow front advanced through the delta at a rate of about 3 km. per day and, by May 20, the southern part of the estuary and a zone of sea ice outside Kay spit, to or beyond the 2 m. isobath, were water covered (Figure 6). At the same time, winter ice in some delta distributaries began to lift free of the bottom but remained in place until mid-June or later (Figure 3). Repeated frosts produced fresh ice cover behind and around the floating winter ice throughout the early part of June.

At B2 (Figure 4), just above the delta, channel ice approximately 1 m. thick began to lift on May 28 but remained in the reach until June 1. Soundings to bottomfast ice suggested a late autumn water level 3.5 m. below the top of the cut bank. Water stage after May 28 fluctuated generally between 2.8 and 2.2 m. below bank top but rose to a peak of 1.9 m on June 8 and again on June 10. Snow against cut banks indicated that no higher flooding had occurred before regular observations began. The June 8 peak produced the first extensive flooding of the Babbage delta plain and flooded the entire estuary over the winter ice. The estuary ice subsequently floated and cleared completely by July 9. Ice remained close against the seaward side of Kay spit until the last week in July, however. It should be noted in this context, though, that sea ice break-up in the Beaufort Sea was exceptionally late in 1974.

Suspended sediment concentrations during break-up flooding at B2 ranged from 50 mg./l. on June 2 to less than 5 mg./l. on June 6 to a maximum of 300 mg./l. twelve hours after the flood peak on June 8. Much of this sediment is deposited on top of bottomfast winter ice in the estuary (Figure 8). In the river and delta channels some bedload movement prior to break-up also occurred over bottomfast ice. This movement was very limited, however. Soundings encountered hard ice surfaces with only occasional patches of sediment except above late autumn water levels where the bottom was soft. Emergent bottom ice in the channels was clean except for rare patches of sand and some gravel. In a few instances, well formed, asymmetrical ripples were observed in the upper surface of bottomfast ice; the lee faces of some of these ripples carried thin slip-face accumulations of sand but the ripple surface itself is apparently thermo-erosional in origin. Thermo-erosional bedforms were also observed in floating bottom ice in the Babbage estuary (Figure 8) by McDonald and Lewis (1973). Bottomfast ice in channels clearly inhibits bed scour during pre-break-up flooding. Peak spring discharge may occur after break-up, however, and the extent to which scour may then be inhibited by a frozen channel perimeter is not known.

Continuous water stage records were obtained for Deep Creek from July 4 to August 22 and for the Babbage River over the same period with some breaks. The data indicate an initially strong diurnal fluctuation on both streams, diminishing with time, but persisting into August. These fluctuations were also noted by McDonald and Lewis (1973) on the Babbage in June and early July 1972. The general reduction in discharge throughout the 1974 record was interrupted by brief floods on five occasions: the largest, August 13-15, produced a rise in stage on the Babbage of 1.25 m. in 48 hours, of which 1.00 m. occurred in 14 hours. Babbage discharge exceeded 60 $m.^3$/sec. during less than 10 per cent of the 50 day record and 20 $m.^3$/sec. during 75 per cent of the record. Deep Creek showed the same pattern as the Babbage, but with lower more attenuated peaks.

In late June, suspended sediment concentrations were higher in Deep Creek than in the Babbage: typical values on June 19 at D3 and B4 (Figure 4) were 100 and 10 mg./1. respectively. This difference was also noted during storm floods later in the summer. Except for these floods, suspended sediment discharge decreased with water discharge through the summer, concentrations in August being generally less than 1 mg./1. Surface water and sediment discharge to the delta probably ceases in late autumn or early winter, although extensive icings on the Crow and upper Babbage in August 1974 attest to winter discharge at some points in the basin.

Preliminary measurements of salinity, conductivity and temperature were made in the Babbage estuary in mid-July. The maximum salinity, 2.5°/₀₀, was recorded in the estuary behind Kay spit and the minimum, 0.2°/₀₀, in river water of Niakolik Point (Figure 4). Water temperatures varied from 7.0°C in river water to 2.5°C in water of intermediate salinity off the distal end of Kay spit. No significant vertical variations in salinity, conductivity or temperature were encountered.

6.1.2 Coastal cliffs

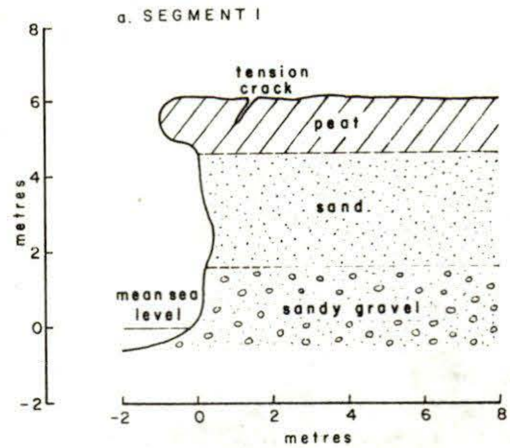
To both the east and west of the Babbage estuary the shoreline is fronted by rapidly retreating coastal cliffs. Sediment is fed from both directions into the Phillips Bay sediment sink. The coastal cliff southeast of Kay Point (Figure 4), probably the most rapidly retreating along the entire Yukon coast (McDonald and Lewis, 1973) has been chosen for detailed study.

This portion of cliff may be divided into two segments (Figure 4). In segment 1, the cliff is 5-10 m. high, vertical, often undercut and has no visible beach at normal water levels (Figure 9). A generalized section is given in Figure 11a. Retreat has ranged from 25-90 m. in 16-18 years (McDonald and Lewis, 1973) and is controlled by melting and gulleying along ice wedge lines, undercutting, and subsequent block slumping.

In segment 2, the cliff (Figure 10) rises to 90-100 m., becomes less steep, changes in stratigraphy and is fronted by pocket beaches. A 60 m. drill log section near the edge of the cliff (Figure 4) taken in March 1974 is shown in Figure 11b. Sediments are finer and ice content higher than in segment 1. Ground ice slumps and associated mudflows play an important role in retreat which has been in the order of 25-50 m. over the last 16-18 years (McDonald and Lewis, 1973). Similar slumps are encountered west of the Babbage estuary (Figure 12).

Figure 9. Undercut cliff at Kay Point during August storm; view northeast from Kay spit. (20 August 1974; GSC 202717-A)

Figure 10. Cliffs southeast of Kay Point; view southwest along March 1974 drilling line. (16 May 1974; GSC 202717-M)



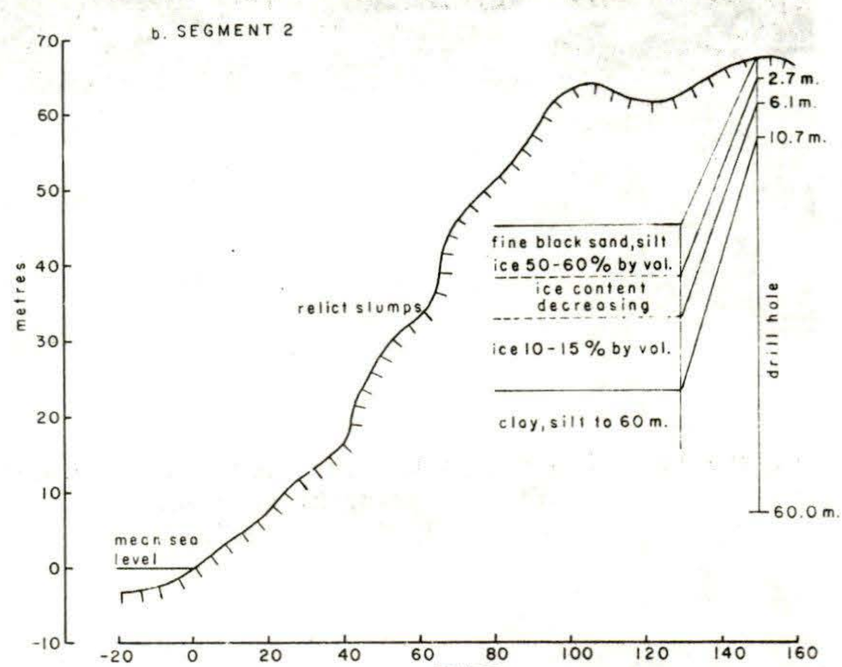


Figure 11. Generalized Sections and Stratigraphy, Cliffs southeast of Kay Point.

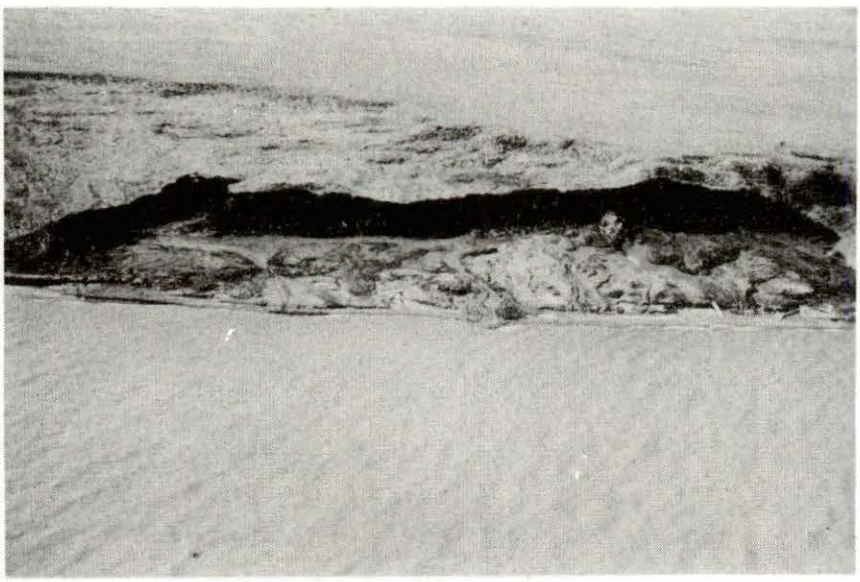


Figure 12. Coastal ground ice slump and associated mudflows, Spring River area. (8 August 1974; GSC 202717-G)

Bathymetric profiles off both cliff segments are concave upward with the 5 m. isobath 150-200 m. from the shoreline. Analysis of seismic refraction data indicates the presence of sub-bottom frozen ground in nearshore areas (Carson et al, 1975).

6.1.3 Kay Point spit

Much of the coarser sediment eroded from the cliff segments is carried northwest around Kay Point and deposited on Kay spit (Figure 1). This linear feature (Figure 13) is approximately 4.9 km. long, averages 61 m. in subaerial width and consists largely of gravelly sand (Figure 14) deposited over the estuarine sandy silts. A March 1974 drill hole (Figure 4) showed sand and medium gravel to a depth of 5.2 m., gravel decreasing to zero at 10.7 m. and silt content increasing with depth. A typical spit cross-section near the drill hole is given in Figure 15. Permanently frozen ground exists along the length of the spit but the drill hole penetrated a thin talik (unfrozen zone) beginning at 11.0 m.

The spit protects much of the Babbage estuary from marine wave activity and appears to be quite active, having extended about 400 m. and retreated on line with Kay Point between 1952 and 1970 (McDonald and Lewis, 1973). Most sediment movement occurs during storm surges. A surge which reached the high driftwood line on the Babbage delta, several metres above the astronomical tide of about 0.7 m., would completely inundate the spit. The transport of sediment is also greatly influenced by sea ice, both directly, through the movement of sediment by ice push - observed in 1972 but not in 1974 - and indirectly, through the effect of the ice on storm surges and associated wave activity. As has been mentioned, ice conditions during the summer of 1974 were among the worst on record. The sea ice remained solid off Kay spit until late July and, although broken, persisted near shore for the rest of the summer. A storm in late August, with winds exceeding 64 km/hr., caused only a slight surge and only small waves (Figure 9) because of the very short ice-free fetch. Because of the ice protection, the upper foreshore of the spit beach maintained its winter profile throughout the open water season.

As off the coastal cliffs, bathymetric profiles off the spit are concave upward but the 5 m. isobath is 400-600 m. from the shoreline, two to three times its distance from the cliffs. One or two nearshore bars, 0.5-1.0 m. in height, parallel the spit for most of its length and occasional sand wave fields with lee faces toward shore lie seaward of the bars. Side scan sonar showed little evidence of ice scour out to the 10 m. isobath, the maximum depth scanned. Again, seismic refraction data indicate sub-bottom frozen ground, in this case extending offshore to a distance of at least 400 m., its upper surface 20-30 m. below the bottom 200 m. from shore (Carson et al, 1975).

6.2 Coastal Susceptibility to Oil Spills, 1974 Fieldwork

This portion of the project represents, basically, an extension, in considerably less detail, of the Kay Point study to other areas of the Yukon coast subject to frequent inundation by sea water.

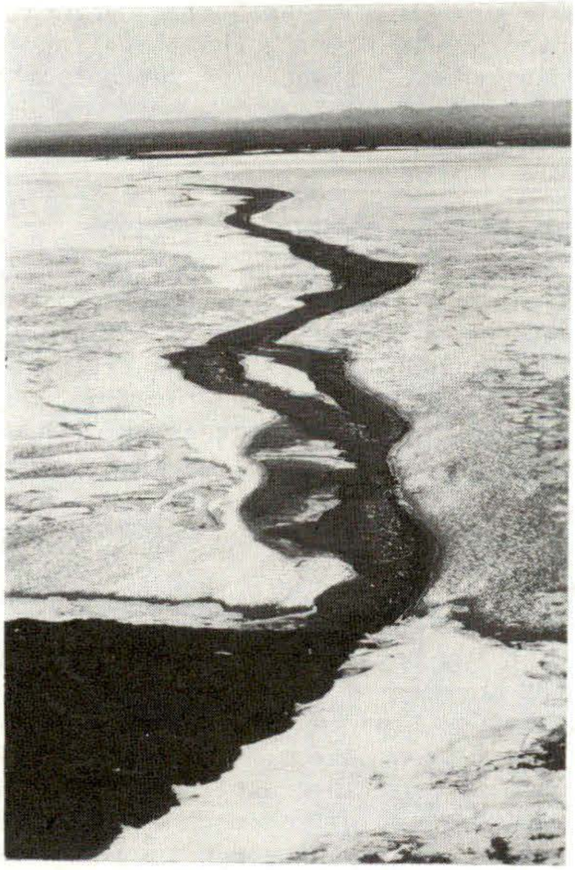


Figure 13. Kay Point spit; view southwest.
(26 June 1974; GSC 202717-H)

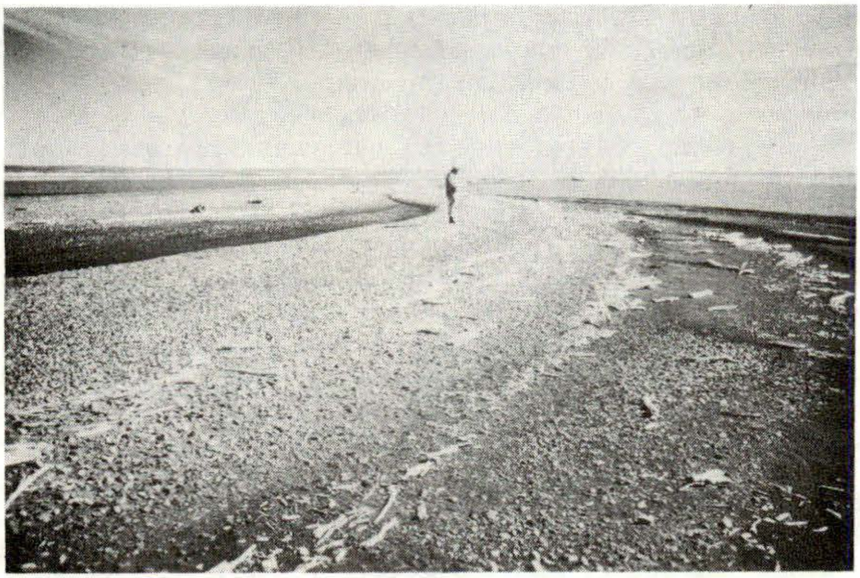


Figure 14. Kay spit, distal island; view southwest along foreshore.
(12 June 1972; GSC 202717-K)

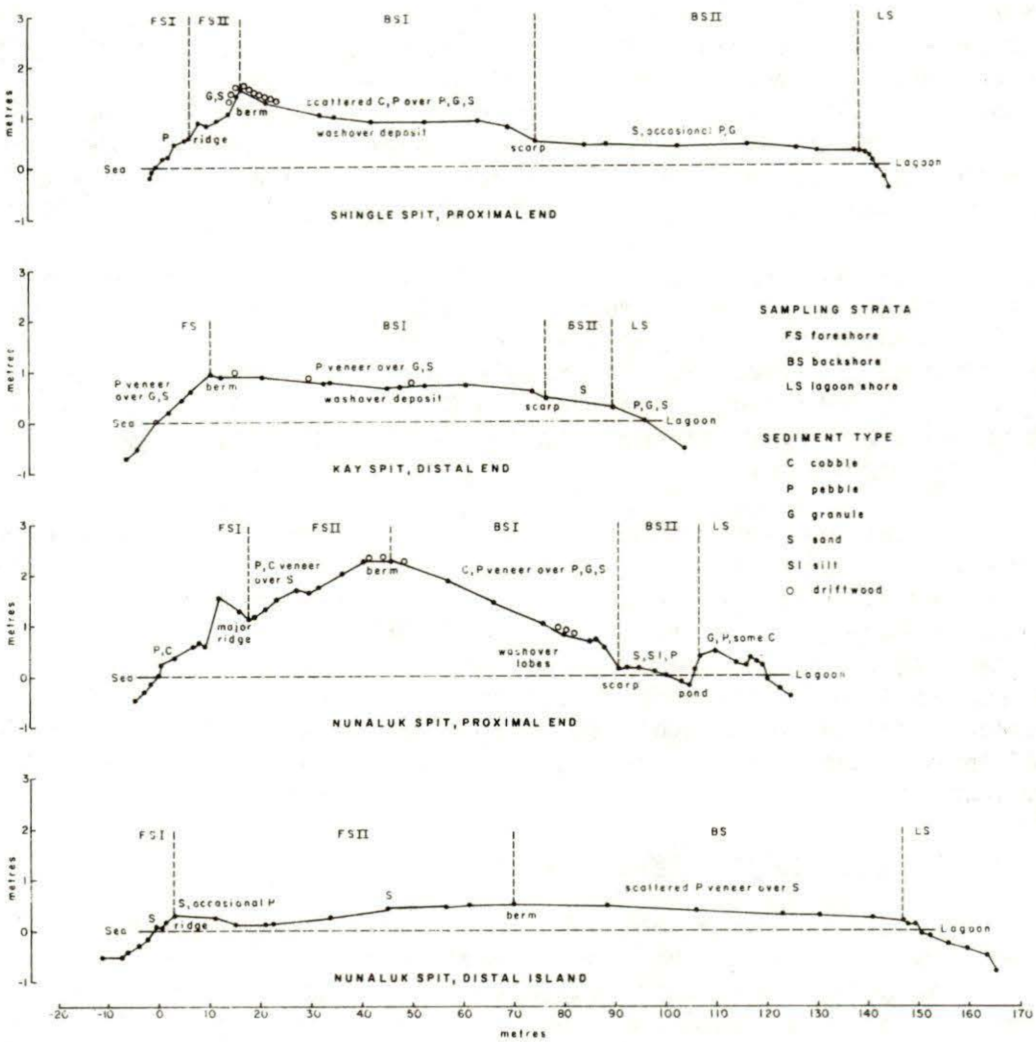


Figure 15. Selected Cross-sections with Sediment Types, Yukon Coast Spits.

6.2.1 Blow River Delta

The Blow River is somewhat smaller than the Babbage but its delta has approximately twice the subaerial extent of the Babbage delta (Table I). Unlike the estuarine Babbage delta, the Blow delta is arcuate in form, protruding out from the coastal cliffs rather than being protected by them.

Except in outline and exposure, the two delta plains are quite similar. Both contain several major distributary channels, extensive vegetated inter-levee flats and numerous lakes, some with connecting channels to the distributaries. Like the Babbage, levees in the lower Blow delta are almost indistinguishable, their relief seldom exceeding 0.5 m. Because of its proximity to the Mackenzie, much more driftwood has been stranded on the surface of the Blow delta than on the Babbage. The highest driftwood line on the Blow was formed during a storm surge which reached more than 2 m. above normal high tide and covered considerably more than 50 per cent of the subaerial surface in front of the coastal cliffs.

Texturally, the two deltas are also alike. Fine gravel in the upper Blow delta changes abruptly to silt in the lower (Walker and McCloy, 1969). Organic detritus appears to be more prominent in the Blow than in the Babbage, however. All lower delta plain samples show a high percentage of organics, with low scarps (up to 0.8 m. in height) cut into the vegetated delta-front alluvial islands being composed almost entirely of organic material (Figure 16).

These scarps, together with the absence of significant inter-tidal flats except near the mouths of active distributaries, suggest retreat of the subaerial front of the Blow delta, perhaps even more rapidly than the Babbage. Water depths off the front of the Blow are very shallow, though, so the retreat may depend upon the temporary location of distributary mouths and thus be more apparent than real. At one site near the major western distributary mouth, water depth was less than 1.0 m. out to 1.2 km. off-shore, increased in a series of steps to 2.5 m. at 1.3 km. and was constant at 2.5 m. depth to at least 2.1 km. from shore.

6.2.2 Shingle Region Coastal Cliffs

Cliffed shorelines offer only small areas which are regularly covered by sea water. They are, however, the prime sources of sediment for the major spits to be discussed in the next section of this report. Between Shingle spit and the Blow River delta the coastline is cliffed except at the delta of the Running River. Two areas of this cliff were examined in 1974, primarily for comparison with the Kay Point cliff study.

East of the Running River a largely unvegetated gravel scarp, gulleyed at intervals along its length, rises at an angle of 32-35^{o} to an elevation of 15-20 m. Sediment eroded from this scarp is moved eastward along the narrow beach which fronts it and is the source of gravel found in a sequence of beach ridges on the western Blow River delta. West of the Running River the scarp reaches elevations of more than 30 m. but is

Figure 16. Blow River delta plain, east side; view southeast of organic coastal foreshore scarp. (7 July 1974; GSC 202717-I)

Figure 17. Shingle Point spit; view west; note shoreline pressure ridge at upper right and prominent driftwood line. (21 June 1974; GSC 202717-N)

less steep, mostly vegetated and composed predominantly of silts. Material reaches sea level primarily by mudflows and by erosion in gulleys. This cliff segment is similar in many ways to segment 2 at Kay Point.

6.2.3 Coastal Spits

The three spit areas studied - Shingle, Kay and Nunaluk (Figure 1) - are among the most prominent depositional features found along the Yukon coast. Of these, Kay has already been discussed. Shingle (Figure 17) and Nunaluk are longer, wider and higher (Table II) but are similar in form

TABLE II

Yukon Coast Spit Morphometry

Spit	Length (km.)	Mean Subaerial Width (m.)	Mean Berm Height (m.)	Foreshore[a] Slope	Nearshore[b] Slope
Shingle	5.4	141	1.53	0.085	0.006
Kay	4.9	61	0.96	0.066	0.010
Nunaluk	12.2	163	1.49	0.041	0.017

[a]Berm crest to shoreline

[b]Shoreline to 5 m. isobath

and, with localized exceptions, in the presence of both sand and gravel sediment types. The lower berm elevation of Kay spit may be due to the protection against the dominant southeasterly moving storm waves offered by Herschel Island and the bar between it and Kay Point (Figure 1). It does not appear to be related to nearshore slope (Table II).

Typical subaerial profiles and sediment types for each spit are shown in Figure 15. Four morphologic components (sampling strata) are common to most of the spit zones examined: foreshore, backshore I, backshore II, and lagoon shore. The significance of the surveyed foreshore geometry is difficult to evaluate because the upper portion is relic, undisturbed during the 1974 open water season. Berm elevation over the length of all spits is relatively constant except for a sudden drop from the end of the main Nunaluk spit to the distal islands (Figures 15, 18 and 19). Behind the berm crest, the backshore I stratum consists of washover deposits which overlie older backshore II sediments. The boundary between the two is commonly an abrupt scarp. In the proximal zones of Shingle (Figure 20) and Nunaluk spits, the washover deposits appear to be transgressing, possible evidence of shoreline retreat. The lagoon shore stratum in all cases is lower and displays fewer and smaller ridges than the foreshore because of shallow depths, seldom exceeding 2 m., and short fetch in the lagoons.

Figure 18. Nunaluk spit, proximal end; view west along foreshore storm ridge, berm at far left. (22 August 1974; GSC 202717-E)

Figure 19. Nunaluk spit, second distal island; view west along foreshore. (16 August 1974; GSC 202717-L)

Figure 20. Shingle spit: unvegetated backshore I sediments (washover lobes) advancing over backshore II.
(7 July 1974; GSC 202717)

No consistent pattern of lengthwise variation in mean sediment size is apparent among the spits. Preliminary observations show Shingle to be relatively constant along its length; Kay coarsest at its proximal end and constant thereafter; and Nunaluk (Figures 18 and 19) with a gradual increase toward its distal end and a sharp decrease to almost pure sand on the second and third distal islands. Laterally, the foreshore stratum is both coarsest and most variable. Backshore II is much finer than backshore I with silt commonly present in addition to the usual sand and some gravel. Mean size increases, but not to foreshore levels, on the lagoon shore. These lateral changes are normal for spits at any latitude.

Nearshore bars exist off Shingle as well as off Kay, but are neither numerous nor prominent. No bars were found off the attached segment of Nunaluk spit in 1972 but a complex system of bars and channels existed seaward and between the distal islands, probably due, at least in part, to Firth River discharge (McDonald and Lewis, 1973). As at Kay, little evidence of ice scour was found in the nearshore areas of Shingle and Nunaluk spits, this phenomenon apparently ceasing at about the 10 m. isobath where winter shorefast ice begins (J.M. Shearer, pers. comm.). Nor were significant ice-related sedimentological features observed on the beaches of these two spits in 1974 but Alaskan observations (Hume and Schalk, 1964 and 1973; etc.) and 1972 observations on Kay spit (McDonald and Lewis, 1973) suggest that 1974 was an unusual year in this regard. A major shoreline pressure ridge lay off the proximal half of Shingle spit for most of the summer of 1974 (Figure 17) but, while it undoubtedly moved considerable quantities of sediment in the nearshore, it had no direct effect on the subaerial beach.

7. DISCUSSION

Because the areal extent of 1974 fieldwork represents only part of that covered by Geological Survey coastal investigations in the Beaufort Sea, it seems appropriate in this section to briefly discuss previous work to the east of the Yukon-Northwest Territories border in the context of the Yukon coast results.

The estuarine Babbage delta appeared to be of particular interest because, in a morphologic sense, it is similar to the modern Mackenzie delta. Hydrologically, however, the two are not nearly as similar. Unlike the Babbage, the Mackenzie flows all winter along its full length and is exotic, its break-up and flow being influenced to some extent by non-arctic conditions to the south. But like the Babbage, significant sediment transport events are confined to the break-up and summer flow periods and storm tides on the Beaufort Sea play an important role in deltaic sedimentation.

East of the Mackenzie delta, the northwest coast of the Tuktoyaktuk Peninsula, unlike the Yukon coast, is deeply embayed along much of its length, its shape reflecting the breaching of thermokarst lakes which cover large portions of the coastal plain. Large spits and long barrier bar sequences have formed because of the low offshore gradient, much lower than off most of the Yukon coast. These features protect much of the coast from direct wave attack.

The materials in the spits and bars reflect largely the nature of nearby and underlying deposits. To the south and west of the settlement of Tuktoyaktuk, beach materials are similar to those of the Yukon coast: pebble gravel in medium sand matrix, derived from gravel lenses in fluvial outwash and from a pebbly clay till. To the north and east of Tuktoyaktuk, the gravel disappears and beaches are composed of medium to fine sand eroded from the more distal portions of fluvial and deltaic outwash deposits. Because of the predominance of sand, it can be difficult to distinguish stratigraphically between the depositional features and the underlying outwash (McDonald, Edwards and Rampton, 1973). Stabilized and partially stabilized dune zones are common along this segment of coast.

Like the Yukon coast, the northwest coast of the Tuktoyaktuk Peninsula is retreating, with both rates of retreat and resulting coastal configuration affected greatly by the nature and distribution of frozen ground. This effect is both direct, in that local rates of retreat are greatest where coastal cliff sediments contain considerable ground ice, and indirect, in that the shape of a large part of the coastline is controlled by apparent retreat due to the breaching of thermokarst lakes. Relic submarine frozen ground exists in many nearshore areas (Mackay, 1972; McDonald, Edwards and Rampton, 1973) because of this coastal retreat.

Although steep, cliffed shorelines occupy a much smaller proportion of the total length of the Tuktoyaktuk Peninsula than of the Yukon coast and no major rivers enter the sea along it, the size and number of depositional features suggest, even with the low offshore gradient, a ready availability of sediment. Much of this material is moved northeast, under the control of offshore currents and of discharge from the East Channel of the Mackenzie River. In Kugmallit Bay, the effect of this regional drift on depositional shore features is very weak and these deposits primarily reflect local factors such as wind direction, nearshore bathymetry and coastal orientation. To the east, however, the regional transport direction has more influence and large spits and barrier bars suggest coastal sediment transport northeast to Liverpool Bay.

8. CONCLUSIONS

The main scientific conclusions resulting from this study are:

1. The major geomorphologic features of the Yukon Beaufort Sea coast are: (a) steep coastal cliffs, often containing significant amounts of ground ice, and fronted by narrow beaches; (b) spits and barriers up to 10 or more kilometres in subaerial length and several hundred metres wide; and (c) deltas of coastal plain rivers with vegetated or partially vegetated subaerial delta plains up to 50 $km.^2$ in area.

2. Cliff sediments range from gravel to icy clay. The fine material is moved off shore and beaches, spits and barriers are usually composed of remnant gravels and sands. Coastal plain rivers have gravel beds but this gravel does not reach the lower delta plains where sediments are primarily organic-rich silts and fine sands.

3. Cliff retreat of up to 90 m. in 16-18 years has occurred, largely through undercutting and subsequent block slumping, gulleying, and mud flow associated with ground ice slumps. Sediment derived from this retreat is moved along shore and has led to hundreds of metres of spit and barrier extension over the same time period.

4. Significant sediment transport events are associated with spring break-up and storm floods on the rivers and with meteorological tides and wave activity during these storms along the coast. Berm elevations of over 1.5 m. on spits and driftwood lines more than 2 m. above normal high tide on subaerial delta plains attest to the rise in sea level and inundation of coastal depositional features during these storms, most commonly in the summer and fall but occasionally during the winter.

5. First flow in rivers, deltas and estuaries occurs well before sea ice break-up and is commonly over bottomfast winter ice. This ice inhibits bed scour during early flooding. Following spring break-up, river discharge declines except for brief rises during storm events.

6. The direct effects of sea ice on the stability of coastal features appear to be small. Only minor examples of the movement of beach sediment by ice push and scour of the nearshore sea bed by ice have been observed, this latter phenomenon apparently ceasing shoreward of the 10 m. isobath. Indirect effects, particularly the influence of the amount and location of ice on storm surges and associated wave activity, are much more important.

7. Offshore gradients can be quite steep off many portions of the Yukon coast, most commonly where the shoreline is cliffed. Profiles are generally concave upward and few nearshore bars exist. Off river deltas, though, depths are very shallow, seldom exceeding 2 m. a kilometre or more from shore. Shallow depths in the Babbage estuary prevent the development of significant vertical variations in water temperature and salinity.

8. Rapid coastal retreat, shallow water depths and low water temperatures have enabled the preservation or formation of permanently frozen ground beneath estuary and nearshore areas.

9. Unlike the Yukon coast, the northwest coast of the Tuktoyaktuk Peninsula is deeply embayed along its length, its shape reflecting the breaching of thermokarst lakes which cover large portions of the coastal plain. Major spits and long barrier bar sequences have formed because of the much lower offshore gradient than off the Yukon coast. Sediments in coastal depositional features are mixed gravels and sands west of the settlement of Tuktoyaktuk and, most commonly, pure sand east of Tuktoyaktuk. Like the Yukon coast, the shoreline of the Tuktoyaktuk Peninsula is retreating, with most of the derived sediment being moved northeast toward Liverpool Bay.

9. IMPLICATIONS AND RECOMMENDATIONS

9.1 General Scientific

In an average year, the southern Beaufort Sea coast, particularly east of Herschel Island, has a relatively long open water season and cannot be considered true arctic in nature. Normal marine processes dominate for about three months of the year. During this time period, the arctic environment influences these processes only through the increased relative importance of extreme storm events, the occasional movement of sea ice near shore during these events and, as was so well demonstrated during the summer of 1974, through the major year to year variations in climate and sea ice conditions which may occur.

The response of coastal materials to summer marine processes, however, is conditioned by the arctic environment. Frozen ground plays an important role in the coastal zone, most importantly through its influence on rates of coastal retreat and, along the Tuktoyaktuk Peninsula, through the control of thermokarst lakes of coastal configuration.

9.2 Matters Relevant to Development

Development is considered here primarily with respect to the potential effects on the Beaufort Sea coastal zone of an oil spill during exploratory offshore drilling. Consideration is given as well, however, to the possible use of the coast for staging areas or other shore installations associated with petroleum exploration and development.

The details of coastal processes and responses, particularly for short-period events, are not yet well understood in the Beaufort Sea area.

The studies undertaken at Kay Point will go far toward remedying this situation. The discussion which follows, however, precedes the completion of these studies and its value must be considered in the context of this knowledge.

1. The coastal zone is a dynamic one, particularly so in this part of the Arctic where shore materials are unconsolidated and often contain significant quantities of ground ice. Its instability must be taken into account in considerations of both oil spills and coastline development.

2. The largest areas subject to frequent inundation by sea water and thus, potentially, by oil in that water are the river deltas, particularly the Mackenzie itself and, along the Yukon coast, the Blow and Babbage deltas. These deltas have a high silt content and their sediments are frozen to considerable depths. Thermal disturbance through vegetation damage could lead to considerable consolidation. Because the delta plains are major wildfowl nesting areas, oil must be prevented from reaching them.

3. Oil is most likely to reach the coast during summer and fall but open water and wave activity are possible even during winter. The sea ice was broken up off Kay Point and the Babbage estuary flooded during a severe storm in early January 1974 (R. Mackenzie, pers. comm.).

4. Shoreline materials are constantly in motion during the open water season and, with the continuous possibility of storm surges, oil from a spill could cover depositional coastal features at any time, be buried by subsequent sediment accumulation, exposed again, transported along the shore, re-buried, and so on.

5. In the event of an oil spill approaching the coastline, it may be possible to use lagoons behind spits and bars or, along the Tuktoyaktuk Peninsula, breached thermokarst lakes to contain it. The resultant potential for destruction of fish and wildlife is critical to this suggestion but, if other methods of containment are less reliable or cause even greater destruction, use of natural features may become viable.

6. Shore installations must be carefully located so as to avoid areas where large amounts of ground ice are present. Disturbance of the ground thermal regime will only serve to further increase already rapid rates of coastal retreat. Construction off shore must take into account the likely present of and, because of low sea water temperatures, the possible growth of sub-bottom frozen ground.

7. Beach material is primarily local in origin, its maximum travel defined by the distance to the outer boundary of the feeder area of the near-shore sediment sink toward which it is moving. Removal of material or blockage of longshore drift for construction purposes will have effects both up- and down-drift. Because disturbance at one construction site may

affect conditions at another, final selection of sites should be made only after the detailed nature of sediment supply in the area is known.

10. NEEDS FOR FURTHER STUDY

Work which has been completed to date has largely been descriptive in nature. Both the Yukon and Tukotyaktuk Peninsula coasts have been covered in some detail. There remains possibly the most critical area of all: the modern Mackenzie delta below the highest storm surge driftwood line and the rapidly retreating Pleistocene islands which border it. Field operations will be more difficult to carry out in this area but should be completed before any judgements on the susceptibility of the Beaufort Sea coast to oil spills are made.

The second important gap in present knowledge has been mentioned several times in this report: the lack of information on the details of sediment movement during short-period storm events. Data on this question will be available following the completion of the Kay Point process-response study in 1977.

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12. APPENDIX: Physical Aspects of the Beaufort Sea Coast.
Prepared Testimony Presented to the
Mackenzie Valley Pipeline Inquiry, February 13, 1976.

Introduction

1. My intention is to discuss those physical aspects of the Beaufort Sea coast which might be important in any plan to develop hydrocarbon resources offshore.

2. In this development I include both construction and operational requirements: for example, pipelines coming ashore, harbour development, staging facilities, and the coarse aggregate mining necessary for their construction.

3. Because any pipeline from offshore will probably need to move crude oil as well as gas, the consequences of an oil spill are also relevant.

The Coastal Zone

4. For the purposes of this discussion I have defined the coastal zone as the area between the highest storm tide line on land (about 3 m. above mean sea level) and the 10 m. water depth (commonly assumed to be the seaward limit of bottom material movement by waves).

5. The effects of development in this zone are of particular importance because it contains large bird and fish populations and is the part of the Beaufort Sea most used by man at the present time.

Slide 1*

(Map of Southern Canadian Beaufort Sea Coast)

6. The length of coast with which I am personally familiar and which I will consider today extends from the Alaskan border to the eastern end of the Tuktoyaktuk Peninsula at Cape Dalhousie.

7. The topics I intend to cover include: the effects of an Arctic environment, nearshore water circulation, storm surges, coastal landforms and materials, and coastal stability - all set in the context of the influence they should have on the type, extent and location of facilities associated with hydrocarbon resource development.

Effects of an Arctic Environment

8. It is, I think, important to realize that the area under discussion is, in some senses, not "true Arctic" in nature. The open water season, particularly where the influence of the Mackenzie River is felt, is long by arctic standards. For 3 to 4 months a year there can be tens or even hundreds of miles of open water on which wind can generate waves to cut back the coast.

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*Black and white prints of colour slides used during presentation of this testimony are included at the end of the text.

9. The response of coastal materials to wave attack is, however, "true Arctic" in nature. Frozen ground plays an important role in the coastal zone. Unlike areas such as the Canadian west coast, coastal materials along the Beaufort Sea are unconsolidated. No bedrock is present. But because this unconsolidated material is permanently frozen and contains considerable ground ice in many locations, both the nature and rates of coastal change differ considerably from what they might be in a more temperate climatic setting.

10. The net effect of these factors is complex. Because of the long open water season and the unconsolidated nature of the coastal materials, the entire coastline is retreating. The rate of retreat, however, is controlled to a large extent by the nature, amount and location of ground ice in the sediments. Where the coast is composed of coarse sands and gravels, the frozen nature of the materials may slow down wave erosion. But where large amounts of ground ice are present, retreat will be even more rapid than if the materials were unfrozen.

11. From the development point of view, these factors are critical. Facilities must contend with both an active summer marine environment and the presence of frozen ground - a situation for which there is no parallel in past hydrocarbon development.

Nearshore Water Movement

12. The patterns of water movement in the coastal zone are quite different from the offshore circulation. As you will see, they are very relevant to the effect an oil spill might have on the coast.

Slide 2

(Topkak spit)

13. Because the nature of the Beaufort Sea coast has been conditioned by the relatively rapid erosion and redistribution of the materials of which it is composed, the position and orientation of resultant depositional features, like this spit just north of Tuktoyaktuk, can be used to infer the dominant direction of sediment movement and thus the dominant longshore current direction at any location where they are present.

14. Please note that I use the term dominant direction. I don't mean to imply that this is the only direction in which nearshore currents can flow. It is probable, though, that the dominant directions are those in which oil would move during major sediment transport events, that is to say during summer and fall storms when low lying areas could be flooded by the sea level rises associated with strong onshore winds, and thus would be open to inundation by oil.

Slide 3

(Map of Southern Canadian Beaufort Sea Coast)

15. I have plotted dominant current directions for the Beaufort Coast on this map as black arrows and, on the basis of these directions, I've divided the coast into segments. Each segment consists of a sediment sink toward which sediment is being moved and the contributing source area. The segment boundaries are indicated by the light lines on the map and each segment (there are 11 in all) is labelled by the black letters on light backgrounds.

16. The importance of this segmented circulation pattern is that, particularly during storm events, oil reaching the nearshore zone will tend to remain within the coastal segments I have identified and to move toward the sediment sink of each segment.

17. It might appear attractive, as well, to locate shore installations having a high potential for spillage in the sink areas. Unfortunately, however, because these areas are sediment as well as potential oil sinks, they tend to be very shallow and to contain spits and lagoons that make them favorite locations for fish and shore bird populations.

Storm Surges

18. I have already mentioned sea level rises associated with strong onshore winds during summer and fall storms; these rises are sometimes called storm surges.

19. Based on an examination of tide gauge records at Tuktoyaktuk, Dr. R.F. Henry of Ocean and Aquatic Affairs, DOE identified 22 surges which caused water level rises of more than 1 m. between 1962 and 1973, including 2 which caused rises of more than 2 m. A September 1970 storm, for which no tide gauge data are available, may have caused a rise of as much as 3 m. at Tuktoyaktuk.

20. These surges are of importance for several reasons: first, waves associated with them cause much of the erosion and longshore sediment movement which occurs along the Beaufort Sea coast, a topic I will discuss later; and, second, they lead to the inundation of low-lying coastal areas by sea water, water which might contain oil in the event of a spill.

Slide 4

(Kay Point Spit; June 21, 1975)

21. This view is of Kay Point spit on the Yukon coast. The spit is about 5 km. long and its crest is about 1 m. above normal mean sea level.

Slide 5

(Kay Point Spit; Aug. 10, 1975)

22. This view is identical to the last one, but taken during a relatively minor storm surge which occurred in August 1975.

Slide 6

(Map of Southern Canadian Beaufort Sea Coast)

23. Of even greater extent than the spits, bars and beaches are the low lying delta areas of the Beaufort Sea coast, all major wildfowl nesting and staging areas, which could be inundated by a storm surge and by oil or other pollutants contained in the water.

24. Driftwood lines on the Mackenzie delta indicate that the outer delta could be inundated by an extreme surge as far south as the lower black line (3) on this slide, a line which represents the location downstream from which channel banks, the highest parts of the delta plain, are lower than 3 m.

25. This is an area of almost 3900 sq. km., which, if it were square, would have sides over 60 km. long. About 20% of the area is covered by shallow lakes in which pollutants could be dropped and, of this area, almost 30% or 223 sq. km. is connected by channels which eventually reach the sea. Pollutants could be carried into this type of lake even by surges which were not high enough to flood the delta surface.

26. Exactly how far up delta sea water might penetrate during a surge is dependent upon the influence of river flow as well as upon surge flooding. To my knowledge no research has been undertaken into water circulation patterns over flooded areas of the delta but Dr. Henry's storm surge studies suggest the possibility that sea water and associated pollutants might be drawn in on the Shallow Bay side and river water diverted out East Channel (Technical Report No. 19 for the Beaufort Sea Project).

Coastal Landforms and Coastal Materials

27. Let us move now to a discussion of the major landform types found along the Beaufort Sea coast and of the importance of their nature to development.

28. Within each of the coastal segments I have defined, one or more of the following types of landform dominate the coastline:

   a. Steep cliffs, often containing significant amounts of ground ice, and fronted by narrow beaches;
   b. Thermokarst lakes breached by coastal erosion;
   c. Spits and barriers up to 12 km. in length and several hundred metres wide; and lastly
   d. River deltas, particularly that of the Mackenzie, one of the largest deltas in the world.

A. <u>Coastal cliffs</u>

29. Of these landforms types, coastal cliffs occupy the largest portion of shoreline in all coastal segments except for the modern Mackenzie delta and the eastern end of the Tuktoyaktuk Peninsula.

30. High and steep cliffs are more common along the Yukon coast than along the lower-lying Tuktoyaktuk Peninsula where a relatively small offshore gradient decreases the effectiveness of wave erosion.

31. The cliff form is largely a function of the materials of which it is composed. Gravel and sand dominate along the Yukon shoreline but layers of silt and clay are common. Gravel is also common along the Tuktoyaktuk Peninsula west of Tuktoyaktuk, but sands and silts prevail to the east.

Slide 7

(Sand bluffs at the mouth of East Channel)

32. Where the material is coarse, cliffs tend to be steep but not vertical, like this sand bluff near Kittigazuit at the mouth of East Channel,

Slide 8

(Cliff at Tuktoyaktuk)

or the sandy gravel cliff at Tuktoyaktuk itself.

Slide 9

(Cliff at Running River mouth)

They may even be vegetated like this one near Shingle Point on the Yukon coast.

Slide 10

(Vertical bluffs at Kay Point)

33. Where the material is fine-grained, on the other hand, the cliffs will be vertical like this one near Kay Point,

Slide 11

(Multi-cyclic ground ice slump area near Tuktoyaktuk)

and if the fine-grained material contains large thicknesses of massive ground ice, ground ice slumps like this one just west of Tuktoyaktuk,

Slide 12

(Exposed massive ice in ground ice slump of Kay Point)

or this one at Kay Point, will develop. The banded material in the centre of this slide is almost pure ice.

34. These cliffed areas may seem desirable as locations for harbours, staging areas, etc. because their tops are well above storm surge levels, water depths offshore from them are usually relatively deep, and, if the cliff material is coarse, a suitable source of construction material is close at hand.

35. But the nature of the cliff material is critical. The most ideal location for a deep water port along the southern Beaufort Sea coast might seem to be in the area of Babbage Bight just east of Kay Point because water depths close to shore are deep. The cliffs in this area, however, are fine-grained and contain considerable massive ice. Vertical bluffs and ground ice slumps predominate. Hardly an ideal location for land facilities associated with a harbour.

36. The presence of frozen ground and massive ice is also relevant to any pipelines which might come ashore in cliffed areas.

Slide 13

(Undercut bluffs at Kay Point)

In areas like this one near Kay Point massive ice bodies extend below sea level and out under the shallow water near shore. Wave erosion during the August 1975 storm I mentioned previously cut a niche at the base of the cliff and exposed the ice behind. This, incidentally, is exactly the situation which exists along the cliffs which front Tuktoyaktuk and is the major reason why it will be so difficult to stabilize the cliffs there. A hot oil pipeline would be subject to failure under these conditions.

B. <u>Thermokarst Lakes</u>

37. In addition to the coastal cliff areas, there is a second type of coast-line in the southern Beaufort Sea which is basically erosional in nature.

Slide 14

(Phillips Island Photomosaic)

This photomosaic is typical of large parts of the coast along the Tuktoyaktuk Peninsula, particularly east of McKinley Bay.

38. At first glance the coastline appears drowned, but in fact, its outline reflects the breaching by coastal erosion of the lakes which cover much of the Peninsula. These lakes are commonly thermokarst in origin, resulting from ponding and resultant differential melting of excess ice in the sands and silts which form their boundaries.

39. Breaching leads to at least partial draining of the lakes and, if this drop in water level is sufficient to enable the lake to freeze to the bottom in winter, to the formation of pingos. The "two-pingo lake" on this slide is about 1 m. deep.

40. As erosion continues, the former lake area is deepened, partly because of wave action and partly because of continued melting of excess ice in the sediments. The area between the barrier bar and the "two pingo lake" on this slide is flat-bottomed and about 2 m. deep but low frequency echo sounding shows an irregular sub-bottom, generally less than 3 m. beneath the present bottom. This sub-bottom may represent the boundary between recent wave-deposited sediments and the older and perhaps still frozen coastal plain deposits beneath.

41. In any case, a newly breached lake provides an excellent trap for an oil spill. Oil could be carried into a lake during normal flood tides or storm surges.

Slide 15

(Two-Pingo Lake)

Granted the oil might be pulled out again by ebb currents. Unfortunately, the eastern end of the Tuktoyaktuk Peninsula, where breached lakes are most numerous, is also the only coastal segment, except for river deltas, which contains extensive tidal flats. This slide shows exposed tidal flats in and near the "two-pingo lake" of the last photograph.

C. Spits and barriers

42. Let us turn now to the depositional features found along the Beaufort Sea coast.

Slide 16

(Warren Point barrier)

Spits, like the ones I have already shown you at Topkak and Kay Points, and barriers, like this one at Warren Point on the Tuktoyaktuk Peninsula, front significant portions of most of the coastal segments I have identified.

43. They are particularly extensive near Herschel Island on the Yukon coast, around the old islands (Pelly, Hooper, etc.) which front the eastern Mackenzie delta, and from Warren Point east on the Tuktoyaktuk Peninsula. In these areas they reach lengths of more than 12 km. and widths in excess of 200 m.

44. As I have already mentioned, they lie, in their entirety, below the highest storm tide line and thus are susceptible, at any time, to inundation by oil. As well, the shallow lagoons behind them could function in much the same way as thermokarst lakes and act as traps for oil.

45. The size of spits and barriers is a function of both offshore gradient and sediment supply. They are largest where offshore water depths are small as they are off the Mackenzie delta and the Tuktoyaktuk Peninsula, or where the supply of sediment is large as it is in the Herschel Island area where material from the Firth and Malcolm rivers is added to that supplied by cliff erosion.

46. Their height and cross-sectional form, on the other hand, are at least partially dependent on sediment size.

Slide 17

(Nunaluk spit, proximal end)

The sandy-gravel spits and barriers of the Yukon coast and west of Tuktoyaktuk on the Tuktoyaktuk Peninsula tend to be higher and narrower than pure sand features east of Tuktoyaktuk. This portion of Nunaluk spit near Herschel Island rises over 2 m. above sea level,

Slide 18

(Atkinson Spit, proximal end)

whereas this sand spit at Atkinson Point reaches a maximum elevation of less than 1 m.

47. The gravel in coastal beaches, spits and bars and their easy accessibility from the sea makes them attractive sources for borrow materials. They are not thick, however. Both drilling and low-frequency sub-bottom echo sounding suggest that significant gravel deposits seldom extend more than 4.5-6.0 m. below the surface, either on land or near shore.

D. <u>River deltas</u>

48. Deltas represent the continuing ability of a river to supply and deposit sediment more rapidly that it can be removed by sea waves and currents. In the case of the Mackenzie delta, the ability of the Mackenzie River to dominate the Beaufort Sea has led to the development of a gently sloping delta plain of almost 13,000 sq. km. in surface area.

49. Of this surface area, as I have already mentioned, about 3900 sq. km. may be subject to inundation by storm surges and thus is properly part of the coastal zone. But even this outer delta is river dominated. The clays, silts and fine sands of which it is composed are almost entirely riverine in origin. The manner in which these sediments are deposited, however, is greatly influenced by coastal processes.

Slide 19

(Outer Mackenzie delta)

50. The most important features of the outer delta plain are the shallow, wide distributary channels; the low, flat vegetated plains which separate the channels; and the lakes which dot the plains. This slide, looking south from the shoreline, includes examples of each. Except for the lakes, the pattern you see is common on most fine-grained deltas in the world.

51. The myriad of lakes on the Mackenzie delta plain are testimony to the effects of an arctic environment: specifically to the relatively low plant productivity of arctic areas and to the presence of frozen ground.

Slide 20

(Organic scarp, Mackenzie delta front)

52. Outer delta sediments are organic rich. This scarp at the front of the delta is largely organic in nature. But this richness is only relative. On deltas in more temperate climates, lakes are a very short-lived feature of delta plains. They are very quickly infilled by plant debris. This rapid infilling does not occur in the Arctic.

53. Frozen ground also plays an important role in lake formation and evolution. The most significant aspect of this role may be in the effect of freezing on the material consolidation or settlement of delta sediments under their own weight.

54. The argument I am about to make is pure speculation. It is not based on hard data but I will present it because of the implications it might have for development on the delta surface and for a pipeline across Shallow Bay.

55. A delta is not only a product of the balance between the river and the sea but also of the balance between river deposition and subsidence. On the Mississipi delta, buried deposits which were above sea level less than 500 years ago are now as much as 20 m. below sea level, solely because of sediment consolidation under its own weight.

56. On the Mackenzie delta, however, the ground begins to freeze as areas are built up to near sea level. Natural consolidation will be stopped at the point in time at which the sediment freezes. If permafrost aggradation is rapid, the frozen sediments at depth will be under-consolidated with respect to the weight of the material over them. Added to this is the continuing addition of new weight in the form of deposition on top of the delta plain.

57. If this frozen ground is thawed for any reason, natural or otherwise, consolidation can begin again. On the outer delta plain, numerous lakes appear to have formed in areas of low-centred ice-wedge polygons, possibly because of water ponding, subsequent permafrost degradation and consolidation.

58. The bottoms of most lakes on the outer delta are above sea level at the present time. But in the Aklavik area, a much older and higher part of the delta, lakes whose bottoms are below present sea level have been reported. That this could occur in spite of infilling during river floods and deposition of organic debris may indicate continuing consolidation of the unfrozen sediments beneath the lakes.

59. Even in the absence of excess ice, then - and there is a little in the sediments of the outer delta plain - thaw consolidation remains an important problem. I am curious, as well, as to what effect natural consolidation might have on a pipeline across Shallow Bay - an area which, because of the presence of frozen ground at depth beneath it, may be a subsiding older part of the Mackenzie delta plain. If the rates are in the range of those found in the Mississipi, and I would guess they will be much lower, consolidation of anywhere from 0.5 to 1.2 m. could occur over a 30-year period.

60. Elsewhere along the Beaufort Sea coast, deltas occupy only a small proportion of the coastal zone. There are none at all on the Tuktoyaktuk Peninsula, although the Peninsula, itself, is composed largely of material deposited in an old Mackenzie delta.

Slide 21

(Blow River delta Plain)

61. Along the Yukon coast the deltas of the Blow and Babbage rivers are similar in form and sediment composition to the Mackenzie but are much smaller: the Blow delta plain covers only 50 sq. km. and the Babbage 25 sq. km. This slide looks north over the Blow delta plain toward the Beaufort Sea.

Slide 22

(Babbage delta during flood)

62. Unlike the Mackenzie, however, both delta plains can be covered in their entirety by storm surges. This view of the Babbage delta during spring river flooding could be repeated at any time during the summer by a major storm surge.

Slide 23

(Firth River fan delta)

63. The relatively steep, gravelly fan deltas of the Firth and Malcolm rivers, on the other hand, do not flood signficantly during storm surges and thus are not as vulnerable to the effects of an oil spill. They also do not contain the low, fine-grained, frozen alluvial flats I mentioned earlier and would not be subject to significant thaw consolidation. This view of the Firth delta shows the aufeis deposits already much discussed in these hearings. Possible borrow pit operations on these deltas have also been covered in earlier testimony.

Coastal Change

64. I have left until the end any detailed discussion of the nature and rates of change of the landforms of the Beaufort Sea coast because I consider coastal stability to be the single most important factor in relation to possible development activities.

65. Under the influence of wave action, particularly during storm surges, the coastal cliffs within each coastal segment I have identified are being cut back and the material moved along shore and deposited, either in the form of spits and bars in the case of coarse sediment or offshore in the case of finer sediment. The coastline is thus a very dynamic environment and, if the design of onshore installations or pipelines from offshore does not take this into account, they will eventually fail.

66. Cliff retreat is most rapid where offshore gradients are steep and where cliff sediments contain considerable pore, wedge or massive ice.

Slide 24

(Kay Point, undercut cliff)

Photogrammetric measurements show that this undercut bluff at Kay Point retreated almost 90 m. between 1952 and 1970. Retreat of 10-50 m. over the same period occurred along most of Babbage Bight, east of Kay Point. Other zones of rapid cliff retreat include the Herschel Island area, the old islands (Pelly, Hooper, etc.) which front the Mackenzie delta, and the Tuktoyaktuk settlement area.

67. The way in which retreat occurs is unique to an Arctic environment and is largely a function of features related to frozen ground. The headwalls of the ground ice slumps I showed you earlier are very rapidly receding: we have measured over 10 m. of retreat in a single year on one.

Slide 25

(Block slumping near Kay Point)

68. Elsewhere, undercutting by waves and melting along ice wedge cracks can cause entire polygon blocks to collapse into the sea. This view was taken near Kay Point this past summer,

Slide 26

(Slumped polygon block, ice-wedge fracture)

and this is a close-up of the fracture zone at the back of the slumped blocks showing the exposed wedge ice.

69. The implications for development of these rates of retreat and of the way in which it occurs must be obvious. I should add only that the rates of retreat are not constant either seasonally or annually. Most retreat occurs during storm surges; 13 m. of land was lost near the RCMP station of Tuktoyaktuk during the major 1970 storm, almost one-quarter of the total retreat between 1950 and 1972.

70. It will be tempting to obtain sand and gravel for construction purposes from the coastal beaches, bars and spits where continued coarse sediment movement from cliff retreat promises rapidly replenished supplies of high quality aggregate. Spits have extended as much as 700 m. in length between 1952 and 1970 (Nunaluk spit).

71. In addition to the biologic consequences that may make extraction of this gravel unsuitable, there are a number of things which should be known before permits to mine gravel are granted.

72. Material supplied to the beaches, bars and spits is in continuous movement along the shore. Extracting gravel will tend to accelerate nearby shore erosion, particularly in the downdrift direction, and the effects of this must be determined. For example, if sand were taken from the beaches north of Tuktoyaktuk the supply to the beach which fronts the townsite would be interrupted and the coastal cliff there would retreat even more rapidly than it already is. A permanently dredged deep channel into Tuktoyaktuk Harbour would have the same effect unless the dredged material was pumped out downdrift from the channel.

73. The sources of material in the beaches is primarily local in nature. Little coarse sediment will move between the coastal segments I have identified. In some segments, the spits and bars may be relic in nature and material, once removed, will not be replaced. For example, Avadlek spit on Herschel Island was formed from sands and gravels supplied by deposits on the north and west sides of the island, deposits which no longer exist because of cliff retreat.

74. The dynamic nature of beaches, spits and bars is also relevant to the effect oil from a spill might have on them. During the small August 1975 storm surge, the beach surface along the spit at Kay Point was cut down by as much as a 0.3 m. and later reburied by almost the same amount of sand and gravel. Thus oil on these features could be buried at any time.

75. In direct contrast to the coastal cliffs and to the beaches, spits and bars, the delta plains of the Beaufort Sea coast, including that of the Mackenzie, are remarkably stable in nature.

76. Examination of aerial photograph sites spaced over a 22 year period revealed little shoreline advance along the front of the Mackenzie delta and no evidence of major channel shifts on the outer delta plain.

Slide 27

(Mackenzie delta shoreline)

In fact, as this slide of the delta shoreline shows, many areas have undergone minor retreat.

77. The rate of advance of a delta plain is dependent to a great extent on the balance between river and wave forces. Wave power at the shoreline, in turn, is dependent upon deep water wave conditions and the offshore gradient. Because the Beaufort Sea is frozen for much of the year and because the offshore gradient of the Mackenzie delta is one of the flattest of any major river delta in the world, we might expect that the total annual wave power exerted in the deltaic coastal zone would be very low in comparison with other major river deltas.

78. Under these conditions the Mackenzie delta should be advancing rapidly - but it is not. The only explanation must be that river power is also low and, now that the river has filled the protected trough between the Caribou Hills and the Richardson Mountains, it is not powerful enought to overcome the erosive wave energy of the open Beaufort Sea.

79. The lack of major channel shifting on the outer delta plain may also be related to low river power. This effect is accentuated by the number of channels which discharge into the Beaufort Sea - almost 60 with a total width of over 30 km. This division of a given amount of river power leaves no single channel with enough to actively erode its banks, particularly since they are frozen and therefore resistant to erosion.

80. This horizontal stability is, in itself, a simplifying factor for possible facilities associated with hydrocarbon development. From this point of view, only, construction which would be unfeasible on most other deltas in the world may be possible on the Mackenzie. There are, of course, other points of view, some of which I have discussed, which make the delta less attractive than horizontal stability considerations alone might suggest.

81. The last aspect of coastal change I wish to discuss is the direct effect of sea ice on the coastal zone and on the resultant need for careful selection of locations for the construction of nearshore facilities such as wharves and jetties. I think this can best be done with a slide and a question.

Slide 28

(Shoreline pressure ridge, Shingle Point spit)

Would you want to be a wharf or a jetty in the path of this 10 m. high shoreline pressure ridge?

Conclusions

82. To briefly summarize and conclude, then:

a. The coastal zone is, in most areas, a dynamic area, particularly so in this part of the arctic, and its instability must be taken into account if it is to be used for pipelines, staging areas or other shore installations.
b. Shore installations must be carefully located so as to avoid areas where large amounts of ground ice are present. Disturbance of the existing thermal regime will serve only to accelerate already rapid rates of coastal retreat.
c. Beach material is primarily local in origin and its removal will lead to increased coastal erosion. As a general principle, therefore, I would recommend that beaches not be considered as sources of construction material.
d. There are very few good harbour locations along the Beaufort Sea coast because of generally low offshore gradients, coastal instability and resultant longshore sediment movement.
e. The hazards of liquid pollutant spills from shore operations could be minimized if these activities take place in bays or lagoons behind spits or barrier bars.
f. Deltas are among the most complex active environments in the world because of the interaction between river and sea forces. The effects of an Arctic environment must be added to normal deltaic processes on the Mackenzie delta and these effects are not well understood. Because of this great complexity and because the Mackenzie delta is a unique North American environment, I would recommend that development on it be kept to a minimum.
g. Oil from a spill reaching the nearshore in a given coastal segment will tend to remain in the segment and to move toward its sediment sink.
h. The largest areas subject to frequent inundation by sea water and thus, potentially, by oil contained in that water are the river deltas, particularly the Mackenzie. Thermal disturbance through vegetation damage could lead to considerable thaw consolidation, even in the absence of excess ice. Other susceptible coastal features are beaches, spits and barriers and breached thermokarst lakes.

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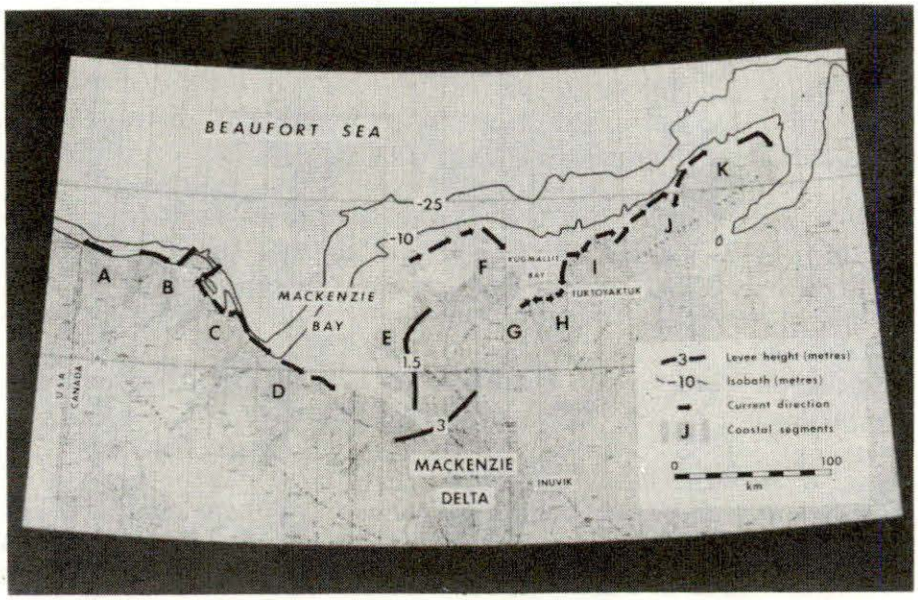
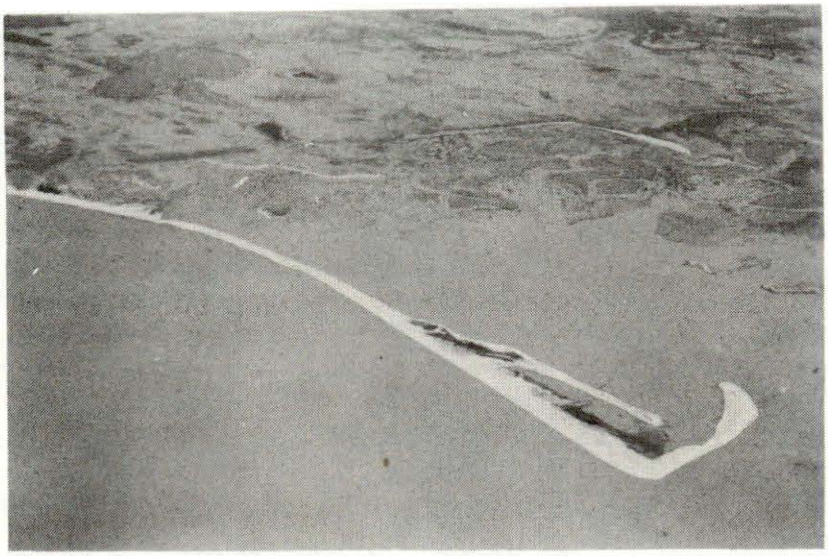


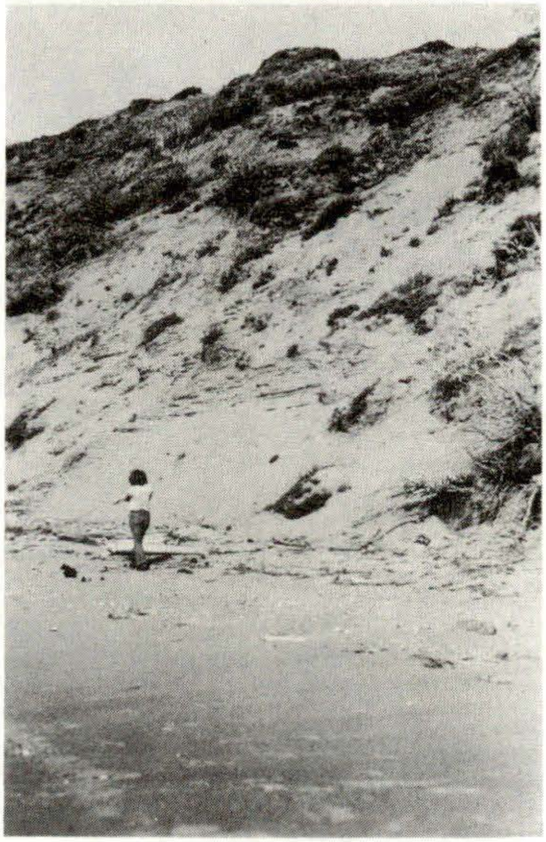
Slides 1,3 and 6. GSC 202773-R



Slide 2. GSC 202925-X

Slide 4. GSC 202958-S

Slide 5. GSC 202958-O



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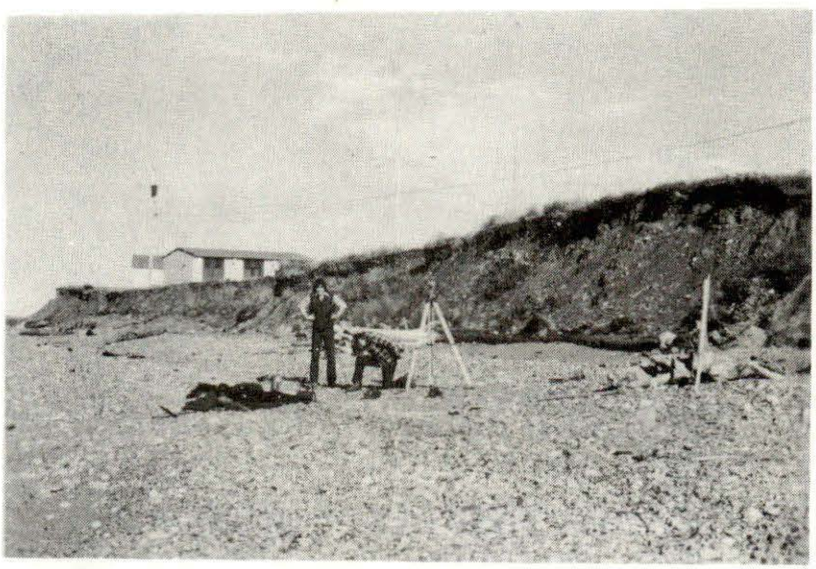
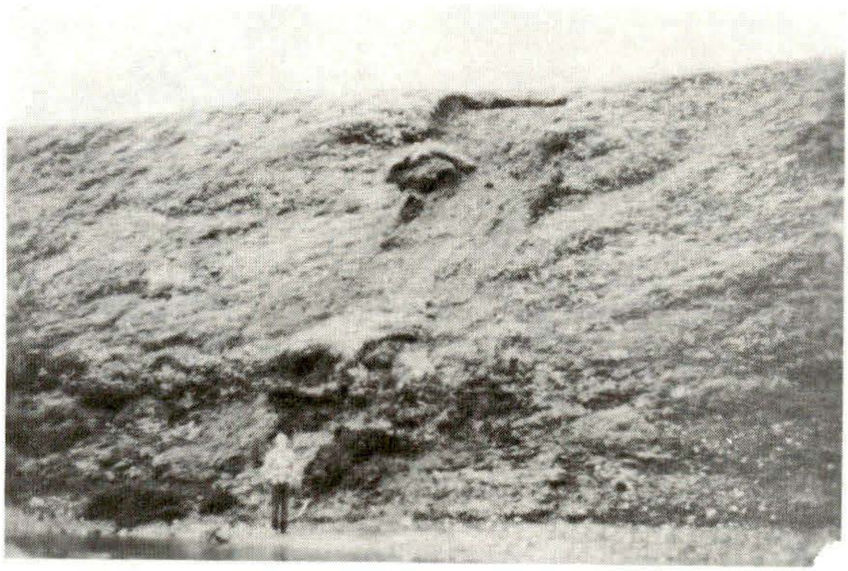


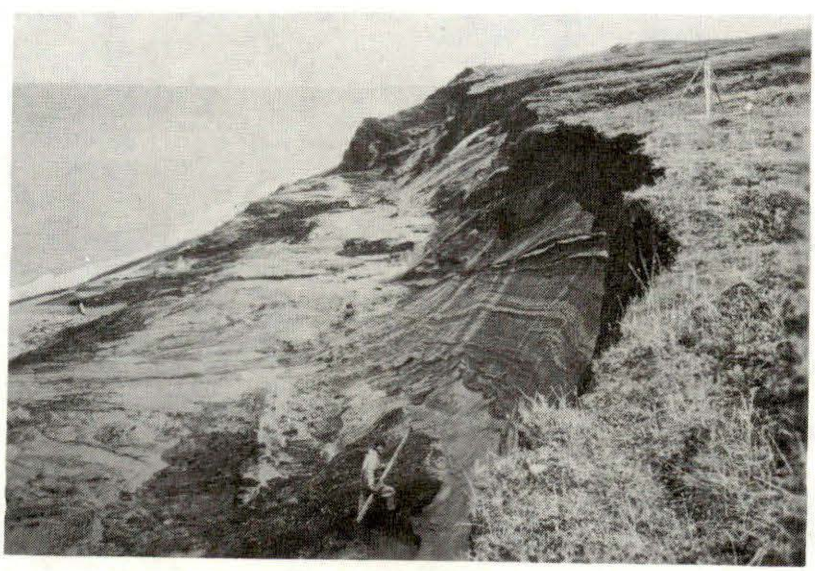
Slide 8. GSC 202925-T



Slide 9. GSC 202773-M

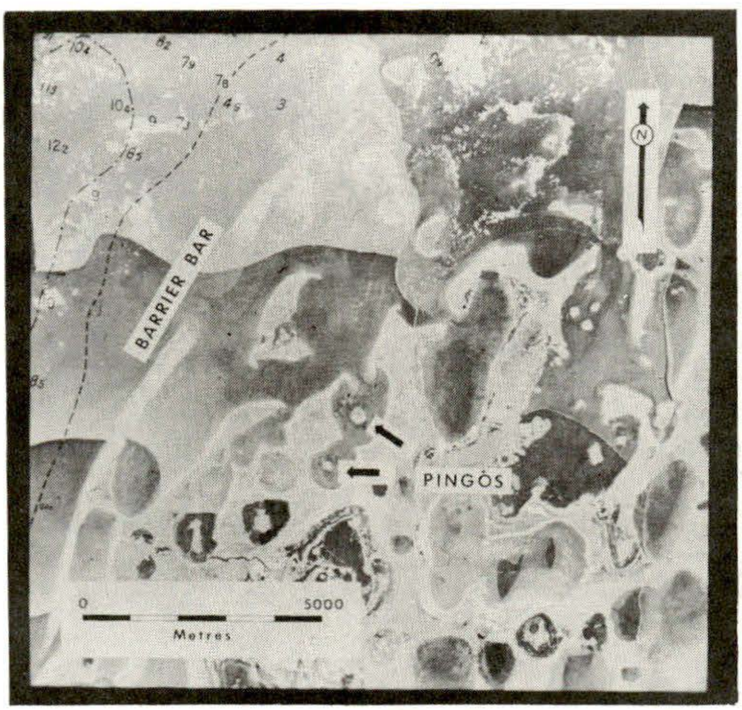
Slide 10. GSC 202960-M

Slide 11. GSC 202773-N



Slide 12. GSC 202959-Y

Slide 13. GSC 202959-N



Slide 14. GSC 202773-S

Slide 15. GSC 202925-W

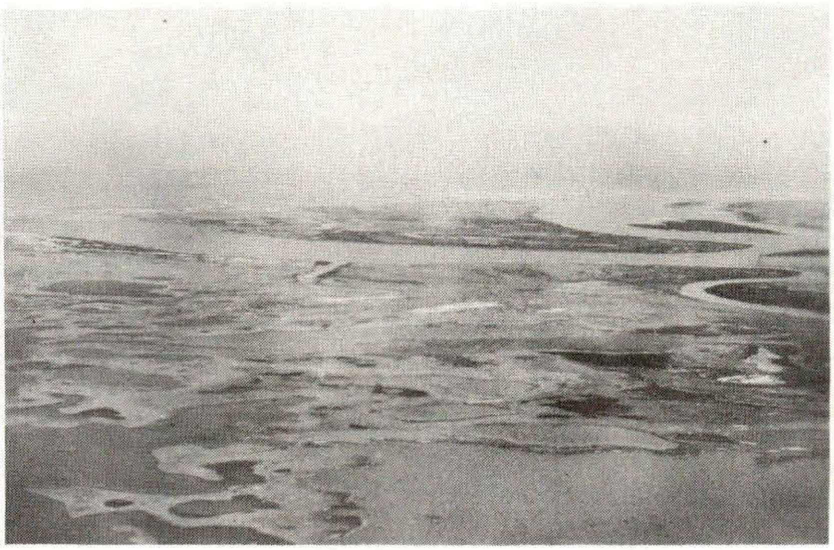
Slide 16. GSC 202773-P

Slide 17. GSC 202717-E

Slide 18. GSC 202925-Y

Slide 19. GSC 202925-U

Slide 20. GSC 202925-V



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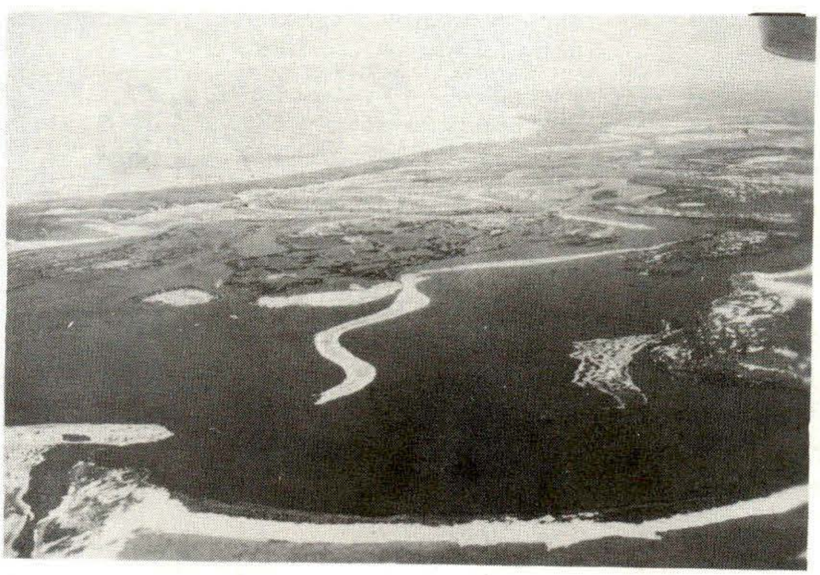


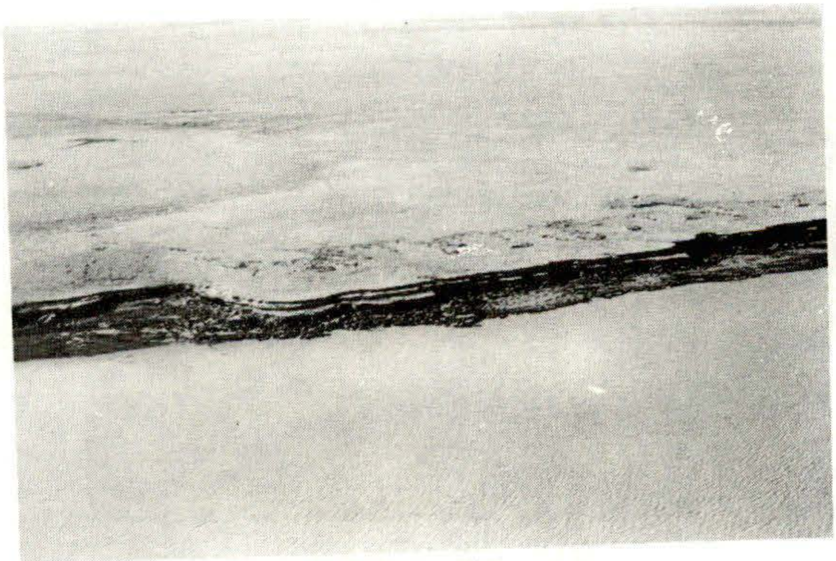
Slide 22. GSC 202717-J

Slide 23. GSC 202717-Y

Slide 24. GSC 202717-A

Slide 25. GSC 202958-U

Slide 26. GSC 202959-K



Slide 27. GSC 202925-Z

Slide 28. GSC 202925-S