ENVIRONMENTAL GEOLOGY AND GEOMORPHOLOGY OF THE BARRIER ISLAND-LAGOON SYSTEM ALONG THE BEAUFORT SEA COASTAL PLAIN FROM PRUDHOE BAY TO THE COLVILLE RIVER

by

P. Jan Cannon and Stuart E. Rawlinson

Division of Geosciences
University of Alaska
Fairbanks, Alaska 99701

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INTRODUCTION

Purpose and Scope

Natural geological conditions and processes, termed here environmental geology, are best indicated by the landforms, the geomorphology, of an area. Recognition of these landforms and knowledge of the processes by which they form enable prediction of future natural and man-induced changes.

This study is part of the multidisciplinary Outer Continental Shelf Environmental Assessment Program (OCSEAP), and considers the environmental geology and geomorphology of the Alaskan Arctic Coastal Plain and the offshore barrier island-lagoon systems. Information from this study is useful in developmental planning, primarily related to petroleum exploration and production, to minimize adverse impact on the environment. Information gathered in this study is applicable to such developmental problems as:

(1) siting of drill pads
(2) siting of landfills
(3) transportation centers
(4) engineering aspects of stability
(5) sources of gravel
(6) stream channel dynamics
(7) shoreline changes

The greatest detail is herein given to the Arctic Coastal Plain and offshore areas between 146 W and 154°W (figure 1). Petroleum exploration is in progress here and production is ongoing at Prudhoe Bay.

Approach

The approach to this study is fivefold: (1) to compile maps and various types of remotely sensed data, (2) to identify landforms and landform assemblages from these data, (3) to measure the magnitude and rates of change in landforms from sequential data, (4) to deduce probable non-real-time landforming processes with multiple working hypotheses, and (5) to perform year-round aerial and/or ground reconnaissance.

This approach, coupled with published literature on the geology and processes of the Alaskan Arctic Coastal Plain and elsewhere, provides a usable assessment of the geomorphology and environmental geology of the area.

Regional Setting

Based on morphology, Payne et al. (1951) divided the Alaskan Arctic Slope into the Arctic Foothills and the Arctic Coastal Plain. Black (1969) summarized these provinces and cited as characteristic of the foothills province: upland topography with reliefs up to 800 m, few thaw and other lakes, braided streams, and intergraded drainage. lle

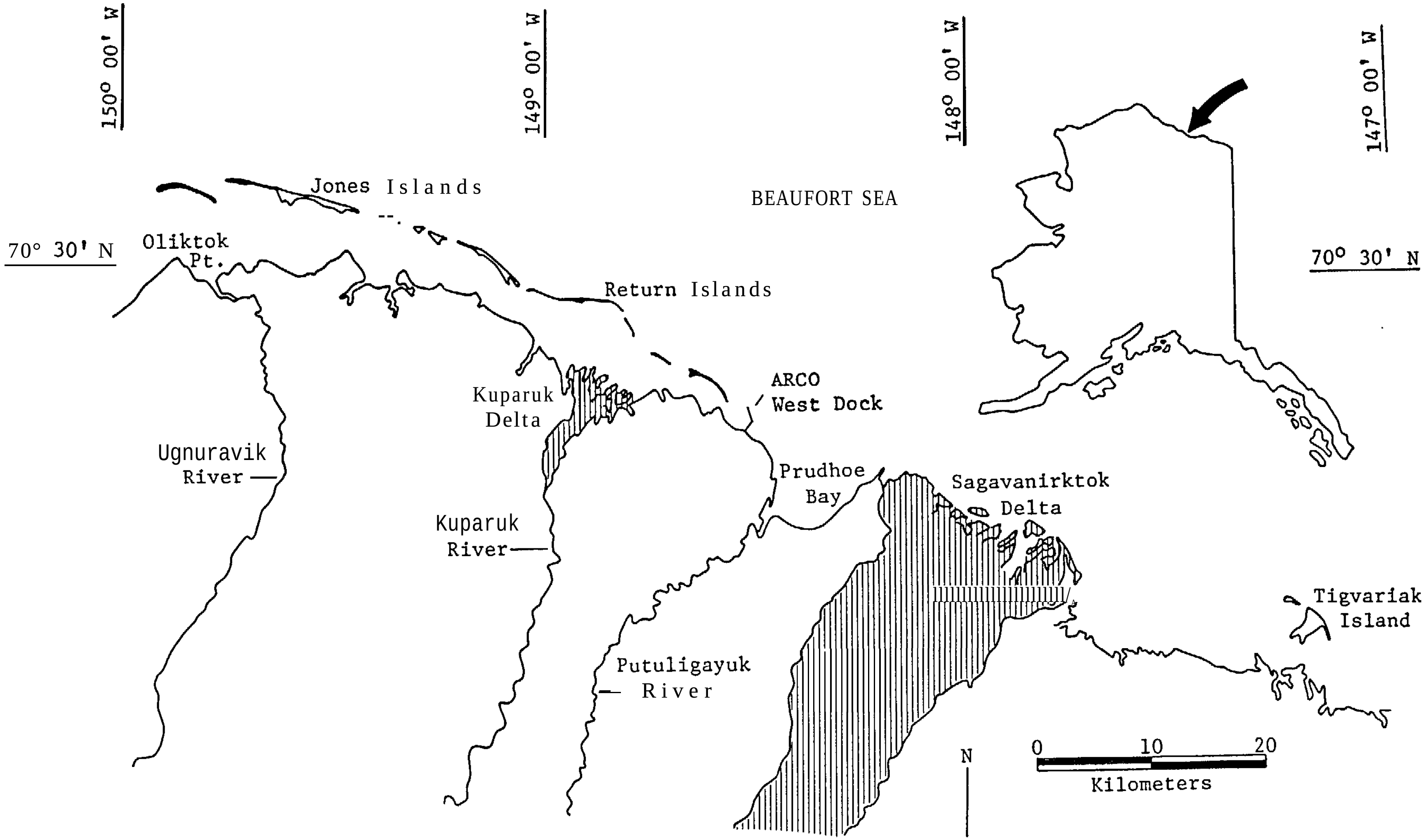

Figure 1- Location map, Arctic Coastal Plain.

cited as characteristic of the coastal plain province: low topographic relief, numerous thaw lakes and meandering streams, non-intergraded drainage, and patterned ground.

The Beaufort Sea coastline and the Arctic Coastal Plain are of primary interest here. The coastal plain borders the Beaufort Sea for about 1000 km from Point Barrow to Demarcation Point and includes coastal geomorphic features such as deltas, estuaries, embayments, salt marshes, and offshore barrier island-lagoon systems. These features are discussed at length later. It covers an area of roughly 71,000 km^2 (27,000 $miles^2$) and averages 2 to 5 m above mean sea level with a seaward gradient between 1 and 2 m/km.

Unconsolidated clay-through-gravel sized elastics of the Tertiary Sagavanirktok Formation (terrestrial) and the Quaternary Gubik Formation (marine) are the surficial deposits of the coastal plain exclusive of eolian sands. These formations overlie Cretaceus sedimentary rocks with slight angular unconformity. Gubik deposits, described in detail by Black (1964), are widespread west of the Colville River. Sagavanirktok deposits underlie or interfinger with Gubik deposits east of the Colville River (Black, 1964).

Coastal plain unconsolidated deposits are within the geomorphic zone of continuous permafrost and ground ice. The most conspicuous geomorphic features of the coastal plain, ice-wedge polygons and thaw lakes, are a consequence of their location within the zone. These features are discussed later. A tundra-mat, which averages less than 1 m thick, overlies the unconsolidated deposits over most of the coastal plain.

Processes and Landforms

Loss of ground ice by thawing is the most important process on the Alaskan Arctic Coastal Plain. The term permafrost is not used here because it refers to subsurface materials with a year-round temperature of O°C or below. It does not infer that ice is present. This landforming process is unique to this planet and is responsible in part for all major landforms of the coastal plain.

Major landforms of the coastal plain include streams and deltas, thaw lakes, barrier islands and lagoons, and coastlines. Attached at the back of this report are geomorphic maps of the Colville, Kuparuk, Sagavanirktok, and Canning River deltas (plates 1-6), and flood hazard maps of part of the Colville, and of the entire Kuparuk and Sagavanirktok River deltas (plates 7-lo) . Except for the Kuparuk the maps show that part of each river from where a single channel or confined floodplain diverges into several channels, to where each river drains into the Beaufort Sea. Because the Kuparuk River is a braided - meandering system it was mapped arbitrarily to several miles inland from its mouth. Also attached are surficial geology maps of the Beaufort Sea coast to about 3 miles inland between Oliktok Point and ARCO west dock, including the barrier islands (plates 11-15) .

The Colville River map nomenclature differs slightly from the other maps because it was the last completed. The main difference between the

Colville River map and the other maps is the usage of Fpa in lieu of Fpapg. All of the units mapped on the Colville River as Fpa are actually Fpapg. Since the delta maps were completed, more appropriate nomenclature (table 1) was formulated for the map units. The old nomenclature was used to map types of landforms and deposits, and their relative positions; often it does not conform to established definitions and usage. Therefore, it should be abandoned and replaced with the new nomenclature. The old nomenclature appears on the delta maps because of insufficient time and support to make the changes, and the unavailability of a good topographic base on which to map.

The new nomenclature arose from surficial geology mapping of the coastal plain from. 1:18,000 scale natural color, aerial photographs. The nomenclature is prefixed by a capital letter, which designates the genesis or sometimes an important process (table 2) followed by one or more lower case letter(s) which may further designate the genesis, and the geomorphology and often the stability of the deposit.

The new nomenclature includes designators for three types of fluvial systems: braided-meandering, braided, and meandering. Therefore, floodplain deposits of the Colville River (meandering) are designated differently than floodplain deposits of the Canning River (braided). Thus, Fpbi indicates fluvial, inactive floodplain deposits of a braided system. Some rivers have a combination of these designators, that is, two or more river types may exist within the system as a whole.

The changes from the old to the new nomenclature are given in table 3. The following notes apply to table 3 and explain the correlation between the old and new nomenclatures. The numbers following some of the units in table 3 refer to these notes.

1: Units without footnotes are either unique to a particular map and correlate from the old nomenclature to the new as shown, or are equivalent and designated as shown.

2: All Fp units (old nomenclature) within the lower deltaic plain shall be listed as Fd followed by the appropriate modifiers unless indicated otherwise. Fp units (old nomenclature) within the upper deltaic plain shall be listed as Fp or Ft followed by the appropriate modifiers.

3: All Fp units (new nomenclature) shall reflect the type of stream; consider the Colville as meandering, the Kuparuk as braided - meandering, and the Sagavanirktok and Canning Rivers as having both braided and meandering sections.

4: All Fpa (old nomenclature) units of the Colville River should be considered Fpapg (old nomenclature), and notes 1 and 4 apply.

5: Fpa and Fpapg units (old nomenclature) should be considered as terraces.

Table 1- Geomorphic map units.

FLUVIAL DEPOSITS (F)

Fm - Fluvial, marsh deposits

Fp - Fluvial, floodplain deposits

Fps - Fluvial, stabilized floodplain deposits

Fpb - Fluvial, braided floodplain deposits

Fpbs - Fluvial, stabilized braided floodplain deposits

Fpm - Fluvial, meandering floodplain deposits

Fpms – Fluvial, stabilized meandering floodplain deposits

Fpi – Fluvial, inactive floodplain deposits

Fpbi - Fluvial, inactive braided floodplain deposits

Fpmi - Fluvial, inactive meandering floodplain deposits

Ftl - Fluvial, low terrace deposits

Fth - Fluvial, high terrace deposits

Ft - Fluvial, terrace deposits

Fd - Fluvial, deltaic deposits

Fds - Fluvial, stabilized deltaic deposits

Fdi - Fluvial, inactive deltaic deposits

Fdtl - Fluvial, low deltaic terrace deposits

Fdth - Fluvial, high deltaic terrace deposits

Fct - Fluvial, thaw channel deposits

Fpt - Fluvial, thaw floodplain deposits

Ftt - Fluvial, thaw terrace deposits

COLLUVIAL DEPOSITS (C)

cc - Colluvial, coastal plain deposits

Table 1- continued.

MARINE DEPOSITS (M)

Mc - Marine, coastal plain deposits

Mb - Marine, beach deposits

Mbs - Marine, stabilized beach deposits

Mm - Marine, saltmarsh deposits

Mi - Marine, island deposits

Ms - Marine, spit deposits

Mr - Marine, bar deposits

Mbo – Marine, organic beach deposits

Mw - Marine, swash zone deposits

LACUSTRINE DEPOSITS (L)

Lt - Lake, thaw

Lo - Lake, oxbow or spit entrapment

Lbo - Lacustrine basin, organic deposits

Lb – Lacustrine basin deposits

Lbt - Lacustrine basin deposits with thaw ponds

Lbpt - Lacustrine basin deposits with polygonal ground and thaw ponds

Lbp - Lacustrine basin deposits with polygonal ground

Lbs - Lacustrine basin terrace deposits

Lbm - Lacustrine basin marsh deposits

Lm – Lacustrine marsh deposits

EOLIAN DEPOSITS (E)

Ed - Eolian, dune deposits

Eds - Eolian, stabilized dune deposits

Table 1- continued.

Eb - Eolian, deflation basin deposits

Ec - Eolian, cover deposits

FILL DEPOSITS (H)

Hf - Fill deposits

Table 2- Genetic prefixes, geomorphic maps.

F - fluvial

C - colluvial

M - marine

L - lacustrine

E - eolian

Table 3- Correlation between the old and new geomorphic nomenclatures. Old nomenclature designations are common to two or more rivers unless indicated in the left column.

RIVER	OLD NOMENCLATURE	NEW NOMENCLATURE
Kuparuk	Sm	Mm
	Smv	Mm
Colville N	Smsc	Mm
	Sms	Mm
Colville N	Tfsc-v (combination unit) Tfsc/tfv	Fd-Fds
	Tfsc	Fd
	Tfs	Fd
	Tfv	Fds
	Sd	Ed
	Sdv	Eds
	Fpa (Fpapg-Colville N)	Ftl[2,4,5]
	Fpapg	Fth[2,4,5]
Sagavanirktok N	Fpapg-s	Fc/Fdth
Sagavanirktok N	Fpa-sc	Fdi
Colville S	Fpav (la)	Lb
Kuparuk	Fpas	Ed/Fdtl
	Fpbac	Fpb
Sagavanirktok S	Fpbac-av (combination unit) Fpbac/Fpav	Fpb-Fpbi
	Fpav	(Fpi, Fpbi, Fpmi)[2,3]
	Cbgs	(Fp, Fpb, Fpm)[3]

Table 3– continued.

RIVER	OLD NOMENCLATURE	NEW NOMENCLATURE
	Cb s	(Fps, Fpb, Fpm)[3]
	Cbv	(Fps, Fpbs, Fpms)[3]
	Cbsc	(Fp, Fpb, Fpm)[3]
	Pbgs	Fpm
	Pbs	Fpm
	Pbsc	Fpm
	Pbv	Fpms
	Ca	N/A
Colville S	Ch	N/A
	L	Lo (if oxbow) Lt (if thaw)
	Cptl	Mc
	Cpau	cc
Canning	Fpat	Ft
Colville N	Cp	Mc
Canning	Cmbsc	Fd
Canning	Cmbgs	Fd
	Bigs	Mi
	Sgs	Ms
Canning	Est	N/A
Canning	Bsc	Lbs
Canning	Auf	N/A
Sagavanirktok N	Tldsc	Lb

Table 3- continued.

RIVER	OLD NOMENCLATURE	NEW NOMENCLATURE
Sagavanirktok S	Esc	N/A
Kuparuk	Gp	Hf
Colville N	Mfv	Lb
Colville N	Mf	Lb
Colville N	Dbsc	Lb
Colville N	Dbs	Lb
Colville N	Tla	Lbpt
Colville S	Tld	Lb
Colville S	Mf	Lbs (if lake basin)
Colville S	Mf	Fpm (if meander scar)

A. When Fpapg and Fpa units are adjacent or stand alone, then Fpapg = Fth and Fpa = Ftl.

B. When two adjacent Fpapg or two adjacent Fpa units (old nomenclature) are separated by a H/L, and the lower unit (L) is adjacent to any Fp (new nomenclature), the higher unit (H) = Fth and the lower unit (L) = Ftl. If the lower unit (L) is not adjacent to a Fp unit (new nomenclature), as with multiple H/L indicators, the lower unit (L) = Fth and the higher unit (H) = Ft.

OBSERVATIONS AND INTERPRETATIONS

Streams and Deltas

Development and History. The initial development of stream channels on the coastal plain is dissimilar to the sequence of stream channel development elsewhere. In general, stream channels enlarge by eroding and transporting alluvium. Stream channels originating on the Arctic Coastal Plain, however, do not initially enlarge by these processes, but rather by the loss of ground ice.

Stream channels on the Arctic Coastal Plain in the initial stage of development are very small--several meters in width--and tend to be intensely meandering or orthogonal. They often have flooded thermokarst depressions (beads) along their course and connect large thaw lakes. Streams flow on top of the tundra-mat in these thaw-depressed channels and may be locally floored with lag sand and gravel where the tundra-mat is eroded. Erosional and depositional landforms such as meander scars and point bars are not associated with these streams.

Expansion of small stream channels to intermediate-size stream channels (e.g., Ugnuravik River) and large stream channels (e.g., Kuparuk, Sagavanirktok, and Colville Rivers) will occur if stream discharge is ever increasing (as by capturing new sources of runoff) and stays at these levels for sufficient time. Stream channel expansion primarily by thawing will progress to expansion by combined thaw and erosion with transport processes. This is not to imply that all small stream channels on the Arctic Coastal Plain will evolve into large stream channels. Intermediate-size stream channels tend to be meandering and are floored with sand and gravel; they show a variety of fluvial landforms. Erosional landforms such as incised channels and meander scars are associated with these streams but generally not within well defined floodplains. Depositional point bars are present but not well developed. The height from the stream surface to the upland coastal plain surface of the bluff along incised channels varies from almost zero to a few meters. The bluff height naturally depends on the age of the stream channel, but is also probably related to subsidence of the land surface. This concept applies also to large stream, lake, and sea shorelines, and is discussed later.

Large stream channels show both erosional and depositional landforms. Erosional floodplains are well defined. Oxbow lakes, meander scars, and point bars are common within floodplains of large meandering streams. These stream channels are floored with clay to gravel-sized elastics. Within large braided floodplains there are generally the main channel and many small distributary channels. These stream channels are floored with sand and gravel.

The Colville River, longest of the streams, drains an area of about 59,400 km^2 (Wright et al., 1974). It originates in the Delong Mountains and roughly parallels the Brooks Range until immediately past Umiat, where it abruptly turns northward and drains into the Beaufort Sea west of Oliktok Point (Black, 1969). This river has meandering and braided characteristics; however, the former is dominant.

The Kuparuk River drains an area of approximately 8,107 km^2 (Carlson, 1977). It originates in the Brooks Range near Galbraith Lake and flows northward to the Beaufort Sea. It drains into the sea immediately west of Prudhoe Bay. Throughout much of its course, individual channels are intensely meandering. These streams merge and become braided within a well defined floodplain in the lower course of the river.

The Putuligayuk River is presently a minor meandering stream that originates on the coastal plain and flows northward where it drains into Prudhoe Bay. The drainage basin area is approximately 456 km^2 (Carlson, 1977).

The Sagavanirktok River drains an area of approximately 5,719 km^2 (Carlson, 1977). It too originates in the Brooks Range near Galbraith Lake and flows northward to the Beaufort Sea. It drains into the sea immediately east of Prudhoe Bay. This stream is braided throughout its course.

Fluvial Gravel Sources. Gravel is among the most important natural resources on the Arctic Coastal Plain of Alaska, especially in areas of active development by the petroleum industry (figure 1). It is used primarily to build roads, airstrips, and building, storage and drill site pads. The usual source of most of the gravel has been floodplains of large rivers such as the Sagavanirktok and Kuparuk. Updike and Howland (1979) mapped potential gravel sources along the floodplains of these rivers. This source has received considerable criticism because of potential impacts to the environment. Because of this criticism and the eastward and westward expansion of development from the Sagavanirktok and Kuparuk River areas, the petroleum industry is now seeking alternative gravel sources.

Limited data suggest that much of the Arctic Coastal Plain currently being developed, especially east of the Kuparuk River, is underlain by gravel (Hopkins and Hartz, 1978; Smith et al., 1980). Because these data are limited, especially for areas west of the Kuparuk River, and gravel exploration studies done by the petroleum industry are proprietary, the widespread distribution of gravel can only be assumed and the actual distribution is not known. This discussion suggests a source of gravel that has advantages over other sources by being easily delineated and often nearby areas of development.

Upland gravel sources are defined here as those on the coastal plain above fluvial flood limits. British Petroleum (BP)/SOHIO has utilized one upland source, and Atlantic-Richfield Company (ARCO) two, within the past three years. Two of these sources are abandoned meanders of the Putuligayuk River; the other is adjacent to the Ugnuravik River. The Ugnuravik and Putuligayuk River pits are on parts of the coastal plain that are particularly visible on black and white LANDSAT imagery and small-scale photography as highly reflective zones that border each side of the existing streams (figure 2). These reflective zones, especially along intermediate- and large-size streams, may represent fluvial terraces. Such terraces are common on the Arctic Coastal Plain and may delineate reserves of gravel. Further field work is required to assess the validity of this interpretation.

The terraces may be nearly level with the upland surfaces, as along most of the Putuligayuk River, or raised slightly above the adjacent upland surfaces, as along the Ugnuravik River and some parts of the Putuligayuk River. The terraces are not discernible from the ground, as presently there are generally no scarps. A terrace by definition requires that it be bounded by scarps. This model assumes the past existence of scarps. However, a scarp which trends roughly parallel to the Putuligayuk River is aligned with the eastern shore of Prudhoe Bay (figure 3). This scarp is only discernible on aerial photographs and can be traced inland for approximately 5 km. Beyond this point the terrace boundary can only be identified on LANDSAT imagery as the boundary of the highly reflective zone.

Cannon and Rawlinson (1979) suggest that the Putuligayuk River was once much larger, and that the indentation of Prudhoe Bay on the Arctic Coastal Plain corresponds roughly to the boundaries of the ancient Putuligayuk River floodplain. They also suggested that the indentation of Prudhoe Bay was formed either by preferential erosion of the floodplain deposits and/or inundation of the river mouth subsequent to the decrease in river discharge. Based on offshore borehole data Smith and Hopkins (1979) suggested that a large paleovalley continued offshore from the mouth of the Putuligayuk River and that Prudhoe Bay is an estuary formed by a rise in sea level. The ancient river left deposits that now are terraces along both sides of the streams. Radiocarbon dates reported in Smith et al. (1980) indicate that the terrace sand and gravel was being deposited as late as 5,500 years ago, and that the new Putuligayuk River was established by 2,150 or possibly 3,900 years ago. Further, the onset of peat accumulation on the coastal plain was determined to be 8,500 years ago.

The two gravel pits along the Putuligayuk River are within abandoned meanders, which are above present flood limits, a fact that definitely establishes at least the near surface sands as terrace deposits. One of these pits was examined in 1979. Below an approximate 1 m soil horizon, about 4 m of fine to medium sand, with some interbedded silt and clay near the top, overlie coarse sand and gravel. The gravel is exposed to about 7 m below the contact with the sand. Smith et al. (1980) reported a radiocarbon date of 35,600 ± 550 years for twigs collected from the gravel 9.5 m below the surface.

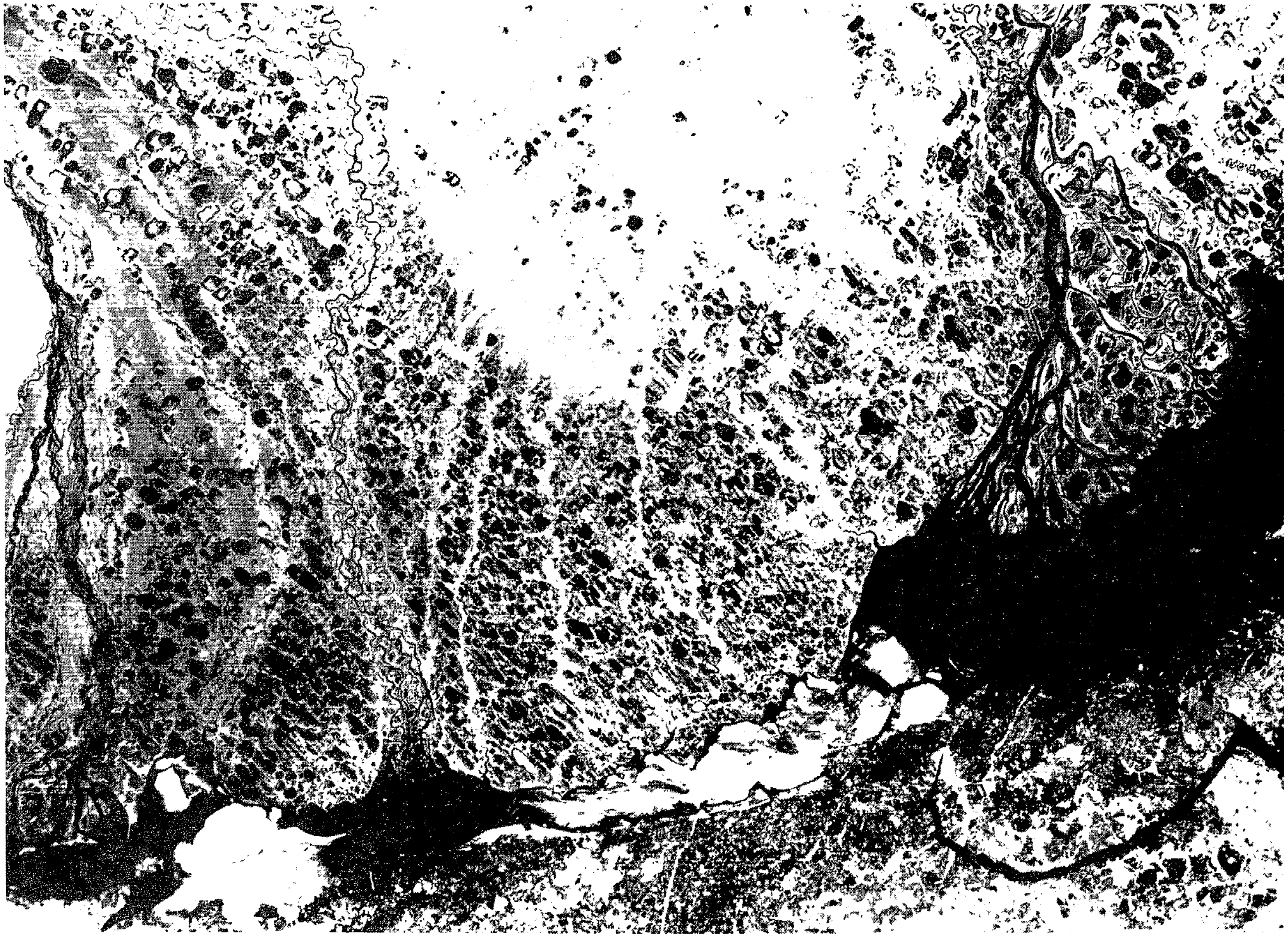

Figure 2- LANDSAT image (2898-20551) showing highly reflective zones interpreted as fluvial terraces.

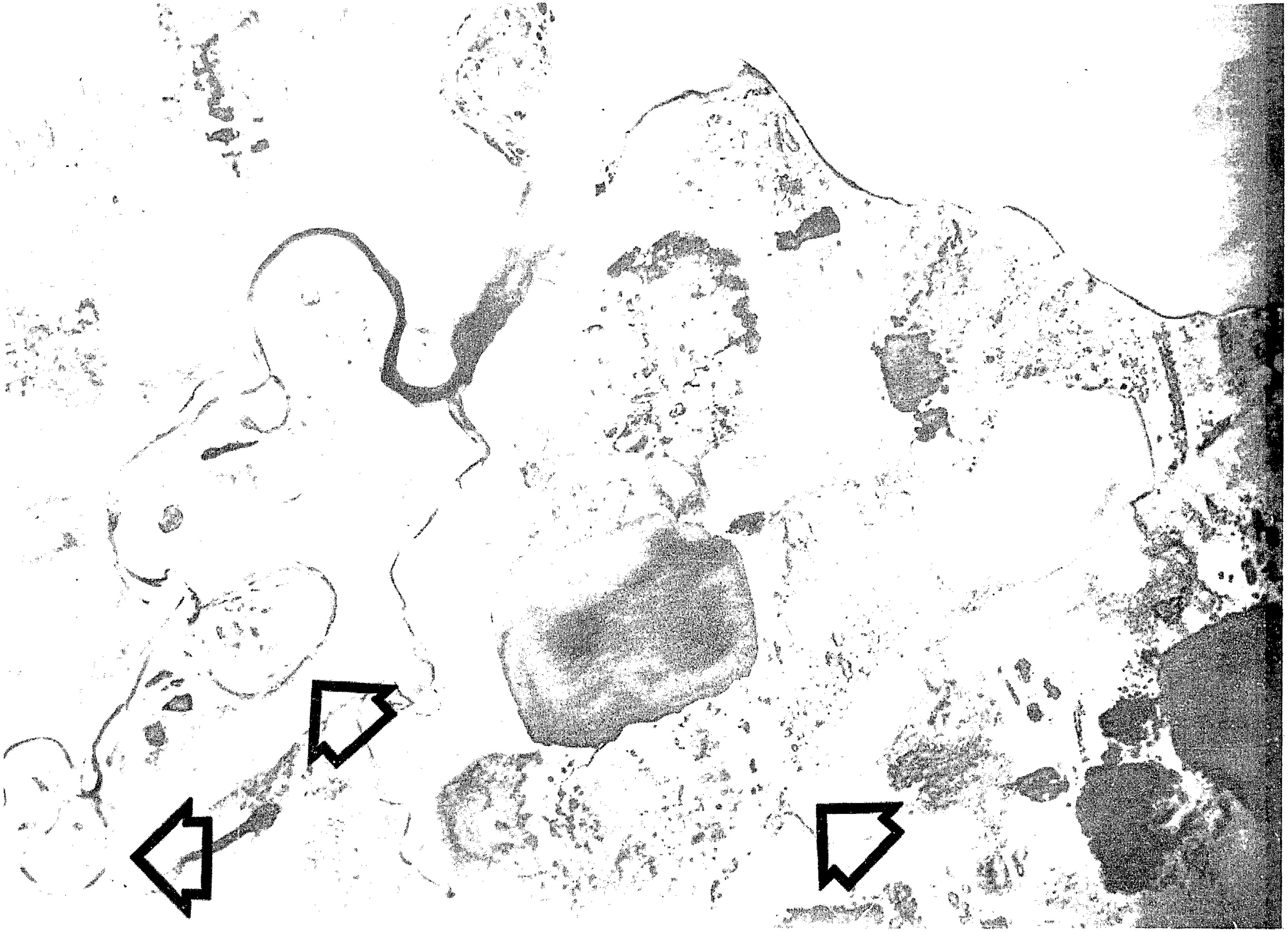

Figure 3- 1955 photograph showing the terrace scarp aligned with the eastern shore of Prudhoe Bay, and the two Putuligayuk River gravel pits.

The surface vegetation and moisture, which are linked to the soil horizon, are the factors that contribute to the high reflectance of the terraces on LANDSAT imagery. Walker *et al.* (1980) mapped the vegetation, soils, and landforms of an area that includes the Putuligayuk River floodplain and the adjacent terraces and coastal plain. Table 4 compares their map units that are dominant on upland surfaces and the terraces.

Data in table 4 suggest a pronounced difference in the soil horizons, a less pronounced difference in the moisture and vegetation, and little difference in the landforms (except immediately adjacent to the Putuligayuk River) between upland surfaces and the terraces. The moisture-vegetation unit M4 is sufficiently more common on upland surfaces than the terraces to indicate wetter conditions in the upland soils. This is consistent with the differences in the soil horizons between the two types of deposits. Organic constituents of the terrace soils are better decomposed than those of upland soils (Walker et al., 1980). This indicates relatively good drainage and aerobic conditions in the terrace soils and poor drainage and anaerobic conditions in upland soils. Aerobic conditions are especially pronounced immediately adjacent to the Putuligayuk River and account for a reduction in the thickness of the organic layer. The reduced organic layer makes these soils very susceptible to frost heaving and boils, and massive ice buildup in the near-surface, fine-grained deposits (Walker et al., 1980). The good drainage and raised surface of the terraces promote a relatively dry surface and a definite paucity of thaw lakes. Smith et al. (1980) noted this lack of thaw lakes adjacent to the Putuligayuk River.

Except in a few areas, the thaw depth in both the terrace and upland deposits ranges between 30 and 55 cm (Walker et al., 1980). Thus, the interpretation that the highly reflective zones delineate sand- and gravel-bearing fluvial terraces is based on the effect that the soil horizon, not the underlying sand and gravel, has on the surface. The differences between the terrace and upland soils are most probably related to their ages and geneses. First, the terrace soils are younger than upland soils because the former are subsequent to the deposition of the gravel and overlying sand. This age difference is corroborated by the radiocarbon dates cited earlier and the fact that the terraces cut across the coastal plain upland surfaces. Second, the terrace soils developed on a sand-rich base, not a silt and clay base as with upland soils.

The terraces that border the Ugnuravik River and many other small streams on the Arctic Coastal Plain are raised slightly above the adjacent coastal plain upland surfaces for the same reasons discussed for some areas immediately adjacent to the Putuligayuk River (figure 4). The link between the surface characteristics and the potential gravel deposits is also the same as discussed for the Putuligayuk River.

The Ugnuravik gravel pit was examined in 1980. The raised terrace visible on stereo air photos was not discernible on a low altitude overflight or from the ground (figure 5, cf. figure 4). Viewed from

Table 4– Soil units dominant on the upland surface and the terraces (Modified from Walker et al., 1980). Unit explanations:

Vegetation (dominant first)
Soil type, landform type

Coastal Plain Unit	Terrace Unit
M4, U4 / 4, 7	U4, M2 / 3, 4
M2, U3 / 4, 4	M2, U3 / 3, 7
M2, U4 / 4, 7	M2, U3 / 3, 4

Vegetation types

M2	Wet, *Carex aquatilis, Drepanocladus brevifolius*
M4	Very wet, *Carex aquatilis, Scorpidium scorpioides*
U3	Moist, *Eriophorum augustifolium, Dryas integrifolia, Tomenthypnum nitens, Thamnolia vermicularis*
U4	Moist, *Carex aquatilis, Dryas integrifolia, Salix arctica, Tomenthypnum nitens*

Soil types

3 Complex of:

1. Histic Pergelic Cryaquept	1) A cold, wet, gray mineral soil, commonly mottled, having a surface horizon >25 cm thick, composed of predominantly organic (peaty) material
2. Pergelic Cryohemist	2) A cold, wet, dark-colored soil consisting of moderately decomposed organic materials to depths>40 cm
3. Pergelic Cryosaprist	3) A cold, wet, dark soil consisting of well-decomposed organic materials to depths>40 cm

4 Complex of:

1. Histic Pergelic Cryaquept	1) As above
2. Pergelic Cryofibrist	2) A cold, wet reddish to yellowish soil consisting of little-decomposed fibrous organic materials to depths>40 cm

Table 4- continued.

Landforms

4 - low-centered polygons, rim center contrast $\leq$0.5 m
7 - Strangmoor and/or large diameter, commonly discontinuous low-centered polygon pattern; little or no microrelief contrast

Figure 4- 1955 photograph showing the raised terrace along the Ugnuravik River. The site of the gravel pit is outlined.

Figure 5- Low altitude aerial photograph of the Ugnuravik River gravel pit. View is from the north. The runway in the foreground is 914 m long.

the south, the pit is shaped like a backwards en. The width and length of the vertical part of the ell are 205 by 320 m, and the width and length of the horizontal part of the ell are 120 by 350 m.

The pit affords a good exposure of the subsurface stratigraphy (figure 6). A sandy silt soil horizon about 1 m in thickness overlies roughly 5 m of fine sand. The contact between this sand and the underlying sandy gravel is abrupt; sandy gravel extends to a depth of at least 7 m below this contact. Organic material within the sand and sandy-gravel was sought for radiocarbon dating; however, none was found.

Landforms and Deposits. Plates 1 through 6 and part of 13a show geomorphic units of the Colville, Kuparuk, Sagavanirktok and Canning Deltas. The nomenclature on these plates, except plate 13a, should be converted to the nomenclature listed previously in table 1 according to table 3. Most of the units on plates 1 through 6 and some of plate 13a are fluvial; fluvial and colluvial, because the latter is common along floodplain and terrace boundaries, unit descriptions are given in table 5. Stabilized floodplain and deltaic deposits differ from active floodplain deposits only by the former's sparse vegetation cover. The elevation of these stabilized deposits is between the elevations of the active and inactive floodplain deposits; their susceptibility to flooding varies accordingly. Only the largest of the delta thaw lakes are shown on plates 1 through 6.

Stream Erosion. Measurement of stream erosion rates is very important in regard to Arctic Slope development. These measurements pertain primarily to retreat of the floodplain bank and not to changes within the channel. The concern for these measurements became apparent after erosion of the Sagavanirktok River bank progressed toward Prudhoe Bay exploration facilities. Knowledge of the rates of riverbank erosion is also important for placement of such facilities as sanitary landfills. Erosion measurements are hampered, however, by a paucity of low-cost, high-resolution sequential photography. For this reason measurements of stream erosion to date concentrate on channel banks of the Sagavanirktok River within the delta.

Table 6 shows the results of the bank erosion measurements within the Sagavanirktok River delta. Further, Appendix A contains comparative photographs (1955 and 1979), of areas within the Colville, Kuparuk, Sagavanirktok and Canning River deltas.

Stream Ice-breakup and Detritus Flow. Arctic Slope streams are frozen for about 6 months of the year from October through and including May. During this period small streams are completely frozen and flow is greatly diminished in the large streams. For about a 3 to 4 week period beginning in late May or early June river ice covers breakup and there is a resultant sharp increase in discharge; this high discharge quickly diminishes and remains relatively constant throughout the summer until freezeup in October (Carlson, 1977).

Before actual river breakup, subice flow increases. This is shown by thinning of the ice, especially in the deltaic and nearshore areas.

Figure 6- Photograph showing the stratigraphy of the Ugnuravik River gravel pit. The dark zone at the top of the section is the soil horizon; the occurrance of rills in the approximate middle of the section indicates the boundary between the sand and the sandy gravel.

Table 5- Fluvial and colluvial deposits unit descriptions, plates 1-6, 11-15.

FLUVIAL DEPOSITS (F)

Fm- Fluvial, marsh deposits - chiefly fine sand and silt, poorly drained with aquatic vegetation; active layer generally less than 0.5 m thick, continuously frozen; ice-rich; marshes common on upland surfaces and serve as drainage basins for thaw streams.

Fp- Fluvial, floodplain deposits - well sorted sand and gravel of braided-meandering fluvial systems (e.g. Kuparuk River), may contain small amounts of silt and organic matter; subject to frequent inundation by streams; no vegetation; subject to icing; perennially unfrozen.

Fps- Fluvial, stabilized floodplain deposits - well sorted sand and gravel of braided-meandering fluvial systems; may contain small amounts of silt and organic matter with a thin silt cover; subject to infrequent inundation by streams; grass and low-brush vegetation; subject to icing; surface perennially unfrozen.

Fpb- Fluvial, braided floodplain deposits - sand and gravel of braided floodplains, may contain small amounts of silt and organic matter; subject to frequent inundation by streams; no vegetation; subject to icing; perennially unfrozen.

Fpbs- Fluvial, stabilized braided floodplain deposits - sand and gravel of braided floodplains; may contain small amounts of silt and organic matter with a thin silt cover; subject to infrequent inundation by streams; grass and low-brush vegetation; subject to icing: surface perennially unfrozen.

Fpm- Fluvial, meandering floodplain deposits - well sorted sand and gravel of meandering fluvial systems (e.g. parts of the Sagavanirktok River), may contain small amounts of silt and organic matter; subject to frequent inundation by streams; no vegetation; subject to icing; perennially unfrozen.

Fpms- Fluvial, stabilized meandering floodplain deposits - well sorted sand and gravel of meandering systems, may contain small amounts of silt and organic matter; with silt cover generally less than 1 m thick; subject to infrequent inundation by streams; grass and low-brush vegetation; subject to icing; surface perennially unfrozen.

Fpi- Fluvial, inactive floodplain deposits - well sorted sand and gravel of braided-meandering fluvial systems, contains some silt and organic matter; with silt cover generally less than 1 m thick; moss, grass and low–brush vegetation; subject to rare inundation by streams; active layer to 1 m thick; continuously frozen.

Table 5- continued.

Fpbi- Fluvial, inactive braided floodplain deposits - sand and gravel of braided fluvial systems, contains some silt and organic matter; with silt cover generally less than 1 m thick; moss, grass and low-brush vegetation; subject to rare inundation by streams; active layer to 1 m thick; continuously frozen.

Fpmi- Fluvial, inactive meandering floodplain deposits - well sorted sand and gravel of meandering fluvial systems, contains some silt and organic matter; with silt cover generally less than 1 m thick; moss, grass and low–brush vegetation; subject to rare inundation by streams; active layer to 1 m thick; continuously frozen.

Ftl- Fluvial, low terrace deposits - silts 1.0 m to 1.5 m thick over sand and gravel with some silt and organic matter; surfaces show old meander scars (some with water) and indistinct polygonal ground; generally bounded by well-defined scarps; terraces tread 1 - 2 m above floodplain surfaces; active eolian sand dune and cover deposits may be present; tundra vegetation; not subject to inundation by streams; active layer to 1 m thick; continuously frozen; moderate ice content.

Fth- Fluvial,high terrace deposits - silts 1.0 to 1.5 m thick over sand and gravel with some silt and organic matter; surfaces show meander scars (some with water) and distinct low-center ice-wedge polygons; pingos and small thaw lakes may be present; generally bounded by well defined scarps; terrace level 2 - 4 m above floodplain surfaces; active and stabilized eolian sand dune and cover deposits may be present; tundra vegetation not subject to inundation by streams; active layer to 1 m thick; continuously frozen; moderate to high ice content.

Ft- Fluvial, terrace deposits - silts 1.0 to 1.5 m thick over sand and gravel with some silt and organic matter; surfaces show modified meander scars and ice–wedge polygons; stabilized dunes, pingos and small thaw lakes may be present; back scarp generally very poorly defined; terrace tread higher above floodplain than with Fth deposits; tundra vegetation; not subject to inundation by streams; active layer to 1 m thick; continuously frozen; moderate to high ice content.

Fd- Fluvial,deltaic deposits - fine sand and silt of the delta plain, with low to moderate amounts of organic matter; no vegetation; subject to frequent inundation by streams and marine storm surge; perennially unfrozen.

Fds- Fluvial, stabilized deltaic deposits - fine sand and silt of the delta plain, with low to moderate amounts of organic matter; subject to infrequent inundation by streams but frequent inundation by marine storm surge; grass vegetation; surface perennially unfrozen.

Table 5- continued.

Fdi- Fluvial, inactive deltaic deposits - fine sand and silt of the delta plain, with low to moderate amounts of organic matter; subject to rare inundation by streams and infrequent inundation by marine storm surge; moss, grass and low-brush vegetation; active layer to 1 m; continuously frozen.

Fdtl- Fluvial, low deltaic terrace deposits - fine sand and silt with low to moderate amounts of organic matter; not subject to inundation by streams or marine storm surge, active layer to 1 m thick; continuously frozen; moderate ice content; tundra vegetation; surfaces show old meander scars (some with water) and indistinct polygonal ground; generally bounded by well defined scarps; terrace tread 1-2 m above delta plain surfaces; active eolian sand dune and cover deposits may be present.

Fdth- Fluvial, high deltaic terrace deposits - fine sand and silt, with low to moderate amounts of organic matter; not subject to inundation by streams or marine storm surge; active layer to 1 m thick; continuously frozen; moderate to high ice content; tundra vegetation; surfaces show meander scars (some with water) and distinct low-center ice-wedge polygons; small thaw lakes may be present; generally bounded by well defined scarps; active and stabilized eolian sand dune and cover deposits may be present; terrace level 2 - 4 m above delta plain surfaces.

Fct- Fluvial, thaw channel deposits - well sorted sand and gravel of thaw channels; silt and fine sand in small channels, may contain small amounts of organic matter; perennially unfrozen; subject to infrequent inundation; no vegetation; these deposits are derived locally from erosion of coastal plain deposits (Me); little sediment transport; channels result primarily from thaw; small thaw channels generally vegetated.

Fpt- Fluvial, thaw floodplain deposits – chiefly silt and fine sand, with small amounts of gravel and organic matter; active layer to 1 m; continuously frozen; moss and grass vegetation; subject to infrequent inundation; floodplain widening results primarily from thaw.

Ftt- Fluvial, thaw terrace deposits - chiefly silt and fine sand, with small amounts of gravel and organic matter; active layer to 1 m; continuously frozen; tundra vegetation; not subject to inundation; terraces along large thaw channels may show meander scars.

COLLUVIAL DEPOSITS (C)

Cc- Colluvial, coastal plain deposits - chiefly silt and fine sand, with small amounts of gravel and organic matter; active layer to 1 m; continuously frozen; moderate to high ice content; tundra vegetation; modified by mass wasting processes; poorly defined downslope linearity of surface features; common along floodplain and terrace boundaries and around fluvial marsh deposits (Fro).

Table 6 - Erosion rates (m/yr) of shorelines within the Sagavanirktok River delta.

Area	No. Meas	Mean
Total Sagavanirktok River bank	14	0.7
East-facing Sagavanirktok River bank	7	0.8
West-facing Sagavanirktok River bank	3	0.5
North-facing Sagavanirktok River bank	4	0.7

This thinning shows as brown-appearing ice with open pools of water laden with particulate matter. Thinning of the ice in these areas may, in part, be from preferential heating of the dark ice. The brown appearance of the ice is from silt and organic matter that is trapped in the ice as it freezes. During diving operations to emplace a current meter in an offshore channel between Long Island and Egg Island, in Simpson Lagoon, and just northeast of the Kuparuk River delta, the particulate laden part of the ice was estimated to be about 1 m thick, about half of the total ice thickness. The particulate laden ice was on top and the contact with the clean ice was sharp. Subsequent diving operations suggest that the maximum thickness of the particulate laden ice may not differ significantly from that observed in this channel.

The pre-break increase in subice flow is also shown from data obtained with this meter. In early June shorefast ice is still frozen to the bottom and polynias have not developed in Gwydyr Bay at the mouth of the Kuparuk River. Beginning the second week of June subice flow from the Kuparuk River increases rapidly and river water overflows the sea ice. For the first few hours of overflow 20 cm/sec flow was recorded in Egg Island channel. This initial river flow accounts for 60% of the mean annual flow and over the next 10 days, for 80% of the mean annual flow (Matthews, 1979).

Plates 7-10 show areas on the Kuparuk and Sagavanirktok River deltas and part of the Colville River delta that are subject to flooding under low, moderate, and high flood conditions. Units of the Canning and the northern part of the Colville River deltas subject to flooding under relatively low flood conditions are Fpm and Fpb; and, units subject to flooding under moderate conditions are Fpms and Fpbs; and, units subject to flooding under high flood conditions are Fpmi and Fpbi.

The over-ice flow carries with it a large quantity of fine-grained inorganic and organic particulate matter. Study of this over-ice flow has been concentrated on the Kuparuk River since it is the only large Arctic Slope river to drain into a relatively shallow barrier island-lagoon system. Barnes and Reimnitz (1972) noted westward over-ice flow from the Kuparuk River to Kavearak Point, a distance of about 17 km. Observations made by this investigator on two June overflights of the area confirm extensive over-ice flow from all of the major rivers. This flow from the Kuparuk River generally extends to the offshore islands, and at channels, beyond the islands. The Colville River over-ice flow is by far the most extensive reaching westward to Thetis Island; eastward, however, over-ice flow does not extend beyond Oliktok Point.

Particulate matter on the sea ice surface is introduced into the nearshore environment through cracks and strudle holes in the ice surface. An estimate of the volume of particulate matter introduced into the nearshore environment from the Kuparuk River was obtained by measuring a representative area of overflow (54 km^2) and multiplying this by the estimated thickness of particulate matter overlying the ice (0.02 m). Matthews (1979) cited an area of 116 km^2. Organic particulate matter introduced into the nearshore environment from large Arctic Slope rivers has an important role in the foodchain of epibenthos populations. It is assumed that because the density of this organic matter is about 1.1 g/cm^3 most of it is transported in the top of the water column and flows over the ice surface rather than under the ice. Approximately 1% of the total particulate matter is organic, based on measured percentages for the Colville River (Schell, 1977, personal communication). Results are given in table 7.

Thaw Lakes

Polygonal ground patterns are ubiquitous on the Arctic Coastal Plain and offshore tundra-covered islands. Thaw lakes occur in depressions between intersecting ice wedges that form these polygons, and often enlarge by "coalescence. The lakes number in the thousands and tend to be elongate and oriented in a northwest-southeast direction (figures 2 and 3). Lengths range from a few meters to as much as 14 km; common length to width ratios are 3:1 and 4:1 (Carson and Hussey, 1959). Depths of these lakes are usually 1 m or less but may exceed 6 m (Black and Barksdale, 1949).

Lake Orientation and Morphology. The lengths and orientations of 512 lakes in the Prudhoe Bay area were measured on 1:63,360 U.S. Geological Survey topographic maps of Beechey Point B5, B4, B3, and A3. The mean orientation of the major axes of these lakes is 350 degrees azimuth and approximately represents most of the coastal plain lakes west of the Sagavanirktok River (figure 2).

Several hypotheses have been suggested for the orientation of the lakes (Carson and Hussey, 1959), but two seem to be most probable: (1) the lakes are formed perpendicular to the prevailing wind which, along east and west shorelines, forms sublittoral shelves that impede mechanical erosion and also distributes insulating peat that allows preferential thermal erosion on the north and south ends ; and (2) the lakes are aligned along jointing that has propagated through the frozen sediments of the coastal plain and caused preferential melting of ground ice.

Subsequent work by Carson and Hussey (1962) and by Maurin and Lathram (1977) suggests that both hypotheses together account for the orientation of the lakes.

Wind data in Walker et al. (1980) show prevailing winds from azimuths between 060 and 100 during the ice-free time of the year. Furthermore, the mean orientation of sand dunes near the Sagavanirktok River delta indicates a prevailing wind from azimuth 070. These azimuths, then, range perpendicular to the mean orientation of the lakes.

Structural control is the other consideration for the orientation of the Arctic Coastal Plain lakes. Short and Wright (1974) and Maurin and Lathram (1977) suggested the long axes of the lakes and the orientation of stream valleys on the coastal plain are similarly aligned with the dominant jointing on the coastal plain and in the foothills of the Brooks Range. Many of the lakes in the foothills are square or even elongate parallel to the prevailing wind direction. Also, in this region chains of 350-azimuth-oriented lakes follow roughly east-west trending structure.

Table 7- Detritus input into Simpson Lagoon from the Kuparuk River spring runoff.

Volume of total detritus	$\sim 1.08 \times 10^6$ m^3
Volume of inorganic detritus	$\sim 1.07 \times 10^6$ m^3
Mass of inorganic detritus	$\sim 2.14 \times 10^9$ kg
Volume of peat detritus	$\sim 1.08 \times 10^4$ m^3
Mass of peat detritus	$\sim 1.19 \times 10^7$ kg

Large, stabilized sand dunes also affect the morphology of the coastal plain lakes. This is particularly evident in an area south of Teshekpuk Lake. Here the lakes are larger than surrounding lakes and the 350-azimuth orientation is poorly developed. Dunes also form many of the linear features apparent on LANDSAT images of the coastal plain.

Landforms and Deposits. Plates 11 through 13a and 15 show geomorphic units of the coastal plain along the coast from Oliktok Point to the ARCO west dock. Most of the units on these plates are lacustrine (table 8). Appendix B compares 1955 and 1979 photographs of lacustrine basins on the coastal plain south of Milne Point.

All of the geomorphic maps (plates 1-6 and 11-15) in this report were mapped directly from aerial photographs. The units are based on ground checks and published literature. An earlier attempt to map surficial deposits from topographic maps based on the assumption that the substrate controls the surface density and morphology of thaw lakes was inconclusive. Figure 7 differentiates 10 units based on visual estimates of lake size and number, distribution and orientation, and on-ground wetness. Each of these units was sampled; the sample localities are shown in figure 7. The grain size distribution for each of these samples was determined and plotted on a ternary diagram after Shepard (1954) (figure 8). Silty sand (38%) is the dominant sediment followed by san-si-cl (29%), and then clayey silt (19%). Sandy silt, silt, and silty clay each represent 5% of the total samples.

Ratios of area of water to area of land were measured for most of the sampled terrain units (table 9). As is evident from table 9, the ratio values are often not in good agreement with the visually assigned nomenclature (figure 7). Plots of water/land vs coarse/fine, ice depth/ coarse/fine, and ice depth vs water/land were made with data given in table 9. There was relatively good correlation of ice depth and grain size. Ice is shallow on clays and silts and becomes increasingly deeper with coarsening grain size (figure 9).

Plots of the area of water to area of land within designated terrain units (figure 7) suggest that the surface expression of lakes as an indicator of substrate and depth to permafrost is useful only in general terms. An exception is clusters of relatively small, closely packed lakes. Both areas of this type that were sampled [samples numer 79SR05 and 79SR13) had a substrate of clayey silt. Furthermore, the depth to permafrost in both areas was only 0.3 m, essentially immediately below the vegetation mat.

Some generalizations regarding lakes and substrate are: 1) ground ice is commonly encountered within 0.3 m below the surface in areas designated “wet”; 2) ground ice is encountered within 1 m below the surface in all lake-based terrain units; 3) areas mapped as river floodplains (RF) contain large amounts of gravel which may be at depth (approximately 10 m); 4) wet areas with a high density of small lakes have about 0.3 m of tundra and peat underlain directly by ice; 5) wet areas with a low density of lakes have a thin tundra cover underlain mostly by silt and sand to a depth of about 1 m, where ice is

TERRAIN AND LANDFORM MAP

OF THE BEECHEY POINT QUADRANGLE

Figure 7

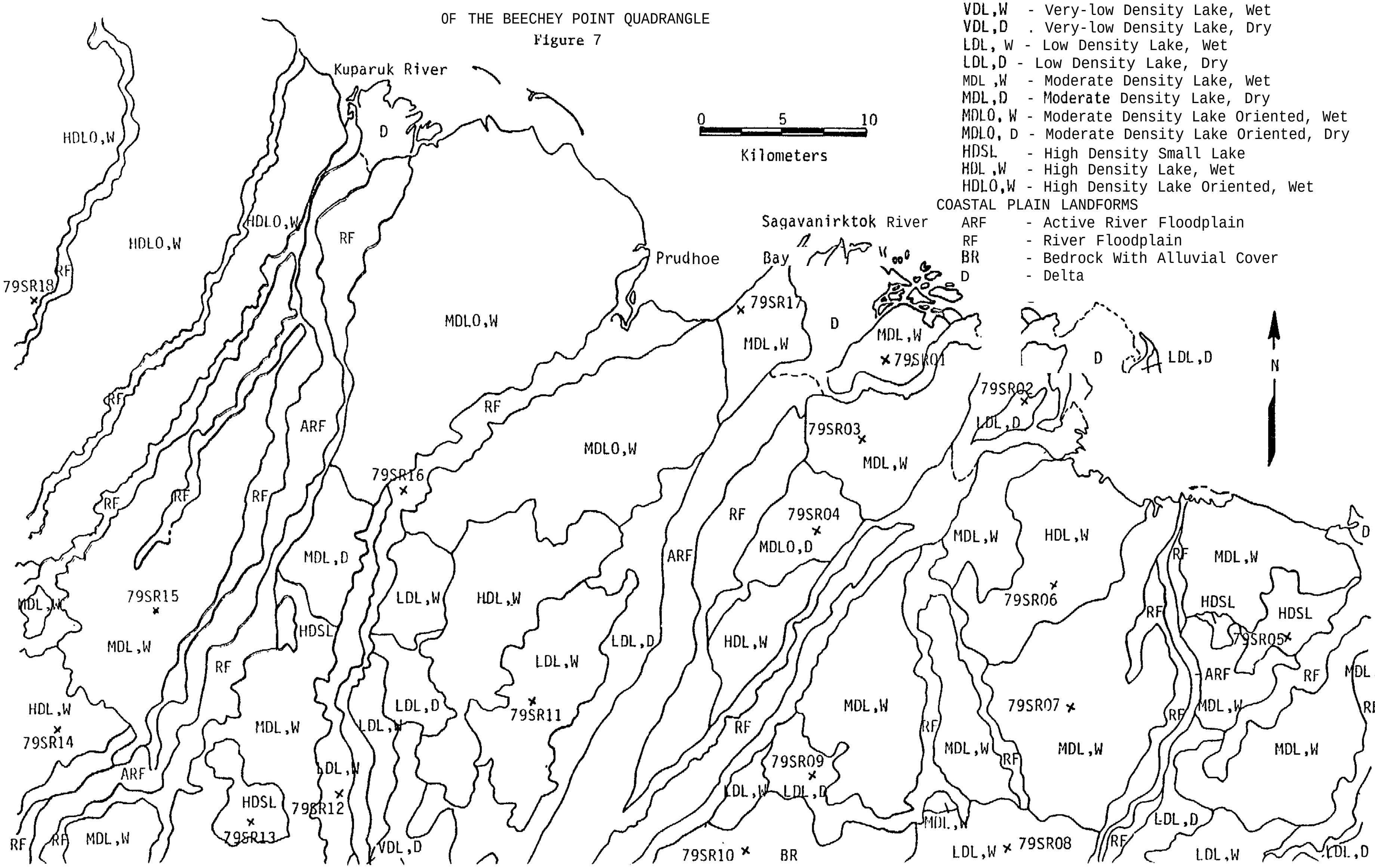

Table 8 - Lacustrine unit descriptions, Plates 1-6, 11-15.

Lt-	Lake, thaw - shallow lake formed by thawing of ground ice; lacustrine silt and organic matter over Mc deposits; thaw bulb below lake; frozen at depth; depth of thaw bulb depends on size of lake.
Lo-	Lake, oxbow or spit entrapment - shallow lake formed by abandonment or meander or enclosure of prograding and recurving spits; for meanders, lacustrine silt and organic matter over silty Fp deposits; thaw bulb below lake; frozen at depth; depth of thaw bulb depends on size of lake; for spits, lake is maintained because of its close proximity to base level.
Lbo-	Lacustrine basin, organic deposits - chiefly mixed organic matter and silt, organic matter dominant near surface; perennially flooded if basin is enclosed, otherwise not perennially flooded; aquatic vegetation where flooded, otherwise only sparse vegetation; active layer to 2 m where flooded, otherwise to 1 m; continuously frozen; little to no ground ice.
Lb-	Lacustrine basin deposits - chiefly silt and fine sand and some organic matter of recently drained basins; overlie Mc deposits; gravel at depth; basin bottoms are featureless except for some remnant ice-wedge polygons; active layer to about 1 m; little or no ground ice depending on the size of the basin - small basins may have some ice preserved, no ice in large basins; permafrost table is unchanged or elevated since drainage of the basin.
Lbt-	Lacustrine basin deposits with thaw ponds - chiefly silt, fine sand, and some organic matter one to several meters thick of drained lake basins; overlie Mc deposits; gravel at depth; very indistinct polygonal ground present but masked by thick tundra vegetation; no thaw bulb; massive ground ice content moderate to high; active layer to 1 m; fair drainage.
Lbpt-	Lacustrine basin deposits with polygonal ground and thaw ponds - chiefly silt, fine sand, and some organic matter one to several meters thick of drained lake basins; overlie Mc deposits; gravel at depth; distinct polygonal ground and numerous small thaw ponds; tundra vegetation; continuously frozen; no thaw bulb; high ground ice content; high, active layer to 1 m; poor drainage.
Lbp-	Lacustrine basin deposit with polygonal ground - chiefly silt, fine sand, and some organic matter one to several meters thick, of drained lake basins, overlie Mc deposits, gravel at depth; distinct polygonal ground; tundra vegetation; no thaw bulb; massive ground ice content moderate to high; active layer to 1 m; fair drainage.

Table 8- continued.

Lbs- Lacustrine basin terrace deposits - chiefly silt and fine sand and some organic matter of recently drained basins; overlie Mc deposits; gravel at depth; basin bottoms are featureless except for some remnant ice-wedge polygons; active layer to 1 m; little or no ground ice depending on the size of the basin - small basins may have some ice preserved, no ice in large basins; permafrost table is unchanged or elevated since drainage of the basin; occur where lake shorelines have recently receded; terraces bounded by scarps which often parallel the existing lake shoreline.

Lbm- Lacustrine basin marsh deposits - chiefly silt, fine sand and some organic matter one to several meters thick of drained lake basins; overlie Mc deposits; gravel at depth; numerous low-center polygons and coalescing, shallow thaw ponds; aquatic vegetation; flooded seasonally; no thaw bulb; high ground ice content; active layer to 1 m; very poor drainage.

Lm- Lacustrine marsh deposits - chiefly silt, fine sand and some organic matter one to several meters thick not bounded by strandlines; overlie Mc deposits; gravel at depth; numerous low–center polygons and coalescing, shallow thaw ponds; aquatic vegetation; flooded seasonally; no thaw bulb; high ground ice content; active layer to 1 m; very poor drainage.

Table 9- Characteristics of units of the Beechey Point Quadrangle terrain and landform map.

Visual Nomenclature	Sample #	Substrate	Water/Land	Coarse/Fine	Depth To Ice
LDL, D	79SR02	sandy-silt	0.17	0.33	>1.0
LDL, D	79SR09	san-si-cl	0.09	1.22	0.4
LDL, W	79SR08	san-si-cl	0.08	0.27	0.4
LDL, W	79SR11	san-si-cl	0.28	0.32	1.0
LDL, W	79SR12	silty-sand	0.25	1.94	0.9
MDL, W	79SR01	silty-sand	0.24	1.00	0.$
MDL, W	79SR03	silty-sand	0.22	1.22	0.9
MDL, W	79SR07	silt	0.14	0.01	0.4
MDL, W	79SR15	san-si-cl	0.20	0.55	0.6
MDL, W	79SR17	silty-sand	0.21	0.92	>1.0
MDLO, D	79SR04	silty-sand	0.21	1.50	0.9
HDSL	79SR05	clayey-silt	0.35	0.02	0.3
HDSL	79SR13	clayey-silt	0.31	0.02	0.3
HDLO, W	79SR18	silty-clay	N/A	0.01	0.0
HDL, W	79SR06	san-si-cl	0.18	0.72	0.3
HDL, W	79SR14	silty-sand	0.16	0.85	0.6
BR	79SR10	san-si-cl	N/A	0.84	0.9
RF	79SR16	clayey-silt	N/A	0.05	0.3

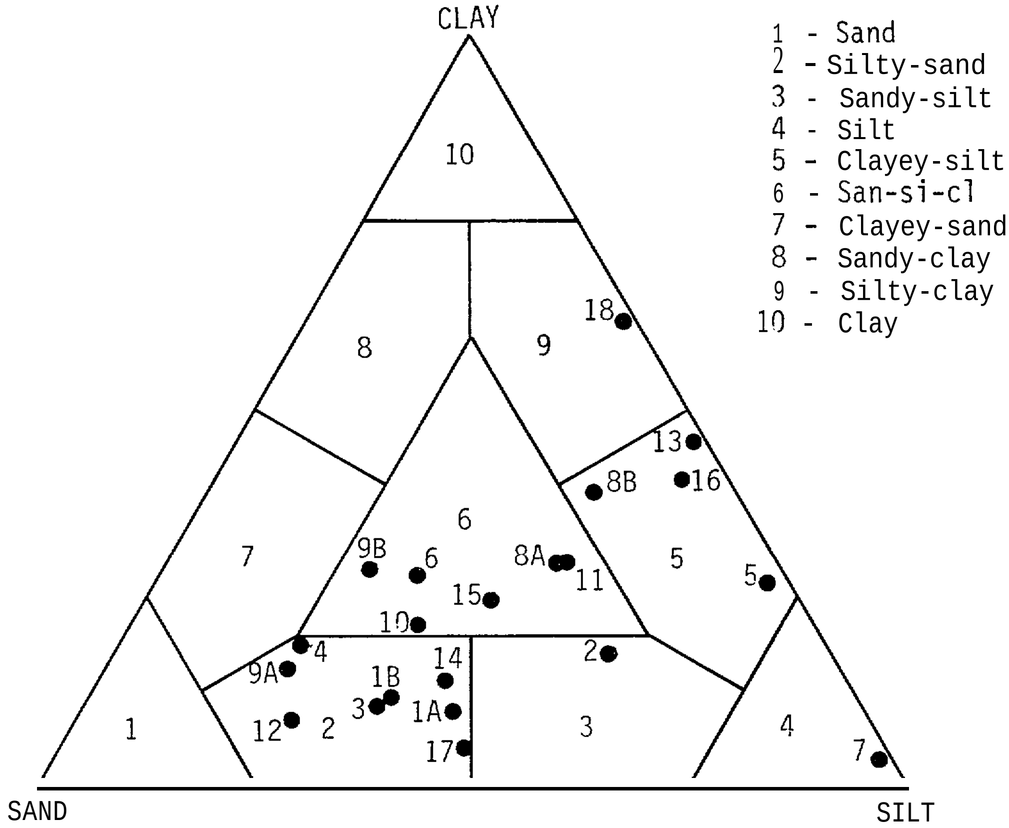

Figure 8- Ternary diagram showing grain size distribution in terrain unit samples.

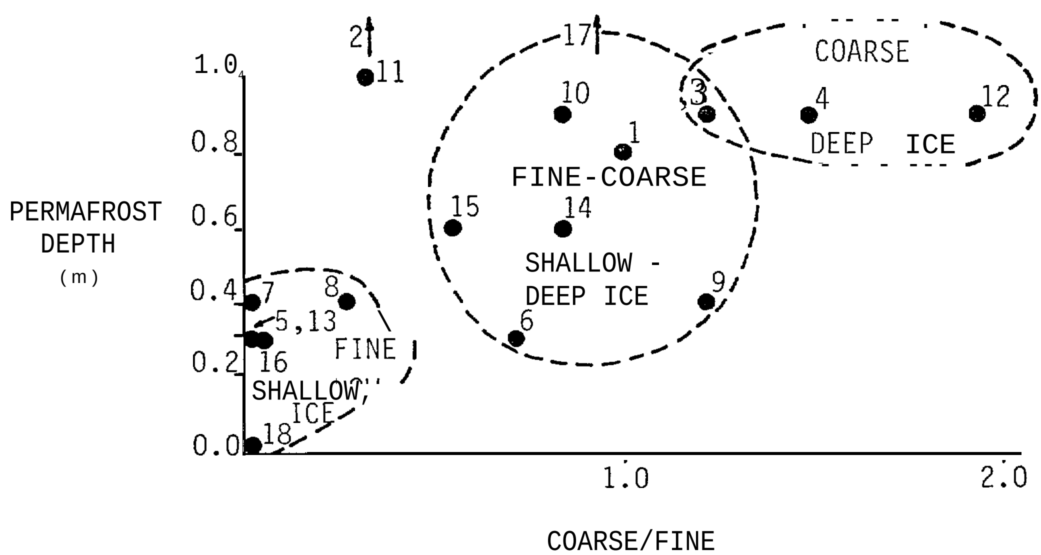

Figure 9- Plot of depth to permafrost versus coarse grains to fine grains in the Beechey Point Quadrangle terrain unit samples.

encountered; 6) pingos (conical mounds raised by hydrostatic pressure and cored with ice) are most common in wet areas with moderate to high lake densities; 7) many of the units with moderate densities of lakes have silty sand substrates; and, 8) many units with low densities of lakes have san-si-cl substrates.

Lake Shorelines. Lake shorelines show a range of morphologies from those with bluffs to those without bluffs. Bluff heights along lake shorelines generally range within one meter. With lakes where no bluff is present the tundra surface slopes to the edge of the water and continues below the lake surface.

Cannon et al. (1978) suggested that morphological changes in the Beaufort Sea"coastline, including development of some barrier islands, are due in part to coalescence of inland lakes. Determination of erosion rates of lake shorelines, therefore, is necessary to assess the contribution of lake coalescence to shoreline morphological changes.

Measurements of horizontal rates of lake shoreline changes in the Prudhoe Bay vicinity and Brownlow Point show a mean retreat rate of 0.35 m/yr.

The Teshekpuk Lake and Kogru River areas perhaps best exemplify the effects of lake coalescence: serrate sides of the river and the rounded edges of Teshekpuk Lake. The large size, strong elongation, and orientation of lakes in this area are clearly contrasted with surrounding coastal plain lakes. Subsurface samples acquired near Teshekpuk Lake show abundant silt and clay.

Headward growth of the Kogru River by erosion and inundation, and coalescence of lakes will eventually connect Teshekpuk Lake with Harrison Bay. Low-altitude aerial reconnaissance suggests that headward inundation of the Kogru River is quite rapid. Small meandering channels connect the nearest westerly lakes with the head of the river, and the salt marsh nature of this area indicates frequent inundation.

Coastline

Landforms and Deposits. Plates 11 through 15 show geomorphic units along the coast from Oliktok Point to the ARCO west dock. Part of Plate 13a and Plates 13b and 14 show the geomorphic units of the barrier islands along this stretch of coast. Appendix B shows comparative photographs (1955, 1979) of coastal features. Many of the units along the coast and on the islands are marine, eolian, and fill (Table 10).

Erosion and Detritus Input. Erosion along the Beaufort Sea coast occurs during the summer months, in mid-June through early October, but especially in August and September (Lewellen, 1977; Hopkins and Hartz, 1978) when large storms are most frequent. During the rest of the year erosion is negligible because the sea and coastal bluffs are frozen. In some areas it is possible that at sea ice breakup in June some sediments or blocks of the coastal plain that are associated with

Table 10- Marine, eolian and fill unit descriptions, plates 1-6, 11-15.

MARINE DEPOSITS (M)

Mc- Marine, coastal plain deposits - chiefly silt and fine sand, with small amounts of gravel and organic matter; active layer to 1 m; continuously frozen; moderate to high ice content; tundra vegetation; no apparent modification.

Mb- Marine, beach deposits - chiefly fine sand, with some silt and organic matter along mainland coastal plain deposits (Me) and well sorted medium to coarse sand and gravel on offshore islands; no vegetation; perennially unfrozen; subject to frequent inundation by storm surge; longshore transport and seasonal ice shove.

Mbs- Marine, stabilized beach deposits - chiefly fine sand, with some silt and organic matter along mainland coastal plain deposits (Me) and well sorted sand and gravel on offshore islands; grass vegetation; infrequent inundation; surface perennially unfrozen.

Mm- Marine, saltmarsh deposits - chiefly fine sand and silt with organic matter; subject to frequent inundation by marine storm surge; grass and moss vegetation, is commonly dead from salt; active layer to 2 m; continuously frozen; generally occur where lacustrine basin deposits (Lb, all variations) are breached by the sea.

Mi- Marine, island deposits - chiefly medium to coarse sand and gravel of the offshore barrier islands; no vegetation; perennially unfrozen; subject to longshore transport; frequent inundation by storm surge and seasonal ice shove.

Ms- Marine, spit deposits - chiefly medium to coarse sand and gravel of the offshore barrier islands; no vegetation; perennially unfrozen; subject to longshore transport; frequent inundation by storm surge and seasonal ice shove; generally form narrow elongated deposits from other marine deposits.

Mr- Marine, bar deposits - chiefly medium to coarse sand and gravel of the offshore barrier islands; no vegetation; perennially unfrozen; subject to longshore transport; frequent inundation by storm surge and seasonal ice shove; form narrow connections between other marine deposits.

Mbo- Marine, organic beach deposits - chiefly finely divided organic matter with some silt. Derived from erosion of Mc deposits.

Mw- Marine, swash zone deposits - chiefly fine sand, with some silt and organic matter along mainland coastal plain deposits (Mc} and well sorted sand and gravel on offshore islands; no vegetation; perennially unfrozen; subject to almost constant longshore transport and wave action.

Table 10– continued.

EOLIAN DEPOSITS (E)

Ed- Eolian, dune deposits - fine and medium sand of active dunes; dry frozen; sand derived chiefly from Mb or Fp deposits; little or no vegetation, grass and low brush where present.

Eds- Eolian, stabilized dune deposits - fine and medium sand of non-active dunes; dry frozen; sand derived chiefly from Mb or Fp deposits; vegetation of grass and low brush.

Eb- Eolian, deltation basin deposits - fine and medium sand, and silt; some ventifacts; flat topography; no vegetation.

Ec- Eolian, cover deposits - fine and medium sand in thin sheets; dry frozen; sand derived chiefly from Mb, Ed or Fp deposits; little or no vegetation, grass and low brush where present.

FILL DEPOSITS (H)

Hf- Fill deposits - sand and gravel deposited by man.

shore-fast ice are detached and transported. Erosion occurs primarily by thawing of the coastal bluff sediments and constituent ice and downslope slumping of the thawed sediments. Mudslumps may occur where there is considerable thawing of ground ice. McDonald and Lewis (1973) cited over 10 m of headwall retreat in a mudslump on the Yukon Coastal Plain over a one-year period.

The coastal bluffs are either faced by a generally narrow beach or descend directly into the sea. Erosion is greatest in the latter case because the impact of waves is constant, resulting in considerable thawing and undercutting; the depth of water is also important in this case: erosion increases with depth (Hopkins and Hartz, 1978). Because of this thawing and undercutting large blocks of the coastal plain detach along planes of weakness at ice-wedges and slump into the sea where they quickly erode (Hopkins and Hartz, 1978). The presence of a beach slows erosion and in some cases the rate of erosion is directly related to the width of the beach, i.e., the wider the beach, the slower the erosion (Cannon and Rawlinson, 1978).

It is stressed that erosion along the Beaufort Sea coast does not occur at an even rate, but primarily during large storms. These storms are common in August and September because the Arctic Slope weather during these months is dominated by cyclonic low pressure systems (Hartz, 1978; Walker et al., 1980). Reflecting the cyclonic low pressure systems, the wind is generally from the west or southwest (Hartz, 1978; Leavitt, 1978; Mungall et al., 1978). Winds from the east generally lower sea level and limit strong wave action on the coast because the waves break offshore (Grider et al. , 1978). Mungall et al. (1978) attributed this set-down to sea level sloping southward in geostrophic balance with Coriolis forces. The tidal range along the Beaufort Sea coast is normally very low. Hume and Schalk (1967) cited a daily variation of about 6 in. with an additional monthly variation of about 5 in. at Barrow, Alaska, and Mungall et al. (1978) cite an August tidal range in the eastern part of Simpson Lagoon of 0.75 ft. Because during storms the wind is generally from the west and southwest, the waves and surge, which may reach 3.0 to 3.5 m above the normal level (Hume and Schalk, 1967; Reimnitz and Maurer, 1978), are also from the west. West-facing shorelines, therefore, generally erode faster than east-facing shorelines (Hopkins, personal communication, 1977). Further, erosion is usually very rapid at points of land (Hopkins and Hartz, 1978). However, points of land generally persist in the same area, and coastal morphology does not vary significantly for many years (Lewellen, 1977). During storms the constant impact of waves on bluffs that descend directly into the sea is increased, but also, thawed sediments and somewhat protective slumped tundra-mat accumulating on beaches at the base of some bluffs are removed, allowing thawing, undercutting, and slumping of these usually protected bluffs.

The topography and landforms other than beaches such as lake basins also control the rate of erosion (Cannon and Rawlinson, 1978). Coastal erosion along the Beaufort Sea averages about 1 m/yr along the Canadian coast, about 1.6 m/yr from the U.S. - Canada border to Point Oliktok (figure 1), and 4.7 m/yr from Harrison Bay to Barrow (Hopkins and Hartz, 1978). Shortterm erosion may often be great; Lewellen (1977) reported up to 30 m/yr at Drew Point and Cape Simpson.

Particulate matter is introduced into the nearshore environment not only by rivers but also by coastal erosion. Volume and mass estimates given below are calculated from measurements and observations along Simpson Lagoon. Published literature and observations in this study suggest that these estimates can roughly apply to the entire Beaufort Sea coastline.

The total volume of particulate matter introduced into Simpson Lagoon per km of coastline is 2.6 x 10^3 m^3/yr. This value is calculated with the average coastline dimensions and vertical dimensions discussed perviously. Here, particulate matter is inorganic elastics and peat soil. Peat soil refers primarily to the topmost tundra-mat, but also, to other vegetative matter intercalated with inorganic elastics throughout the bluff.

Minima of 20 to 30 percent of the total volume are considered peat soil respectively for the moderately high- and low-topographic areas. These are minima because they are based only on the approximate thickness of the top tundra-mat. The volume of peat soil introduced into the nearshore environment per km of coastline is 6.2 x 10^2 m^3/yr. Upon combustion peat soil shows an organic content of about 40% (Schell, personal communication, 1977).

Densities of 2.0 g/cm^3 for inorganic elastics and 1.1 g/cm^3 for peat soil were used to determine the mass of the particulate matter introduced into the nearshore environment from coastal erosion. The mass of the total particulate matter is 4.5 x 10^6 kg/yr, and of peat soil is 6.8 x 10^5 kg/yr per km of coastline. Appendix B contains comparative photographs (1955 and 1979) of coastal areas.

Barrier Islands and Lagoons

Geomorphic Setting. Study of the Barrier Islands (Plates 13a, b and 14; Appendix B) and lagoons is concentrated between the Colville River on the west, and Prudhoe Bay on the east (Figure 1). Here, the Jones and Return Islands and Simpson Lagoon cover an area of roughly 240 km^2, about 60 km long by 4 km wide. The lagoon is shallow, generally less than 1 m (Tucker and Burrell, 1977), but may be as deep as 6 m in channels (Mungall et al., 1978).

The offshore islands are of two types, those with a thick tundra-mat overlying unconsolidated but ice-bound elastics, and those without tundra covers, consisting mainly of gravel and sand. Tundra covered islands, although linear in overall morphology, are quite angular and have long, straight beaches that intersect each other at acute angles. The gravel islands are curvilinear, long, and narrow. Strongly recurved gravel islands illustrate the influence of ocean currents.

Tundra-covered islands terminate at the lagoon as a steep bluff with talus (Hartwell, 1973) and slumped tundra-mat lying on a generally narrow beach. The topographic characteristics of island bluffs are equivalent to mainland bluffs. As in mainland bluffs, ice is often visible in the bluff underlying the tundra-mat or sediments in areas of moderately high relief.

Wide sand and gravel beaches generally occur on the seaward side of the tundra covered islands. These beaches are the source of sand-sized elastics that accumulate as eolian deposits against and on top of the bluff (Plate 13b). The elastics topping the bluff form a linear dune ridge which trends parrallel to the beach and is roughly proportional in width to the width of the beach.

Ice-shoved ridges are observed primarily on offshore island seaward-facing beaches, but also on lagoon-facing beaches and along the mainland. These ridges result from blocks or sheets of ice being pushed upon the beach primarily during storms. This process, however, is not restricted to the summer months. Hume and Schalk (1964) cited an observed ice advance of 140 ft. at Barrow, Alaska in 1961. Ice-shoved ridges may reach a height of about 2 m but most occur nearshore and are commonly 2 ft. high. The latter are usually destroyed annually. Ice shove is responsible for depositing beach gravels on top of the inland tundra in the vicinity of Prudhoe Bay. It does not contribute a significant amount of gravel to the islands. Also, no gravel was observed during four field seasons being ice-rafted to the islands. Pack ice does not generally enter the lagoon; that which does, however, could not raft significant amounts of gravel or large individual rock masses because of its small size and shallow draft.

Spit development is common on both the tundra-covered and gravel islands. Spits forming off the western ends of tundra-covered islands are generally straight and often develop into connective bars between islands. These bars form only where very shallow shoals normally exist between islands. Spits forming on isolated gravel islands are recurved and occur in multiples , most often pointing westward. Multiple recurved spits have formed within the Simpson Lagoon area on the western ends of Stump, Spy, and Thetis Islands and indicate net westward transport of gravel (Short et al., 1974). Although the net longshore current is westward, spits forming off the eastern ends of Bodfish and Cottle Islands suggest local eastward longshore currents as well.

Island Erosion and Duration. Island erosion rates tend to be higher than mainland rates. The mean rate of island erosion in the Simpson Lagoon area is 1.6 m/yr. The seaward side of Pingok Island erodes more slowly than the lagoon side because of wide beach development and a stabilizing dune ridge on the seaward side. The wide beach dissipates waves across its width before they contact the bluff; the dune ridge acts as a barrier to mechanical degradation processes and also insulates the bluff from thermal degradation.

The expected tundra duration on the offshore islands was determined using double the mean erosion rate of 1.6 m/yr. (to account for erosion on both sides of the islands), with the measured distance to be eroded (Table 11). The duration was maximized by using the greatest measured distance across an island perpendicular to the eroding fronts. Two tundra-c.overed isalnds will result as the narrow portion near the center of Pingok Island erodes. The duration of this part of Pingok Island was determined using two spot erosion rate measurements rather than the mean erosion rate.

Table 11- Tundra duration on the offshore islands along Simpson Lagoon.

Tundra Area	Duration (years)
Pingok Island	
Narrow Center	35
East Island	250
West Island	270
Bertoncini Island	80
Bodfish Island	160
Cottle Island (tundra areas east to west)	
East	90
Central	40
West	55

Evolution of the Barrier Islands and Coastal Lagoons. The tundra islands are erosional remnants of a once more extensive coastal plain. The morphology of surface lakes and drained lakes, similar bluff stratigraphy, and like lithologies on the islands and mainland substantiate this hypothesis. These islands form by connection of inland lakes or topographic lows with the ocean through inundation by erosion. Initially inundation may be local. Subsequent coalescence of adjacent lakes enlarges the inundated area, and if inland morphology permits, erosion from two directions creates a lagoon. The size and shape of the barrier island-lagoon system is then modified primarily by thermo-erosional processes.

A potential area for becoming an island-lagoon system is immediately west of Harrison Bay. Here the Kogru River will eventually connect with Teshekpuk Lake. Coalescence of lakes nothwest of Teshekpuk Lake and coastline erosion along Smith Bay could isolate the entire area north of Teshekpuk Lake from the mainland.

The gravel islands are in a sense remnant features, having completely lost their tundra covers, and remaining as lag. The accepted processes of barrier island formation are wave erosion and transport of offshore elastics, with the addition of elastics from longshore currents (Butzer, 1976). The former is the dominant process, and in the Beaufort Sea accounts for reworking of the lag gravel into shoestring islands. Coarse elastics, however, are not presently transported to the islands from other than local sources. The introduction of sand-size elastics from river systems and coastal erosion should temporarily maintain the gravel islands. Transport of sand to the islands will eventually decrease as the coast retreats and the islands will erode below base level.

CONCLUSIONS AND RECOMMENDATIONS

Analysis of the morphology and stability of the major landforms and the effective processes of the Arctic Coastal Plain indicates no geological conditions or processes that will prohibit further coastal plain and planned offshore island development. Conversely, except for noted exceptions, further development will not adversely impact existing geological conditions and processes more than what is occurring naturally. These conclusions are dependent upon measures utilizing present technology to protect developed areas from potentially harmful geological processes, and measures to minimize pollution, erosion, and accelerated loss of ground ice caused by development.

Geological processes potentially hazardous to development are: (1) loss of ground ice and subsidence, (2) coastal erosion, (3) storm surge, and (4) ice-shove. Ground subsidence is indicated in areas where there is little or no bluff along non-depositional shorelines, whether river, lake, or ocean. Wet coastal plain areas usually with a high density of small lakes have the shallowest depths to ground ice and most often exhibit bluffless shorelines. These areas are unstable and if possible should be excluded from development.

Beaufort Sea coastal erosion in most areas, although geologically very rapid, is sufficiently slow not to interfere with properly planned development. Rates of lake shoreline retreat are also sufficiently slow to cause no concern to development.

Storm surge is not a major concern to development on the tundra-covered barrier islands and the coastal plain in areas other than beach deposits and salt marshes (Plates 11-15) and the deltas (Plates 8 and 9). It is, however, a major concern to development on the offshore gravel islands. Elevation of structures or construction of protective seawalls is recommended on these islands.

The effects of ice-shove on the nearshore barrier islands are manageable with present technology. Offshore in deep water, where ice has the potential to move about freely (Stamuki Zone), ice-shove is a very real concern to development; the technology is currently being developed to cope with ice hazards in this zone.

Potentially harmful effects of development to geological processes and conditions are: (1) thermal erosion, (2) ground and surface water blockage and pollution, (3) removal of some non-renewable gravel sources and mechanical erosion, and (4) severe alteration of sediment dynamics. Without protective measures, heat flow from exploration and production facilities, and degradation of insulating tundra-mat will enhance the loss of ground ice on the tundra-covered islands and coastal plain. Preventive measures may include insulation, refrigeration, or elevation of structures during operations, and revegetation after operations.

Imprudent siting of landfills may contaminate suitable water supplies. Ground water flows in permafrost oceans within the active layer (topmost sediments subject to thaw). Siting of landfills in these areas is acceptable provided they are reasonably far from water sources and eroding shorelines. Siting of landfills within active or abandoned floodplains is not recommended as contaminants may be transmitted through subsurface gravels.

Offshore gravel islands are not renewable; removal of gravel from these islands is not recommended. Alternate gravel sources are abandoned or active river floodplains and river terraces. With abandoned floodplains it is recommended that meander scars or talik lakes, which can be reflooded, be used to minimize the non-aesthetic impact. Removal of limited amounts of gravel from active floodplains will have little more geological impact than is already occurring naturally. The approximate natural riverbank retreat is 1 m/yr. Development should be positioned at least beyond the distance expected to erode within the time of operation. If removal of gravel from active floodplains will radically alter the stream flow pattern and increase erosion beyond natural rates, artificial structures (groins and armored embankments) should be utilized.

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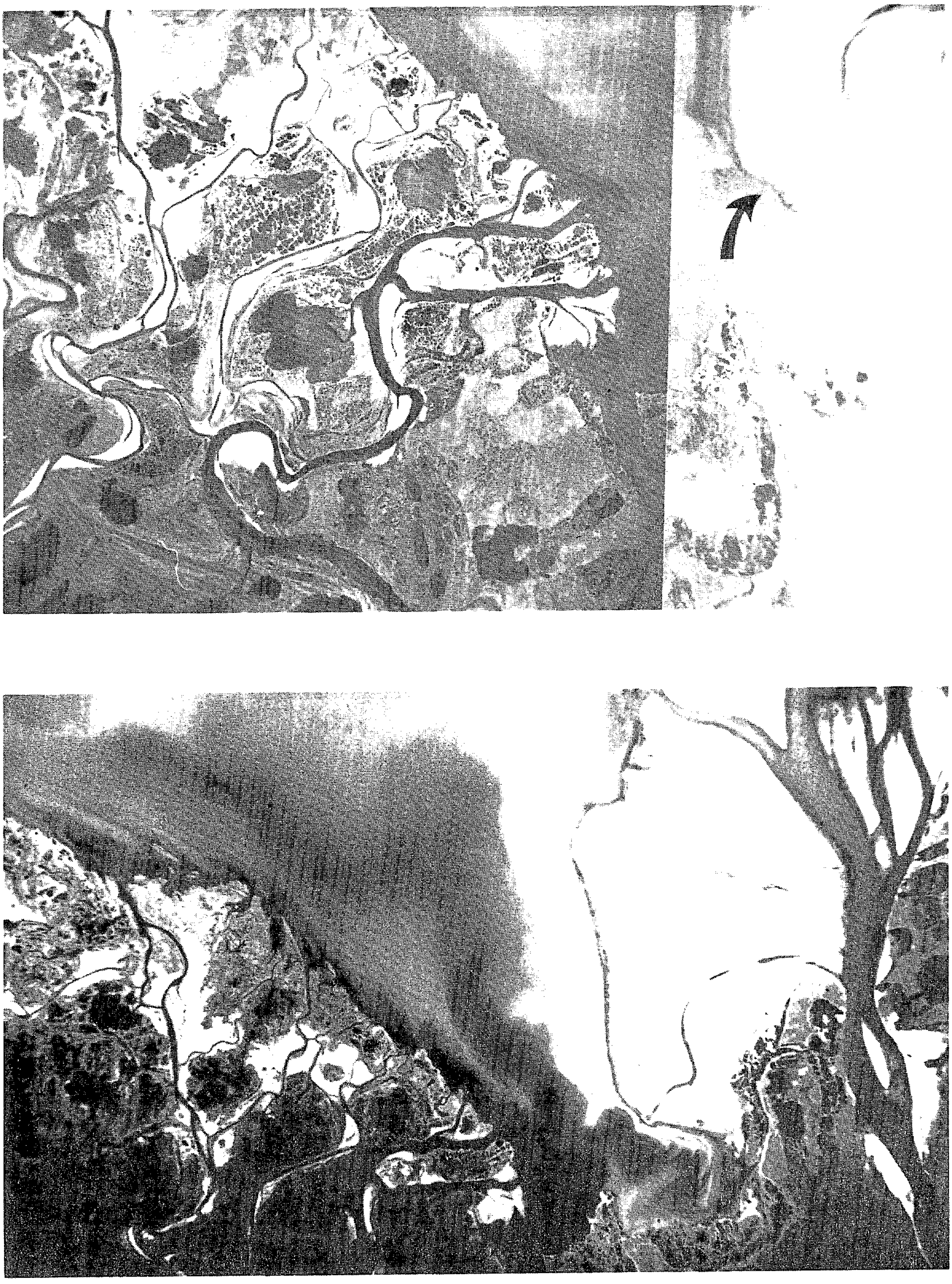
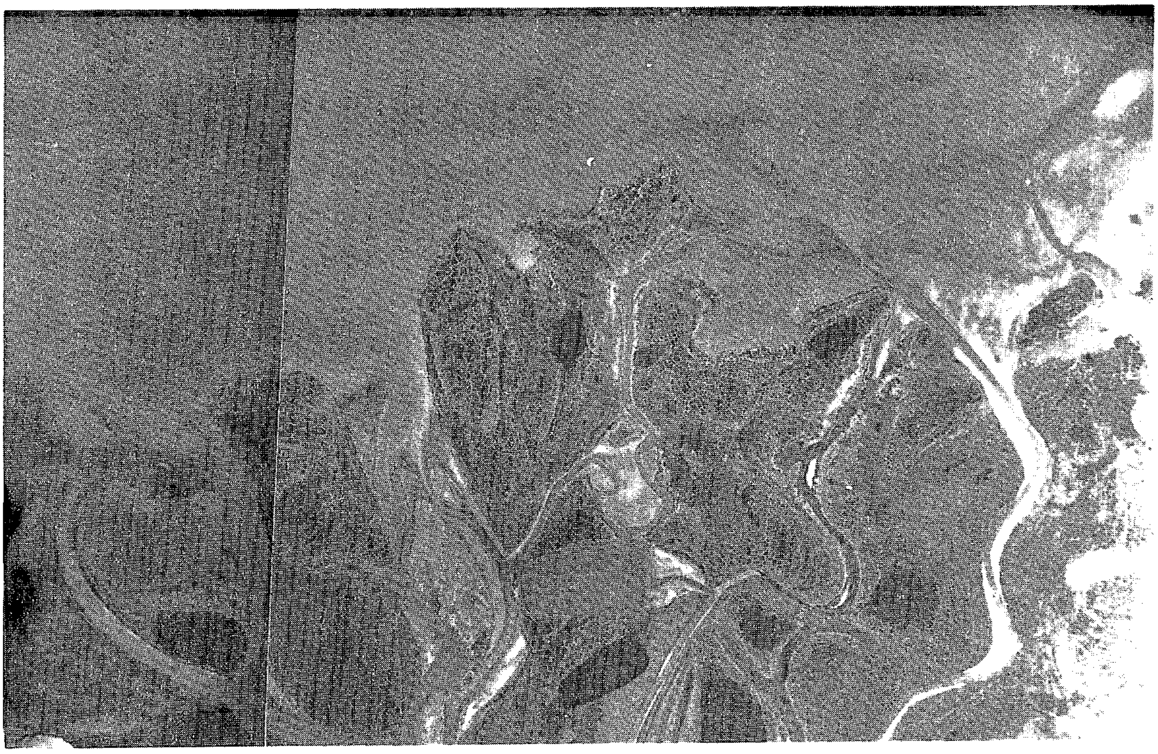
APPENDIX A

Comparative photographs, 1959 and 1979, of areas within the Colville, Kuparuk, Sagavanirktok and Canning River deltas. Top photograph 1955, bottom photograph 1979; scale, coverage and orientation may differ. Substantial orientation differences are noted. Arrows on some 1955 photographs show areas of notable change.

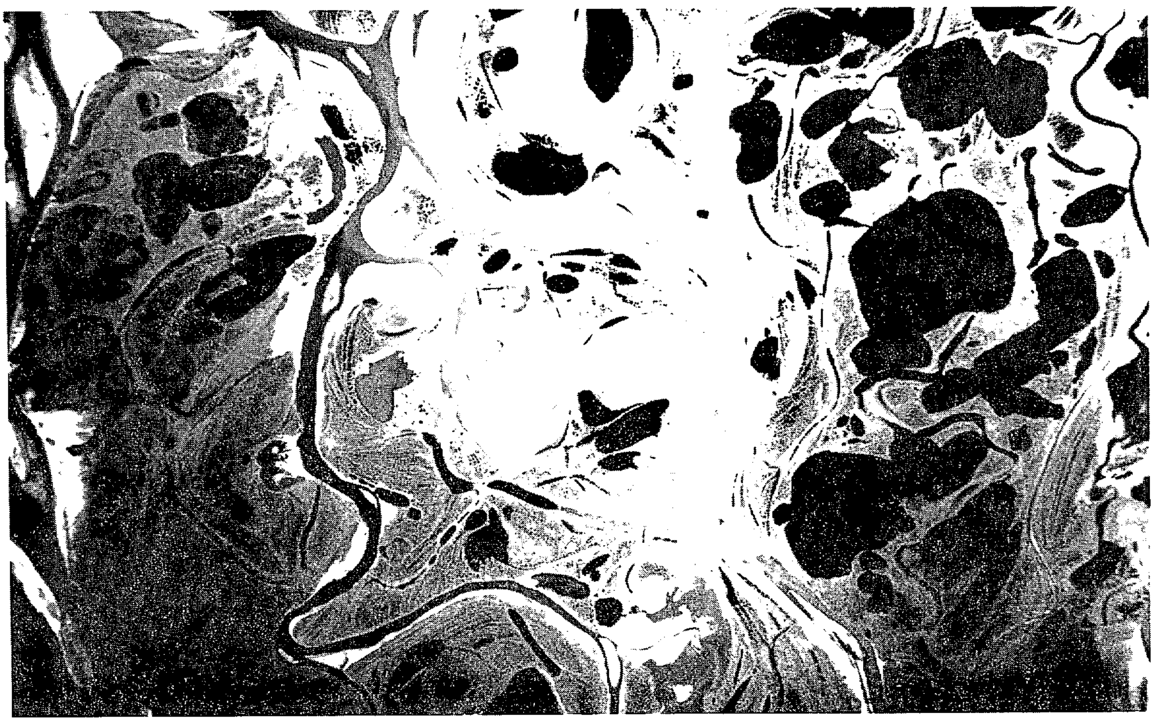


Colville Delta, northwest

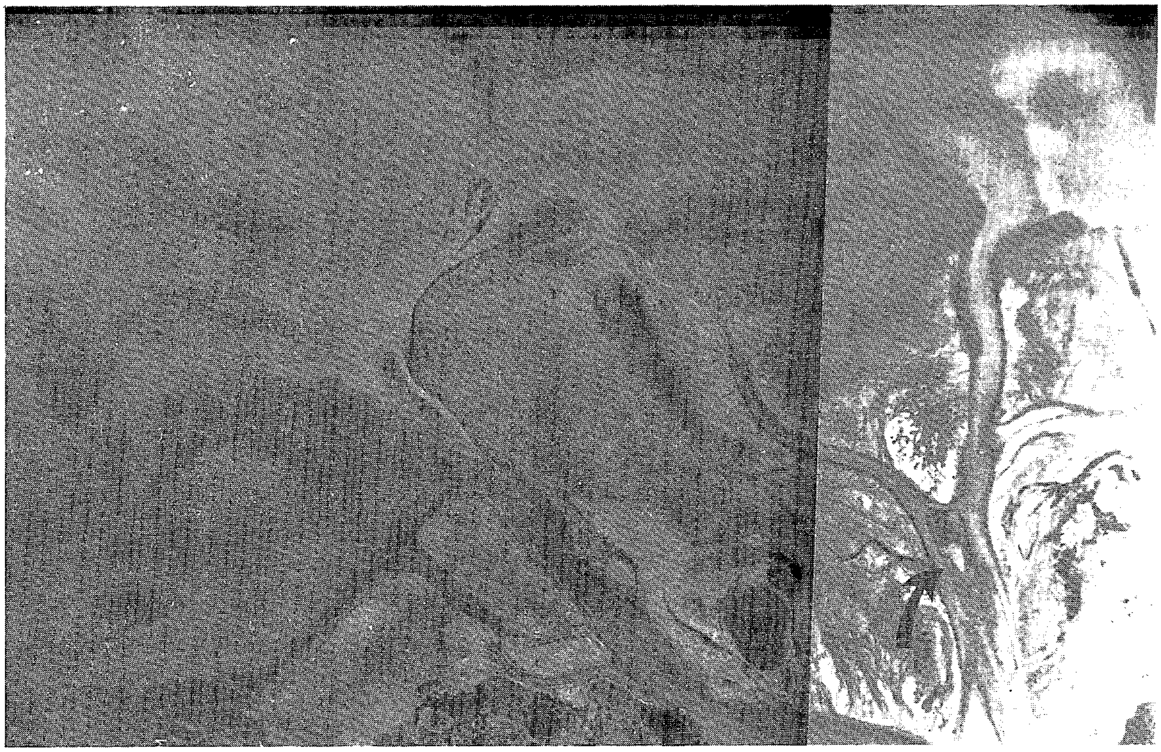
Colville **Delta, northwest**



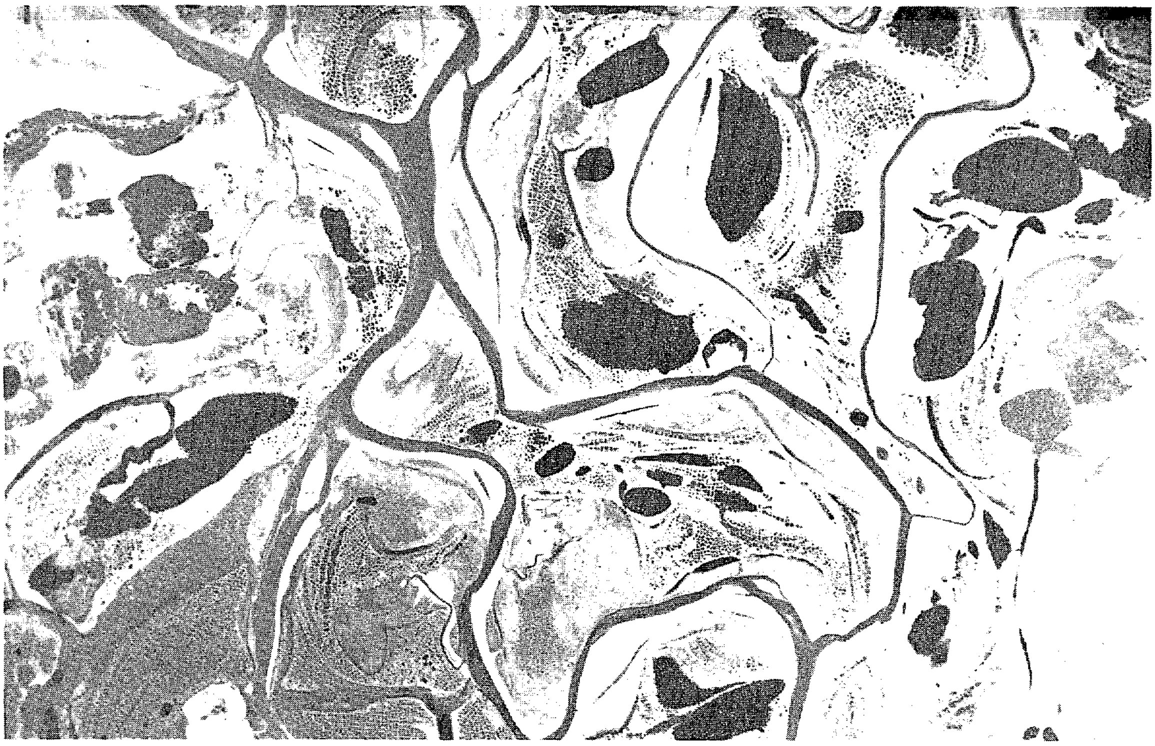
Colville Delta, northwest

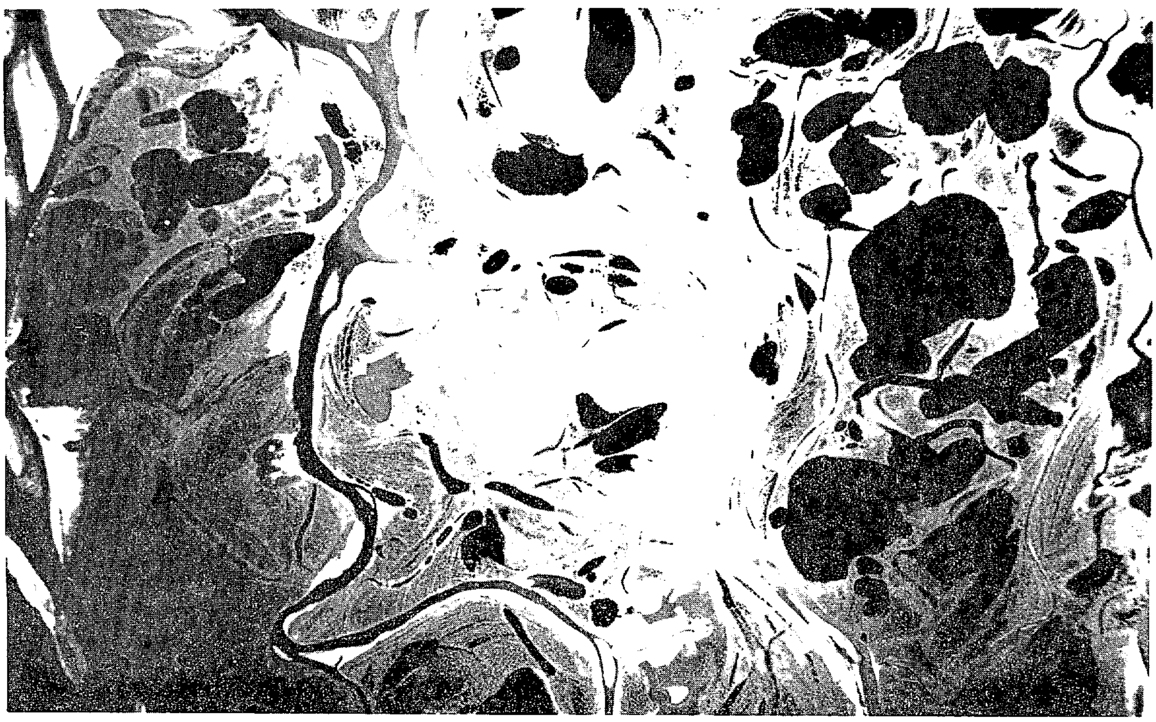


Colville Delta, northwest

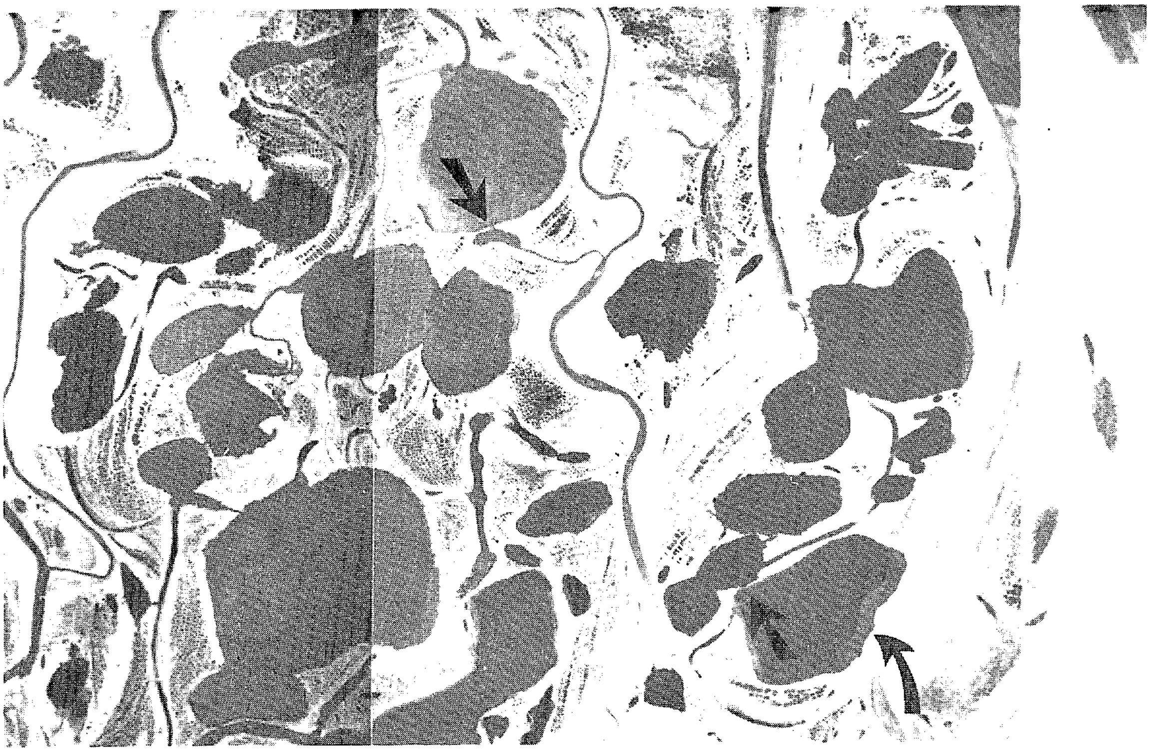


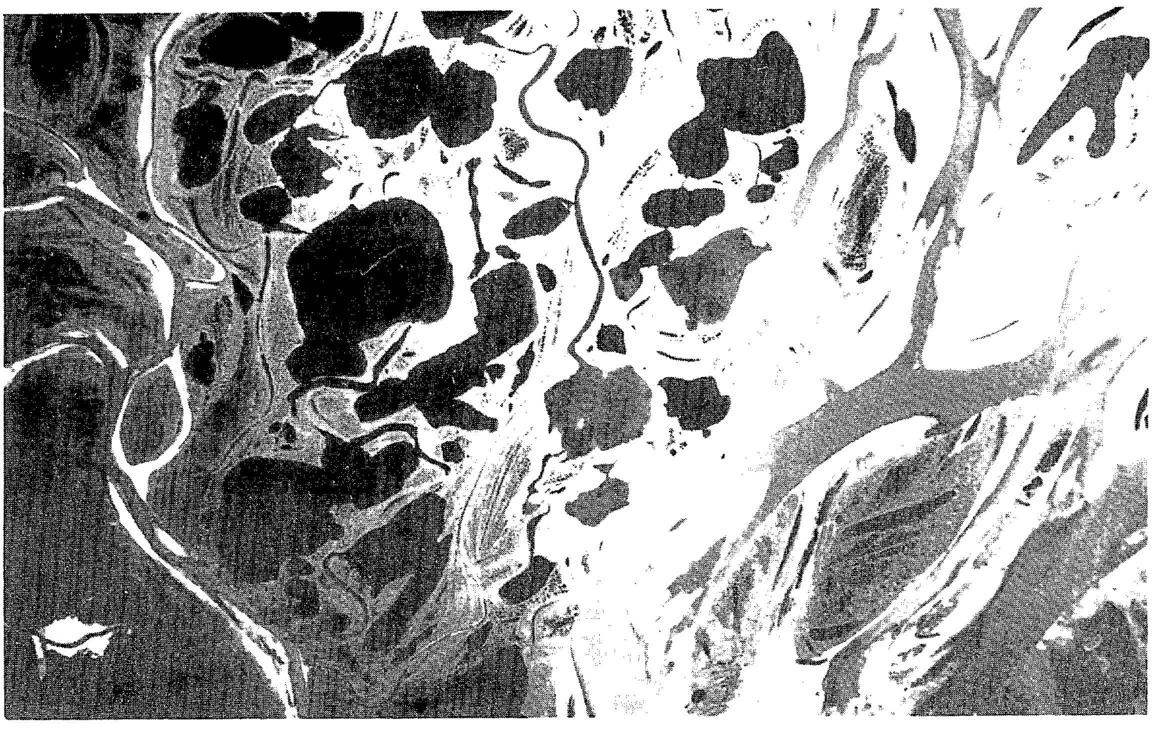
Colville **Delta, north central**



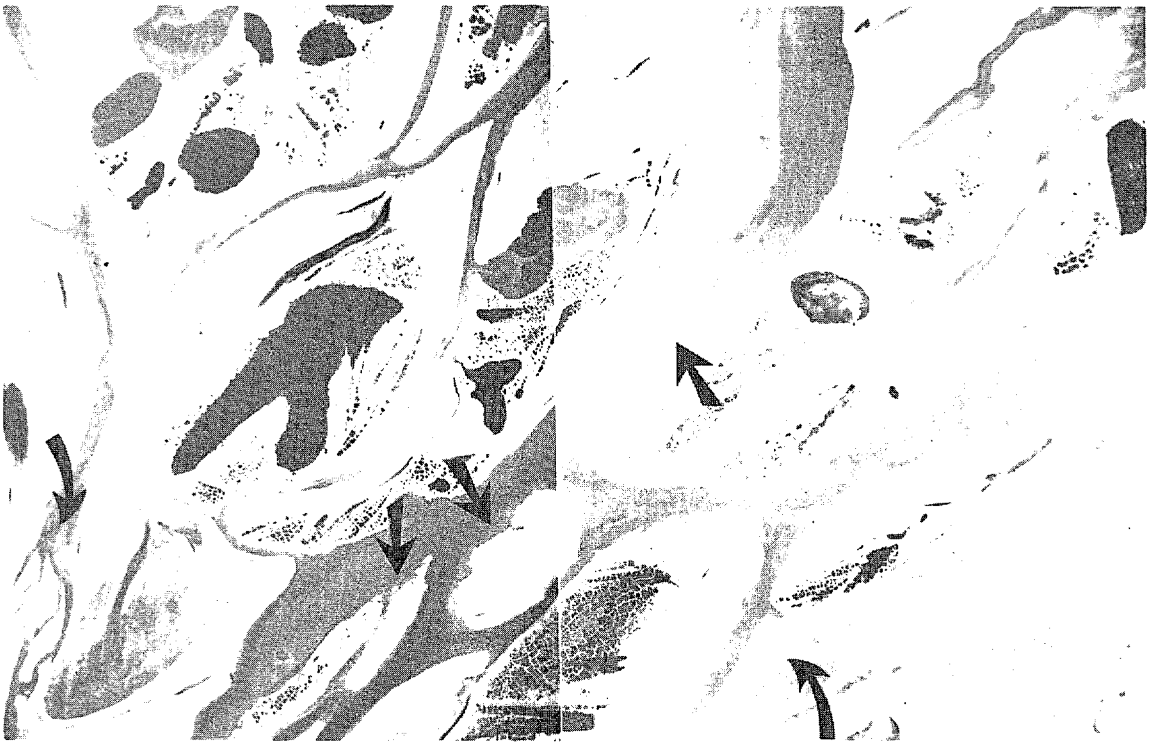


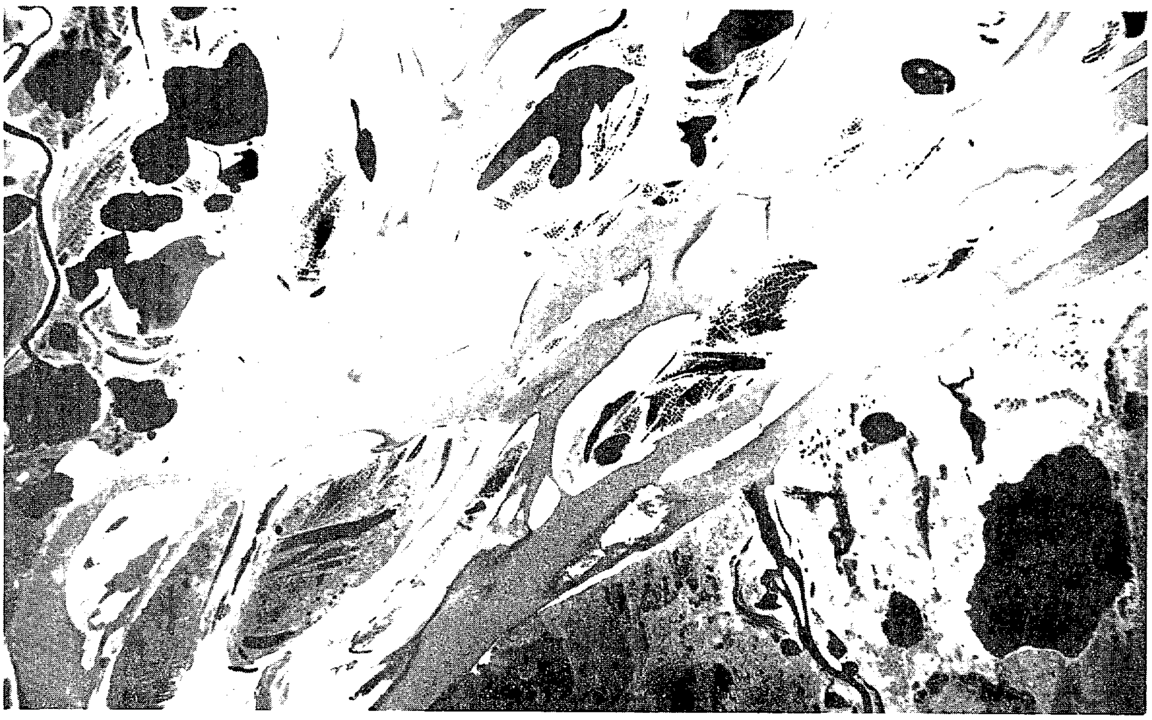
Colville Delta, north central



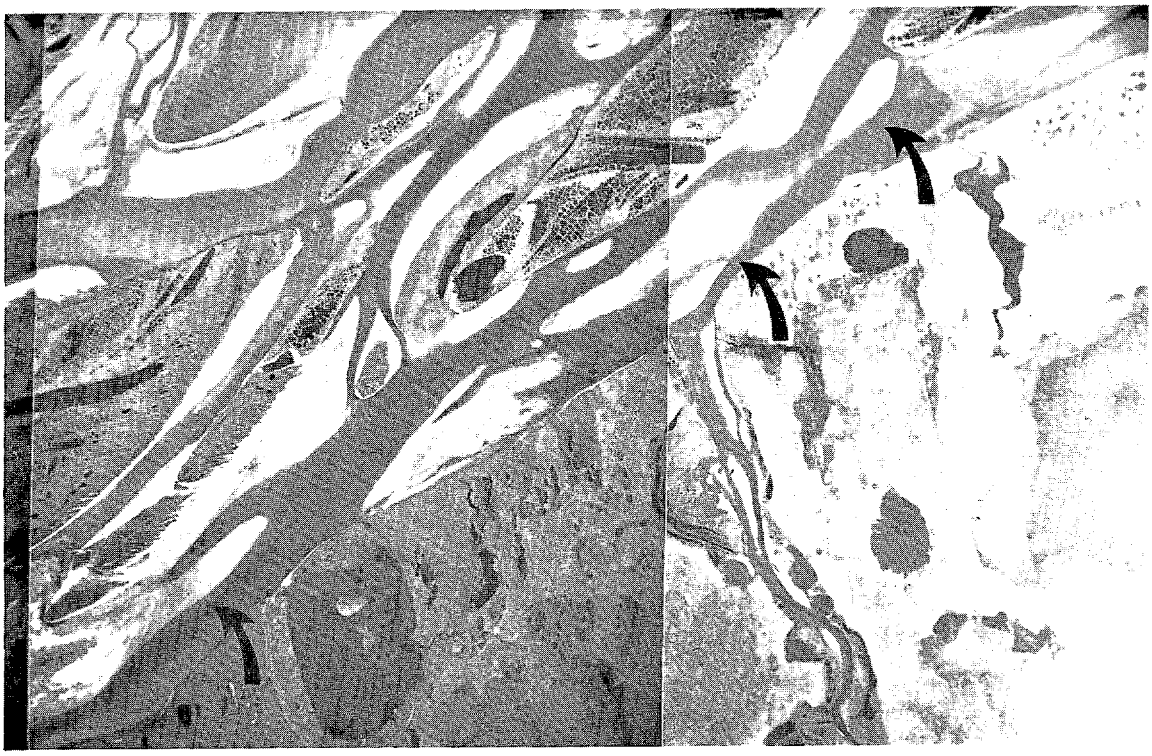


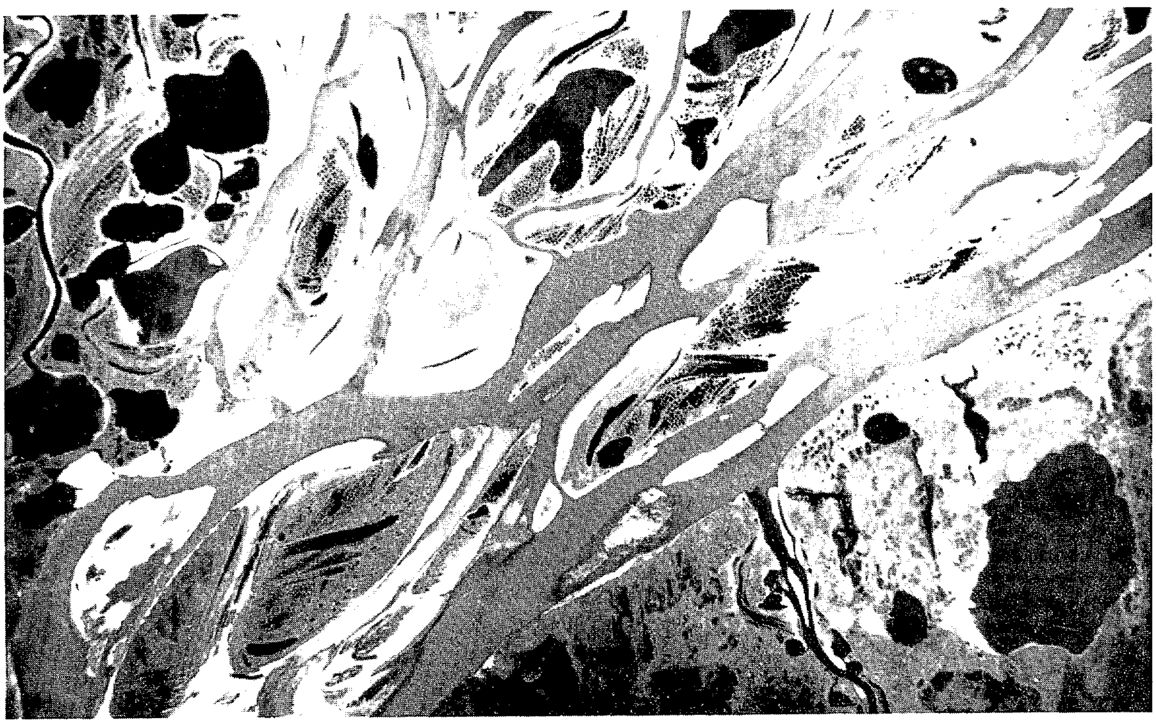
Colville Delta, northcentral





Colville Delta, northeast, note changes in the channel bars, particularly where indicated

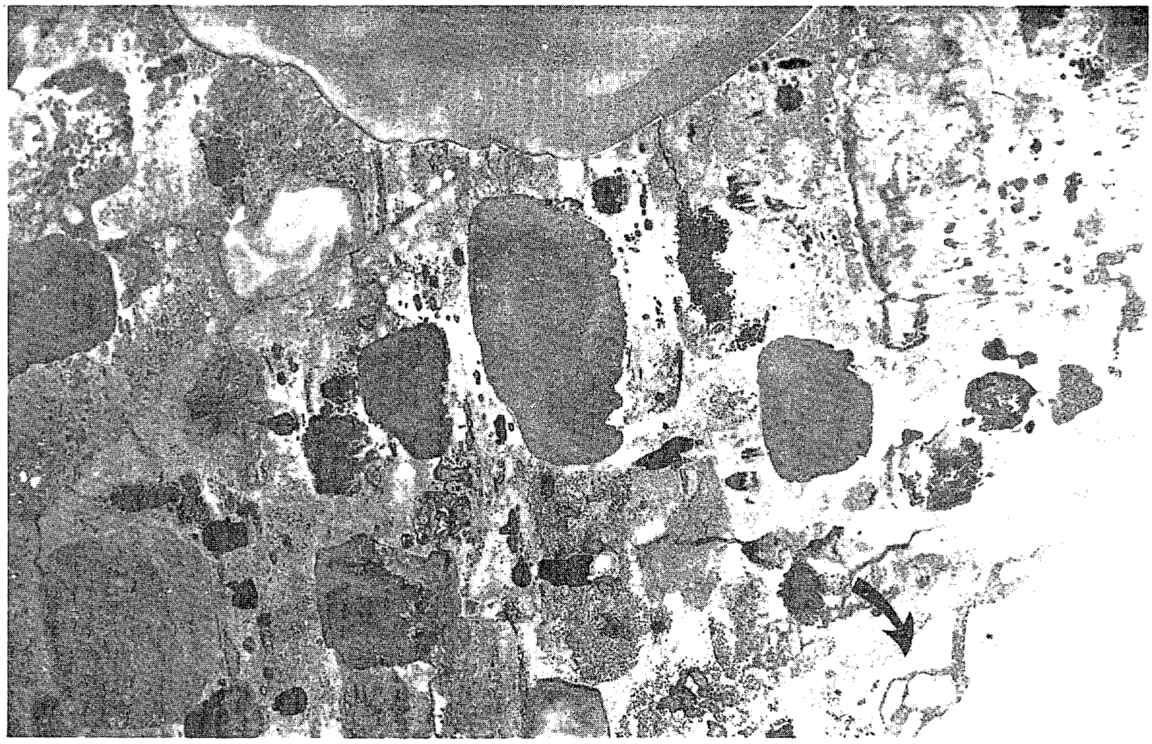


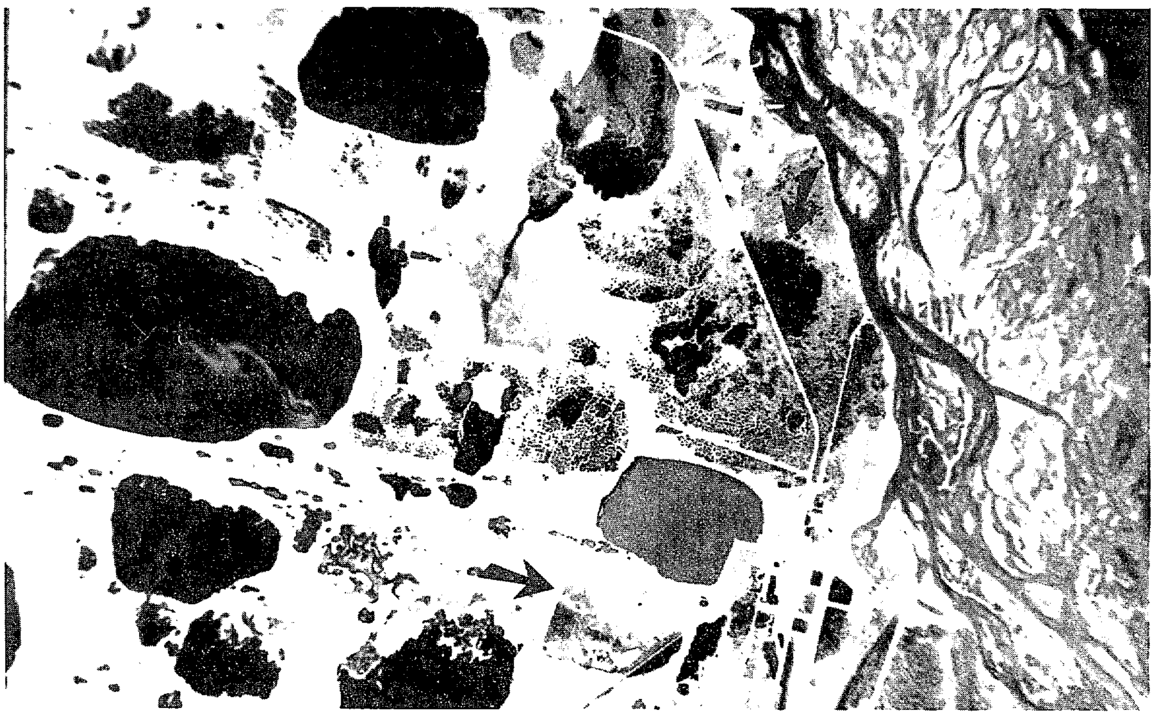


Colville Delta, northeast, note changes in the channel bars particularly where indicated

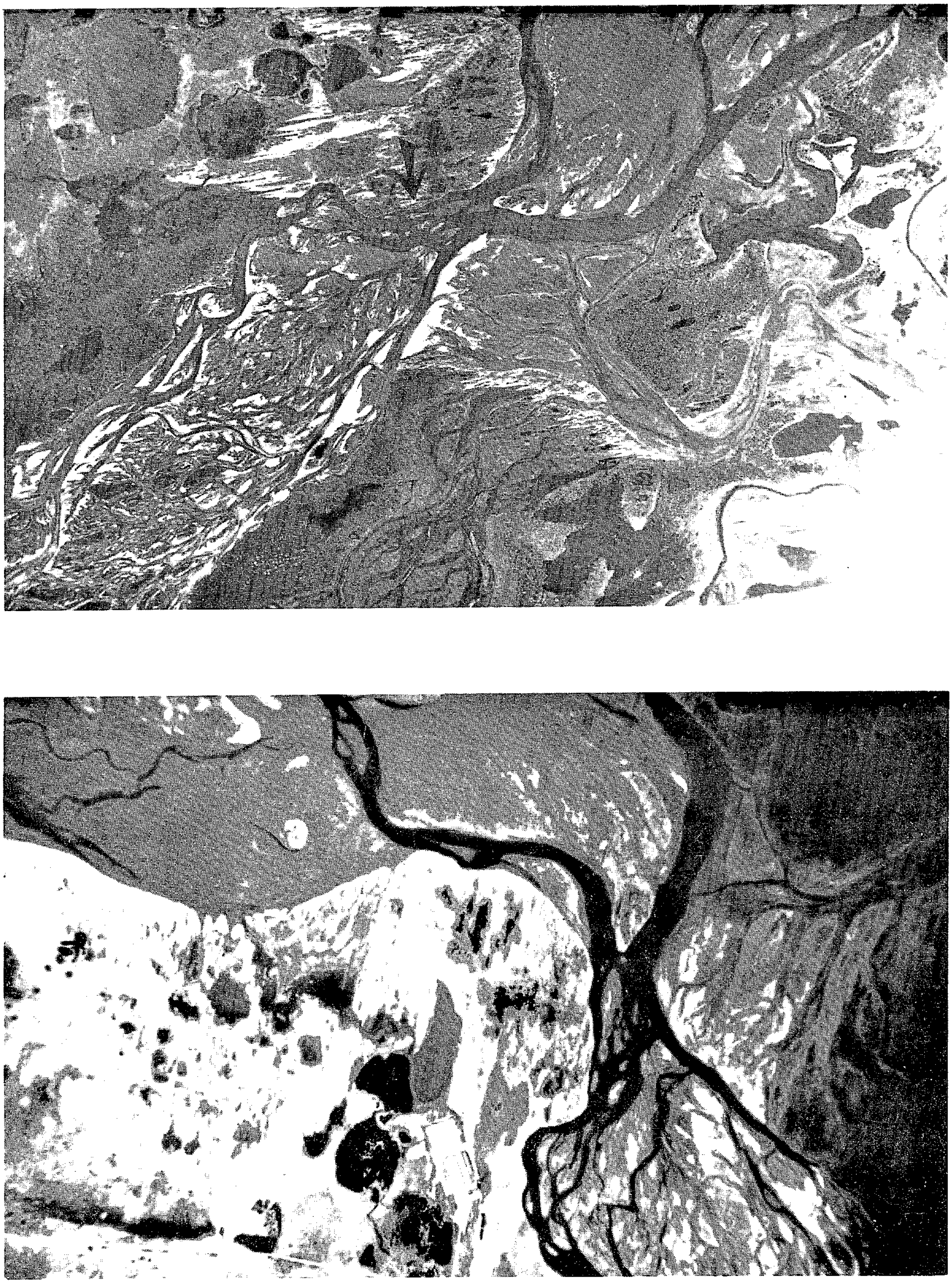
Kuparuk Delta, 1979 photograph about 90°
counterclockwise from 1955 photograph

Kuparuk Delta, northwest

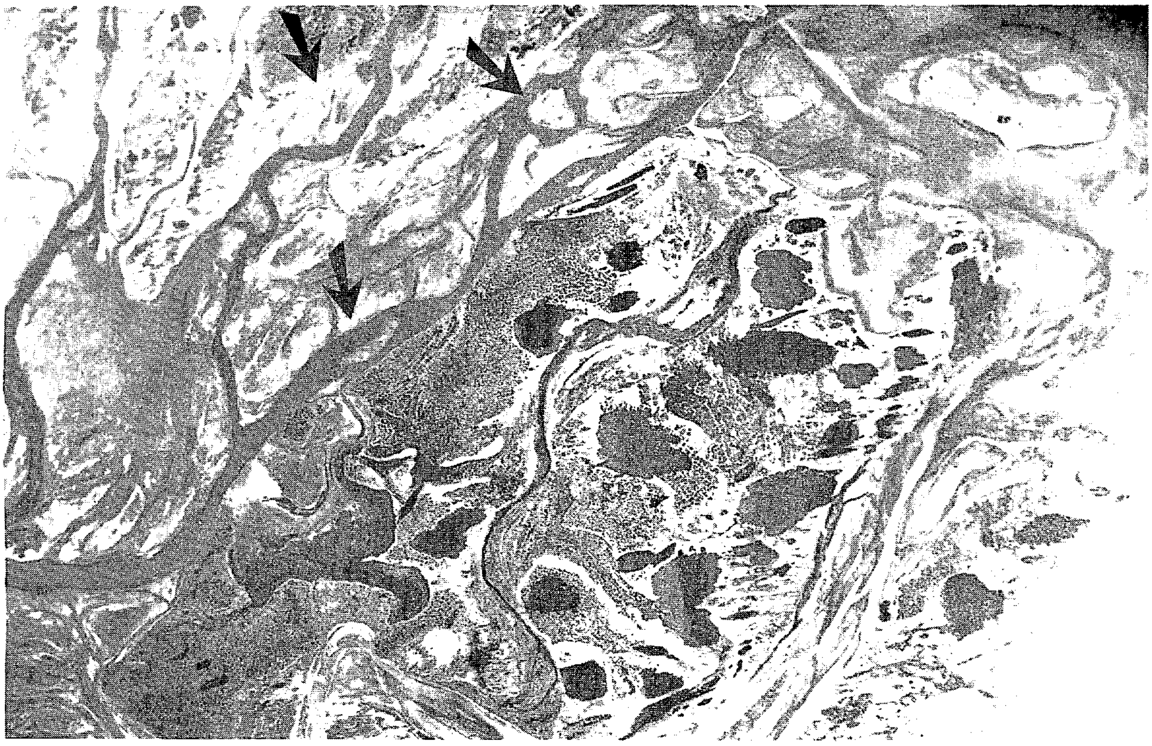


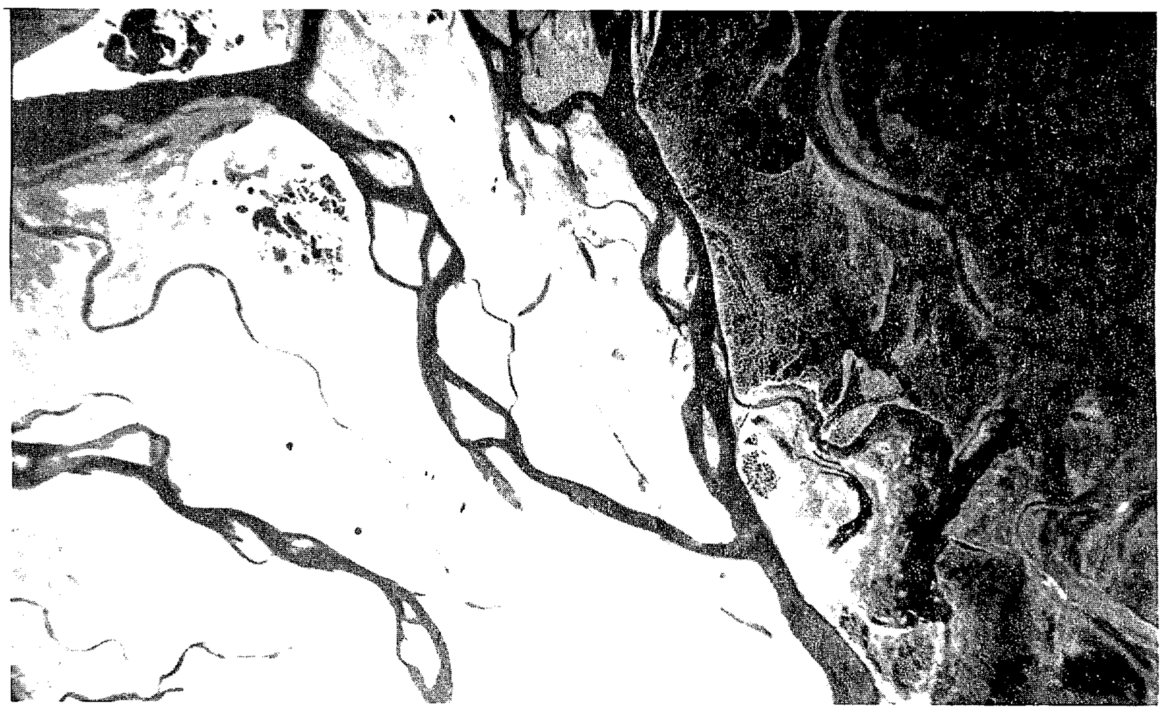


Prudhoe Bay, Sagavanirktok **River, 1979 photograph about 70° counterclockwise from 1955 photograph. Note blockage of groundwater flow by roadways in the 1979 photograph (arrows).**

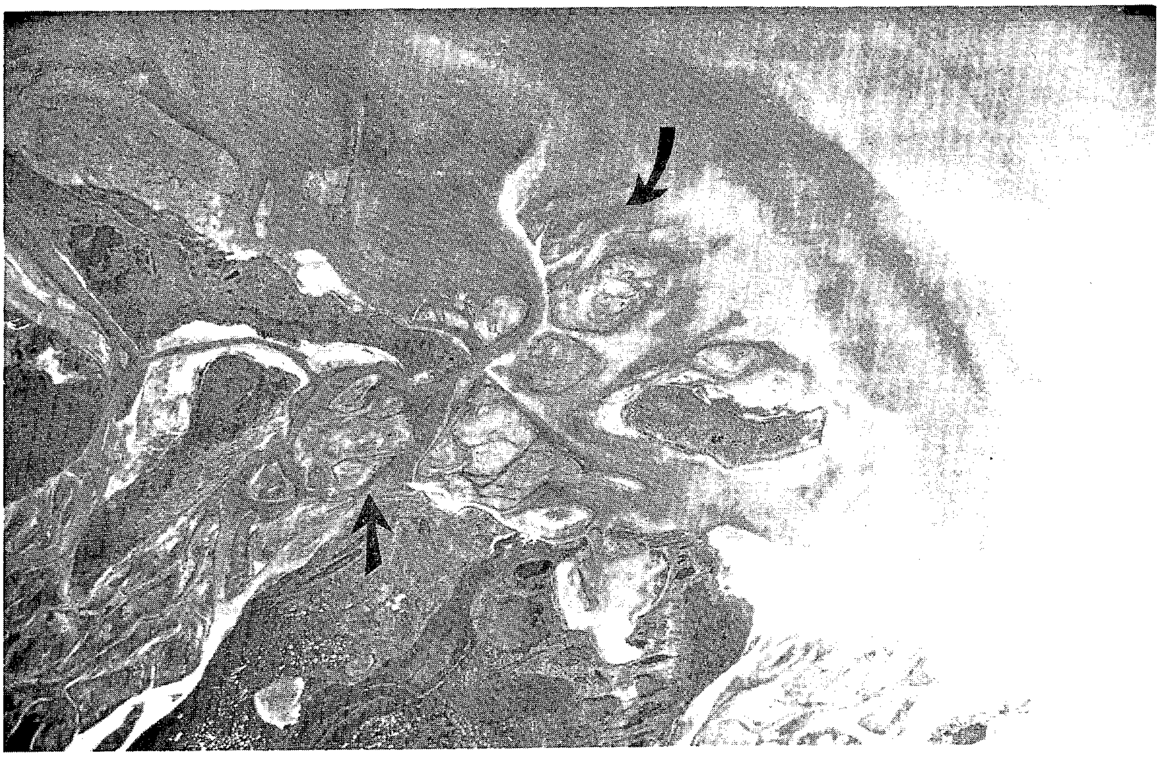


Sagavanirktok Delta, northwest near Prudhoe Bay,
1979 photograph about 70° counterclockwise from
1955 photograph.

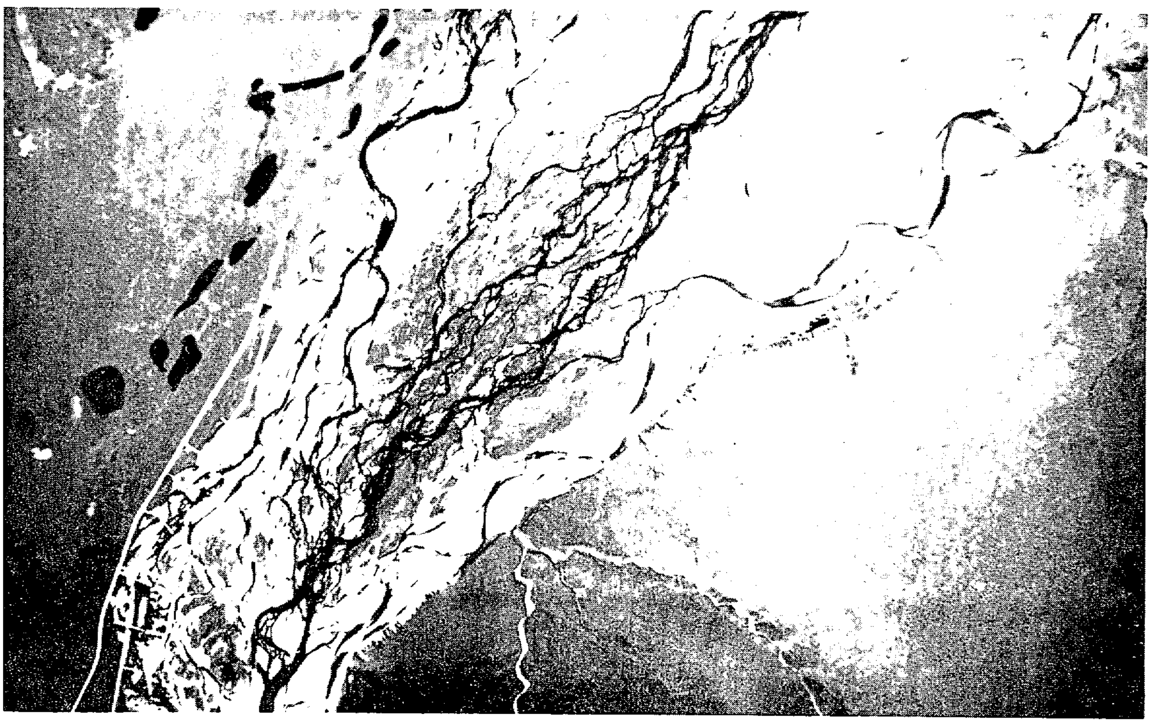




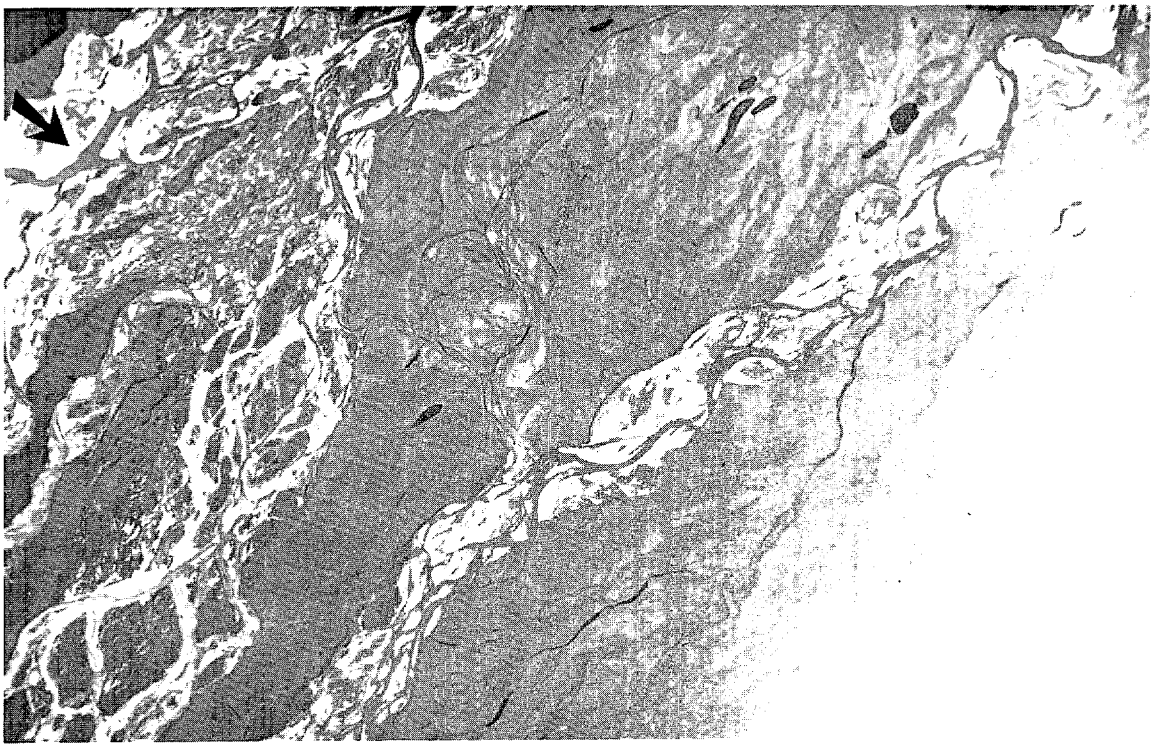
Sagavanirktok Delta, northwest, 1979 photograph about 60° counterclockwise from 1955 photograph.

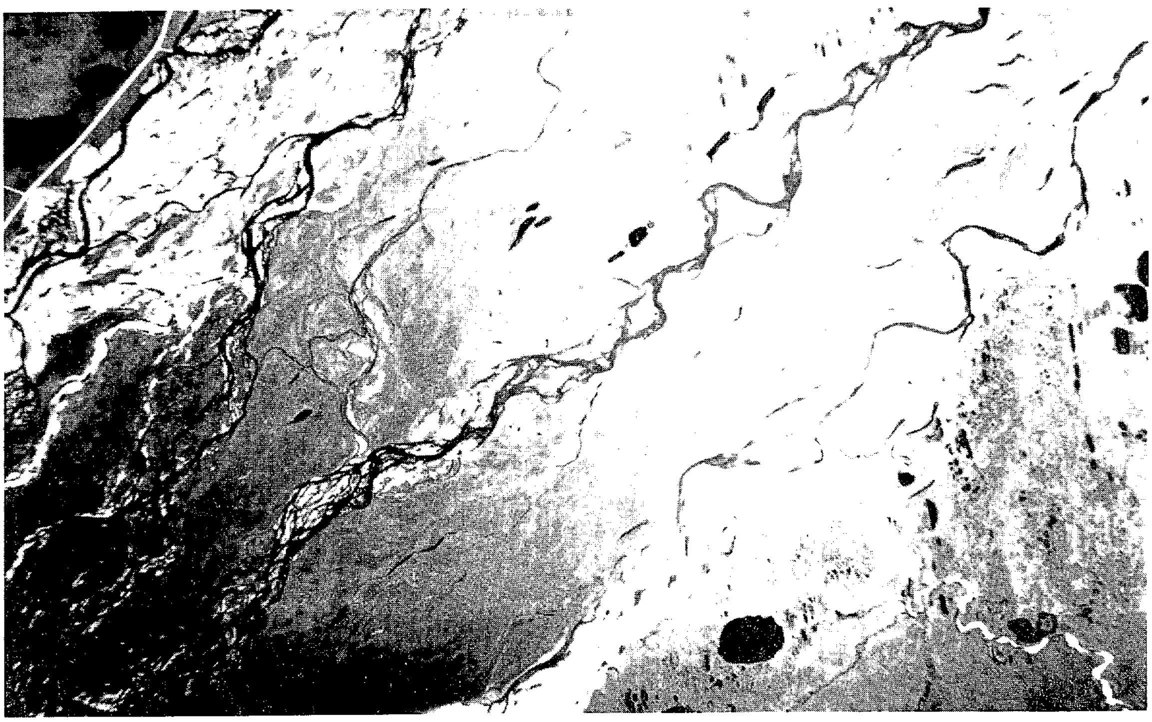


Sagavanirktok Delta, north central, 1979 photograph
about 50° counterclockwise from 1955 photograph.

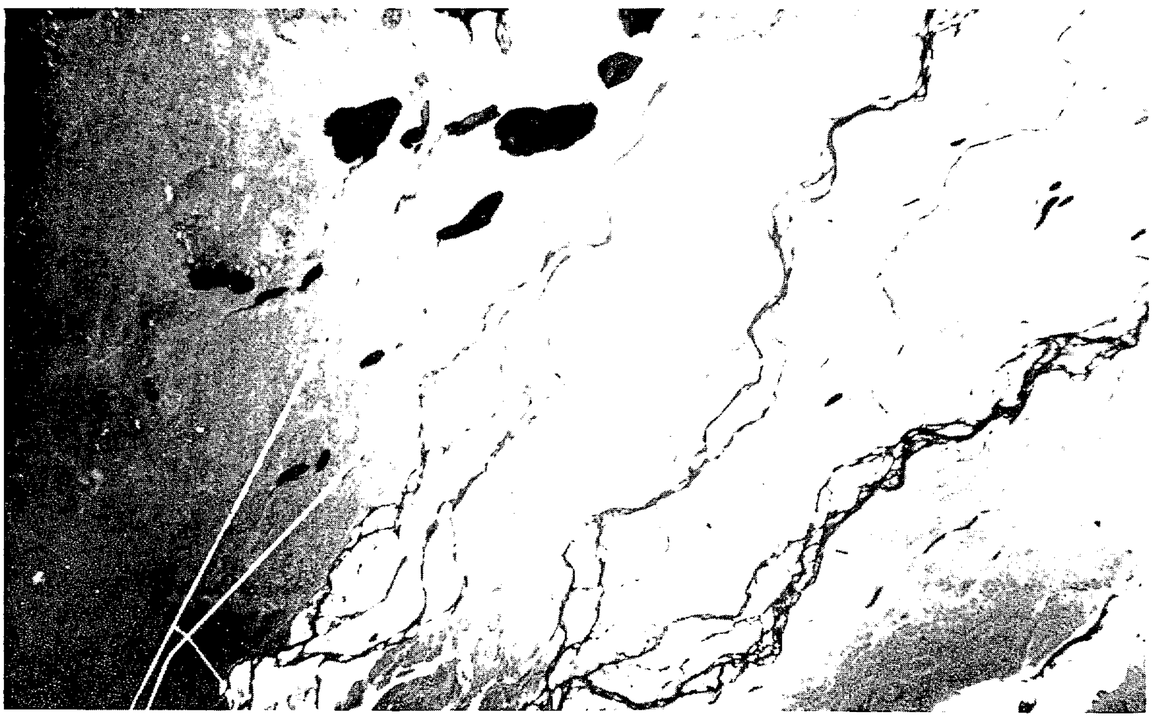


Sagavanirktok Delta, south, bottom quarter of 1955 photograph corresponds roughly to the top quarter of the 1979 photograph.

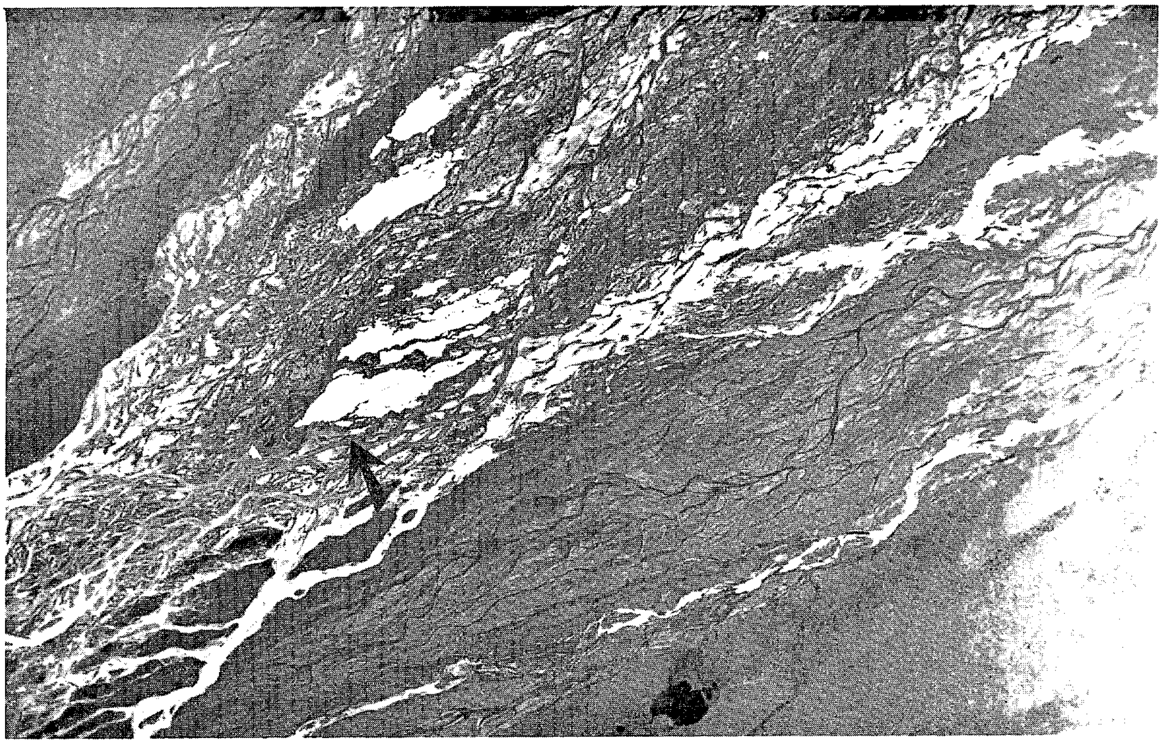




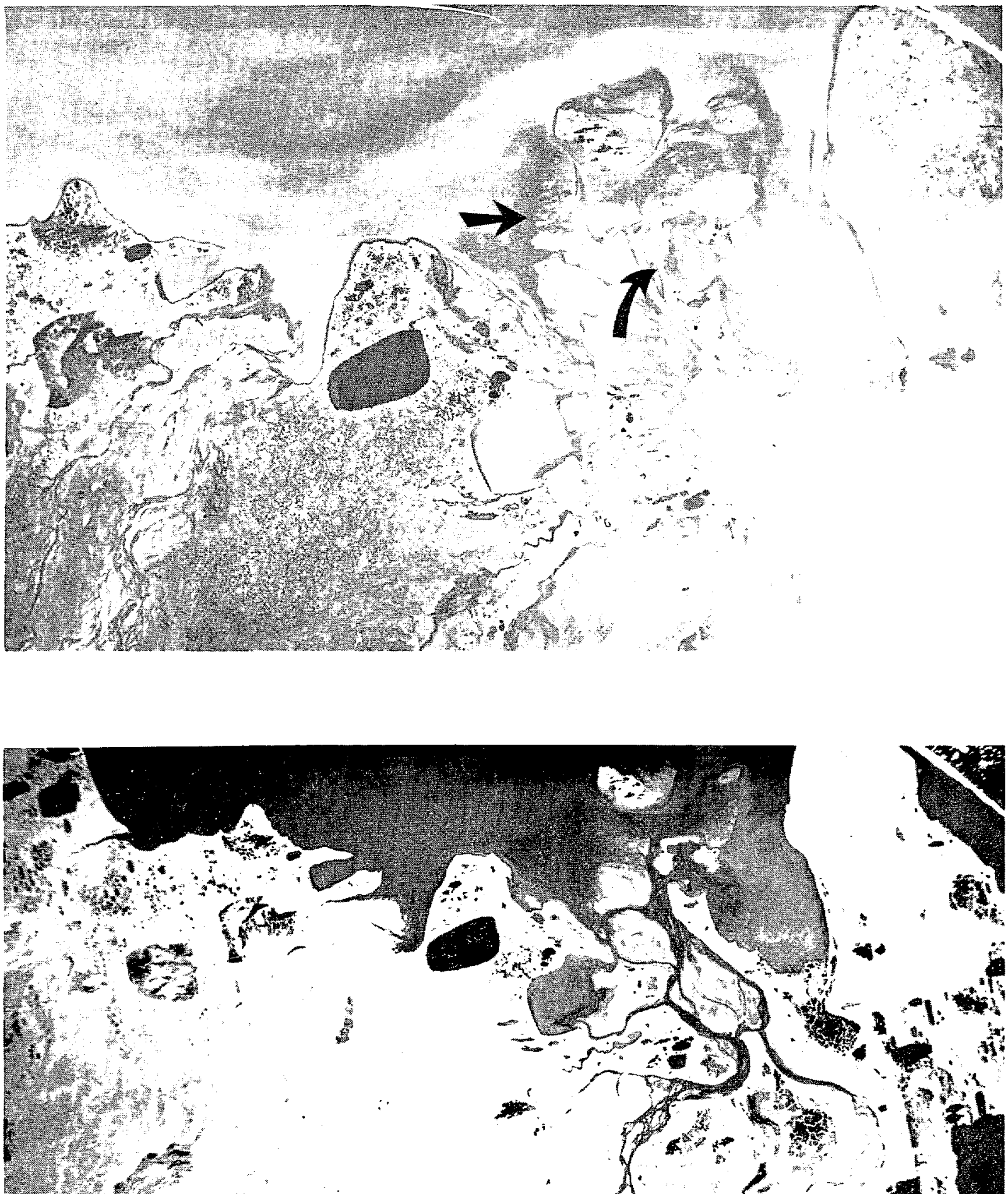
Sagavanirktok Delta, south



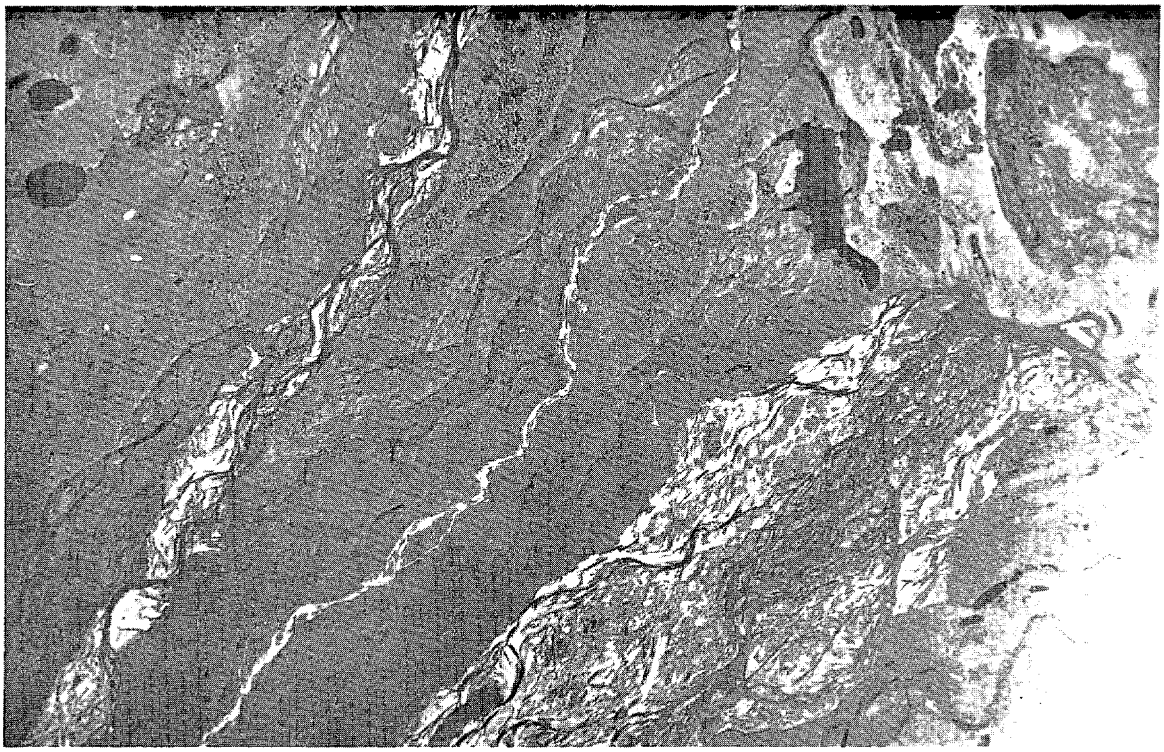
Sagavanirktok Delta, southwest, note changes in all active channels. Note differences in distribution of aufeis. The 1955 photograph is about 1.5X larger than the 1979 photograph.

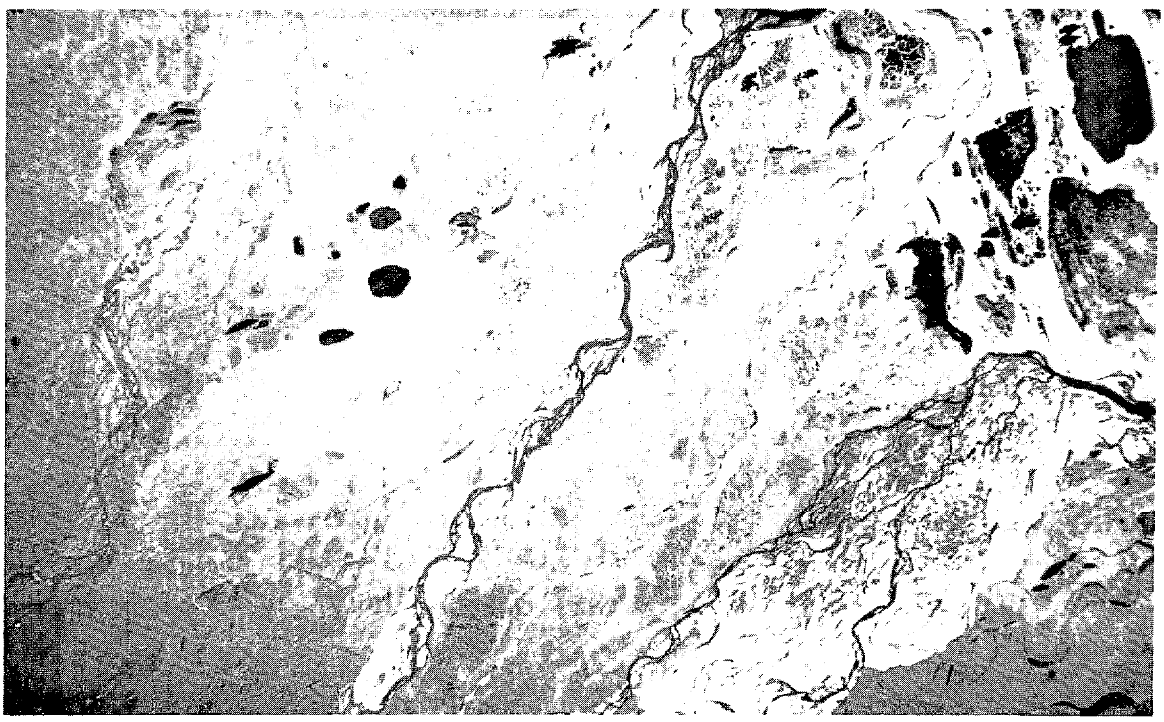


Canning Delta, northwest

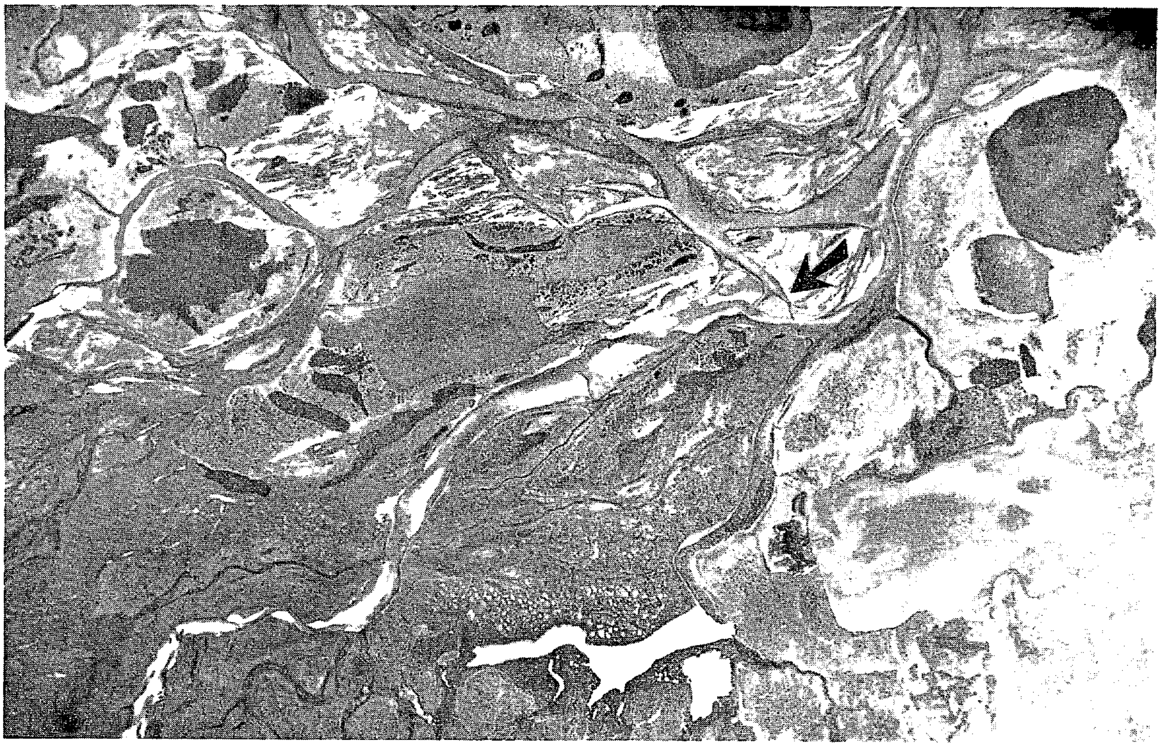


Canning Delta, north central, changes in all active channels.





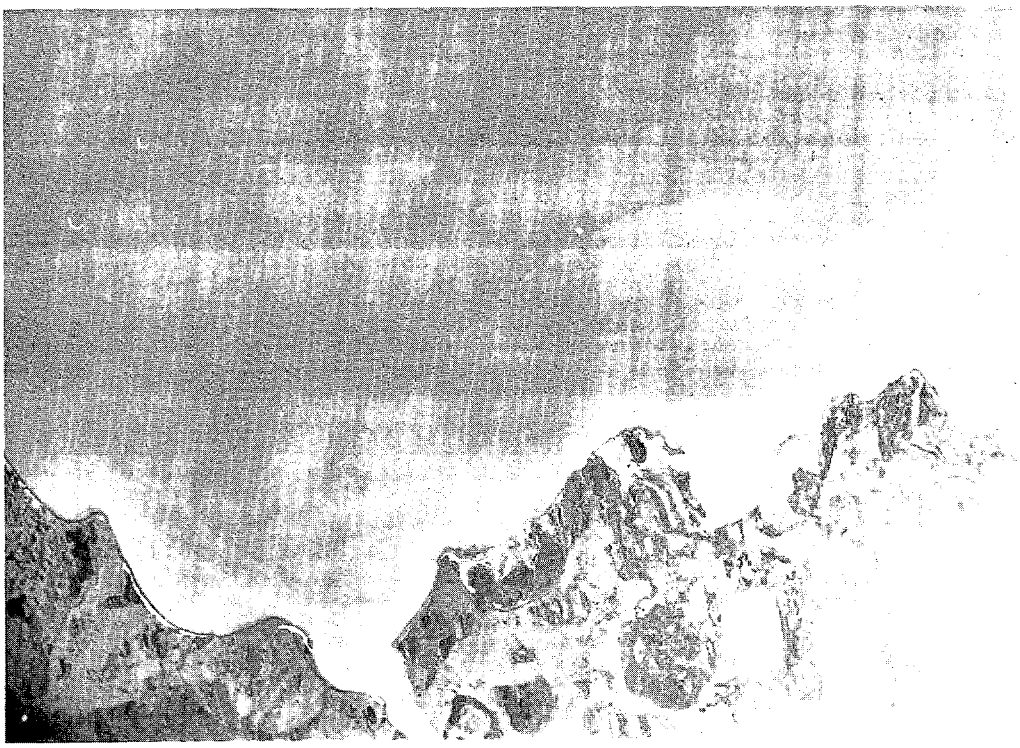
Canning Delta, northeast

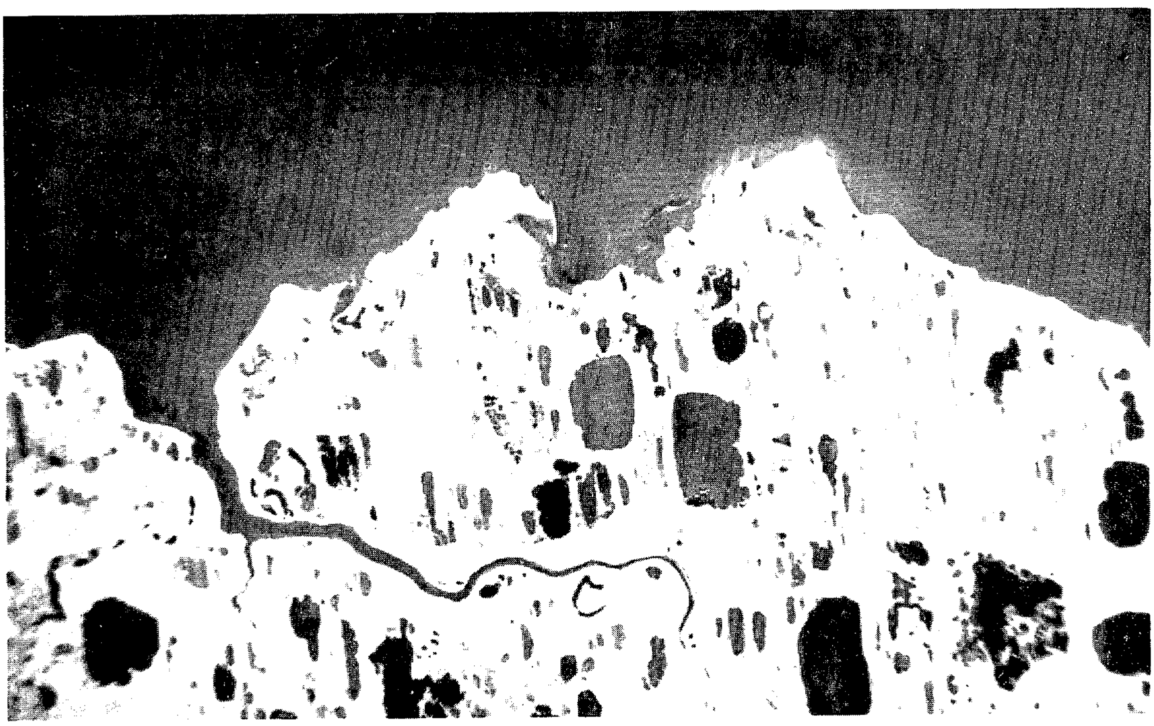


Canning Delta, northeast

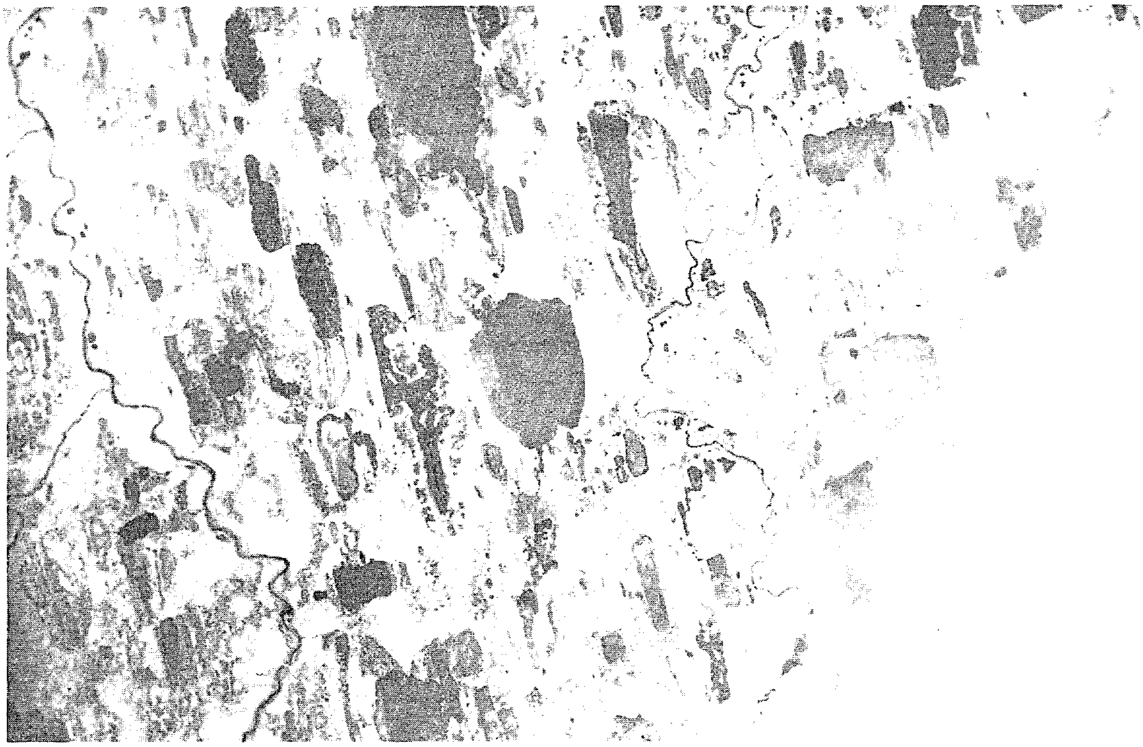
APPENDIX B

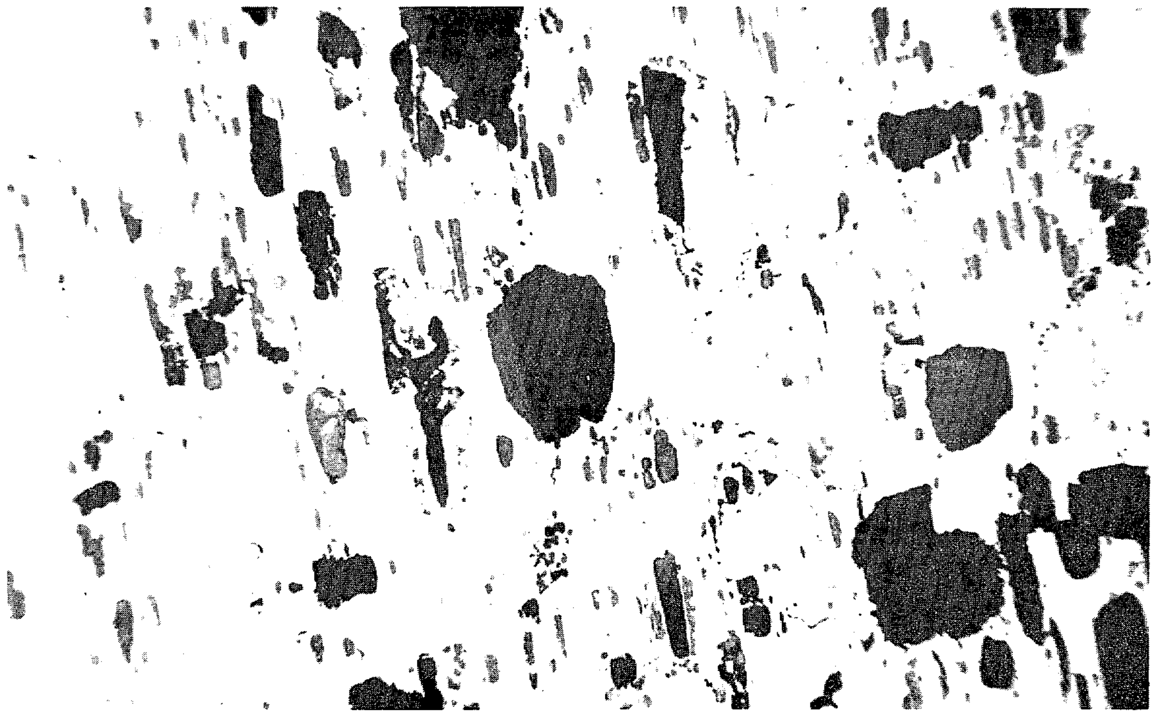
Comparative photographs, 1955 and 1979, of coastline, lacustrine basins, and offshore islands. Top photograph 1955, bottom photograph 1979; scale, coverage and orientation differences are noted. Arrows on some 1955 photographs show areas of notable change.



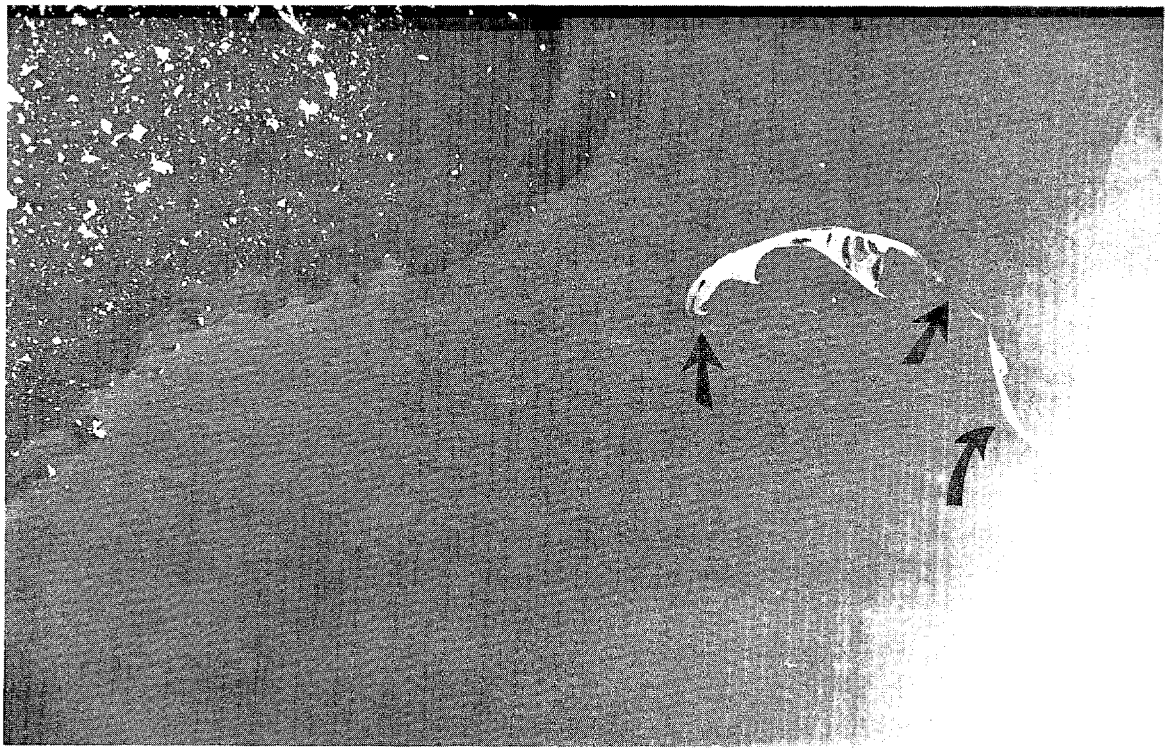


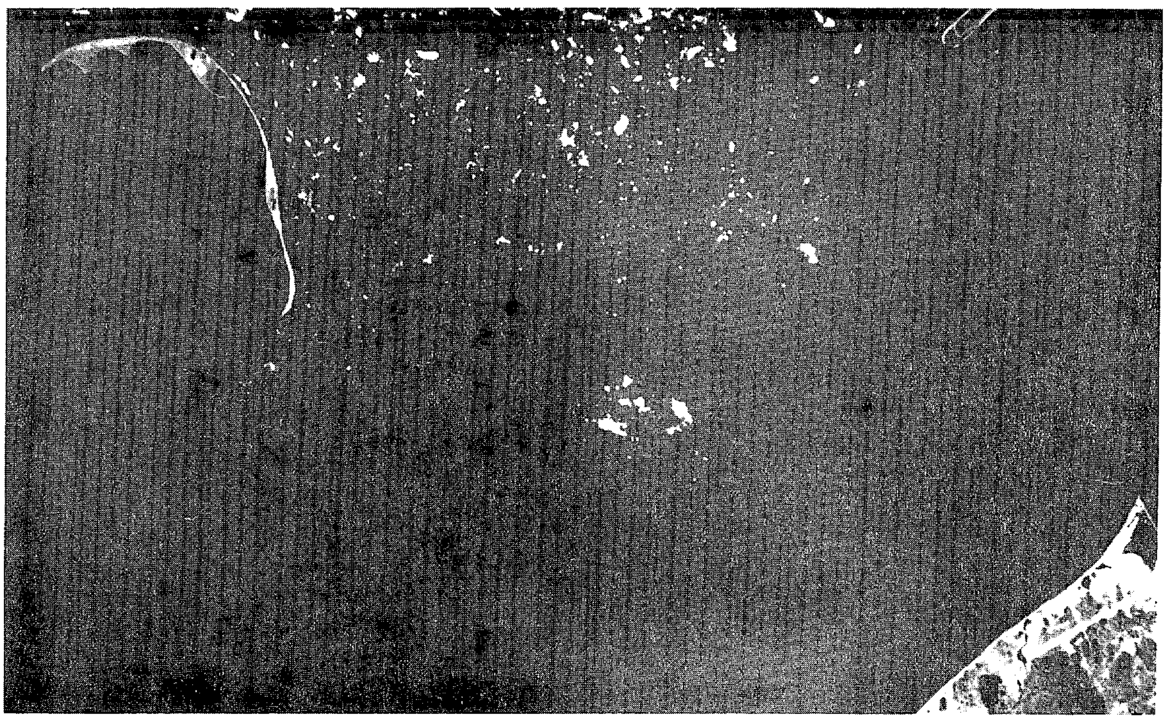
Beaufort Sea coast near Ugnuravik River



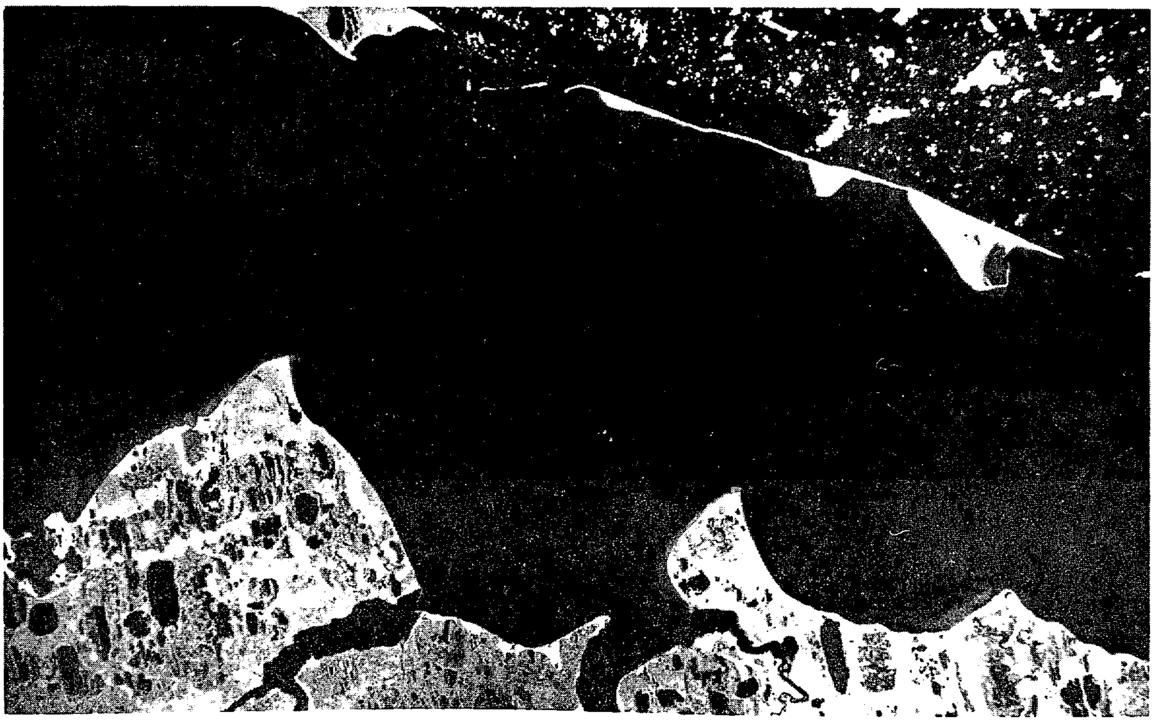


Arctic Coastal Plain about 13 km south of Milne Point

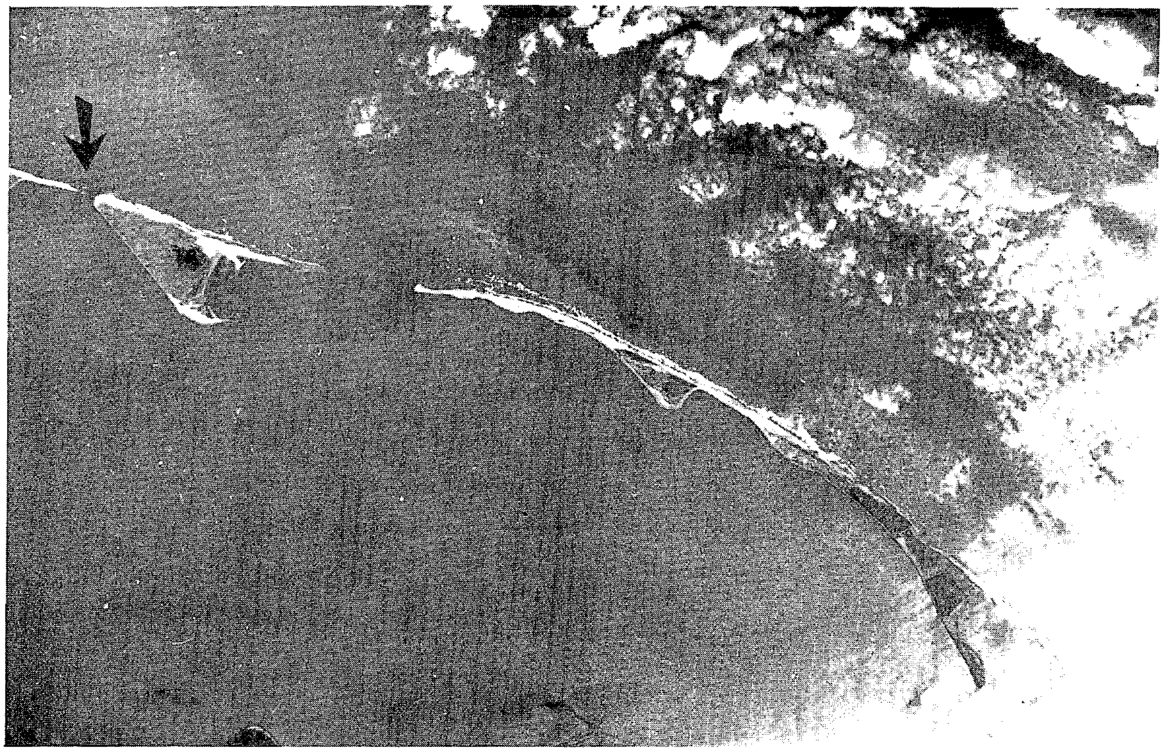


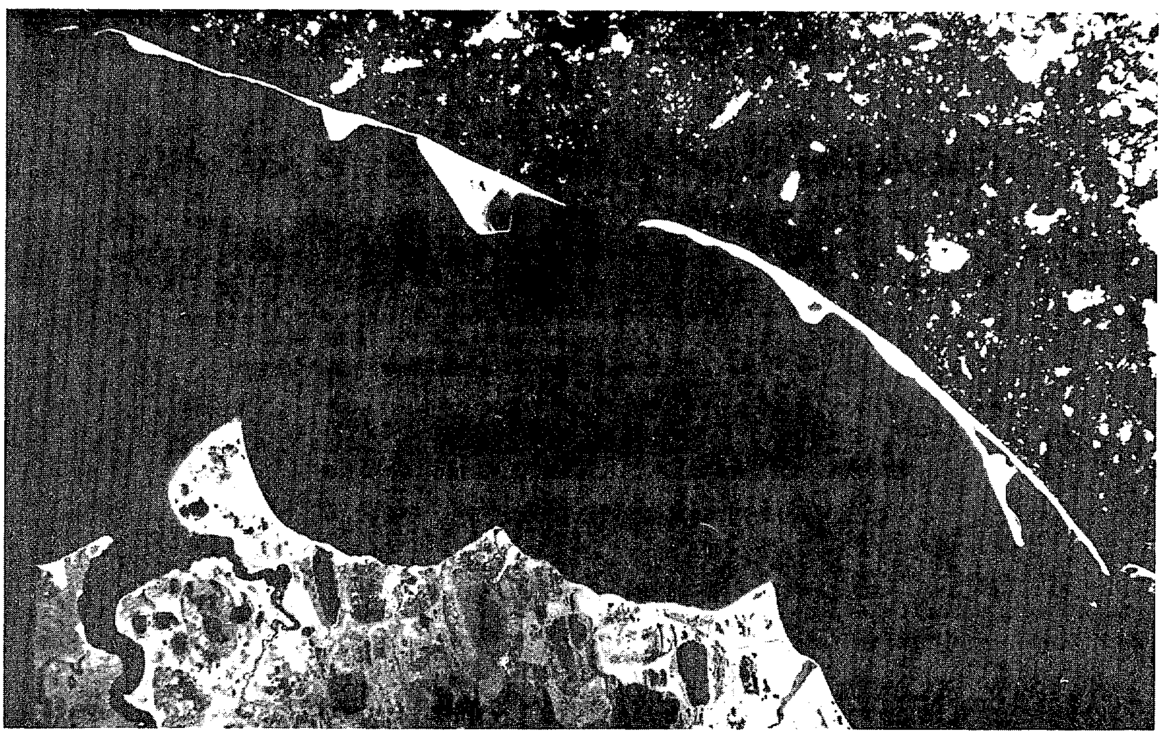


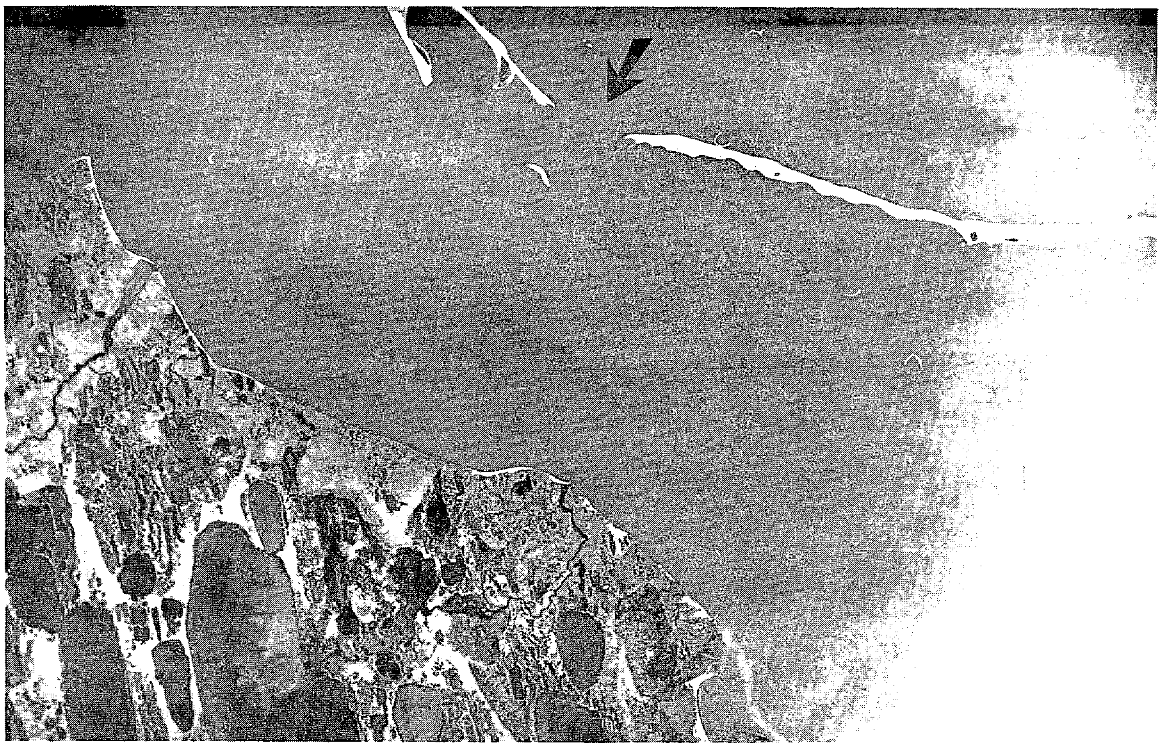
Thetis Island

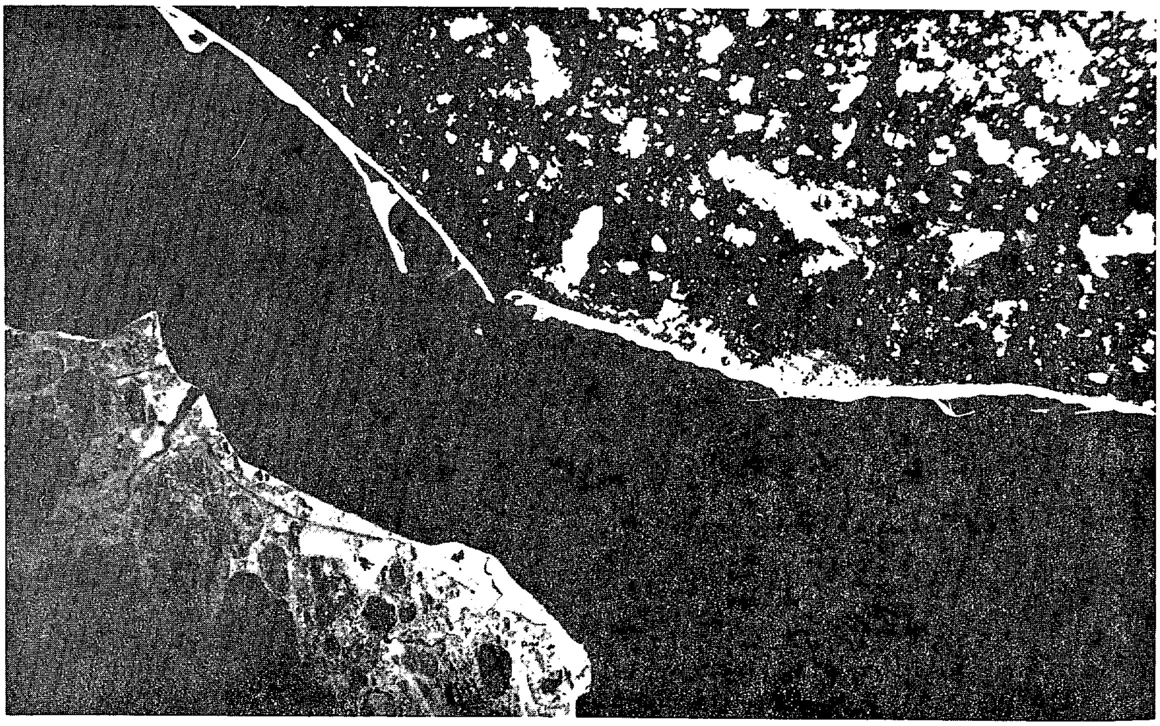


Beaufort Sea coast, Milne Point to Kavearak Point, offshore islands. Note absence of spit on Betoncini Island (arrow).

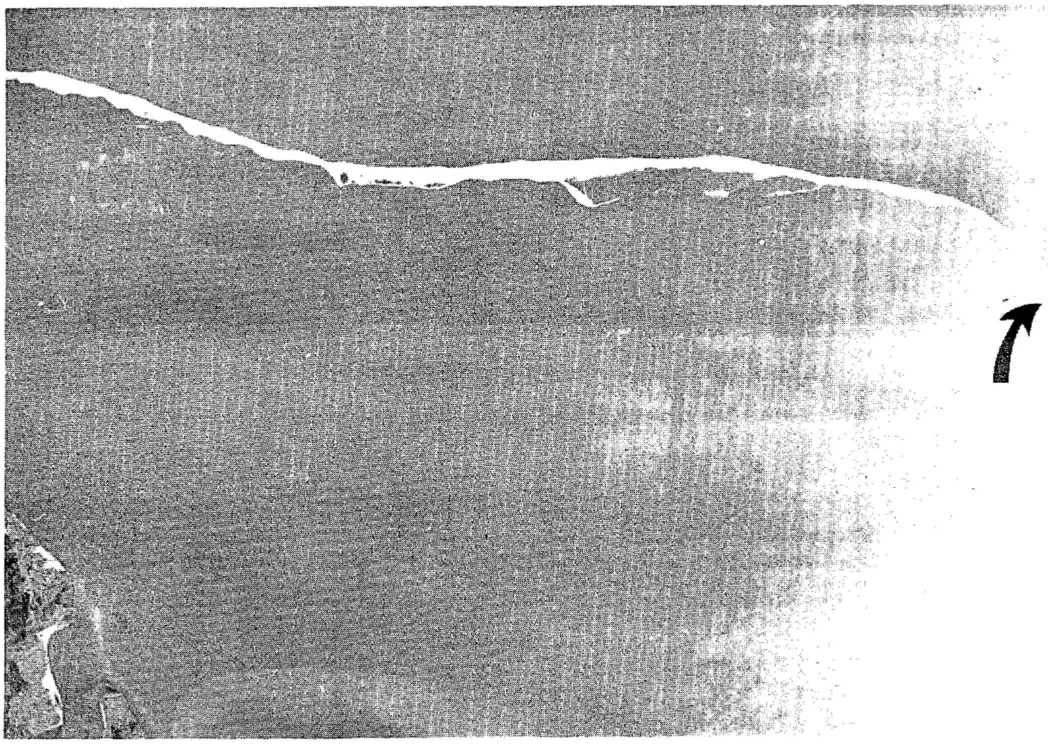


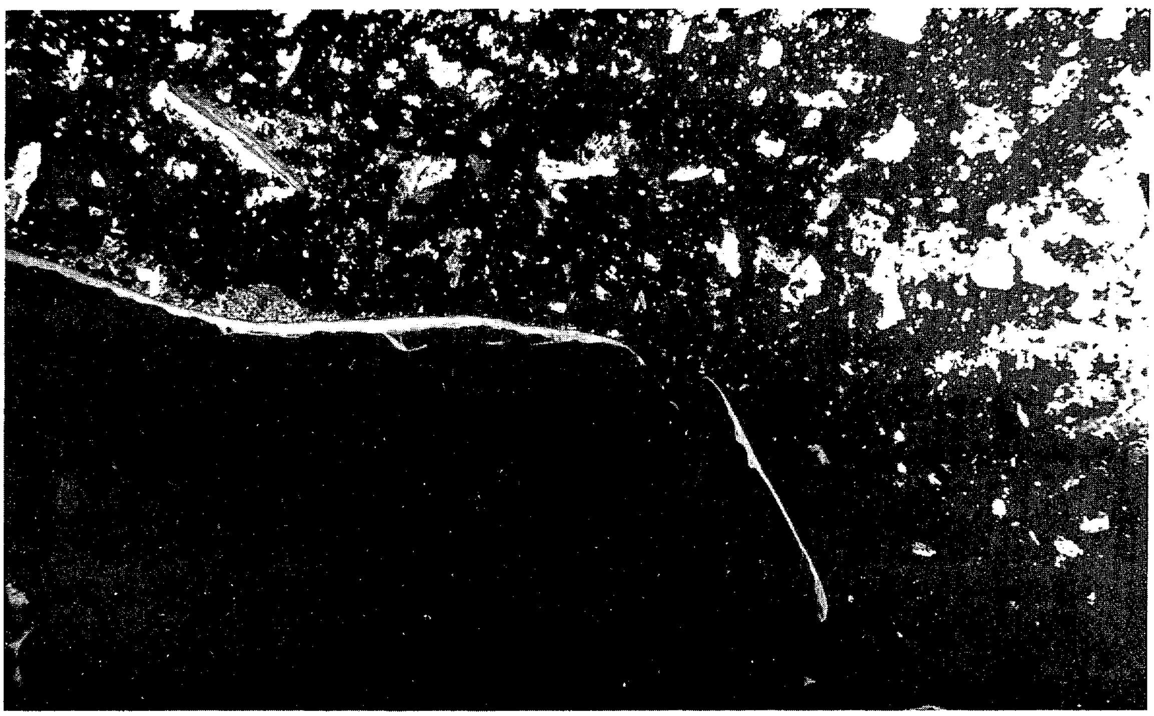


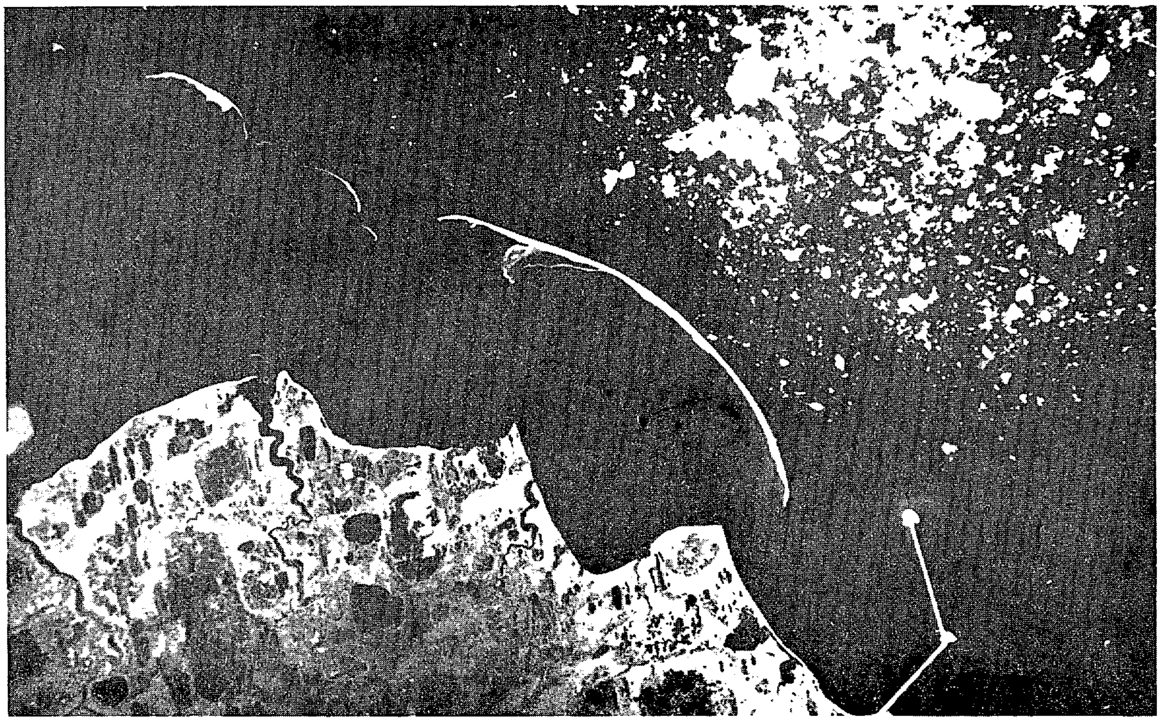




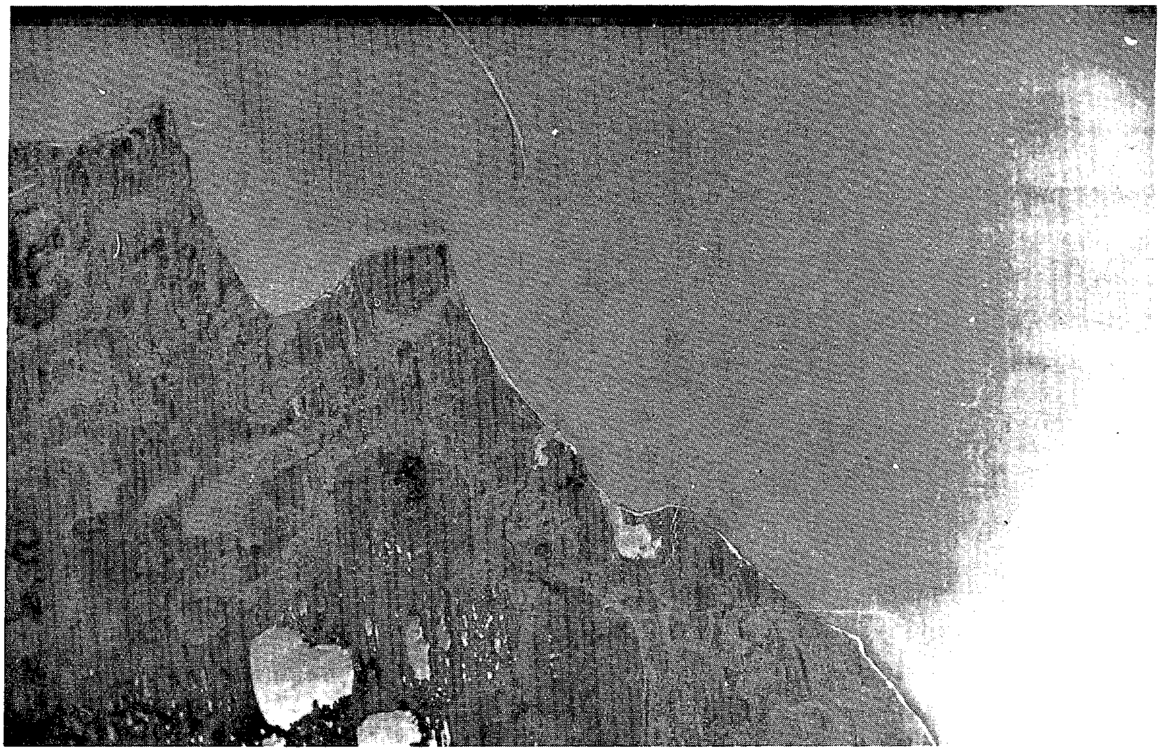
Beaufort Sea coast, Beechey Point to Back Point, offshore islands. Note closure of the gap between Cottle Island (left) and Long Island (right).

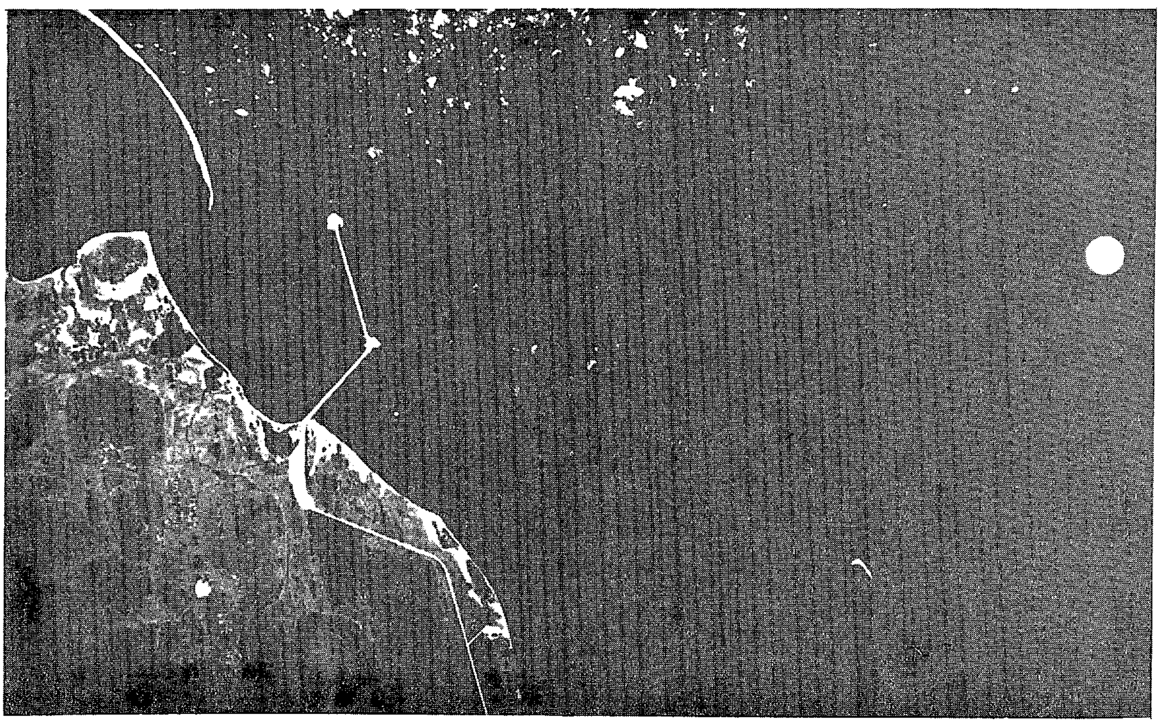




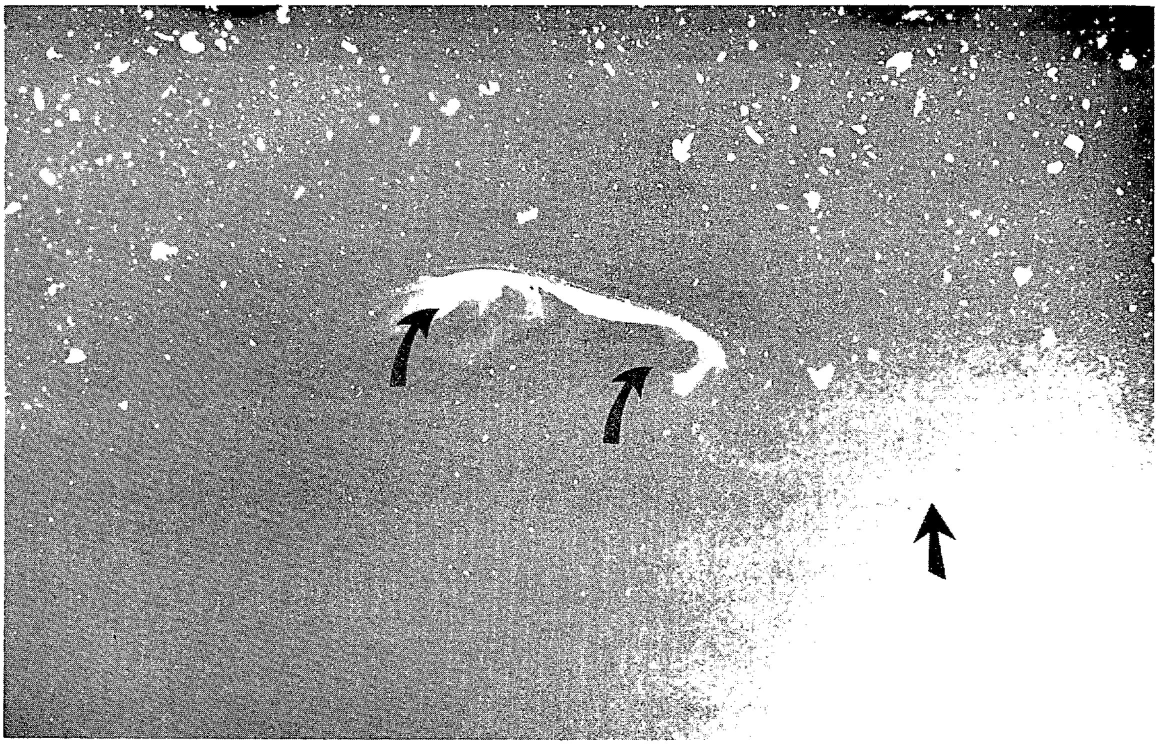


Beaufort Sea coast, Kuparuk River to Pt. McIntyre, offshore islands. Note changes in Egg Island and westward extension of spit on Stump Island.





Beaufort Sea coast, Pt. McIntyre, ARCO west dock,
Stump Island.



Reindeer (left) and Argo Islands

Cross Island