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ARCTIC INSTITUTE OF NORTH AMERICA

MORPHOLOGIC CHANGE IN TWO ARCTIC DELTAS

By

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MORPHOLOGIC CHANGE IN TWO ARCTIC DELTAS

A Preliminary Assessment of the Morphologic Change Occurring in Arctic Deltas During "Spring" Based on Field Studies Conducted in the Blow River Delta, Yukon Territory, Canada and the Colville River Delta Alaska, U.S.A.

by

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FINAL REPORT

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FRONTISPIECE

An Arctic Delta Riverbank Illustrating a Variety of Processes and Forms Including Permafrost, Active Layer, Thermoerosional Niche, Sedimentation and Slumping

FOREWORD

The results presented herein are based to a large extent on field work conducted in the summer of 1967 under the auspices of the Arctic Institute of North America with funds provided by the Army Research Office, Durham, N.C. The report, although specifically prepared for these two organizations, includes data, descriptive examples and photographs which are the result of research conducted on the Arctic Coast of Alaska during several seasons since 1961 mostly with the financial assistance of the Office of Naval Research, Washington, D.C. Thus, many organizations and individuals have contributed greatly over the past seven years in the acquisition and analysis of the data presented.

These, in alphabetical order, are:

The Arctic Institute of North America.
Montreal Office. Brigadier H.W. Love, Director.
Washington Office. Mr. R.C. Faylor, Director.

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To all of these organizations and individuals and to those many others not specifically listed but who have helped us in a variety of ways, we extend our appreciation and thanks.

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I. INTRODUCTION

Much of what uniqueness the Arctic possesses is to be found in the great seasonal variation which characterizes most of the natural landscape and in the rapidity with which this variation occurs. Such variation has been described in general, frequently fanciful, terms for centuries. Recently, however, this highly variable and complex aspect of the Arctic has been receiving increasing amounts of attention. For example, The Arctic Institute of North America is sponsoring a series of investigations aimed specifically at obtaining a better understanding of seasonal change in the Arctic. One such investigation was that by Kurt V. Abrahamsson who studied "... the changes that occur in subarctic and arctic environments as the conditions of winter are replaced by those of summer" (1).*

Abrahamsson was primarily concerned with the change occurring in each of the several parameters he studied. Further, he considered change as it occurred over a large, relatively diverse area in Northwestern Canada. The present study is a logical next step and for two reasons. First, it attempts to analyze the seasonal variations of all parameters from the standpoint of one result -- morphologic change. Second, it directs its areal focus toward a small, relatively homogeneous part of the arctic landscape -- deltas.

The arctic coasts of both the eastern and western hemispheres are crossed by numerous rivers which range in size up to that of the Lena in Siberia, the fourth longest in the world (see Appendix I). Northward flowing rivers are nearly as variable in other ways (for

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*Numbers appearing by themselves in ( ) refer to appropriate references in the Bibliography.

example, discharge and sediment load) as they are in length. Some of these rivers, exemplified well by the Mackenzie of Canada, originate deep in the center of continents and, before draining into the Arctic Ocean, flow across two or more major climatic zones. Only some of the shortest rivers found in northern latitudes are wholly arctic.

In North America one of the areas in which the entire drainage basin of each of its rivers is in the Arctic is the Arctic Slope (Fig. 1). This area which lies north of the Arctic Mountains, is characterized by very severe temperature conditions, long periods of snow and ice cover, continuous permafrost, a thin active layer and, with few exceptions, tundra vegetation.

Arctic rivers, like their counterparts in other climes, frequently form deltas where they flow into the ocean. The morphologic changes occurring in these deltas are the result of the integration of a variety of processes (6,29,67,81). In arctic deltas processes are almost entirely natural and represent both physical (atmospheric, geologic and hydrologic) and biological agents.

Most of these agents are important, not in themselves, but rather in the way they affect the timing and intensity of the processes directly operating on delta forms. The objectives of this preliminary study of the morphologic change which occurs in deltas during "spring" are to analyze the agents involved directly or indirectly in change, to characterize those forms subject to change and to discuss the actual changes that occur.

Because little research has been done on any of these problems, much of the discussion which follows is general in nature. Rather than providing many quantitative data (which are not available in the first place) or setting precise dates, it attempts to describe, sequentialize and analyze events.

Although too few data are yet available to allow the calculation of reliable averages, those which have resulted from field work in the Blow River and Colville River deltas are used for the purpose of approximating the more important cause-and-effect relationships.

II. THE REGIONAL SETTING

Deltas are small when compared with the area within which the numerous processes operate that determine their form. The area of prime importance is the drainage basin of the river which is mainly responsible for the formation of the delta in the first place. However, in an expanded sense, the area of influence must also include those portions of the atmosphere, biosphere and hydrosphere which may influence deltaic development even though outside of the drainage basin. It is in this broad frame of reference that the Regional Setting is discussed.

Drainage Basins

The Arctic Slope, which extends from the crest of the northern-most mountains in Alaska and Northwestern Canada to the Arctic Ocean, varies in width from a few kilometers at both its eastern and western ends to nearly 400 km along the meridian extending south from Barrow, Alaska. Numerous rivers originate between the crest and the ocean and flow, in season, northward. Two of these rivers -- the Blow of the Yukon Territory and the Colville of Alaska -- begin in the mountains and flow across the foothills and coastal plain before debouching into the Arctic Ocean through the deltas which are the main concern of this report.

The drainage basin of the Blow River is 3750 km^2 in area, that of the Colville River, 50,000 km^2 over 13 times as large. Both drainage basins are located entirely within three physiographic provinces; the Arctic Coastal Plain, Arctic Foothills and Arctic Mountains. The proportion of the drainage basins included within each of these provinces is highly variable (Table I, Fig. 3). For both rivers, the portion within the Arctic Coastal Plain is small (Blow - 3%, Colville - 10%). The largest portion (60%) of the drainage basin of the Blow River is in the mountains whereas the largest portion (64%) of that of the Colville is in the Arctic Foothills. Only 37% of the Blow River drainage basin is in the foothills and only 26% of that of the Colville is mountainous.

TABLE I. DRAINAGE-BASIN DIVISIONS

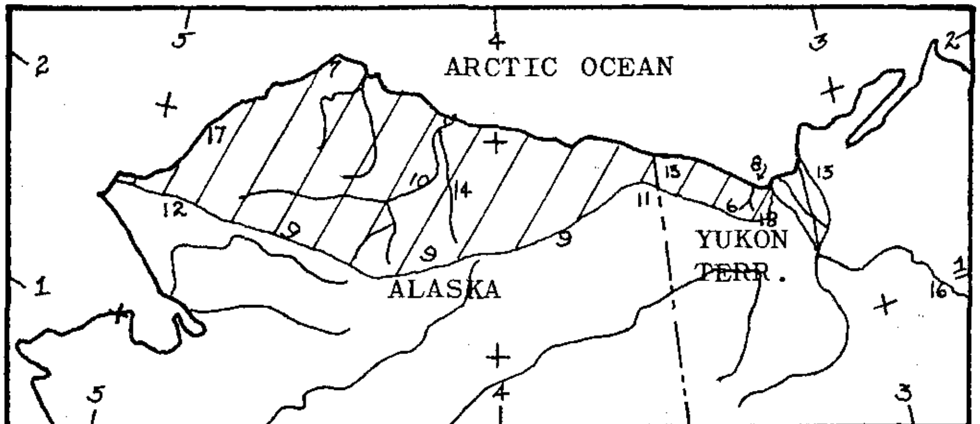
Physiographic Regions	Blow River Area (km^2)	%	Colville River Area (km^2)	%
A. Interior Plains	115	3	5000	10
1. Arctic Coastal Plain	115	3	5000	10
a. Teshekpuk			4000	8
b. White Hills			1000	2
B. Rocky Mountain System	3650	97	45,000	90
2. Arctic Foothills	1400	37	32,000	64
a. Northern			16,000	32
b. Southern			16,000	32
3. Arctic Mountains	2250	60	13,000	26
a. Richardson	1600	43		
b. Barn	650	17		
c. DeLong			750	1.5
d. Central and Eastern Brooks Range			12,250	24.5
Totals	3765	100	50,000	100

Topography and Geology

The three physiographic provinces represented in the two drainage basins are the northern-most extensions of two of the major divisions of North America; the Interior Plains and the Rocky Mountain System. Both the history and general characteristics of these three provinces are similar to those of their more southern counterparts.*

The Arctic Mountains. The Arctic Mountains consist of several ranges that extend more-or-less uninterrupted west

*The material in this section stems mainly from reports by Bostock (12), Martin (54), Norris et al (59), Payne (60), Porter (64), Stearns (71) and Wahrhaftig (78).



1.Arctic Circle	7.Barrow	13.Firth R.
2.70°N Lat	8.Blow R.	14.Itkillik R.
3.132°W Long	9.Brooks Range	15.Mackenzie Delta
4.148°W Long	10.Colville R.	16.Mackenzie R.
5.164°W Long	11.Davidson Mts	17.Point Lay
6.Barn Mts	12.DeLong Mts	18.Richardson Mts

Fig.1. General Location Map. Arctic Slope -///

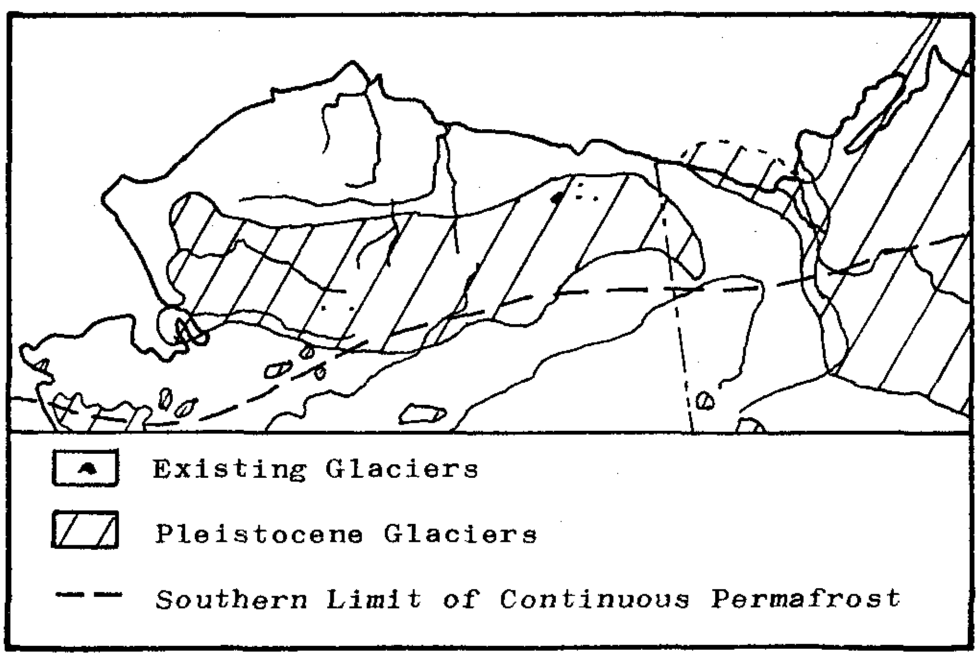


Fig.2. Glaciation and Permafrost (After 20 and 78).

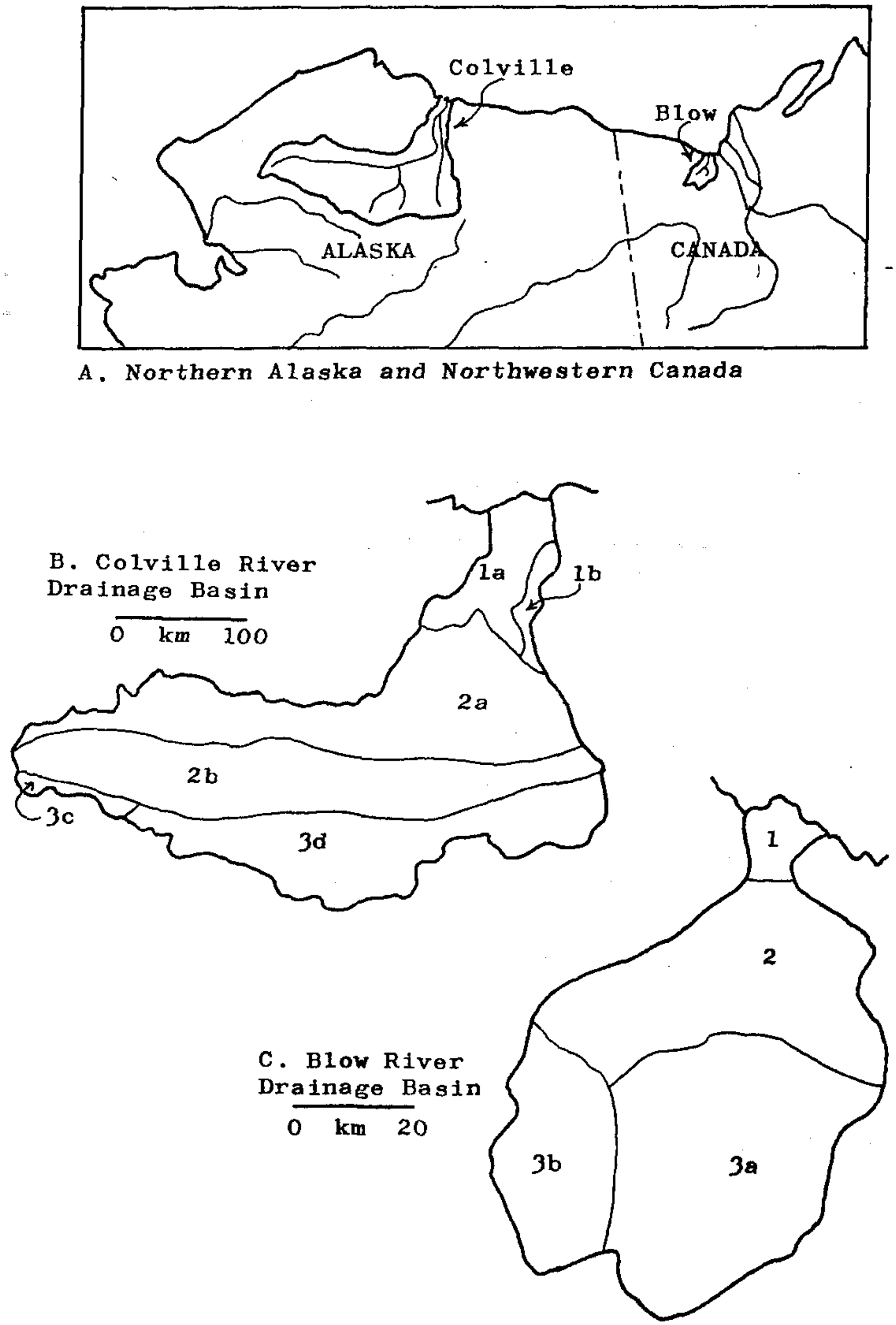


Fig. 3. Drainage Basins. See Table I for Divisions.

as far east as the Barn or Richardson Mountains nor did the Cordilleran ice-sheet of Western Canada extend north or west into these mountains (25). The Arctic Foothills and Arctic Coastal Plain in Alaska were not glaciated except where glacial tongues extended northward from the mountains. However, in Canada, ice moving down the Mackenzie River valley pushed around the northern edge of the Richardson Mountains and moved as far west as the Firth River (25,48).

Glacial activity in the mountainous portion of the Colville drainage basin produced most of the typical alpine glacial landforms including U-shaped valleys, cirques, cliff-and-bench type slopes and a few lakes. In the process of creating these landforms many different types of rocks were exposed. In addition, the material eroded by the ice was deposited along the northward margin of the glaciers and is now being re-eroded by the tributaries of the Colville. Much of this morainal material now stands as river terraces. In contrast, the mountainous portions of the Blow River drainage basin which were not glaciated have a more mature, less rugged form (28).

In the mountains frost action is an extremely important agent. It is less significant in the mountains of the Blow River than in those of the Colville because of the different history of these two areas. The glacially steepened slopes present near the headwaters of the Colville River are protected by little vegetation. Materials loosened by frost action and other processes are moved rapidly down slope to and by streams.

<u>The Arctic Foothills</u>. The Arctic Foothills (often referred to as the Arctic Plateau, especially in Canada) comprises over one-third of the drainage basin of the Blow River and nearly two-thirds of that of the Colville. It is an area of rolling plateaus interrupted by low rolling hills which generally parallel the mountains to the south.

The foothills portion of the Blow River drainage basin is only about 30 km wide. It is nearly all shale and sandstone overlain with unconsolidated gravel, sand, silt and clay. In contrast to its Alaskan counterpart, the foothills, if glaciated at all, were overrun only on the most northern portion by the ice tongue that moved west along the coast. Therefore, glacially derived material from the foothills of the Blow is minimal.

The foothills portion of the Colville River drainage basin has an average width of 165 km (over 5 times that of the Blow). Usually it is divided into two sections, northern and southern. The dividing line between these two sections within the Colville drainage area follows closely along the Colville River itself. Both sections are very nearly equal in size and contain about 32% of the total drainage basin area apiece (Table I, Fig. 3).

The southern section, which is higher and rougher than the northern section, ranges from 400 to 1200 m in elevation. It consists mainly of conglomerate, sandstone, shale, limestone and chert. The more resistant of these rocks, along with the few igneous intrusives that are present, form ridges and irregular buttes and mesas. The more subdued northern section, which varies in elevation from 200 to 400 m, likewise has widely spaced linear ridges.

Although the vast bulk of the Arctic Foothills of Alaska was not glaciated, a number of piedmont glaciers did extend from the mountains north onto the southern part of the foothills. A large amount of morainal material was deposited and today borders most of the valleys leading north from the Brooks Range. Fine material carried by the glacial rivers and by wind was deposited over much of the Arctic Foothills and the Arctic Coastal Plain and today provides sediment to the rivers. Dunes, some of which are still active, are common.

The Arctic Coastal Plain. The Arctic Coastal Plain, which extends northward from the Arctic Foothills to the Arctic Ocean and eastward from Point Lay to the Mackenzie Delta, is highly variable in width. In the vicinity of Blow it is only 10-15 km wide whereas near the Colville it is about 100 km wide. The Colville River itself flows across some 90 km of coastal plain after it leaves the foothills. However, its tributaries in this section of its course are relatively few in number and, except for the Itkillik River, are short. About 3% of the Blow and 10% of the Colville drainage basins are in the Arctic Coastal Plain.

Most of the plain, sloping gently down northward, is low and flat. It contains a great number of lakes and meandering streams and on the whole is poorly drained (Fig. 5). The proportion of the surface area of the Arctic Coastal Plain covered by lakes is highly variable. The area including and extending west of the Colville has many lakes whereas the portion of the plain east of the Colville including the Blow has relatively few.

Most of the plain is mantled by the Gukik Formation which consists primarily of unconsolidated marine sediments although it does also include some nonmarine material. The gravel, sand, silt, clay and peat of the Gubik Formation overlie late Mesozoic and early Cenozoic sediments. Some of these have been exposed by the Colville and the Itkillik. Thus, conglomerate, sandstone, limestone, coal and bentonite are being contributed to the sediment load of the Colville from the plain.

The narrow Arctic Coastal Plain in the vicinity of the Blow River is relatively flat although it does possess a few scattered hills. Formerly glaciated, it is composed mainly of unconsolidated gravel, sand, silt and clay. The Blow River, after leaving the mountains, flows in a broad (0.5-3 km) valley which has steep, rather high and only partially vegetated sides. From these cliffs, which extend to the head of the delta, the Blow River receives great amounts of materials not only from glacial deposits but also from the underlying shale and sandstone (Fig. 6).

Soil and Vegetation

On most of the Arctic Slope, soil and vegetation combine to form a transition zone between the subsurface and the atmosphere. Both are quite diverse separately and in combination. Soil, ranging in composition from mineral to organic, and vegetation, ranging from blanket-type mosses to widely spaced shrubs, greatly affect local heat and water budgets and therefore permafrost and active-layer thickness. Further, through their influence on percolation and runoff and their stabilization of riverbanks, they exert much control over environmental change such as the amount and type of sediment contributed to runoff and the amount and type of bank erosion.

Soil. The five major genetic soil groups commonly recognized for the Arctic Slope are the Lithosols, Regosols, Arctic Brown, Tundra and Bog soils (26,76).

Lithosols, most common in the glaciated portion of mountains, are generally frost-shattered fragments of bedrock. Steep slopes, intensive frost action and rapid removal allow, at the most, the formation of only a thin, ephemeral weathered layer. Such material usually rapidly becomes a part of some streams load and therefore a potential deltaic deposit. Regosols, on the other hand, are materials which, already transported and deposited, have been little altered in their new location. These relatively fresh deposits may be the result of eolian, alluvial, marine or gravitational activity and are found in all of the provinces of the Arctic Slope.

Arctic Brown soils are mineral soils which form under well-drained conditions. Not extensive on the Arctic Slope,

Fig. 4. Folded Sedimentary Rocks, Northern Brooks Range, Alaska.

Fig. 5. Coastal Plain, Arctic Alaska.

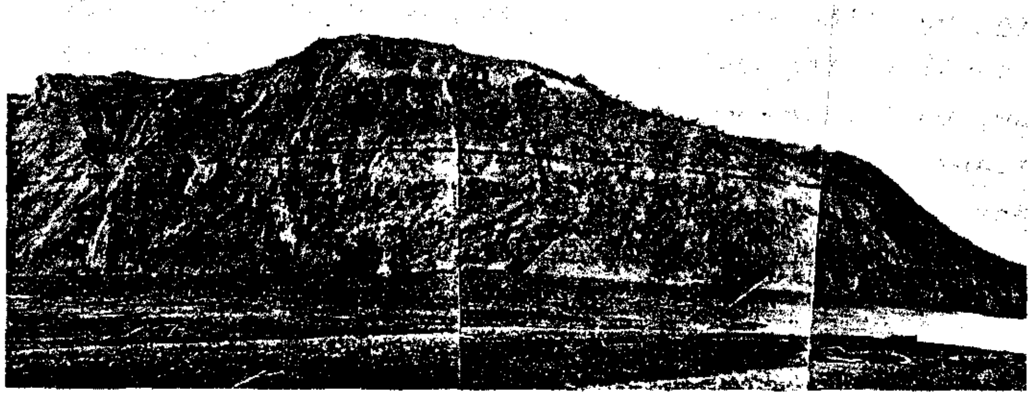


Fig. 6. Thirty-four Meter Bluff at Head of Blow River Delta.

they are generally restricted to "... escarpments, shoulders, ridges, terrace edges, stabilized dunes, and similar locations ..." (76). Such locations when combined with a relatively thick active layer account for much less inhibited drainage than is present in most other arctic soils.

Tundra soils are the most extensive of the major soil groups on the Arctic Slope. They normally are found in gentle sloping, poorly drained areas. Variations in the characteristics of these soils usually correlate closely with variations in drainage. Although they are mineral soils, in the main, the amount of organic matter on top may nonetheless be great because low temperatures coupled with poor drainage result in slow vegetal decay and rapid accumulation. Unlike in the case of Arctic Brown soil, the active layer, although variable, is usually thin. Nonetheless, local drainage varies greatly because of variations in microrelief, especially in the upland tundra (52).

Bog soils form on level or depressed areas, have much standing water in summer and possess a thin active layer. They have a thick layer of relatively undecomposed vegetal material overlying a peat layer of variable thickness. These soils, although occupying up to 50% of the northern part of the Arctic Coastal Plain, are generally limited to swales in the southern part of the plain and in the foothills (74).

Vegetation. The Arctic Slope, dominated by tundra vegetation, lies north of the tree line. Although trees and shrubs -- willow, poplar and alder, for example -- do occur in favorable locations, their distribution is sparse. Nonetheless, one of the most conspicuous features of both deltas is the trunks, roots and branches, small though they may be, of these trees and shrubs. Although on the macroscale Tundra is a distinctive type of vegetation, it has a great number of varieties.

Spetzman (70), whose classification is followed herein, divided the Arctic Slope of Alaska into six major plant communities: 1. Outcrop and Talus vegetation, 2. Dry Upland Meadows, 3. Niggerhead Meadows, 4. Wet Sedge Meadows, 5. Aquatic vegetation and 6. Flood-plain and Cutbank vegetation.

Outcrop and Talus vegetation is found at elevations above 500 m in the foothills and mountains where steep slopes and little soil prevail. At the highest elevations (above 1500 m) lichens occur on rock surfaces which have been exposed for a period of time sufficiently long to allow growth. Only in favorable niches do other plants, such as some of the flowering variety, occur. Even on the less steep slopes plant patches are often separated by areas of bare rock.

Dry Upland Meadows are also generally found above 500 m. They are best developed on the north-facing front in the mountains in conditions of good drainage such as on river terraces, alluvial fans and along ridges. A wide variety of low plants are found although Dryas octopetula and lichens predominate. Other types include grasses, sedges, herbs and ground shrubs.

Niggerhead Meadows (Fig. 7) cover more of the Colville drainage basin and possibly more of the Blow drainage basin than any other vegetation group. The dominant community of the foothills and much of the plain, it extends from the least steep slopes of the mountains at elevations of at least 1000 m across the foothills to the coast. The major plant is cottongrass, Eriophorum vaginatum, which forms the almost ubiquitous tussock. Tussocks, ranging in form from cylindric to cubic and in heighth and breadth from 15 to 30 cm, are separated from each other by spaces of similar dimensions. In and between them grow various grasses, herbs, sedges and small shrubs such as low willows.

Wet Sedge Meadows are most commonly found in the flatter portions of the Northern Foothills and the Arctic Coastal Plain where they occupy poorly drained soils. They are normally associated with peat and frequently with icewedge polygons. If the polygons are of the low-center variety the meadows will usually be under water in summer (Fig. 8). The dominant plant is Carex although cotton grass, sedges, rushes, herbs and small willows are also present.

Aquatic vegetation is rare in the rivers of the Arctic Slope but quite abundant in some of the lakes, especially the shallow ones common in the plain. However, because of the small proportion of the two drainage basins actually in the Arctic Coastal Plain, these lakes are not as significant to the problem at hand as one might assume after a cursory glance at a hydrographic map of the Arctic Coastal Plain.

The same condition does not hold for flood plains and cutbanks, however. The numerous streams of the Arctic Slope (i.e., the tributaries of the Blow and Colville Rivers) often have wide flood plains and steep cutbanks on both of which rapid and drastic change is common. Thus, Flood-plain and Cutbank vegetation whose composition depends primarily on the stage of its development is highly varied (70). Horsetails, grasses, sedges, herbs, shrubs and trees are common (Fig. 9). Trees and shrubs, including Populus, Salix, Alnus and Shepherdia, are present along many of the tributaries.

Weather and Climate

Whereas the mineral and organic matter of a drainage basin provide the bulk of the material of which deltas are made, it is climate and weather which are primarily responsible for the timing of morphologic change. This fact is no more clearly demonstrated than in the Arctic. Further, the wide amplitude of the seasonal oscillation of the climatic

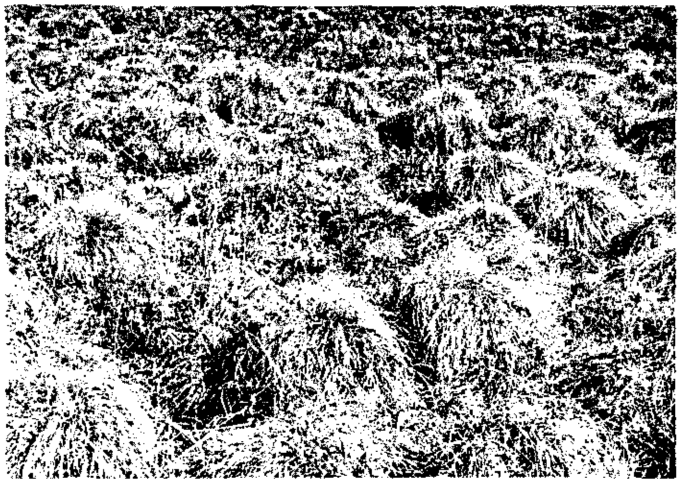


Fig. 7. Nigger-head Meadow.

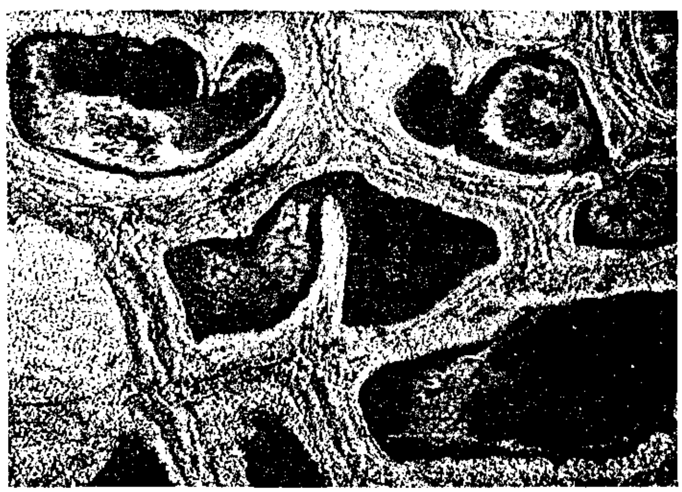


Fig. 8. Low-Centered Polygons.

Fig. 9. Cutbank Vegetation.

elements is primarily responsible for an equally wide amplitude in the oscillation of virtually all deltaic processes.

A complete analysis of weather and climate is not attempted. Indeed, data are insufficient for the areas here considered to allow more than a cursory consideration. The three stations (see Appendix II) of greatest relevance to this report are Shingle Point, Barter Island and Barrow all of which are coastal. Although there are no records from within the Blow River drainage basin, that of the Colville has some records from Umiat and Anaktuvuk Pass which are of value. That which follows is an analysis of those weather and climatic elements which are directly or indirectly (as for example, through their influence on vegetation growth and runoff) most significant to or responsible for the type, amount and timing of the deltaic changes that occur during the period of transition between winter and summer. The sequence of events will be emphasized.

The weather and climate of the Arctic Slope are affected by the same "controls" which operate in other parts of the world; e.g., solar radiation, air masses, land-sea relationship and topography. Likewise, the elements (radiation, temperature, precipitation and wind) and their regimes are all represented and significant. Although specific variations in general conditions have definite effects upon deltaic processes, it is nonetheless the climatic pattern that sets the overall sequence of events.

In the gross sense, much of the area under consideration is continental in character in winter and maritime in summer. Thus, the transition from winter to summer is, climatically speaking, a transition from continental to maritime conditions. As the parameters typical of these two climatic types are quite different in both time and space the rapid change from one to the other is complex.

Mid-winter is a period during which there is continuous darkness, a net loss of radiation, very low surface temperature, atmospheric stability, a strong temperature inversion, little water vapor in the air, little cloud cover and a thin ice and snow cover over all of the surface.

Mid-summer, on the other hand, is characterized by continuous daylight, a net gain of radiation, low albedo, low surface temperature, atmospheric instability, high humidity, heavy cloud cover, frequent fog, no snow (except in highly protected areas) and no surface ice (except at sea).

The transition from winter to summer is variable in time of onset, duration and degree of change and therefore in importance to deltaic processes. Those changes which directly or indirectly affect snow melt and therefore runoff, breakup and flooding are of main significance.

Radiative Regime. The amount of effective solar radiation at the surface depends upon several interrelated factors which can be grouped into the following categories: celestial, atmospheric and terrestrial.

Given a tilted, rotating body such as the earth, the celestial factors (duration of daylight and darkness and the angle of the sun's rays) are dependent upon the latitude of the location considered. At latitudes poleward of the Arctic Circle extreme conditions prevail in that in mid-winter there is a complete absence of direct sunlight whereas in mid-summer continuous sunshine occurs (Fig. 10). However, even during the period of continuous sunshine, solar elevations are low (Fig. 11). At these latitudes twilight, although of long duration (Fig. 10), is relatively unimportant in the context of the present discussion.

Atmospheric factors affecting the radiative regime along the arctic coast include thickness and composition (including the amount of water vapor and the amount and type of cloud as well as the less variable constituents). Thickness, which varies seasonally, is important in that as it increases the chance of sunshine reaching the surface decreases. The effect of clouds on the radiative regime is great. Figure 12 illustrates the variation in insolation that can occur between relatively cloudless and cloudy days.

The primary terrestrial factors affecting the radiative regime are those influencing the albedo. Recent studies have shown that the relative albedo increases as solar elevation decreases but by a few percent only (45). Although albedo varies with solar angle it is mainly determined by the nature of the surface. For any given angle of incidence, the difference in the albedo can vary as much as 60%. Freshly fallen snow may have an albedo of greater than 80% whereas most snow-free surfaces have albedos of less than 20% (87). Thus, from the standpoint of the radiative regime, one of the most important seasonal occurrences is the loss of the snow cover. This loss will be accompanied by a large reduction in the albedo which may also be rapid (Fig. 13).

Although the greatest variation in albedo occurs between snow-covered and snow-free surfaces, there is a sizeable variation over snow-free tundra surfaces themselves. For example, recent (1964) measurements near Barrow show that the albedo over various tundra surfaces during July and August ranged from 4% to 34% under varying cloud types and cover (45).

The period of radiational loss in the Arctic lasts until there is a balance between the incoming and outgoing energy. Net total radiation for Barrow in 1964 is shown in Figure 14 (45). The isopleths illustrate the rapidity with which net radiation increased as the snow cover disappeared in late May and early June. The period of radiational loss

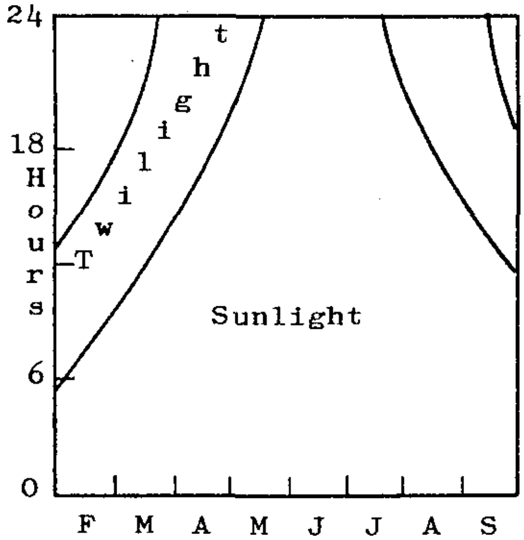


Fig. 10. Duration of Sunlight and Twilight at 70°N.

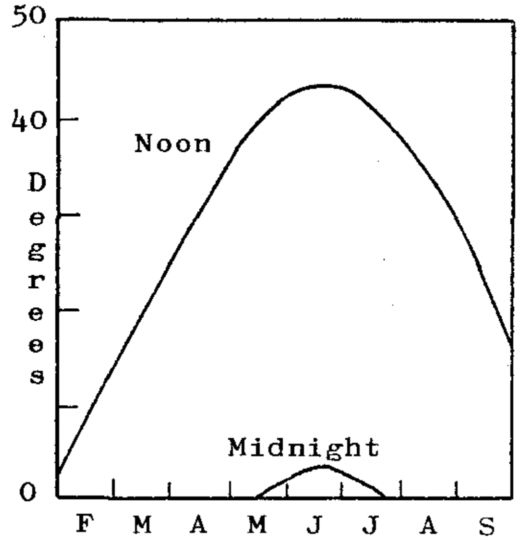


Fig. 11. Solar Elevation at 70°N.

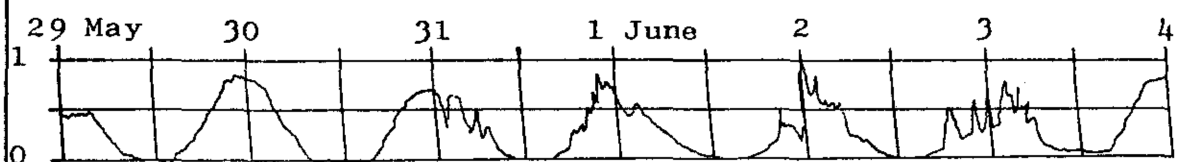


Fig. 12. Recording Pryheliometer Record, May 29 - June 4, 1968 Blow River Delta. Calories per Minute per Square Centimeter.

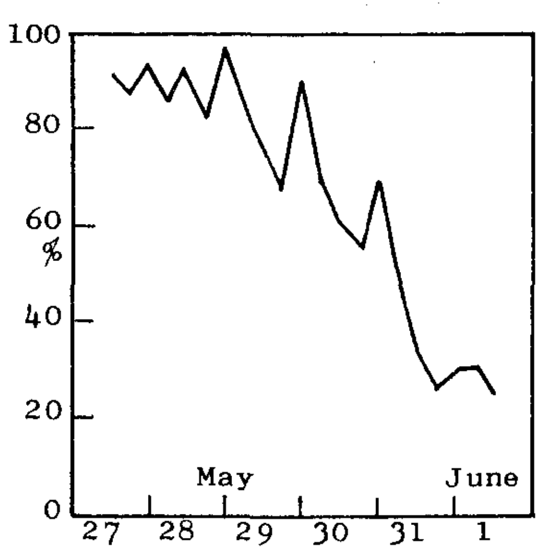


Fig. 13. Decay in Albedo, Barrow, 1964 (After Fig.4 in Ref. 23).

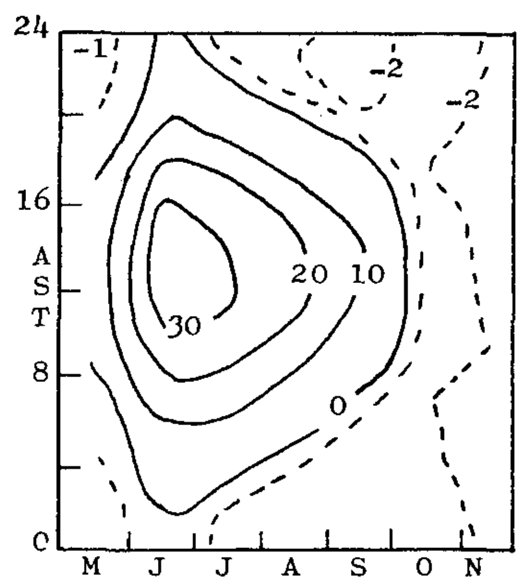


Fig. 14. Net Total Radiation, Barrow, 1964, $mWcm^{-3}$ (After Fig.2 in Ref. 23).

is so long that the annual heat loss is greater than incoming energy (1).

Temperature Regime. *From the month of minimum temperature* (normally February although in any given year either January or March) there is an increase in temperature to the month of maximum, usually July. The rate of change from one month to the next is highly variable (Table II).

TABLE II. MONTH TO MONTH TEMPERATURE CHANGE, °F

	Feb	Mar	Apl	May	Jun	Jul
Shingle Point	-3	17	24	18	9	
Barter Island	5	15	22	13	5	
Barrow	4	16	19	14	5	

All three stations have the same general sequence and at all three the greatest increase occurs between April and May. On the average along the arctic coast May has a temperature about 20°F higher than April. Temperature continues to rise but at a slower rate until July.

Although the greatest change in temperature occurs between April and May the mean monthly temperature of May is 25°F at Shingle Point, 23°F at Barter Island and 20.5°F at Barrow. It is not until June 18 at Barter Island and June 11 at Barrow that the average daily temperature reaches 32°F.

The temperature regimes prevailing upstream in the drainage basins are more significant to what happens morphologically in the deltas than are the temperature regimes in the deltas themselves. During the period of snow melt and breakup several factors affect the situation at higher elevations. Although during winter higher elevations may frequently experience higher temperatures than lowlands because of the prevailing inversion, during the months of May and June it is likely that more normal temperature profiles prevail. However, because of more southerly positions at some distance from the cooling effect of the ocean, temperatures during spring rise at a more rapid rate. Temperatures at Inuvik, Anaktuvuk Pass and Umiat rise above 32°F earlier in the season and also reach higher values in mid-summer than they do at coastal stations.

Precipitation Regime. From the standpoint of this report the most important characteristic of the precipitation on the Arctic Slope is the amount of snow that is on the ground at the beginning of the melt season. Although snow and rain may fall during the period of melting, the amount of water contributed would normally be small in comparison to that present in the form of snow on the surface and therefore would not directly contribute much to the rivers. However, by increasing the rate of snow melt, rain may have a very important even if indirect effect on discharge.

On the Arctic Slope the total annual precipitation is low -- less than 25 cm except possibly in the upper portions of the drainage basins. As much of this precipitation comes in the form of rain in summer, it does not contribute much to the rivers during breakup.

The total amount of snow that falls varies greatly from year to year. The records, because of measurement difficulties, are considered to be poor indications of the total fall (9,22). In any event, more important is the amount of snow that accumulates on the surface. However, information about snow depth and density on the Arctic Slope is very sparse.

Throughout the Arctic Slope the snow cover is usually formed by the end of September and lasts until early or mid-June. By late September the thin active layer is partially or completely refrozen so that percolation, in the event of snow melt, cannot occur. Snow gradually deepens during winter until a maximum depth is reached sometime during April. The actual depth varies greatly with topographic position and wind direction and speed. During winter, drifting is common. However, most of the time drifting results only in a repositioning of the snow and does not necessarily cause it to be lost to the next seasons floods.

Average annual snowfalls recorded at the several stations significant to this report are summarized in Table III as are the amounts present on the ground at the time of maximum depth in spring. The records show that the maximum depth on the surface is approximately half the amount that falls.

TABLE III. SNOWFALL AND ACCUMULATION

	Average Annual Snowfall, cm.	Average Maximum on Surface, cm.	Length of Record, yrs.
Shingle Point	75	--	5
Barter Island	117	55	12
Barrow	67	35	40
Umiat	83	38	5
Anaktuvuk Pass	220	70	2

Such reduction in amount reflects packing and densification as well as loss to the surface. The quantity of water such depths of snow will produce depends on density, data for which are lacking (85).

The precipitation of the Arctic Slope comes mainly from cyclonic storms which move along the Arctic Slope from the west. The wide plain west of Barter Island has little orographic effect on storms and thus receives relatively small amounts of snow (7). From Barter Island eastward orographically induced snowfall is important. Most of the Blow River drainage basin receives such snow.

The disappearance of the snow cover, which usually begins in May, is rapid especially from flat surfaces such as lake, river and sea ice, sandbars and mud flats. It also disappears quite rapidly from the general tundra surface. Only where deep drifts, as along riverbanks and in sand dunes, does snow tend to persist. However, removal from riverbanks may be rapid also. Floodwater, which undercuts snow banks frequently results in collapse and removal of large blocks of snow (Fig. 15).

One of the most important (and least studied) factors involved with the amount of runoff from the drainage basin is that of the loss of snow through evaporation. Although the actual amount of such loss will vary from year to year depending upon the nature of the radiative regime, any loss from the relatively thin cover will have a marked effect on the discharge. A recent calculation by Benson (7) shows that evaporation may reduce the snow cover in some areas of the Arctic Slope (such as tussock flats) by more than half.

Wind. Wind serves a variety of functions in deltaic change. It is an eroding, transporting and depositing agent in its own right. Further, it is often indirectly significant. For example, wind-induced waves on the ocean and in lakes and rivers are frequently responsible for severe erosion (79).

Before the melt season begins very little of the surface is snow free. Therefore, wind has little effect on forms buried beneath the blanket of snow. However, once snow is removed, whether by wind, evaporation or melting, wind becomes effective. Removal of snow from sandbars and mud flats, as discussed above, usually precedes removal from the general tundra surface. Therefore, sandstorms are not uncommon while snow is still on the tundra (Fig. 16).

Winds in the Arctic Slope tend to be predominantly northeasterly and southwesterly as is evidenced by the orientation of the ephemeral sastrugi and by sand dunes. Local katabatic winds also occur. Although they are unimportant to the Colville delta they are very significant to the Blow River delta. Indeed, the name "Blow River" stems from winds which move down the deep valley of the Blow. During the field season of 1967 such winds proved to be the strongest experienced and invariably raised dust to heights sufficient to mask the mountains from view. Unfortunately, wind records are not kept regularly at the DEW Line Stations so that no summary is available for Shingle Point.

Permafrost

One of the results of the thermal regime which prevails in the Arctic is the maintenance of subsurface temperatures at values below 32°F. Permafrost, as this condition is called, is continuous (Fig. 2) in the Arctic Slope except for zones beneath the deeper lakes and rivers. The deep permafrost characteristic of the Arctic Slope is topped by a very thin active layer.

Permafrost, affected by soils and vegetation as well as climate, is very important as a geomorphic factor (16,19). Although not entirely responsible for it, at least it is very influential in the creation of several of the very distinctive forms found in the Arctic such as pingos, ice-wedge polygons and thaw lakes.

Even more significant from the standpoint of delta morphology is the effect permafrost has on many of the processes operating in both the drainage basins and deltas.

In drainage basins its effect on runoff and on weathering and erosion are both critical. As in many ways permafrost behaves much like bedrock -- albeit with a seasonally variable upper surface -- it prohibits percolation and thereby accentuates runoff (Fig. 17). During the period of the

Fig. 15. Snowblock Collapse.

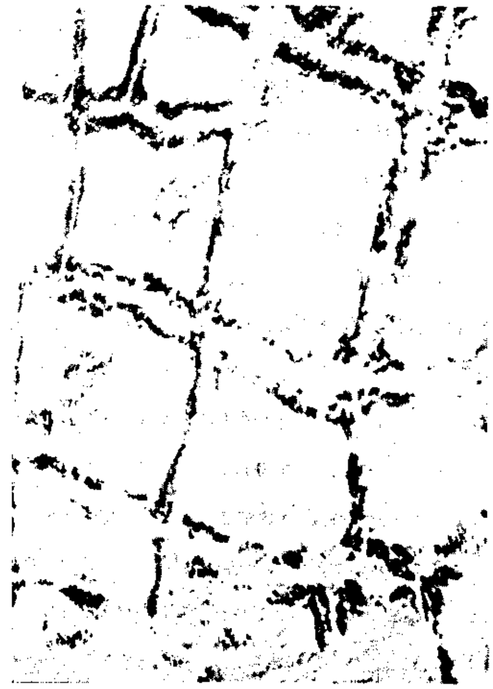


Fig. 16. Polygonal Surface Accentuated by Sediment Deposited during Sandstorm.

Fig. 17. Permafrost Table and Mud Flat Drainage.

NOTE: pages 28 + 29 are out of order

Hydrology

In the above sections an attempt has been made to establish the character of the environment which has a bearing on the development of arctic deltas. Some of the agents act directly; most, however, act indirectly. As far as delta change is concerned, they tend to be concentrated in the river. For example, the amount and timing of snow melt in the mountains will be reflected in the discharge characteristics of delta distributaries.

Arctic rivers, like all rivers in other areas of great seasonal contrast in precipitation, have distinct periods in their annual cycle. In the case of the rivers of the Arctic Slope four periods, highly variable in duration, appear to fit the conditions as outlined in Table IV (4,80). These periods have been given the familiar seasonal names primarily for convenience.

The precise timing of these four periods varies from year to year, from river to river and from one portion of the river to another. However, the sequence is relatively precise. The information that follows should show some of these variables and limits to them. It illustrates further that one (in the case of the Blow) and five (in the case of the Colville) seasons are insufficient to establish an "average" situation. Indeed, it appears that every year during which observations have been made at the Colville was exceptional.

Although concentration in this report is on Period II of Table IV, i.e., a period centered around breakup, the characteristics of the river prior to breakup are very significant in affecting its timing and character.

NOTE: pages 28 + 29 are out of order

year under consideration the ground is still frozen to the surface so percolation is practically nil. Thus, runoff correlates almost directly with snow melt.

By influencing the alternation of freezing and thawing along its upper surface it affects the movement of soil particles (23). Even more significant, however, is the fact that it provides a semi-liquid surface along which gravitational flow of surface sediments can occur which, in turn, provides materials for later transport by the drainage systems.

The limitations placed by permafrost on biota, especially plants, is relevant (62). Although the vegetal cover is extensive and dense, root systems are restricted to the surface layers as are burrowing animals. Retardation of decomposition leads to the accumulation of organic matter so that a sizeable proportion of arctic terrain is nonmineral in composition.

In addition, permafrost and its related phenomena, such as ice wedges, modify the rate of erosion by both wind and water and also influence the forms that result (80). Because permafrost is resistant to erosion due to its low temperature, exposure in relation to the sun and the temperature of both the air and water coming in contact with it become more relevant to bank erosion than otherwise would be the case.

The active layer (Frontispiece) on the Arctic Slope rarely exceeds 0.5 m. In that part covered by dense vegetation, which includes most of the area, the active layer is as thin as 1 cm. Only in non-vegetated, coarse-textured materials such as sand dunes does it become as thick as 2 m or more. The thickness of this non-frozen zone and the rapidity with which it forms, especially on eroding banks, affects erosion rates (see Chapter IV).

TABLE IV. ANNUAL CYCLE OF THE RIVERS OF THE ARCTIC SLOPE

	Season	Initiated by	Characteristics	Duration (Approx.)
I.	Winter	Appearance of a solid ice cover		33 weeks
	Early		Discharge under ice to ocean	
	Late		No discharge under ice	
II.	Spring	Appearance of melt water		3 weeks
	Pre-breakup		Snow melt-water accumulating on and flowing over and under ice	
	Breakup		Removal of ice from river	
	Post-breakup		Flooding following breakup	
III.	Summer	End of post-breakup flooding	Dry periods, low flow Rainy periods, increased flow	12 weeks
IV.	Fall	Reduction of average air temperature to 0°C	Low air and water temperatures and low, stable stage	4 weeks

The longest, and in many ways, least significant of the periods of the Hydrologic Year is that during which the rivers are frozen. On the Arctic Slope river ice normally acquires a thickness ranging between about 1.5-2 m. The lesser thicknesses are more characteristic of the Blow, the greater of the Colville. Although river ice thickness in the Blow could not be measured in 1967, it was found that lake ice thickness in the Blow was 1.55 m. This compared with 1.80 m in the Colville during the same season.

The thicknesses discussed here reflect water in channels sufficiently deep so that they do not freeze to the bottom. The Blow River tends to be shallow therefore relatively small portions of it will have ice this thick. The Colville on the other hand has some channels sufficiently deep such that they do not freeze to the bottom although several of its distributaries do freeze to the bottom.

The amount of bottom-fast ice varies from year to year depending on the stage of the river at freezeup and the severity (i.e., the thickness the ice will attain in a particular winter) of the season. In deltas the thickness of the ice is not as dependent upon stage as it is upstream because, although freezeup occurs at low stage, the stage in deltas is somewhat controlled by the level of the sea. Nonetheless, discharge in fall is so low that some channels will be dry as was the case of the eastern tributary of the Blow in 1956. The relatively few blocks of stranded ice observed in the river channels and at the front of the Blow delta upon arrival in May 1967, suggests that most of the ice was from scour pools rather than from a river with an appreciable flow at time of freezeup.

For a period of eight or so months no water (except for rare outflows from under the ice) is present in the liquid state at the surface. After surface ice has formed some water continues to flow under the ice but gradually ceases. In the case of large north-flowing rivers which originate south of the Arctic, there is discharge throughout the winter. Such a condition almost certainly does not exist for any of the rivers on the Arctic Slope.

As long as the river is not frozen to the bottom, water from the sea will penetrate upstream under the ice. As discharge decreases in the fall, sea water gradually becomes the dominant type under the river ice for a limited distance upstream. As the distributaries freeze to the bottom, this influx of sea water is cut off such that by the end of the winter various portions of the channel will have different proportions of sea water trapped in them.

Period II is here considered as beginning when water first appears on the river ice. The date on which this occurs is slightly earlier for the Blow than the Colville although no precise dates are available for the Blow. Further, the date varies from year to year (Fig. 18). In the Colville three years (1962, 1964, 1967) of observations show that the date of the appearance of the first melt water on the ice varies from May 8 (1967) to May 30 (1964). In 1967, as discussed below, the season was very early.

Once a sufficient depth of melt water accumulates on the ice, it begins to flow downstream over the ice. Generally, the change in state begins relatively gradually but then increases rapidly (Fig. 18). At some time during the period of melt-water accumulation, flow begins under the ice which is not bottom fast. This water begins to replace the sea water which had accumulated beneath the delta's river ice during winter. The exchange is rapid; in both 1962 and 1964 the flushing action was essentially completed within two days (Fig. 19).

The time between the appearance of the first melt water on the ice and breakup also varies. For the two years for which complete records are available for the Colville this period varied from six days (1964) to 19 days (1962). It is probable that in 1967 an even longer period of time was involved, for a few days after the initial melt water began to accumulate (May 8) temperatures returned to nearly normal for this time of the year and the melt water refroze (Fig. 21). The earliness of the season in 1967 was not unique at the two deltas; indeed, it was recorded across much of the American Arctic and out over the sea ice, as well.

By May 9 melt water had already begun to accumulate on the river ice of the Colville and by May 1 was about 2 m deep. River flow began on May 10 and by the 12th was moving at 0.5 m/s. As the stage rose the water spread out over both river ice and sea ice. On May 11 the temperature dropped and ice began to form on top of the melt water. By the 14th the new ice was thick enough to walk on. During these few days small amounts of snow fell several times. At first, all of it melted from the tundra surface but by the 14th new snow formed a thin blanket over all surfaces except on sand dunes.

However, the situation was entirely different in the case of the Blow River. The initial flow which also began in the Blow in early May, probably a few days before it began in the Colville, was sufficient to carry the Blow River through the stage of breakup itself. Thus, by the time of arrival at the Blow delta on May 19, the breakup had already occurred and post-breakup flow was in progress. Just how many days prior to arrival breakup occurred is unknown. However, the fresh appearance of stranded blocks and undercut snowbanks would lead to the conclusion that breakup had occurred not many days before. Countering this conclusion, however, is the fact that lower temperatures (which caused refreezing of surface water in the Colville) would tend to preserve snow and ice.

Because of the early breakup in 1967 in the Blow River, no direct data are available on the breakup itself. However, indirect evidence was available in the form of water marks left along riverbanks and thermoerosional niches cut into snowbanks (Fig. 22) both of which provided indications of stages reached. In the case of the Blow River these indications show that the stage reached prior to arrival at the delta was about 0.5 m above the base mark utilized at the head of the delta. This level is approximately the same as the average of the stage maintained during the postbreakup flooding period during the first two weeks of June (Fig. 20).

The nature of flooding at time of breakup is very important. The effect of the ice on riverbanks and what happens to the ice is largely dependent upon whether the stage is rising or falling at the time the ice is in motion. Stage variation during this period of time is highly variable, dependent primarily upon the changing rate of snow melt in the drainage basin. For example, in 1962 at the Colville the stage had three peaks, two before and one after breakup (Fig. 18). More important from the standpoint of delta morphology, the breakup itself occurred on a rising stage. In contrast, 1964 had only one maximum and breakup occurred on a falling stage. The effects of such variability are discussed in the section on morphologic change.

Postbreakup flooding lasts from the time of breakup until a more or less steady summer regime is established. It undoubtedly reflects the last of the major snow melt in the mountains. Some snow, as discussed above, may remain throughout the summer on northfacing slopes where drifts are deep (Fig. 23). Subsequent flooding is almost certainly the result of summer rain. The intensity and duration of the postbreakup flood period will depend upon the proportion of the snow-melt water that flowed prior to and during breakup and the rate of melting of the remaining snow during the postbreakup period. The length of the postbreakup period based on the years of records presently available are: Colville (1962, 15 days; 1964, 18 days; 1966, 15 days) and Blow (1967, between 35-40 days) (Figs. 18 and 20). The extremely long period between breakup and the establishment of the summer regime in the Blow River is the result of the

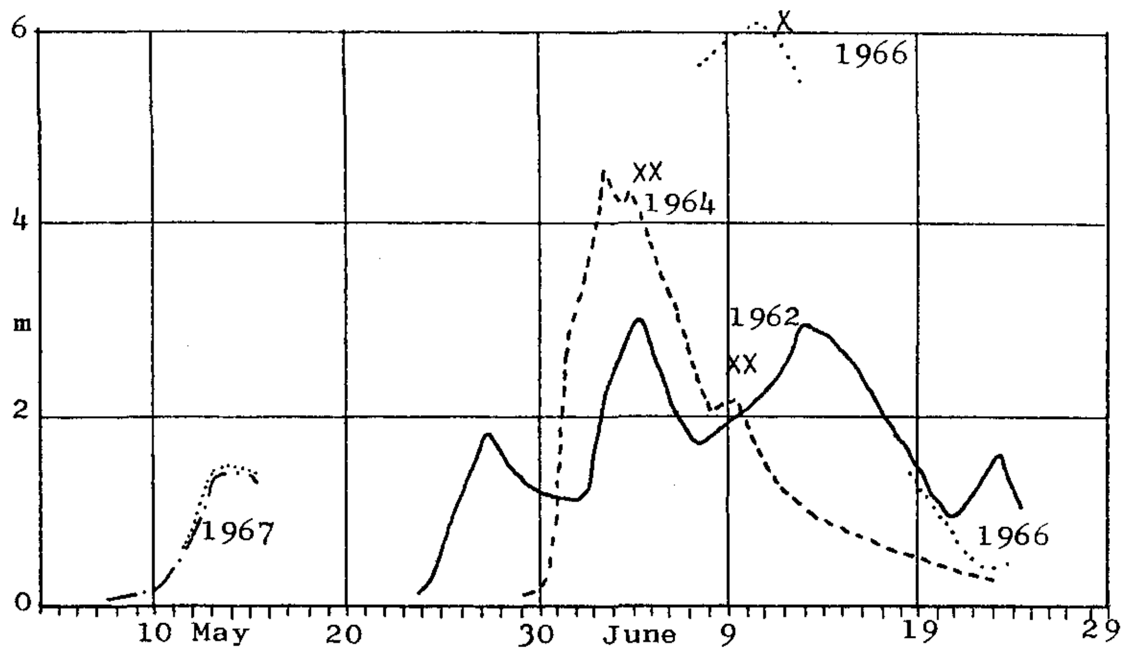


Fig. 18. Stage and Breakup, Selected Years, Colville Delta.

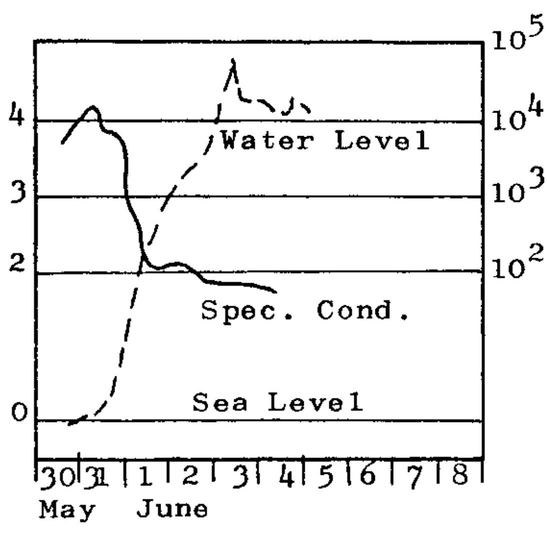


Fig. 19. Specific Conductance, Micromhos/cm^2 at 25° C. and Stage at Putu (C4-32), 1964.

Fig. 20. Stage, 1967, Blow River Delta.

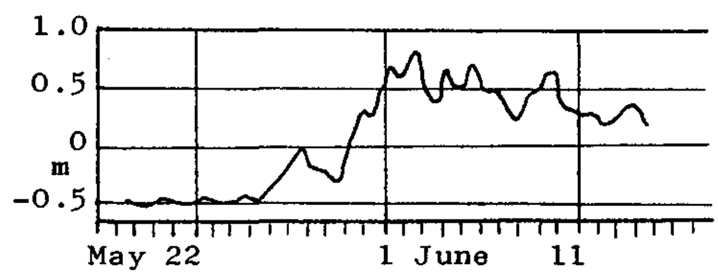


Fig. 21. Colville River Refrozen After Early Thaw, May 1967.

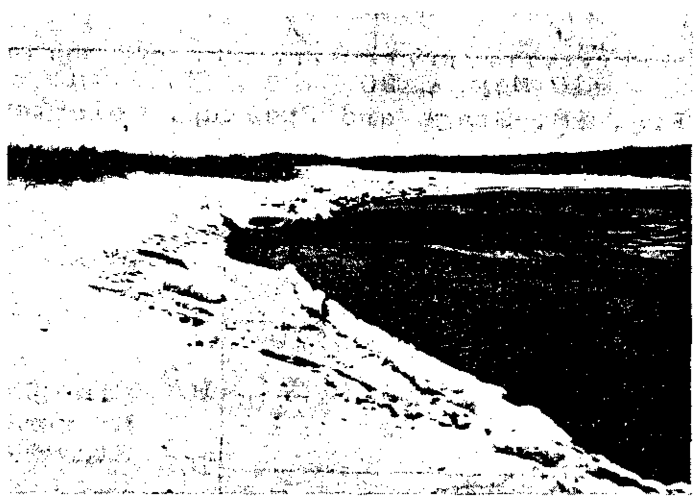


Fig. 22. Thermo-erosional Niche in Snowbank (Blow).

Fig. 23. Snow-bank on Aug.15, 1967 (Blow).

very early breakup. In fact, nearly the first half of this period can hardly qualify as a period of flooding. True post-breakup flooding began during the last few days of May and lasted until the middle of June (Fig. 20).

The materials (inorganic and organic; in solution, in suspension and as bedload) carried by a river to its delta have a direct affect on delta morphology as both erosive agents are deposits.

The character and quantity of a river's load varies with many factors including discharge characteristics and availability of materials. In the case of arctic rivers timing is especially important in determining the relative importance of various factors.

During prebreakup flooding the water which first begins to flow over the ice is exceptionally free of sediments as it comes directly from the snow. However, as snow melt increases, the active layer begins to thaw and water will carry sediments from dunes, sandbars, mud flats and from the tundra itself (Fig. 17). Records from the Colville show that during pre-breakup and breakup flooding the load increases at a more rapid rate than discharge (5).

The bulk of the suspended load of rivers of the Arctic Slope is carried during the relatively short time involved in the pre- through postbreakup periods. In the case of the Colville River in 1962, 75% of the annual total suspended load was transported between May 24 - June 21. The load itself was quite high ranging up to a maximum of 1658 ppm on June 12. The maximum load in a 24-hour period was 520,000 tons.

The suspended load of the Blow River during the period following breakup is shown in Table V. These values appear to reflect the fact that after breakup the return of colder weather refroze many of the source areas thus reducing the availability of material to the stream. However, when warmer

TABLE V. SUSPENDED LOAD, BLOW RIVER, 1967

Date	Time	Stage (m)	ppm
May 21	1800	-0.52	20
27	1445	0.00	85
Jun 1	2000	0.25	535

weather brought increased snow melt and increased discharge in late May, suspended load increased greatly. The June 1 value of 535 ppm would provide approximately 20,000 tons in 24 hours at a calculated discharge of 500 m^3/s. The maximum discharge during the period of postbreakup flooding did not occur until two days later at a stage nearly a half-meter higher.

In addition to the suspended load, a river transports sediments along the bottom and other materials in solution. Based on calculations for the Colville the portion of the total river load transported as dissolved material may amount to a little more than 20% whereas that transported as bedload represents only about .02%. Judging from the nature of the bed materials and the steepness of the gradient, it is likely that the bedload of the Blow River is a larger proportion of the total than in the case of the Colville.

III. THE DELTAIC SETTING

The two deltas, in their subaerial portions, have very heterogeneous surfaces despite low relief. The three most conspicuous forms common to both deltas are lakes, distributary channels and polygons. In addition, the Blow River delta has associated with it an intricate beach-ridge system and has a large portion of its surface covered with tree trunks (Fig. 25) which have floated down the Mackenzie River. In contrast, the Colville River delta possesses only a few such tree trunks, also of Mackenzie River origin. However, it has numerous active and stabilized sand dunes, features missing from the Blow delta. At the front of both deltas evidence of both construction and destruction is present. Construction is occurring in the vicinity of the most active distributaries whereas destruction is occurring between distributaries and also where inactive distributaries exist.

In each of the deltas there are other forms which vary greatly in number, frequency and degree of development. Included are such depositional forms as channel bars, levees and mud flats and, in addition to the polygons mentioned above, frost mounds and pingos.

Deltaic materials range greatly in type and texture. Peat deposits are especially common and other organic materials such as driftwood and woodchips are abundant. Mineral matter varies in texture up to boulder size. Although large sized materials (especially gravels) are very common in the Blow delta, they are rare in the Colville occurring only in a few isolated areas.

Human activity has been and is relatively unimportant in both deltas. Vehicle tracks, which frequently endure for many years on tundra surfaces, old camp sites and oil drums, gasoline cans and other cultural debris are to be found along channel banks and at the front of the deltas. Although there are no buildings on the Blow delta, in the 550 km^2 Colville delta there are three locations with buildings standing.

Blow River Delta

The Blow River delta (Fig. 24), slightly more than 50 km^2 in area (approximately 1.4% the size of its drainage basin), is prograding over the western edge of the older subaqueous Mackenzie delta. The nearshore zone is shallow and is an area where Blow River and Mackenzie River water mix. During much of the year the water off the mouth of the Blow River has a low salinity because of the presence of Mackenzie River water.

There are over 250 lakes of highly varied sizes and shapes in the Blow River delta. Most of the lakes in the upper portion of the delta are remnants of abandoned channels. The vast majority of the lakes are shallow and near the outer margin of the delta many are connected with distributaries and with the ocean so that interchange of water is frequent. Interchange results in great contrasts in water chemistry between lakes and within particular lakes with time (see Appendix III). Lakes of the lower delta not connected with the sea but low enough to be subject to storm surges had higher salinity than those in contact with the sea during 1967, emphasizing the importance of Mackenzie River water.

The delta has several well-defined active and inactive distributaries. The location of the delta apex, the point at which the Blow River first divides, during normal stage is situated at BO-53 (Figs. 24 and 26). This location is only temporary, however, for the Blow

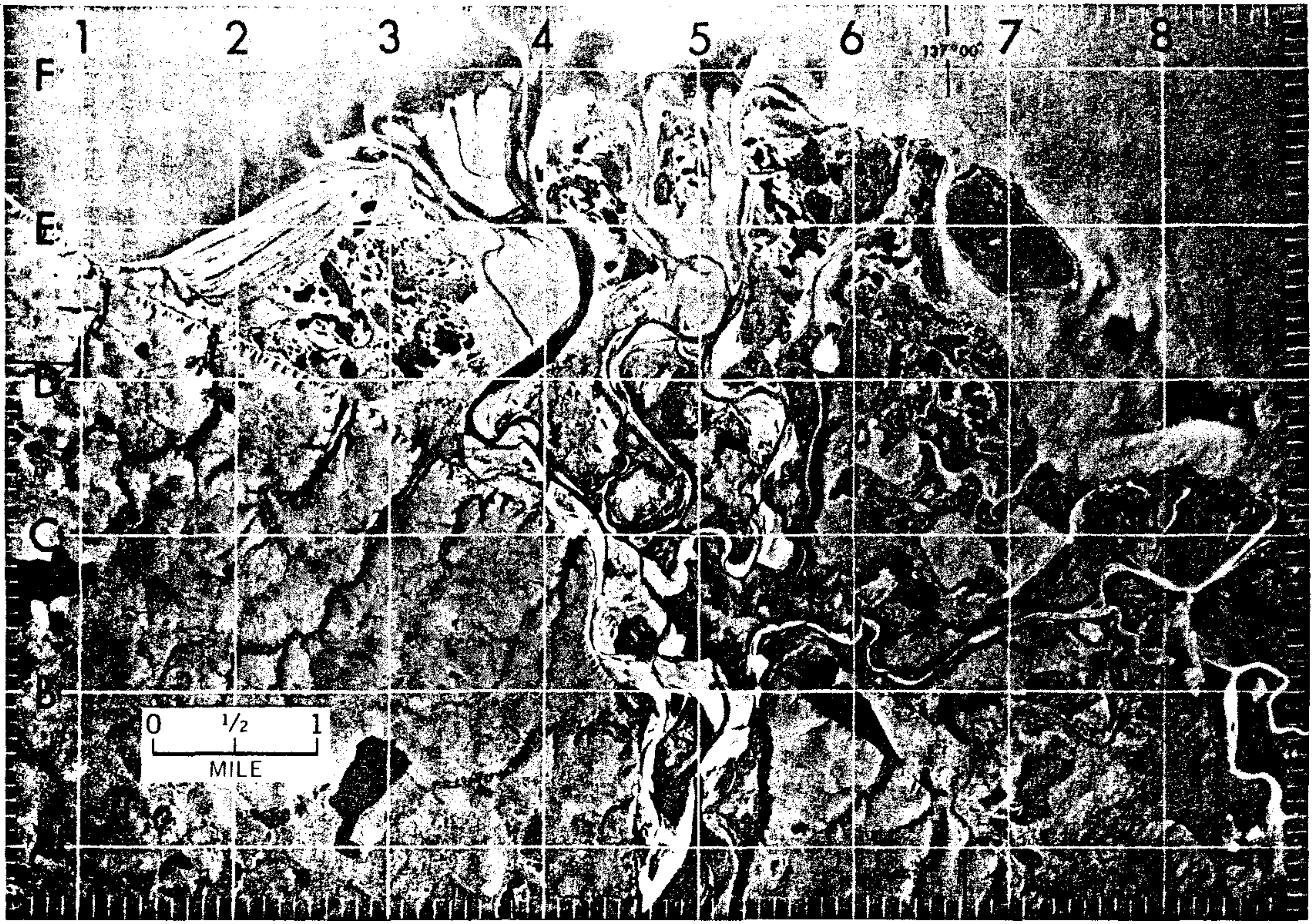


Fig. 24. Blow River Delta. Based on Photo No. 44, Flight Line A-13232, Air Photo Div., Eng. Mines & Res., Canada, 1957.

River frequently changes position in its gravel-floored valley. Indeed the diversion point changes position with changing stage. At a high stage the first diversion occurs more than 1.5 km upstream, at A0-47. On the other hand, at exceptionally low stages, as was the case when the Aerial Photograph used for Figure 24 was taken, the first flow out of the main channel may not occur until it reaches a point far down the west channel.

At the present time the west channel, at least during low and normal stages, has a higher discharge than the east channel. Each of these two major distributaries have additional bifurcations. Some of these additional distributaries, because they are blocked by gravel deposits, carry water only during periods of flooding (B7-48). In all there are some six major outlets to the sea, all of which discharge water into the sea at high stages. However, during low stages only the two western-most channels actually carry water.

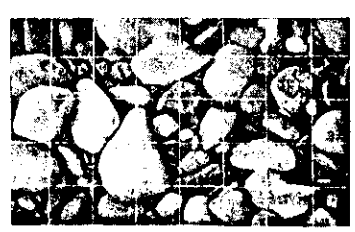
The channels of the Blow delta have various types of depositional features throughout their full length and in the upper delta during low stages pools and riffles frequently alternate. In this portion of the delta the youngest bars are composed almost entirely of cobbles and gravels (Figs. 27 and 28). Generally there is a decrease in grain size of bar materials downstream, however those bars formed from secondary gravel and cobble sources (Fig. 29) are exceptions. No point bars are composed of sand, sources of which are limited. Faceted bluffs provide sand from exposed shale and sandstone. The shale fragments are distinct in that they are flat, soft and have a high specific gravity (2.96). They remain in the large textured categories only a relatively short period of time. In the delta the transition from deposits of fine gravel to those predominantly silt is generally sharp.

Fig. 25. Driftwood, Blow River Delta.

Fig. 26. Delta Apex, Blow River Delta, BO-53.

Fig.27. Cobble and Gravel Bar.

Fig.28. Representative Bar Materials. Scale, 5 cm per unit.



Older and higher bars contain finer sediments and a variety of vegetation forms ranging from scattered clumps of grass (Figs. 30 and 31) through dense grass (Fig. 32) to willow patches (Fig. 33). Bars at this stage in their development normally have quite conspicuous levees which are much better developed in the upper than in the lower delta as is usually the case. However, in the Blow delta the levees of the upper delta are higher than might be expected because of the sediments added by the wind. The highest levees are quite clearly outlined by willow and alder vegetation which shows up as dark bands paralleling the upper channels in photographs (Fig. 24). Lower delta levees are composed almost entirely of fluvial materials and are low and sometimes difficult to discern visually. However, many of them are rendered more conspicuous by an accumulation of logs along their crest (Fig. 34).

The front of the Blow River delta varies in both morphology and composition. Along the seaward edge of the westernmost portion, the beach is narrow and composed primarily of gravel although much fine organic matter is also present (Fig. 35). Eastward, the beach is much wider and is mainly composed of woodchips and other organics. In places the organic layers are thin enough so that the mineral deposits beneath are visible. These organic beaches are stratified and exhibit a variety of microforms (Fig. 36). Tidal flats in the Blow delta tend to be small and are found primarily near the areas of most active deposition.

A beach-ridge system is present near the delta's western edge (D8-20). Primarily it is not deltaic in origin as the bulk of the mineral materials which have formed it originate in the bluffs to the west and the organics (for example, tree trunks) come from the Mackenzie to the east. The system is characterized by ridges and swales (Fig. 37)

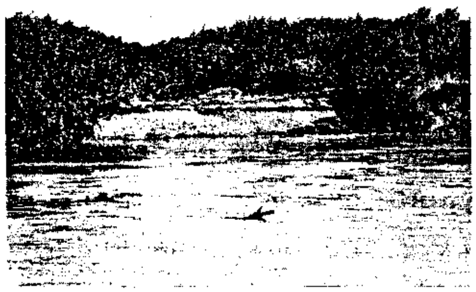


Fig. 29. Relict Channel Deposits, (B9-46).

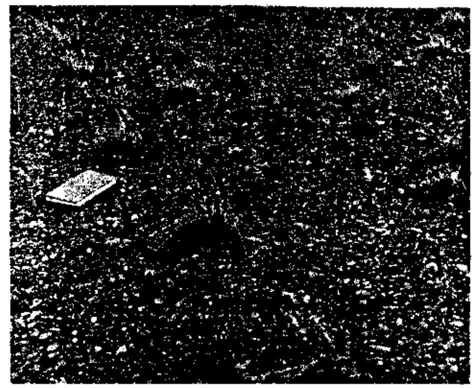


Fig. 30. Initial Colonization of Gravel Bar.

Fig. 31. Well Established Grass on Gravel Bar.

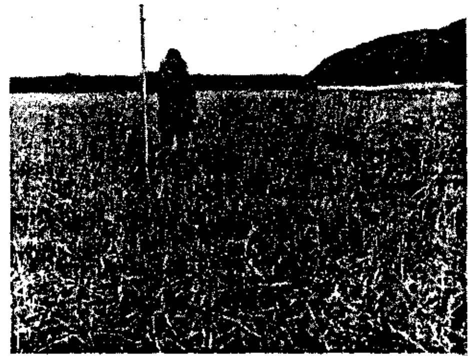


Fig. 32. Vegetated Flat.

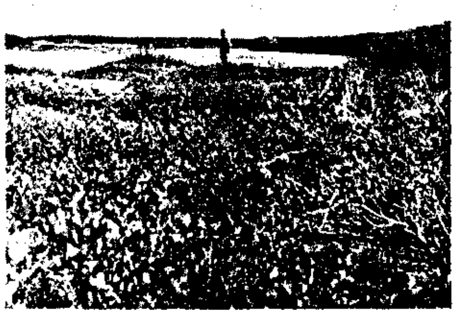


Fig. 33. Willow and Alder Vegetation on Mature Flat.

Fig. 34. Logs on Lower Delta Levee.

with the seawardmost ridge being the highest. In addition, *several isolated piles of logs and gravel have accumulated* (Fig. 38). Although not mainly deltaic these ridges do exert a control on the flow of water and therefore on sedimentation in the western portion of the delta.

In the flood-plain portion of the delta when relief is relatively low, low-centered ice-wedge polygons are common (Fig. 39). The centers of the polygons are marshy, many even under water, during summer. Normally, the polygons are grass covered although willows may occur along the frost cracks. The Blow delta has few frost mounds and only one small (2.7 m high) form was observed that might be an incipient pingo.

Colville River Delta

The Colville River delta (Fig. 40) approximately 550 km^2 in area, is about 1.1% the size of its drainage basin. The head of the delta is located 40 km south of the Arctic Ocean and about 3 km north of the river's last major tributary, the Itkillik River.

The Colville delta has a great number of lakes many of which are several square kilometers in area. Some of the lakes, especially those that are old river channels, are as much as 10 m deep. Most, especially those near the front of the delta, tend to be shallow. From the standpoint of this paper the lakes of most significance are those connected to the distributaries and thus affected directly during breakup.

In contrast to the situation prevailing in the Blow delta, more water is carried by the east channel (ca. 75%) than the west channel (ca. 20%). These values vary seasonally but only by a few percentage points (4). The rest of the water is discharged through three other distributaries which branch in a northwesterly direction from the east channel. The combined length of these distributaries in the Colville delta is over 200 km.

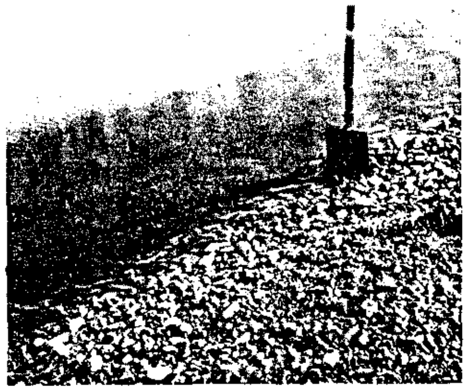


Fig. 35. Gravel Beach, (D9-17).

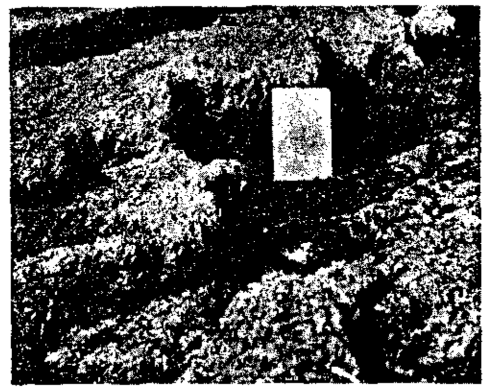


Fig. 36. Organic Beach, (E7-58).

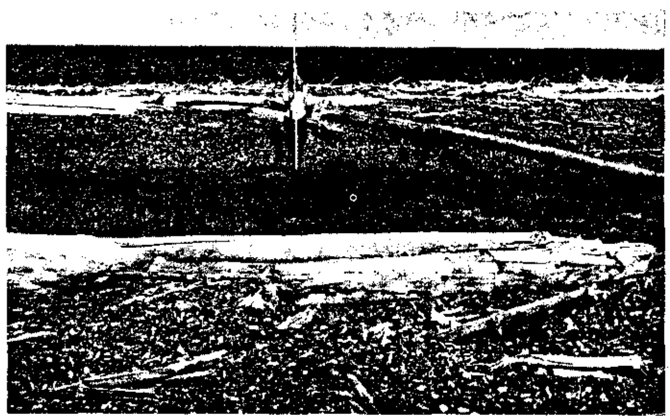


Fig. 37. Ridge and Swale Topography (D9-17).

Fig. 38. Pile of Logs and Gravel.

Fig. 39. Low-Centered Ice-Wedge Polygons (B2-68).

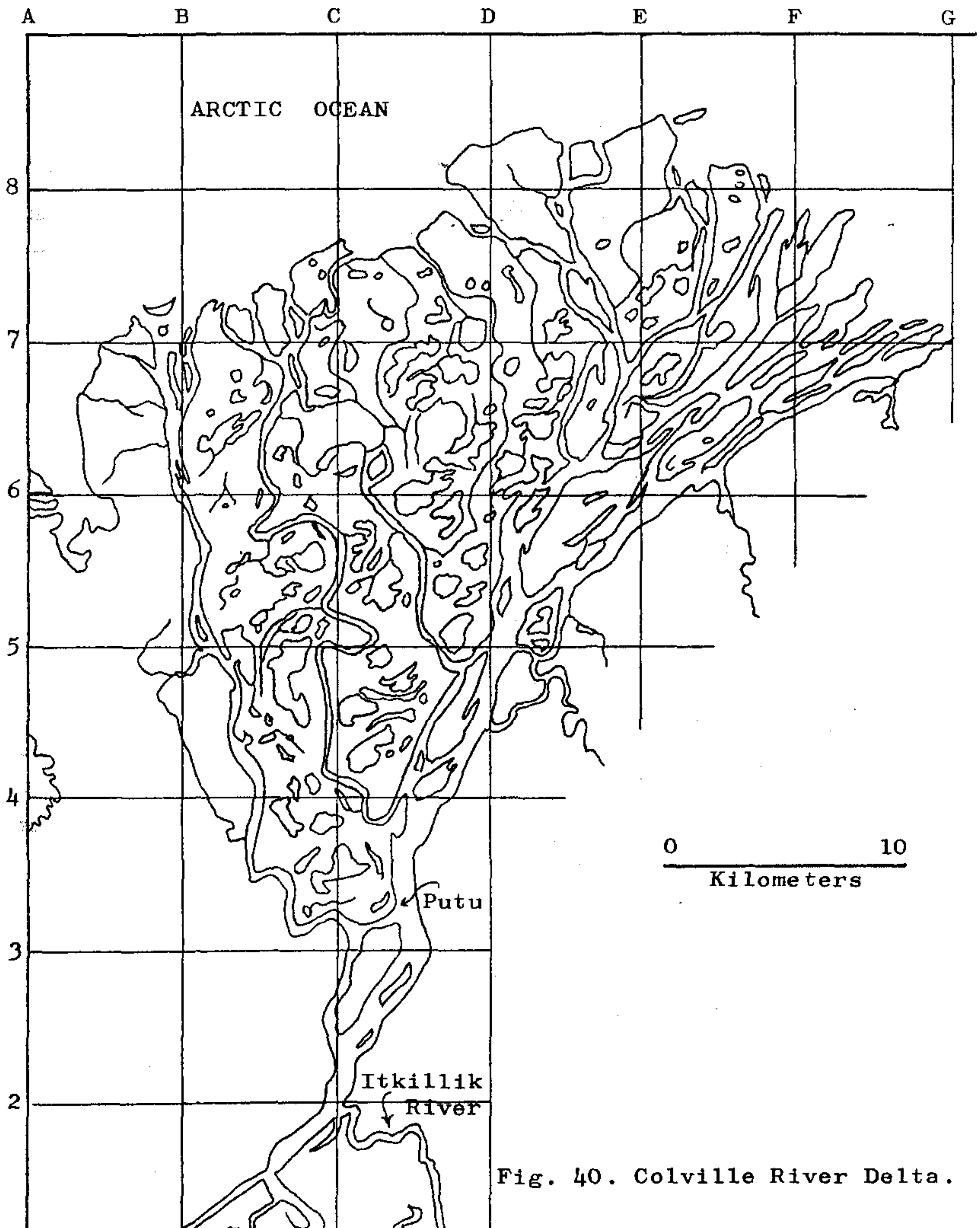


Fig. 40. Colville River Delta.

These channels cut through a great variety of materials and forms including peat banks (Fig. 41), sand dunes (Fig. 42), former sandbars and mud flats, and the Gubik Formation (Fig. 43). Most of the banks of the Colville delta range between 2.5 m and 5 m above mean river level. Although riverbanks are highest near the head of the delta, the Gubik banks (up to 10 m) on the west channel and those banks formed where the river has cut through sand dunes are exceptions.

Gravel and cobble bars are rare in the Colville delta. Most are residual from erosion of the Gubik (Fig. 43). However, sandbars and mud flats are common along and in all of the distributaries. Many of the mid-channel bars have become sizable islands (Fig. 44). Well developed ridge and swale topography is found especially along the west channel. In places such features are emphasized by the pattern of the polygons which form in them. The east bank of the east channel is relatively free of deposits and contrasts greatly with the west side of the channel where extensive sandbars and mud flats occur. The bars support a varied amount of vegetation ranging from grass to short willow trees in the case of the more well developed portions of the bars. Mud flats near the front of the delta are extensive and are occasionally submerged by wind waves.

Natural levees are not generally as well developed in the Colville as in the Blow. However, they frequently are more conspicuous because of the water-logged nature of the ice-wedge polygons which form behind them.

Although sand dunes are absent from the Blow River delta they are very common in the Colville delta. Both stabilized and active dunes are present. Stabilized dunes are generally rounded and frequently have associated

Fig. 41. Peat Bank, Colville Delta (B8-32).

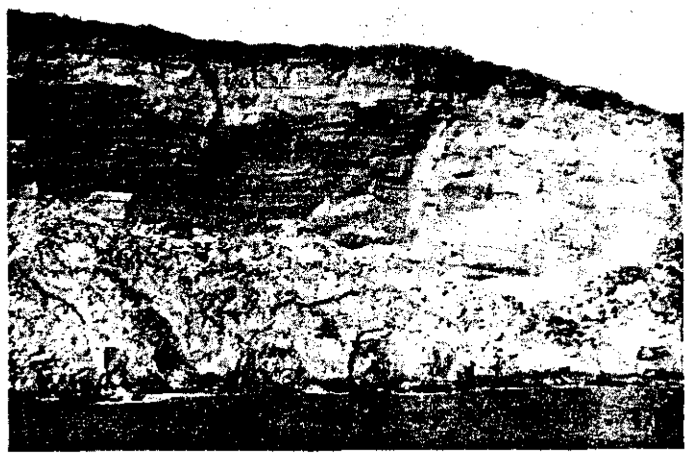


Fig. 42. Sand Dune Bank, Colville Delta (B7-32).

Fig. 43. Gubik Formation, Colville Delta (B4-35).

peat deposits which have formed in the interdune basins. Thus alternation results in highly contrasting exposures when the dunes are cut by the river. Active dunes are found on the inner portion of the extensive mud flats near the ocean and on the left bank of several portions of the river and its distributaries. Delta dunes are composed primarily of fine or very fine sand although in blowouts coarser materials are present (79).

Frost mounds (Fig. 45) and pingos (Fig. 46), although more common in the Colville than in the Blow delta, are nonetheless not numerous. Frost mounds tend to be located in relatively low, swampy areas near the front of the delta. Only three pingos are known to exist in the delta proper. However, many others can be seen on the tundra surface surrounding the delta.

Ice-wedge polygons (Fig. 47) are very well developed and both types -- low-centered and high-centered -- are common. They vary greatly in size, shape and depth. The ice wedges which form them are also highly variable, being largest in areas of peat and smallest in sand where they frequently are narrow veins of ice only (Figs. 48 and 49). These wedges are very important in bank erosion and in the control of bank form (80).

Permafrost in the Colville River delta occurs in all areas except under the deeper channels and lakes. All riverbanks are frozen and have only a thin active layer. The active layer is thickest (up to 1.7 m) in sand dunes and thinnest (as low as 0.15 m) under tundra mats.

Fig. 44. Mid-Channel Island.

Fig. 45. Frost Mounds (B3-56).

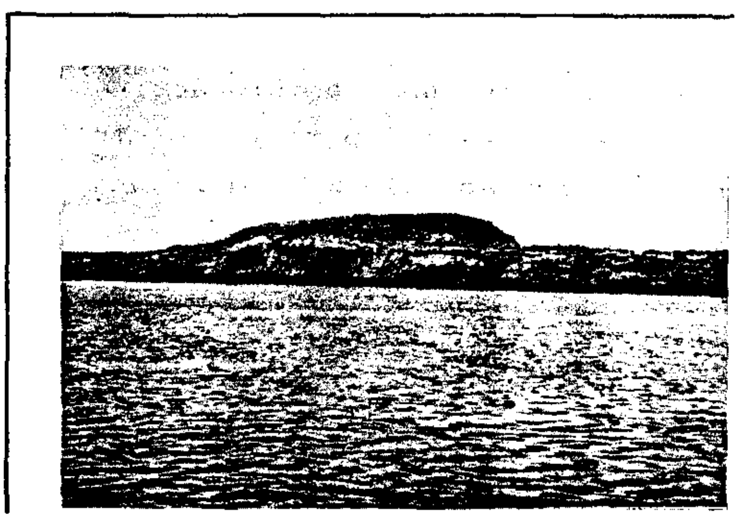


Fig. 46. Pingo (C1-32).

Fig. 47. Ice-Wedge Polygons

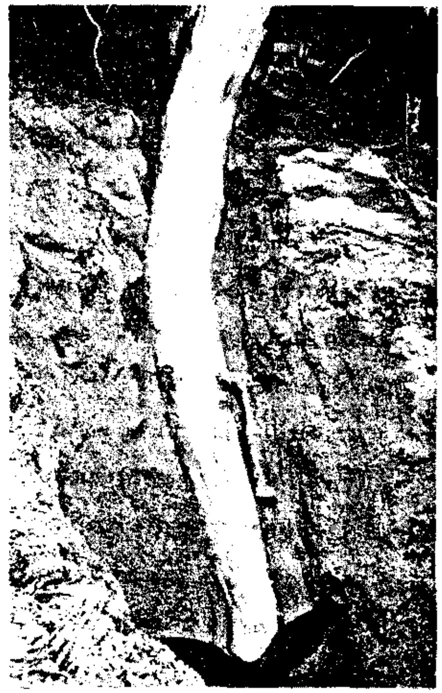


Fig. 48. Ice Wedge in Sand.

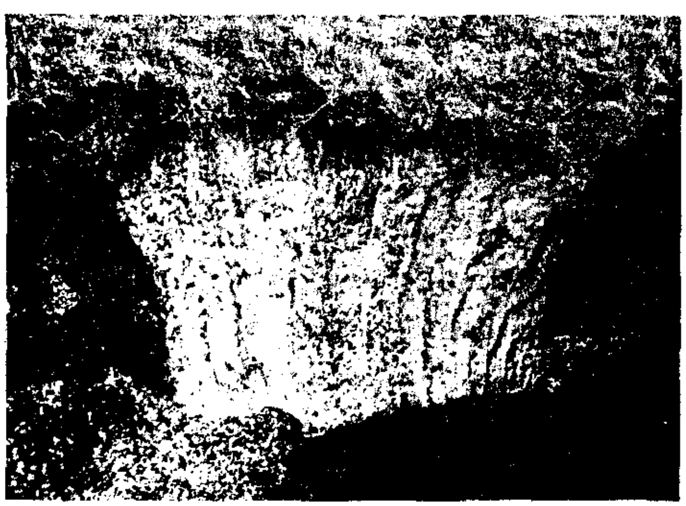


Fig. 49. Ice Wedge in Peat, 5 m wide.

IV. MORPHOLOGIC CHANGE

In the foregoing chapters the agents responsible for change and the forms within arctic deltas which are subject to change have been considered. It now remains to discuss the changes, themselves. Arctic morphologic change like most seasonally affected change in the Arctic tends to be concentrated in a relatively short period of time -- a period of time that nearly coincides with the period during which a protective blanket of snow and ice is absent. This period of time in much of the Arctic is on the order of one-third of the year. Even within this limited time period the amount of change is very unevenly distributed. Based on observations over several field seasons on the Arctic Slope, it is obvious that most change is concentrated in the period of a month or so around the time of breakup.

In the discussion which follows, emphasis is placed on each of the processes operating during this relatively short period of time and on the forms resulting therefrom. Although the sections are based on different processes, it does not follow that each of the processes is distinct; indeed, most of them affect each other to varying degrees. Further, the amount and type of activity of some processes depend upon the activity that preceded and, of course, some have a definite effect on activity that follows.

Wind

The surface, except in a few isolated situations, is covered with a blanket of hard snow throughout the winter. Although on the whole this snow cover is thin, there are variations in thickness. Over the relatively flat tundra surface much of the variation that does exist is due to the roughness caused by vegetation type (tussocks, for example). Snow normally is thick only where it drifts against such features as river or lake banks. Even though most of the cover tends to be thin it is, nonetheless, a very effective blanket. Thus, wind during winter has little effect on forms so protected. However, the snow itself is eroded, deposited, hardened and altered.

The major exception to this relative ineffectiveness of the wind during winter occurs where snow does not cover the surface. Banks, too high to be covered by drifts or situated in relation to wind direction such that snow is not allowed to accumulate, are uncommon in deltas. The vertical cliffs (Fig. 6) near the head of the Blow River delta are likely to be exposed during most, if not all, of the winter for both reasons, their height and the direction of the wind. Thus, theoretically, at least, winds which blow down the Blow River valley during winter can erode such exposed banks. Wind in winter becomes an even more effective eroding agent than it is at other seasons because of the good "tools" (snow grains at great hardness due to low temperatures) it carries. However, the fact that the banks themselves are frozen probably reduces the amount of actual erosion that can occur.

In the case of the Colville delta, which is far from cliffs such as those associated with the Blow delta, the only exposed surfaces during most of the winter are occasional blowouts in sand dunes and between some of the peat buttresses which have formed near the river as the result of the melting of ice wedges (80). Such peat blocks tend to be somewhat protected by plant fibers which hang on the outside as a result of the removal of mineral matter during the thaw season.

Substantiating the fact that little wind transport of non-snow material occurs in these deltas during winter is the occurrence of snow drifts which are remarkably free of mineral and organic layers except near their base and near their top (Fig. 50).

Toward the end of winter (in the context of this report, i.e., before meltwater begins to appear on the river ice) wind may become a very effective eroding and depositing agent. Snow, which tends to be thin over mud flats and sandbars, is removed from such surfaces before most others. Some of this removal may be through evaporation, some by melting and some by wind. Nonetheless, in the process of removal the underlying surface begins to thaw. Once it becomes exposed, wind can act on it. During the pre-meltwater accumulation period, clay, silt and sand may be carried and deposited rather extensively over the delta's surface (Fig. 16). It is deposited on the snow in the lee of banks and emphasizes the microrelief forms of the surface. One of the common features observed is the sand stripe. Stripes of sand and silt as much as 30 m long, 1 m wide and several cm thick have been measured in many locations within the Colville delta.

Sandbars and mud flats, although exposed early in the melt season, soon are covered with floodwater and cease to be sources of wind-blown sand. By the time water has covered these bars and flats other source areas such as the high riverbanks of the Blow River and the active sand dunes of the Colville delta are snow free or in the process of becoming so.

The results of the deposition of wind-transported material is especially conspicuous in the natural levees near the head of the Blow delta. Indeed, these levees seem to be at heights above maximum floodstage and are obviously "growing." The dense vegetation with rather tall trees (willows and alders as much as 4-5 m tall) on these levees helps create a very effective natural "snow fence" (Fig. 51).

Just what proportion of the wind-transported material observed on the levees on top of the snow in late May, 1967 was transported during late winter and early spring is unknown. However, because of the lack of interbedding in the snow it is apparent that the snow of the levees accumulated after the source areas of sand were frozen in winter and before they again became source areas -- presumably when the snow blanket was removed from river bars and/or when the high cliffs up river were thawed sufficiently to be effectively wind eroded.

Type and amount of deposits on such levees are variable. Figure 52 shows a snowbank topped with organic matter whereas figure 50 shows a layer of wind-blown sand which ranges in thickness between 10 and 15 cm on top of a 1 to 2 m thick snow cover which itself is on top of a natural levee.

The melting rate of snow which is covered with wind-blown sediment varies with the thickness of the "insulating" layer along with other factors. As the snow melts, the mineral and organic layer on the surface is gradually lowered to a solid surface beneath (Fig. 54). This solid surface may temporarily be tree branches or grass (Fig. 53). Also, the sediment deposited on the snow retains its form until rain or the new season's vegetal growth alters or masks it, often long after the snow has melted.

Ice

Ice, like snow, serves during much of the year as a protective blanket over all water in both deltas.

Fig. 50. Clean Snow Overlain by Sand (B3-54, Blow).

Fig. 51. "Snow Fence" (B3-54, Blow).

Fig. 52. Organic Debris on Snow (B3-54, Blow)

Fig. 53. Sand Temporarily Lodged on Willow Branches (C4-33, Colville).

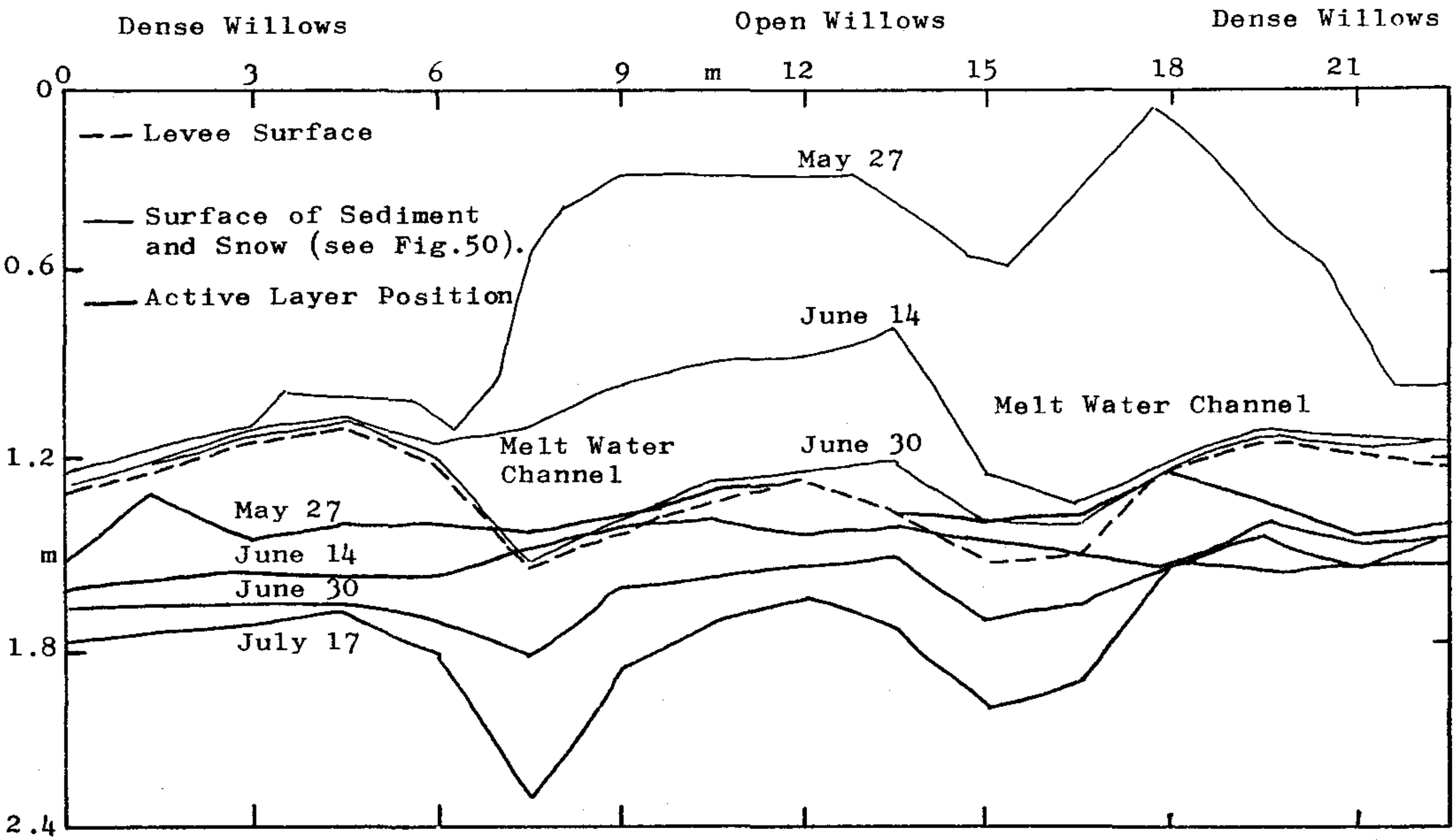


Fig. 54. Snow Melt and Development of Active Layer, 1967, Blow River Delta (B3-54).

In the deep channels and lakes (over 2 m, or so) it will have water beneath whereas in shallow bodies of water it will be bottom fast.

When water begins to accumulate in spring and flow seaward, deep-water ice will float whereas bottom-fast ice will serve as a temporary riverbed for the new season's flow. Floating ice fluctuates up and down with changing stage.

During this period of time ice has little effect except that it protects the bed from fluvial action where bottom fast, helps increase the stage by an amount equal to the volume of the channel occupied by ice and serves as a base upon which sediment might be deposited. Observation suggests that the ice floating in the deep portions of channels has relatively little effect on riverbanks even though it does move up and down with changing stage. Banks at this time are protected by snow drifts which apparently absorb much of the action.

Thus, during all but a few days, ice itself is more or less a passive agent. It is not until downstream movement begins that it becomes an active agent at which time it may be effective in erosion, transportation and deposition.

Although there is a tendency to think of ice primarily as a powerful eroding agent, its actual role in delta alteration is highly variable. One of the most important factors affecting the amount of actual erosion and deposition is whether breakup occurs on a rising or falling stage. Ice in rivers of the Arctic Slope forms at a time when the stage is at or very near its lowest annual level. Thus, river ice is confined to a relatively narrow portion of the river.

At the time ice begins to move oceanward it tends to follow the thread of current. However, there is some spreading of the ice to the more shallow portions being flooded at the time. If breakup occurs on a rising stage shallower portions can accommodate floating ice such that it can be carried seaward without much grounding. At bends in the river, even on a rising stage, ice jams do occur. However, when a normally rising stage is coupled with the rise in level caused by the ice dam, blockages are not frequent nor long-lasting.

Erosion by ice under such conditions tends to be minimal. On steep banks -- some of which may still possess a snow cover -- ice action may not be severe. It appears that on rising water banks are only rammed in connection with the then relatively rare ice jams.

If, on the other hand, breakup occurs on a falling stage, both erosion and deposition are likely to be somewhat greater than otherwise. Ice which has been moved from the main channel where it formed the previous winter to shallower areas may become stranded on sandbars and mud flats (Fig. 55). Such stranding especially when it occurs on point bars and therefore near bends in the river frequently results in ice jams that become quite severe. Although these jams are eventually flushed out by the rising water behind they frequently result in ice being forced over banks causing some bank modification (Fig. 56). Ice in moving onto or over point bars results in shoving and gouging. However, if it becomes stranded, it can protect inner parts from ice shove by smaller pieces. Minor derangement of the surface by ice shove is illustrated in Figure 57 where the meter-thick block of ice shoved a 10 cm layer of gravel into a ridge.

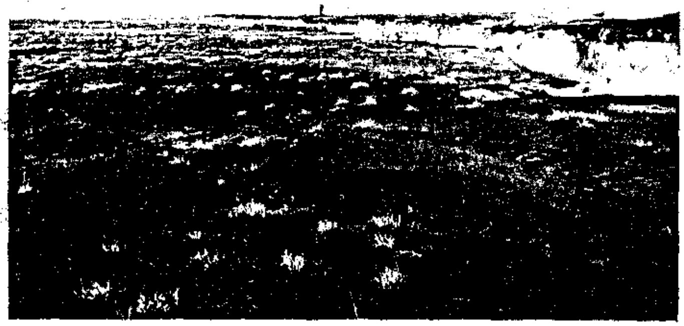


Fig. 55. Large Mass of River Ice Stranded on Sandbar (Colville).

Fig. 56. Ice Shove (Colville).

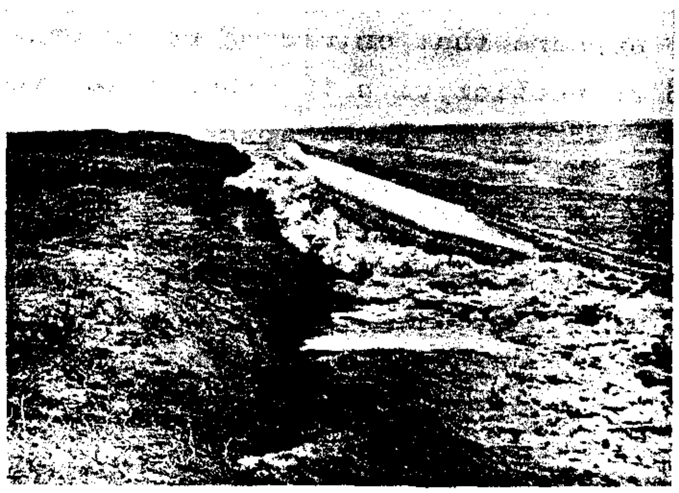


Fig. 57. Ice Shove on Gravel Bar (Blow).

Such ridges, even though small, will affect the flow characteristics of the river, once the ice has melted.

In addition, ice is frequently forced into lakes, old river channels and onto other relatively low lying but river connected areas. When melted, stranded blocks leave whatever material (organic or inorganic) they had been carrying. These materials range widely in quantity, size and type (Figs. 58 and 59).

Those areas upon which ice is stranded are modified not only by the addition of material carried by the ice but also by the fact the ice remains in place until it melts which may be several weeks after it is stranded. The surface is kept wet by the meltwater which in turn flows over the surface transporting some sediment from the bar to the river. Ice, in preventing bars from drying as soon as they otherwise might, delay their possible use by aircraft.

Often incorporated in the ice is debris (Fig. 60) which, when forced along a surface, acts as an eroding agent. Tree trunks or boulders, for example, frequently leave tell-tale traces on the surface over which they have been moved by floating ice (Fig. 61). Such microfeatures are more common in the Blow than Colville. Ice blocks which have formed near riverbanks or which when moving jam against banks frequently carry material that has fallen on them. Most of the larger pieces of vegetation are willows in both rivers although also common are alder in the Blow and cottonwood in the Colville.

During the relatively short period of breakup thermoerosional niches (see below), initiated prior to breakup, continue to develop. However, it is unlikely that floating ice itself has any direct effect upon their formation. Indirectly, as when jams cause a variation in stage, ice will influence the development of niches.

Fig. 58. Ice-Transported Debris (Colville).

Fig. 59. Ice-Deposited Debris (Colville).

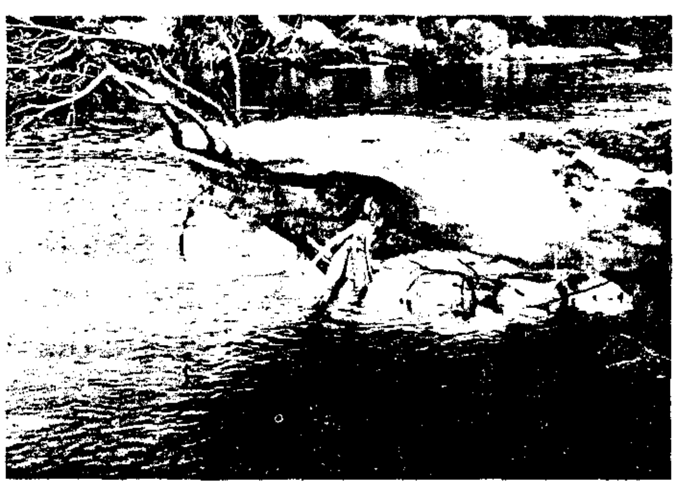


Fig. 60. Debris Incorporated in Ice Block (Blow).

Although the major ice action is the result of the movement of winter ice, it is also possible to have, as happened in both the Blow and the Colville in 1967, new ice forming after meltwater has begun to accumulate or even after breakup (Fig. 62).

Water

By the time meltwater begins to accumulate on the river ice many of the bars and flats of the delta are free of snow so that most of the meltwater comes from the melting of the snow on the ice itself, snowbanks along the river and from snow on the tundra surface. The first meltwater to accumulate is quite free of sediment. For example, water collected at the Colville 12 hours after it began to accumulate on the ice, contained only 19 ppm of suspended inorganics (5). Winter eolian deposits of mineral and organic matter on the snow are normally not great. The erosive and transportive effect of this initial meltwater is thus minimal. Indeed, at first it only accumulates on the ice and possesses no measurable flow downstream.

However, once melting increases and water begins to flow from dunes or tundra and across mud flats the suspended load increases rapidly. If snow drifts are thick, meltwater usually flows in channels beneath the snow. Sheetwash from the base of the drifts is also common (Fig. 63). Meltwater itself helps increase the thickness of the active layer making sediment available for transport. Water flowing from higher surfaces not only carries sediment to the channel but also deposits some at the break in the slope. Fans are often formed on top of snow, river ice and flats (Fig. 64). As they

Fig. 61. Gravel Bar Scour Trails (Blow).

Fig. 62. Late Spring River Ice (Blow).

Fig. 63. Meltwater Erosion on Mud Flat (Colville).

usually form at levels below that of the maximum flood stage they are features which are later altered by the river itself. These ephemeral forms have a very complex history. Meltwater erosion and deposition, river erosion and deposition and ice erosion and deposition when combined with the tenuous positioning of these deposits on snow, ice, mud flat or sandbar at the base of riverbanks result in very rapid and drastic changes in portions, if not all, of these structures.

However, occasionally these forms remain through one or more seasons depending primarily on the flooding characteristics of the river. The sediment deposited on top of the snow or ice may at times become very thick and protect the snow or ice beneath for varying lengths of time and in some instances late into summer.

Meltwater accumulating on top of river ice increases in depth at a rate dependent upon the rate of snow melt. Eventually a depth sufficient to initiate flow downstream on the ice surface is reached. In the Colville depths as much as 0.5 m of meltwater accumulate without perceptible flow. In moving downstream water first flows against snowbanks which it begins to melt and erode. In the banks a thermoerosional niche is begun. Because at this initial stage it is snow into which the flowing water is eroding, little sediment enters the stream.

Snow may protect river forms during the early erosional period where it occurs in deep drifts. Figure 65 shows a chute cutoff in the Blow delta (B3-79) in summer at a low stage. Figure 66 shows the same cutoff protected by a snow plug which effectively blocked the cutoff during prebreakup and breakup flooding.

As the stage continues to rise, water flowing on top of the ice begins to flow over exposed sandbars and mud flats and against the riverbanks which by this time

Fig. 64. Sand from Sand Dune Deposited on Snow and River Ice by Melt Water.

Fig. 65. Chute Cutoff in Summer (B3-79, Blow).

Fig. 66. Chute Cutoff Protected by Snow.

are usually snow free. The sediment load of the river then begins to increase. Prior to this type of flooding virtually all sediment in the river came from that contributed by meltwater. The only portion of the river in which such erosion can occur during the early stage is that portion where ice is not bottomfast. Those portions of the channel over 1.5 m deep in the Blow River and 2 m in the Colville at the time of freezeup would likely fit these conditions. However, these channels are adjusted to high velocities and thus could contribute relatively little sediment to the initial prebreakup flooding. Sediment that had been deposited in the deep channels during late fall and winter would be rapidly flushed out.

As water level continues to rise the ice over the deeper channels and pools floats whereas water flows over the bottom-fast ice which in the process is eroded from the top. Floating ice, on the other hand, is eroded from the bottom. Both are reduced in thickness as a result of this erosion.

This initial prebreakup flooding and its accompanying erosion and deposition may be highly varied in character and duration. Figure 18, which shows the variation in stage for several seasons at the Colville, suggests the variety that might occur. The stage may rise more or less steadily (1964), it may rise and fall once or more times (1962) or it may rise and refreeze (1967). Further, the rate at which the stage varies and the temperature and the velocity of the water all affect both erosion and deposition.

Thermoerosional niches which are initiated in snowbanks, as in the case of some of those in the Blow delta in 1967, may not be deepened sufficiently to reach the mineral or organic banks beneath although they may be sufficient to cause collapse of the snow (Fig. 15). If continued a niche forming in a snowbank will eventually begin to form in the riverbank. The relatively-warm, moving water, by thawing the frozen bank and removing the loosened material, gradually deepens the niche. The bank above remains in the frozen state. The character of the niche, whether shallow or deep, narrow or broad and whether single or multiple (Fig. 67) depends primarily upon the way the stage varies. Thermoerosional niches, which are usually initiated during prebreakup flooding, normally continue to develop during both the breakup and postbreakup periods.

During prebreakup flooding deposition also may occur especially if the period of flooding is accompanied by any alternations of rising and falling water. On dropping stage deposition occurs on top of the ice, snow, sandbars, mud flats and riverbanks over which the water may be flowing (Figs. 68 and 69). The amount of deposition varies greatly and thicknesses of as much as 10 cm have been recorded in favorable locations in the Colville.

The sediment deposited on bottom-fast ice may eventually be brought to the surface and carried seaward on the ice during breakup (Fig. 70). It also has an effect on the bouyancy of the ice on which it is deposited, delaying in some cases the time of release of the bottom-fast ice. Indeed, under certain circumstances layers of sediment (they may be the result of a combination of melt-water and river deposition) protect and preserve bottom-fast ice. In 1966 at Putu in the Colville delta such protected ice was gradually melted and eroded by the river from the side over a period of six weeks. None of it actually floated to the surface.

The sediment thus deposited may later be re-added to the river's load if ice in floodwater or floodwater

Fig. 67. Multiple Niches (Colville).

Fig. 68. Sediment Deposited on Snowbank (Colville).

Fig. 69. River Deposits on Snow (Colville).

Fig. 70. Deposits on River Ice (Colville).

itself reclaim it to be carried further downstream or on into the ocean.

During this period of time sediment is deposited on both lake ice (in the case of those lakes connected with the river) and sea ice. The first flow results in little deposition on the ice of lakes and ocean (Fig. 71) whereas later flow can deposit great amounts of sediment on such ice (Fig. 72). Because of the dispersive action of water as it flows in over lake ice and out over sea ice, much sediment is deposited on the ice in both situations. In the case of lakes where the ice melts in place sediment is eventually added to the lake bottom. In the case of the ocean where at least some of the ice is carried away from the delta front during the breakup of the sea ice sediment is lost to the delta. This may occur as much as a month after breakup in the river.

During breakup the erosional, transportational and depositional characteristics of water continue although they are affected to some extent by the movement of the ice. Often the most important effect floating ice has is indirect, i.e., through its control over stage and velocity. Ice results in raising stages and sometimes causes very rapid flow in temporary channels around the ice dams. This higher-than-normal flow is felt downstream from the ice dam once the dam breaks as happened in 1966 in the Colville. Erosion of the riverbank may be relatively rapid under such a situation but usually such concentrated erosive power is very limited in duration. Ice dams often cause the highest stages in the year in localized areas and despite relatively short duration often result in comparatively large amounts of erosion in such locations.

Once ice is removed from the river, the action is again mainly that of water, water that normally is at a higher temperature even if not at a higher stage or velocity than it was before breakup. Because the ice, which formed a portion of the volume of the river, is no longer present the actual quantity of water needed to result in stages as high or higher than those of the prebreakup and breakup periods must be greater.

The period of postbreakup flooding is considered to last until a more or less stabilized summer flow is attained. The duration of this period may vary greatly as discussed in Chapter II. Generally, there will eventually be a decrease in stage after breakup (as snowmelt becomes less significant) and it is the action occurring during this period of time that rounds out "spring" activities.

For the most part, the processes which originated in the prebreakup and breakup periods are continued and may become even more effective. Floodwaters deepen thermoerosional niches and at an increased rate because of the higher temperatures of the river water. Those banks from which the snow has been removed, and by the time breakup occurs nearly all are snow free, are actively sloughing into the river beneath. The conversion of nearly vertical banks into sloping banks is initiated. Those banks which are nearly vertical during this period of time slough relatively evenly so long as sloughed material is removed from the base of the banks. While the river is at such a level, the thermoerosional niche deepens at a faster rate than the bank face retreats.

Once the river begins to subside, the niche, along with the exposed bank, is subjected to the agents of air and gravity only. Thaw is quite rapid and sediment dropping from the roof of the niche rapidly accumulates on the floor (Fig. ~3). Because of the lowered stage, material from the cliff face begins to pile up at the base of the bank and gradually seals the mouth of the niche itself (Fig. 74). The rate of sealing of niches depends on several factors. In all but the widest it occurs within a few days after the river level begins to drop. Thus, such niches are hidden from view often by the time it is possible to get out onto the river in boats.

As the mineral matter beneath the tundra surface thaws rapidly there are frequently large peat or turf cornices left. These eventually break and roll downslope to be added, usually as blocks, to the accumulation at the foot of the slope. As this material begins to collect, the rate of thaw of the surface decreases near the base while continuing above. This process continues until an angle of repose is established consistent with the nature of the material. Thus, at the base of these slopes, relatively thick layers (often sealing a niche) have accumulated. This material gradually thins upward. Beneath this layer the non-sloughed portion of the bank is thawed to various depths.

In those cases where the bank is not high, the overhanging tundra mats which are often held together by the roots of trees and shrubs, do not break completely loose. Instead they bend down usually forming a cavern beneath. These mats form a rather continuous and still growing vegetation surface which often extends from the tundra surface to the water. They also protect the mineral portions of the banks beneath from the erosion they would be subjected to if exposed directly to flowing river water. Portions of the hanging mats, if hanging into water at the time of freezeup, become incorporated in the ice and are torn out at the time of the next breakup.

Fig. 71. Air View of Sea Ice with Clear Meltwater from Initial Flow (Colville).

Fig. 72. Deposits on Lake Ice as Result of River Floods (D4-65, Colville).

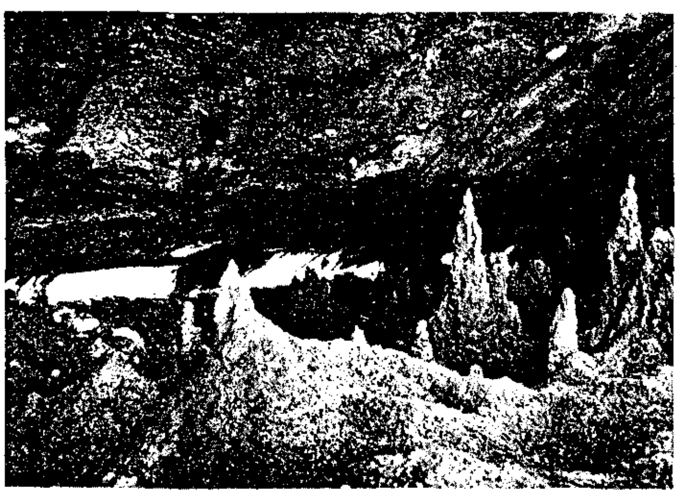


Fig. 73. Roof and Floor with Accumulating Sediments in Thermoerosional Niche (Colville).

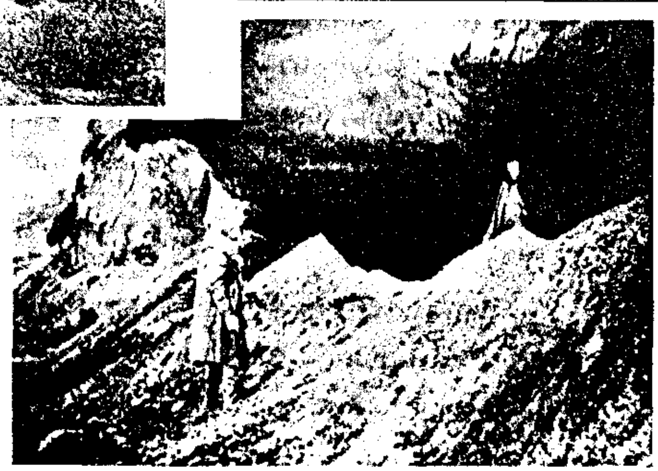


Fig. 74. Mouth of Thermoerosional Niche Nearly Sealed (Colville).

Although most mineral banks retreat by sloughing, there are exceptions. A much more spectacular type of retreat results when the undercut bank collapses. All major collapse thus far observed has occurred shortly after the level of the river has receded. At the time water level recession begins the thermoerosional niche has its greatest depth and the weight of the overhanging block will be at a maximum.

Collapsing blocks are especially common in mineral banks and may in theory be of almost any size and shape (Fig. 75). Shape depends partly on those factors which control the lines of weakness along which the blocks break. Many of the fractures occur along ice wedges. Wedges were not observed in the exposed banks of the Blow River and apparently exert little control on collapse of levee banks.

Banks of peat react in quite different fashion. Their verticality continues through the year. There is some undercutting but observation shows that the niche is usually quite narrow (Fig. 76). Collapse, when it does occur, results mainly in only a slight tilting of the block. A further and more striking contrast results from the different rates at which ice wedges and the peat areas between erode. In mineral banks the rate of thaw of the frozen sediments is about the same as that of the ice wedges. In peat banks, however, ice wedges retreat rapidly in comparison with the retreat of peat blocks. Isolated peat blocks, from around which the ice wedges have been eroded (by river water) and melted, are numerous (Fig. 77).

In sand dunes, in which ice wedges do not develop to the extent they do in banks composed of finer sediments or organic matter, collapse is usually much more irregular

Fig. 75. Collapse of 8-m High Bank, 1962 (B7-32, Colville).

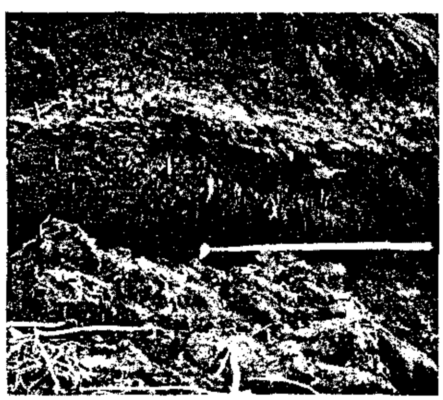


Fig. 76. Narrow Niche in Peat Bank (C1-22, Colville).

Fig. 77. East Bank of Colville Illustrating Forms Resulting From Differential Erosion.

in both shape and size. Low banks as at the front of the delta are eroded more in the fashion of those of temperate deltas. The active layer may be sufficiently thick and the vegetal binding sufficiently fine so that small block collapse is common (Fig. 78).

Two facts especially stand out about bank erosion in arctic deltas. First, the recession of highly mineralized riverbanks is frequently rapid. Second, the bulk of the activity accounting for this erosion occurs during a two-to-three-week period.

Deposition during postbreakup flooding is also a continuation of that prevailing during prebreakup and breakup periods. It may not be quite so erratic as during breakup when floodwater may be raised quite high due to ice damming and thus backed into areas it would not otherwise reach. These areas act as settlement basins and because the sediment load is high have much deposition. During postbreakup flooding, connected lakes continue to receive large amounts of sediment. Some sediment, of course, is carried out to sea and deposited at the front of the delta.

The amount of tree or shrub remains found stranded in the delta is greater in the Blow than the Colville. Most trees are found deposited in such a manner that their roots face upstream. Smaller debris captured by the larger mass is usually found lodged horizontally. The factors governing the location of these masses include river stage, depth of the debris mass occurring below the water surface when floating, current velocity, current direction and ice shove.

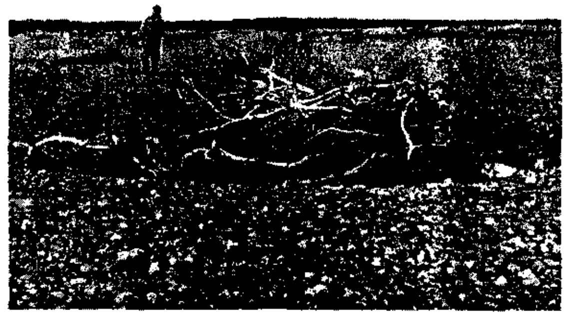
After large debris masses are deposited on bars, scouring action often occurs. These forms are more numerous and better developed on bars in the Blow than in the Colville delta. Around the masses scour forms vary from rather symmetrical, horseshoe-shaped features which have scour holes at the heads of their vegetal masses to very unsymmetrical scour forms with linear scour trenches along one side or without accompanying scour holes at the front (Figs. 79 and 80).

Wake-zone deposition proceeds with scour and may be finer gravel in the case of the upper-delta forms in the Blow delta and sand and silt in the case of Colville and the lower Blow forms. Some of the debris masses have been surrounded to such depths by subsequent deposition that their tops are little higher than the rest of the bar. They also serve as locations where willows and other vegetation forms can grow (Fig. 27).

Deposition occurs on tussock flats (Fig. 31), in areas where counter currents occur (Fig. 81) and at the exit of chute cutoffs. As chute cutoffs tend to widen downstream, they normally have an increasing thickness of sediment in that direction. After the water lowered from its highest stages in 1967 in the Blow River all large accretionary channel features observed had lee-side counter-current patterns. In the Blow in 1967 these sediments varied in depth up to 15 cm. They possess microfeatures such as polygonal frost-cracks which result from freezing of the thin layer of recent sediment.

Fig. 78. Bank Collapse Along Low Banks (Blow).

Fig. 79. Horseshow Type Scour Feature (Blow).



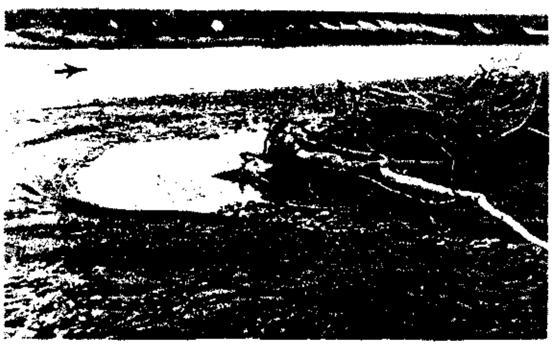
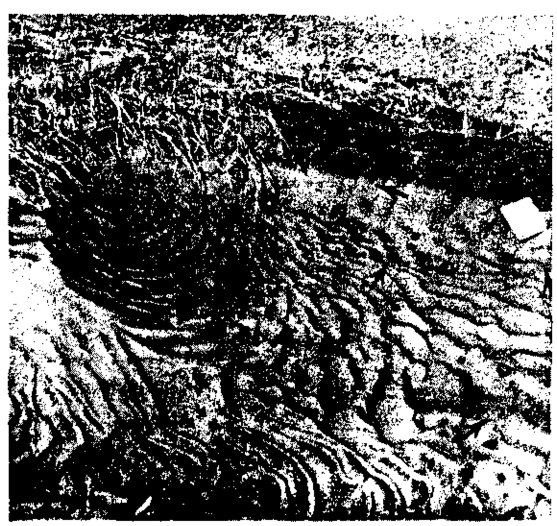


Fig. 80. Nonsymmetrical Scour Feature (Blow).

Fig. 81. Counter-Current Forms (B4-55, Blow).



V. SUMMARY AND CONCLUSIONS

Several seasons of field work conducted along the arctic coast since 1961 have provided information about the hydrologic-morphologic character of arctic rivers and their deltas. Most of the field work has been concentrated in two deltas; one, the Blow, a small delta in Western Canada (1967); the other, the Colville, a moderate-sized delta in Alaska (1961, 1962, 1964, 1966 and 1967). One of the major objectives of this work was to gather information on the type and rate of change in form that occurs during the hydrologic year.

The drainage basins of the Blow and Colville Rivers are confined to the Arctic Slope and are characterized by arctic conditions most of which have a bearing on morphologic change. Low temperature, characteristic of the area even in summer, is reflected in the presence of continuous permafrost, a thin active layer, tundra vegetation, a long-lasting but thin snow cover and a frozen-state of all surface water for approximately eight months.

The deltaic portions of the Blow and Colville Rivers consist of a variety of forms including distributaries, gravel- and sandbars, mud flats, various sized lakes, sand dunes and ice-wedge polygons among others. Distributaries cut through a variety of inorganic materials which range from the boulders and gravels of bars and former channels through sands to the finer sediments associated with mud flats and eroding lake basins. Also present are banks composed of thick layers of dense peat in which large ice wedges are common. The banks themselves vary in height above river level from a few centimeters near the front of the deltas to several meters near their heads.

Based on the hydrologic sequence of arctic rivers, the calendar year can be divided into numerous distinct periods, periods which vary greatly in duration and in importance to morphologic change. The period centered around breakup is characterized by seasonally extreme conditions. It begins when meltwater accumulates on and flows over bottom-fast ice and under floating ice. The length of this period depends on several factors but especially on the time of the beginning of snow melt and the nature of temperature variations which lead to breakup. Next is breakup itself which, although lasting only a few days, is very important. Breakup is usually followed by a period of flooding. It is also highly variable in duration and depends upon the amount of snow left in the drainage basin and the rate at which this snow melts.

The combined duration of these three periods is only about a month. Yet, during that relatively short period of time, water and ice accomplish most of their season's work.

Although wind is present throughout the year, its effectiveness as an agent in morphologic change is reduced by the snow cover which blankets the surface for some eight months of the year. However, the effectiveness of wind is evidenced by the occurrence of sand dunes in the Colville delta and in the presence of extraordinarily high natural levees near the head of the Blow delta. Seasonal increments in some specific localities are frequently high, the amount depending upon such factors as the speed, direction and time of occurrence of wind. Much of that wind-blown material which is added each year is first deposited on snow -- especially toward the beginning and end of the period of snow cover.

Ice, like snow, is a passive agent during most of the time it is present. Its erosional, transportational and depositional effectiveness varies with river stage and especially with the nature and amount of fluctuation in stage during breakup. Locally, activity is frequently accentuated by ice jams which cause increased ice action and the raising of water level. Ice and therefore the sediment it is carrying is then carried to and deposited in parts of the delta it normally would not otherwise reach.

By far the most important agent in deltaic change is water which begins to operate once flow onto and over the ice is initiated and continues until flow ceases sometime during winter. Sediment carried by the river during the first part of the season may be deposited on sandbars, mud flats and on bottom-fast river, lake and sea ice. The sediment deposited on lake ice will be added to the lake bottom as the ice melts in place. That deposited on bottom-fast river and sea ice will be transferred when the ice itself is released from the bottom and moved downstream or away from the front of the delta.

Bank erosion is initiated as soon as the flowing water rises sufficiently to allow it to come in contact with the riverbank. As these banks are frozen two major processes operate; relatively warm water thaws and flowing water erodes and transports. These processes create a thermo-erosional niche the size and form of which depends on the nature of the materials in the bank as well as the variations in stage, velocity and temperature of the flowing water. Bank retreat results from both sloughing of bank materials and from bank collapse. Such collapse is often conditioned by the presence of ice wedges.

Morphologic change in arctic deltas, like most other physical and biologic change in the Arctic, tends to be concentrated in a short period of time and is frequently great. Although observations to date allow a general description of such morphologic change and permit a preliminary sequentialization of events, they are not sufficient for a refined quantitative presentation nor for the determination of precise cause-and-effect relationships. Such a presentation will only become possible with the collection of data on all of the variables which are involved directly or indirectly in determining the hydrologic-morphologic character of arctic rivers and deltas.

APPENDIX I. RIVER AND DELTA CHARACTERISTICS

	Drainage Area $km^2 x 10^3$	River Length km	Delta Area km^2	Avg. Daily Discharge $m^3/sec \times 10^3$	Tidal Range m
LARGEST					
Amazon	5778	6437	estuary	991	5.7
Congo	4014	4667	2072	396	1.7
Mississippi	3212	6260	26159	172	0.5
Lena*	3028	4828	25900	155	0.3
Nile	2978	6695	20228	28	0.5
Ob*	2914	4506	2849	125	0.7
Yenisey*	2699	3798	2460	174	0.4
Parana	2305	3219	3419	149	1.0
Yangtze	1942	4828	estuary	218	4.2
Amur	1844	2848	estuary	96	2.3
Mackenzie*	1805	4055	6527	79	0.4
OTHER ARCTIC RIVERS					
Kolyma	645	1250	3704	-	0.1
Indigirka	360	1790	9169	18	0.1
Colville	50	600	550	1±	0.5
Blow	4	110	50	-	0.4

*Arctic or subarctic

APPENDIX II. MEAN TEMPERATURE (°F) AND PRECIPITATION (mm)

	Barrow (15)* T	Barrow (15)* P	Barter Island (15)* T	Barter Island (15)* P	Shingle Point (5-10)* T	Shingle Point (5-10)* P
Jan	-16	4.5	-16	10.0	-17	4.5
Feb	-21	4.3	-21	8.7	-17	3.7
Mar	-18	2.7	-17	5.0	-12	7.0
Apr	- 1	3.0	- 1	13.7	2	9.0
May	21	3.0	23	5.7	24	8.2
Jun	34	9.0	36	13.2	42	14.0
Jul	40	19.3	41	22.0	51	31.0
Aug	39	22.5	40	25.5	47	37.6
Sep	32	16.0	33	23.5	36	26.8
Oct	16	12.5	17	21.5	16	25.6
Nov	- 2	5.7	- 1	10.0	- 3	6.0
Dec	-15	4.3	-14	10.7	- 8	2.7
Ann	9	107	10	174	14	176

*Years of record

APPENDIX III. SELECTED WATER SAMPLES - BLOW RIVER DELTA

Sam. No.	Location and Condition	Date (1967)	pH	Soluble Residue ppm	Cl ppm	Na, K Ca, Mg ppm
14	B3-56 (1)*	6/25	6.5	100	9	10
27	B3-56 (2)	7/10	5.5	64	14	8
24	B1-58 (3)	7/8	6.7	72	20	44
20	D7-56 (4)	7/5	6.3	4416	2118	1602
21	E3-57 (4)	7/5	6.5	5004	2269	1618
29	C9-66 (4)	7/11	6.2	3792	1860	1370
31	E2-41 (5)	7/13	6.9	108	25	15
16	D4-29 (6)	6/28	6.6	480	238	158
28	C7-61 (6)	7/11	6.2	256	121	87
30	D8-12 (7)	7/13	6.9	108	46	37
37	F8-10 (7)	7/19	7.2	2628	1321	1024

*Condition

1. River, falling stage
2. River, flood stage
3. Upper delta lake, not flushed
4. Lower delta lake, not frequently flushed
5. Lake, flushed by flood
6. Lake, flushed by sea
7. Ocean position, with floodwater from Mackenzie

BIBLIOGRAPHY

1. ABRAHAMSSON, K.V., 1966, Arctic environmental changes, Montreal, The Arctic Inst. of North America.
2. ABRAMOV, R.V., 1957, "Thaw-out niches," Priroda, Vol. 46, No. 7.
3. ARCTIC, DESERT, TROPIC INFORMATION CENTER, 1955, Glossary of arctic and sub-arctic terms, Maxwell A.F.B., Alabama, Research Study Institute.
4. ARNBORG, L., WALKER, H.J. and PEIPPO, J., 1966, "Water discharge in the Colville River, Alaska, 1962," Geog. Ann. Vol. 48, Ser. A.
5. ____________, 1967, "Suspended load in the Colville River, Alaska, 1962," Geog. Ann., Vol. 49, Ser. A.
6. AXELSSON, V., 1967, "The Laitaure delta - a study of deltaic morphology and processes," Geog. Ann., Vol. 49, Ser. A.
7. BENSON, C.S., 1968, "The seasonal snow cover of Arctic Alaska," Montreal, The Arctic Inst. of North America.
8. BILELLO, M.A., 1957, "A survey of arctic snow-cover properties as related to climatic conditions," SIPRE Report 39.
9. BLACK, R.F., 1954, "Precipitation at Barrow, Alaska greater than recorded," Trans. Amer. Geophys. Union, Vol. XXXV, No. 2.
10. ____________, 1956, "Permafrost as a natural phenomenon," The Dynamic North, II, No. 1.
11. BOSTOCK, H.S., 1961, "Physiography and resources of the Northern Yukon," Can. Geog. Jour., Vol. 43, No. 4.
12. ____________, 1965, Physiography of the Canadian Cordillera, with special reference to the area north of the 55th parallel, Ottawa, Geol. Surv. Canada, Mem. 247.
13. BREWER, M., 1958, "The thermal regime of an arctic lake," Trans., Amer. Geophys. Union, Vol. 39, No. 2.
14. BRITTON, M.E., 1957, Vegetation of the arctic tundra, Arctic Biology, 18th Biology Colloquium, Corvallis.
15. BROWN, J., 1966, "Ice-wedge chemistry and related frozen ground processes, Barrow, Alaska," Proc., Permafrost Internat. Conf., Washington, D.C.
16. ____________, 1967, "Tundra soils formed over ice wedges, northern Alaska," Proc., Soil Science Soc. of Am., Vol. 31, No. 5.
17. BROWN, R.J.F., 1957, "Observations on break-up in the Mackenzie River and its delta in 1954," Journ. Glaciol., Vol. 3, No. 22.
18. ____________, 1960, "The distribution of permafrost and its relation to air temperature in Canada and the U.S.S.R.," Arctic, Vol. 13, No. 3.

19. BROWN, R.J.E., 1966, "Influence of vegetation on permafrost," Proc., Permafrost Internat. Conf., Washington, D.C.
20. __________, 1968, Glacial map of Canada, Geol. Sur. of Canada, Publ. 1253A.
21. CODY, W.J., 1965, Plants of the Mackenzie River delta and reindeer grazing preserve, Canada, Dept. of Agriculture.
22. CONNOVER, J.H., 1960, Macro- and microclimatology of the Arctic Slope of Alaska, Natick, Tech. Rept. EP-139.
23. COOK, F.A., 1963, Permafrost as a geomorphic process, Ottawa, Nat. Res. Council of Canada, Tech. Memo No. 76.
24. __________, 1966, "Patterned-ground research in Canada," Proc., Permafrost Internat. Conf., Washington, D.C.
25. CRAIG, B.G. and FYLES, J.G., 1961, "Pleistocene geology of arctic Canada," Geol. of the Arctic, Vol. 1.
26. DREW, J.V. and TEDROW, J.C.F., 1962, "Arctic soil classification and patterned ground," Arctic, Vol. 15, No. 2.
27. FROST, R.E., 1950, "Evaluation of soils and permafrost conditions in Alaska by means of aerial photographs," St. Paul District, Corps of Engineers, Dept. of the Army.
28. GABRIELESE, H., 1957, "Geological reconnaissance in the northern Richardson Mountains, Yukon and Northwest Territories," Ottawa, Geol. Surv., Canada.
29. GAGLIANO, S.M. and McINTIRE, W.G., 1968, "Reports on the Mekong River delta," Baton Rouge.
30. GIDDINGS, J.L., 1947, "Mackenzie River Delta Chronology," Tree-Ring Bull., Vol. 13.
31. HAMILTON, T.D., 1965, "Alaskan temperature fluctuations and trends: analysis of recorded data," Arctic, Vol. 18, No. 2.
32. HARE, F.K., 1956, "The climate of the American northlands," The dynamic North, Vol. 1, No. 3.
33. HENOCH, W.E.S., 1960, "Observations of Mackenzie River discharge," Can. Geog., No. 15.
34. HJULSTROM, P., 1935, "Studies of the morphological activity of rivers as illustrated by the river Fyris," Bull. Geog. Inst., Uppsala, Vol. 25.
35. HOPKINS, D.M., 1949, "Thaw lakes and thaw sinks in the Imuruk Lake area, Seward Peninsular, Alaska," Jour. Geol., Vol. 57, No. 2.
36. JENNESS, J.L., 1953, "The physical geography of the waters of the western Canadian Arctic," Geog. Bull., No. 4.
37. JOHNSON, P.L. and KISTNER, F.B., 1967, Breakup of ice, Meade River, Alaska, Hanover, Special Rept. 118, CRREL.
38. KINDLE, E.M., 1920, "Arrival and departure of winter conditions in the Mackenzie River Basin," Geog. Rev., Vol. 10.

39. KINDLE, E.M., 1921, "Mackenzie River driftwood," Geog. Rev., Vol. 11.
40. LACHENBRUCH, A.H., 1962, Mechanics of thermal contraction cracks and ice-wedge polygons in permafrost, New York, Geol. Soc. America, Spec. Paper No.70.
41. ____________, 1966, "Contraction theory of ice-wedge polygons: a qualitative discussion," Proc., Permafrost Internat. Conf., Washington, D.C.
42. LEFFINGWELL, E. DeK., 1919, The Canning River Region, Northern Alaska, Washington, D.C., U.S. Govt. Print. Off.
43. ____________, 1919, "Ground-Ice Wedges," Journ. Geol., Vol. 23.
44. LEOPOLD, L.B., WOLMAN, M.G. and MILLER, J.P., 1964, Fluvial processes in geomorphology, San Francisco.
45. LIESKE, B.J. and STROSCHEIN, L.A., 1968, Radiative regime over arctic tundra, Washington, Sci. Rept. ONR.
46. MACKAY, J.R., 1957, "Notes on small boat harbours, N.W.T.," Geog. Paper No. 13, Ottawa.
47. ____________, 1961, "Freeze-up and break-up of the Lower Mackenzie River, N.W.T.," Geol. of the Arctic, Vol. 2.
48. ____________, 1963a, The Mackenzie delta area, N.W.T., Ottawa, Dept. Mines and Tech. Surveys, Geog. Branch Mem. No. 8.
49. ____________, 1963b, "Progress of break-up and freeze-up along the Mackenzie River," Geog. Bull., No. 19.
50. ____________, 1966, "Pingos in Canada," Proc., Permafrost Internat. Conf., Washington, D.C.
51. MACKAY, J.R. and STAGER, J.K., 1966, "The Structure of some pingos in the Mackenzie delta, N.W.T," Geog. Bull., Vol. 8, No. 4.
52. MACNAMARA, E.E., 1964, Soils of the Howard Pass Area, Northern Alaska, Special Report, The Arctic Inst. of North America.
53. McCLOY, J.E., 1969, Morphologic characteristics of the Blow River delta, Yukon Territory, Canada, Unpub. dissertation, Louisiana State Univ.
54. MARTIN, L.J., 1959a, Geology of the Mackenzie delta area, Calgary, Report for Petcal Ltd., No. 155.
55. ____________, 1959b, "Stratigraphy and depositional tectonics of north Yukon-lower Mackenzie area, Canada," Bull. Amer. Assoc. Petrol. Geol., Vol. 43, No. 10.
56. MULLER, S.W., 1957, Permafrost or permanently frozen ground and related engineering problems, Ann Arbor.
57. NICHOLS, R., 1953, "Marine and lacustrine ice-pushed ridges," Jour. Glac., Vol. 2, No. 13.
58. ____________, 1961, "Characteristics of beaches formed in polar climates," Amer. Jour. Sci., Vol. 259, No. 9.

59. NORRIS, D.K., PRICE, R.A. and MOUNTJOY, E.W., 1963, Geology of the Nörthern Yukon Territory and Northwestern District of Mackenzie, Ottawa, Geol. Sur., Canada, Map 10.
60. PAYNE, T.G., 1951, Geology of the Arctic Slope of Alaska, Washington, D.C., Oil and Gas Map OM 126, Sheets 1, 2, and 3.
61. PETTERSON, S., 1956, "Meteorology of the Arctic," The Dynamic North, Vol. 1, No. 2.
62. PÉWÉ, T.L., 1958, Permafrost and its effect on life in the North, Arctic Biology, 18th Biology Colloquium, Corvallis.
63. ___________, 1966, Ice-wedges in Alaska -- Classification, distribution, and climatic significance, Washington, D.C.
64. PORTER, S.C., 1966, Pleistocene geology of Anaktuvuk Pass, Central Brooks Range, Alaska, Tech. Paper No. 18, The Arctic Inst. of North America.
65. RICKERT, D.A., 1965, Pedological investigations of some aeolian deposits of northern Alaska, Special Report, The Arctic Inst. of North America.
66. RIKHTER, G.D., 1954, "Snow cover, its formation and properties," SIPRE Trans. 6.
67. RUSSELL, R.J., 1967, River and delta morphology, Baton Rouge.
68. SANTEMA, P., 1966, The effect of tides, coastal currents, waves and storm surges on the natural conditions prevailing in deltas, Dacca Symp., 1964, UNESCO.
69. SCHALK, M., 1957, "Relation of arctic storms to shoreline changes at Point Barrow, Alaska," Bull. Geol. Soc. America, Vol. 68, No. 12, Pt. 2.
70. SPETZMAN, L., 1959, Vegetation of the Arctic Slope of Alaska, U.S. Geol. Surv., Prof. Paper No. 302-B.
71. STEARNS, S.R., 1965, Selected aspects of geology and physiography of the cold regions, Hanover, Publ. 1-Al CRREL.
72. STEFANSSON, V., 1909, "Northern Alaska in winter," Bull. American Geographical Society, Vol. XLI, No. 10.
73. SUNDBORG, A., 1956, "The river Klarälven, a study of fluvial processes," Geog. Ann., Vol. 38, No. 2-3.
74. TEDROW, J.C.F., 1966, "Arctic soils," Proc., Permafrost Internat. Conf., Washington, D.C.
75. TEDROW, J.C.F. and CANTLON, J.E., 1958, "Concepts of soil formation and classification in arctic regions," Arctic, Vol. 11.
76. TEDROW, J.C.F., DREW, J.V., HILL, D.E. and DOUGLAS, L.A., 1958, "Major genetic soils of the Arctic Slope of Alaska," Jour. Soil Sci., Vol. 9.
77. VAN STRAATEN, L.M.J.U., Ed., 1964, Deltaic and shallow marine deposits, Amsterdam.
78. WAHRHIFTIG, C., 1967, Physiographic provinces of Alaska, U.S. Geol. Survey, Prof. Paper 482.

79. WALKER, H.J., 1967,"Riverbank dunes in the Colville delta," Coastal Studies Bull., No. 1, Baton Rouge.
80. WALKER, H.J. and ARNBORG, L., 1965, "Permafrost and ice-wedge effect on riverbank erosion," Proc., Permafrost Internat. Conf., Washington, D.C.
81. WALKER, H.J. and MORGAN, H.M., 1964, "Unusual weather and river bank erosion in the delta of the Colville River, Alaska," Arctic, Vol. 17, No. 1.
82. WALLACE, R.E., 1948, "Cave-in lakes in the Nebesna, Chisana, and Tanana river valleys, eastern Alaska," Jour. Geol., Vol. 56, No. 3.
83. WELDER, F.A., 1959, Processes of deltaic sedimentation in the lower Mississippi River, Baton Rouge, Coastal Studies Inst., Tech. Rept. No. 12.
84. WILIMOVSKY, N.J., Ed., 1966, Environment of the Cape Thompson region, Alaska, U.S. Atomic Energy Com., PNE-481.
85. WILLIAMS, G.P., 1957, An analysis of snow cover characteristics at Aklavik and Resolute, Northwest Territories, Ottawa, Div. of Building Res., Res. Paper No. 40.
86. WILLIAMS, J.R., 1955, "Observation of freeze-up and break-up of the Yukon River at Beaver, Alaska," Journ. Glaciology, Vol. 11.
87. WILSON, C., 1967, Climatology of the cold regions, Hanover, CRREL Publ. 1-A3a.
88. WILSON, J.T., 1946, "Geology of northern Canada," Canadian North, Chap. XIV.
89. WILSON, J.W., 1958, "Dirt on snow patches," Jour. Ecol., Vol. 46, No. 1.
90. WOLMAN, M.G. and LEOPOLD, L.B., 1957, River flood plains; some observations on their formation, Washington, U.S. Geol. Survey Prof. Paper 282-C.

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13. ABSTRACT

Morphologic change in the deltas of two rivers, the Blow in northwestern Canada and the Colville in Alaska, is described and analyzed. The drainage basin of each river is confined to the Arctic Slope and is characterized by arctic conditions. Morphologic change is the result of the integration of a variety of processes some of which do not operate in temperate or tropical deltas. Although ice, like snow, is a passive agent during most of the time it is present, its erosional, transportational and depositional effectiveness may be great. However, by far the most important agent in deltaic change is flowing water which begins to operate once flow onto and over the ice is initiated. Permafrost which is present except beneath the largest lakes greatly influences erosion. Bank retreat may proceed gradually or by the sudden collapse of blocks from banks which have been undercut by as much as eight meters. Morphologic change in arctic deltas, like most other physical and biologic change in the Arctic, tends to be concentrated in a short period of time, a period of time centered around breakup.

14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
Arctic						
Blow River, Canada						
Colville River, Alaska						
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Geomorphology						
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