Distribution and Character of Naleds in Northeastern Alaska

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ABSTRACT. Satellite imagery and high- and low-altitude aerial photography of the North Slope of Alaska indicate that naleds (features formed during river icing) are widespread east of the Colville River but less abundant to its west. Where naleds occur, stream channels are wide and often braided. Their distribution can be related to changes in stream gradient and to the occurrence of springs. Large naleds, such as occur on the Kongakut River, often survive the summer melt season to form the nucleus of icing in the succeeding winter. Major naleds also are likely to significantly influence the nature of permafrost in their immediate vicinity. A map of naleds may serve as a guide to sources of perennially flowing water.

RÉSUMÉ. *Répartition et caractéristiques des naleds dans le nord-est de l'Alaska.* Les indications transmises par satellite et les photos prises à haute et basse altitude au-dessus de la partie septentrionale de l'Alaska montrent que les naleds (monticules se formant au cours de la glaciation des rivières) se retrouvent en grande quantité à l'est de la rivière Colville, mais en petite quantité à l'ouest de la même rivière. Là où se forment les naleds, le lit des cours d'eau est large et souvent tortueux. La répartition des naleds correspond aux changements survenant dans la déclivité des cours d'eau et à l'apparition de sources. Les gros naleds, comme ceux qu'on trouve sur la rivière Kongakut, résistent souvent aux fontes de l'été et forment le noyau de glaciation de l'hiver suivant. Les plus gros naleds influencent probablement de façon significative la nature du pergélisol dans leur voisinage immédiat. Une carte des naleds pourrait constituer un guide des cours d'eau coulant en permanence.

Резюме. *Места образования наледи и ее характер.* Изображения, получаемые со спутников, и аэрофотосъемка северного склона Аляски с больших и малых высот указывают, что наледь /специфические формы покровов, образующиеся в процессе замерзания рек/ широко распространена к востоку от р. Колвилл и реже встречается у западу от нее. Наледь образуется в широких и часто разветвленных потоках. Распределение наледи может быть связано с изменением градиента потока и местонахождением родников. Наледь больших размеров, набюдаемая, например, на р. Конгакут, часто сохраняется в период летнего таяния и служит ядрамн, на которых начинается образование льда в последующую зиму. Крупная наледь, по всей вероятности, значительно влияет и на характер граничащей с ней многолетней мерзлоты. Карта наледи может использоваться как указатель источников постоянной проточной воды.

INTRODUCTION

"Icing" is a term which refers to the process of progressive ice growth or accretion on a frozen surface. It is imprecise in that it is also used to designate many other related phenomena. In reference to rivers, it has been used to designate both the process of ice build-up and the actual bodies of ice formed as a result (Carey 1973). The present authors prefer to use the term for the processes only. For the physical features formed they have chosen, notwithstanding the more common

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adoption of "icings" or "aufeis" in North America, to use the Russian term "naled" — in part because of the abundance of the literature on the subject which has been provided by Soviet writers.

Naleds occur when water repeatedly or continuously seeps from the ground, from a river, or from a spring, onto a land or ice surface during winter periods of subfreezing temperatures and freezes in successive layers (Carey 1973; Anisimova *et al.* 1973; Hopkins *et al.* 1955). Naleds may thus be genetically classified as ground-, river-, or spring-naleds, although most of them result from a combination of the three types of water seepage.

In some river basins in northeastern Siberia, naleds store up to 25-30% of the annual volume of river discharge and up to 60-80% of the subsurface drainage. Their size and location are determined by water source, hydrostatic head and geologic setting (Anisimova *et al.* 1973). Naleds commonly form year after year in the same locations, generally with the same shape and size. River flood plains are commonly widened due to spring floodwaters being forced to flow around them.

Two conditions must exist before icing occurs and a naled forms: first, a source of flowing water beneath a surface whose temperature is below 0°C, and second, a barrier to the flow of water that forces it to the surface. Such a barrier is commonly provided by the total freezing of the cross section of a river, by ground freezing, or by reduction in aquifer permeability due to permafrost or outcrops of impermeable strata (Sokolov 1973; Carey 1973).

River naleds develop after the formation of the seasonal ice cover (Carey 1973). If water remains unfrozen below the ice cover in the stream channel or in an alluvial layer above the permafrost or bedrock, it will continue to flow as long as water is supplied to the system. If flow is sufficiently restricted, as, for example, by a sudden change in stream gradient, or by a decrease in the permeability or thickness of the channel fill, water is forced upward over the river ice. Continuing or subsequent overflows cause sheets of fresh ice to form over the original naled surface. The total thickness may reach 5-6 metres under such conditions (Péwé 1973; Williams 1970).

The North Slope of Alaska is shown by Wahrhaftig (1965) to fall into three major physiographic provinces: the Arctic Coastal Plain, the Arctic Foothills Province, and the Brooks Range (see folded map). The Coastal Plain is a broad, flat tundra surface with numerous lakes which includes the deltas and streams draining the higher terrain to the south; west of the Colville River the streams are meandering, while to the east braiding is more common. The Foothills Province is characterized by rolling terrain with some bluffs along the river courses. Most of the known springs occur where river gradients decrease abruptly in this province. Both the Arctic Coastal Plain and the Foothills Province narrow toward the east, where the Brooks Range approaches the coast near the boundary between Alaska and Canada. The Brooks Range is the source for all of the major north-flowing rivers.

The seasonal freeze-thaw cycle controls the development and dissipation of river ice in northern Alaska. All of the rivers of the North Slope flow in the zone of continuous permafrost (Walker 1974). River ice forms during mid to late September, after mean temperatures have fallen below 0°C. By the end of December, when temperatures are often below −20°C, river ice is commonly more than one metre thick. Ice continues to thicken to a maximum of about two metres until May, when temperatures rise above freezing point and the melt season begins. During late May and early June, thawing proceeds rapidly, water begins to flow on top of the river ice, and eventually most of the latter breaks up and flows downstream (Walker 1974). During summer, temperatures are above freezing point and streams flow unimpeded by ice.

Although the existence of naleds on the North Slope of Alaska has been known for some time (Leffingwell 1919), regional mapping and seasonal monitoring of them have not been attempted. Naleds that appear to persist and continue to grow throughout the winter indicate the presence of usable fresh water sources (Hopkins *et al.* 1955). Considering that the present rapid development of the Arctic is occurring under conditions of scarcity of fresh water, knowledge of the distribution and character of naleds could have important implications. Construction projects such as roads are affected by both naturally occurring and man-induced naleds (Anderson *et al.* 1973), and potentially, any alteration of a balanced hydrologic-permafrost-geologic regime may induce naleds to form. The present paper constitutes a study of the distribution, longevity, and character of Arctic river naleds and speculates on their causes and effects.

METHODS

Images from the multispectral scanner (MSS) of the Landsat-1 satellite were used to delineate naleds over an area of the North Slope of Alaska and adjacent areas of Canada extending from the coast to about 200 km inland. They were received from late July 1972 through the fall of 1973 (except during the Arctic night (mid-October through late February). Thus, it was possible to monitor one seasonal cycle of river icing and to compare naled remnants found during August and September 1972 with those found during the same period of 1973.

The study area was fully scanned at 18-day intervals. Overlap of successive images often made possible three consecutive days of coverage of a given location. However, since delineation of ground features is dependent on the absence of cloud cover, the frequency of the observations was often limited by weather conditions.

Each image covered an area approximately 185 km square at a scale of about 1:1,000,000, one which made possible the clear identification of naleds larger than about 300 metres square. Smaller naleds were discernible when high degrees of contrast between ice and tundra, or water and snow, existed.

The MSS operated in four spectral bands: band 4, 500-600 nanometres (green); band 5, 600-700 nm (red); band 6, 700-800 nm (visible-near infra-red); and band 7, 800-1100 nm (near infra-red). One image was taken in each band for every satellite pass.

During the summer months, the greatest contrast between the naleds, the unfrozen channels and the surrounding tundra was shown on the images taken in bands 4 and 5, in which naleds appear white, channels and deltas are light-toned, and the higher ground a darker shade (Figs. 1a, d). During the winter, the

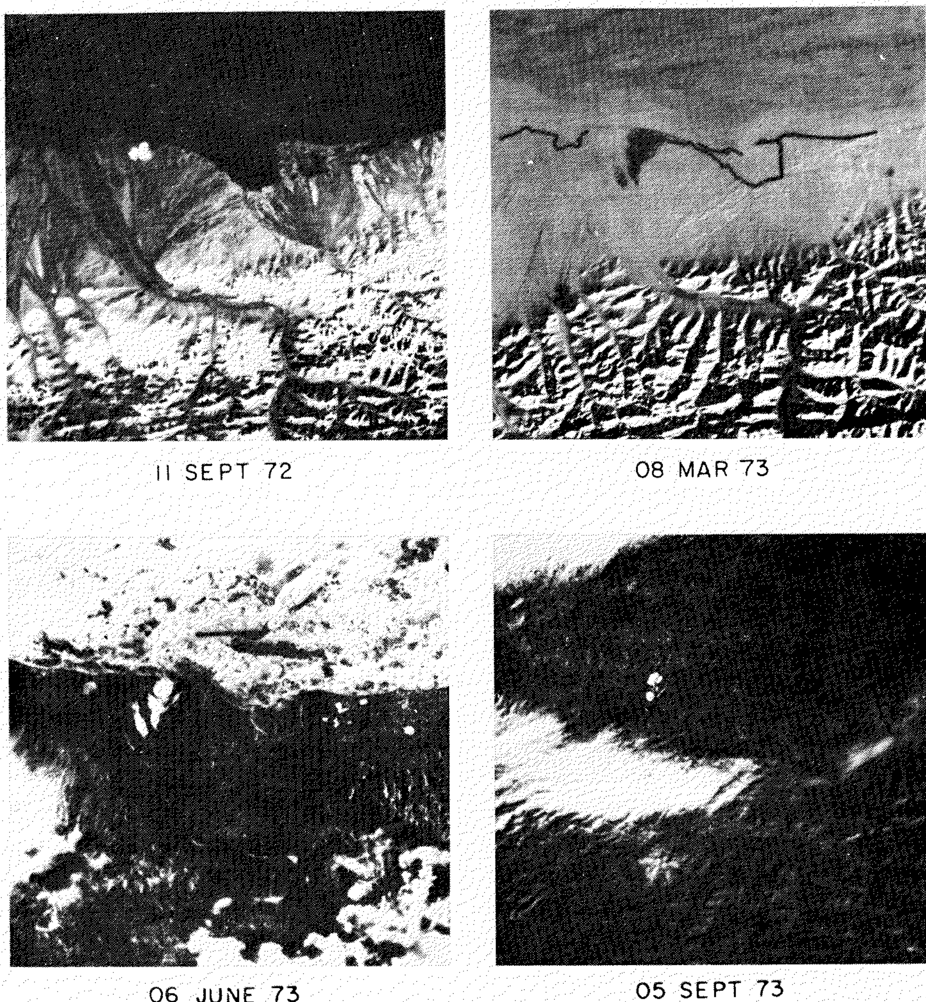


FIG. 1. Comparative satellite imagery of the naleds on the Kongakut River delta, (a) 11 Sept. 1972, (b) 8 Mar. 1973, (c) 6 June 1973, and (d) 5 Sept. 1973. Note that during the summer, naleds appear white on the darker tundra (a, c and d), but that in winter the naled is a dark feature against the snow background (b). Demarcation Bay (see Fig. 3) is about 10 km wide at its mouth.

greatest contrast between the naleds and the snow-covered tundra and stream channels was shown in the images of band 7 (Fig. 1b). In all the images, fresh ice or water appears dark and the surrounding terrain white, except where relief is sufficient to produce shadows.

Additional information was available from a high-altitude reconnaissance (U-2) flight carried out on 21 June 1974 (U.S. National Aeronautics and Space Administration (NASA) flight no. 74-101). On it a large-format aerial camera with colour infra-red film was utilized at an altitude of nearly 20,000 metres on flight lines north and south over the Sagavanirktok River and east and west across the middle of the Arctic Coastal Plain.

DISTRIBUTION OF NALEDS

River naleds detectable on Landsat-1 images obtained during last winter are shown in red on the folded map. A cursory inspection of images of the lower Colville River and streams to its west revealed almost no naleds, with the exception of a questionable one along the Ikpikpuk River (approximately 155°W), about 40 km from the coast. The upper reaches of the Colville River, which is the largest river in the study area, also have few naleds. East of the Colville River, naleds occur on most of the larger streams between the Anaktuvuk and Firth Rivers. They are most common where streams first leave confined channels at the base of the Arctic Foothills, and they are also common at the upstream ends of the larger deltas. Naleds are less common in the reaches between the foothills and the river mouths.

The downstream ends of naleds are diffuse and feathery, presumably because surface flow continues for varying distances after initial overflow to produce tails which may extend downstream for considerable distances, even to the next naled. For instance, along the Canning River, almost one continuous naled extends from the Brooks Range to within about 10 km of its mouth (see folded map and Fig. 2).

The distribution of naleds correlates well with that of the shallow reaches of braided streams (folded map and Fig. 3). The morphology of North Slope streams where icing occurs may be strongly influenced by the naled masses. They may be the cause or the result of braiding. During spring flooding and summer, the elevated surfaces of naled remnants may divert channels around ice patches, causing the channels to widen or new channels to form. Once formed, the new shallow channels readily freeze down to the bottom, creating conditions favourable to blocking streamflow and forcing overflow. Most of the braided sections of streams shown on the folded map are probable locations of recent or present-day naleds.

Naleds do not always cause stream diversion, as may be seen on low-altitude aerial photographs (e.g., Fig. 3), where channels which dissect naleds can be seen subsequent to spring flooding. Naleds on river deltas appear to be readily dissected by the seasonal river flow, although the location of the channels may differ from year to year (Figs. 1a, d; 4b, c). When floodwaters are high enough to overtop the naled, the flow seeks low areas in the ice mass, which then form the forerunners of dissecting channels.

A comparison of known perennial springs (Childers *et al.* 1973) with the sites of river naleds indicates a correspondence between them (see folded map). Naleds may therefore serve to indicate the presence of unmapped springs, especially in areas with no apparent upstream water sources (Williams and Van Everdingen 1973). Presumably, perennially flowing springs exist at, or upstream from, such naleds.

DEVELOPMENT OF NALEDS

Satellite images obtained between mid-September 1972 and the beginning of the Arctic night in late October do not indicate any new naled development. Many rivers were still flowing at that time, indicating that the basic requirements for naled development of an initial ice cover and a barrier to water flow had not yet been met.

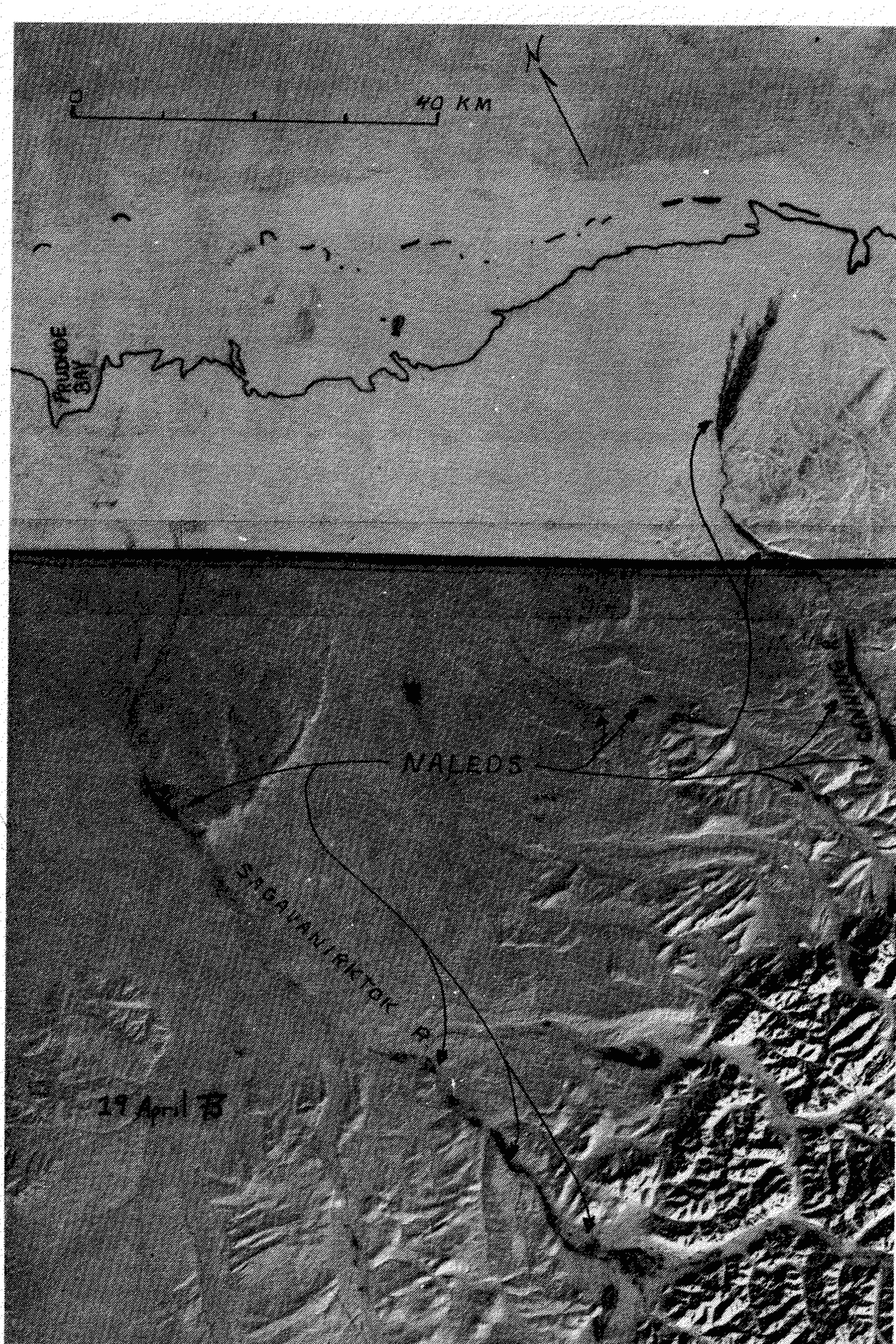


FIG. 2. Extensive naleds on lower Canning and Sagavanirktok Rivers, 19 April 1973. Landsat-1 images nos. 1270-21175 and 1270-21181, with coastline and offshore islands added. The naleds appear as darker areas of new ice formation in the river channels. The high relief feature, in the lower right belongs to the northern part of the Brooks Range.

During the period from the obtaining of the first images of 1973 in early March until spring break-up in June, many naleds increased in size. However, some apparently remained unchanged throughout this latter part of the winter, indicating that their water sources were cut off, greatly decreased in volume, or froze prior to March.

During the first week of August 1973, weather conditions permitted excellent coverage of most of the study area by satellite imagery. At this time, remnants

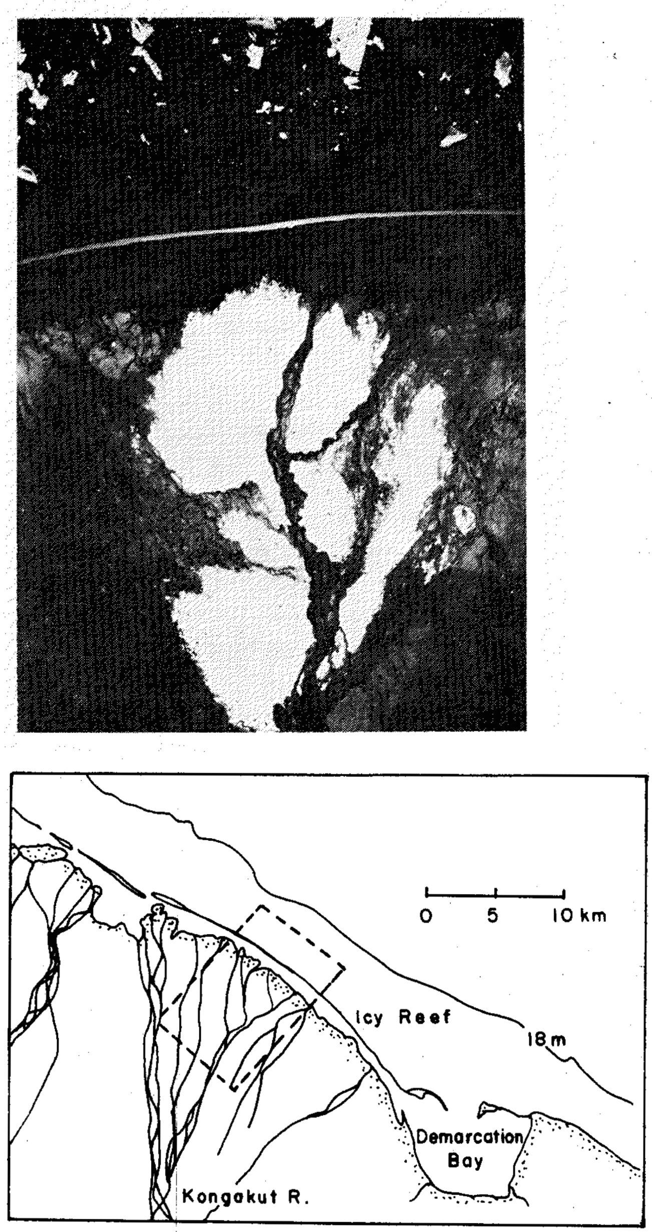
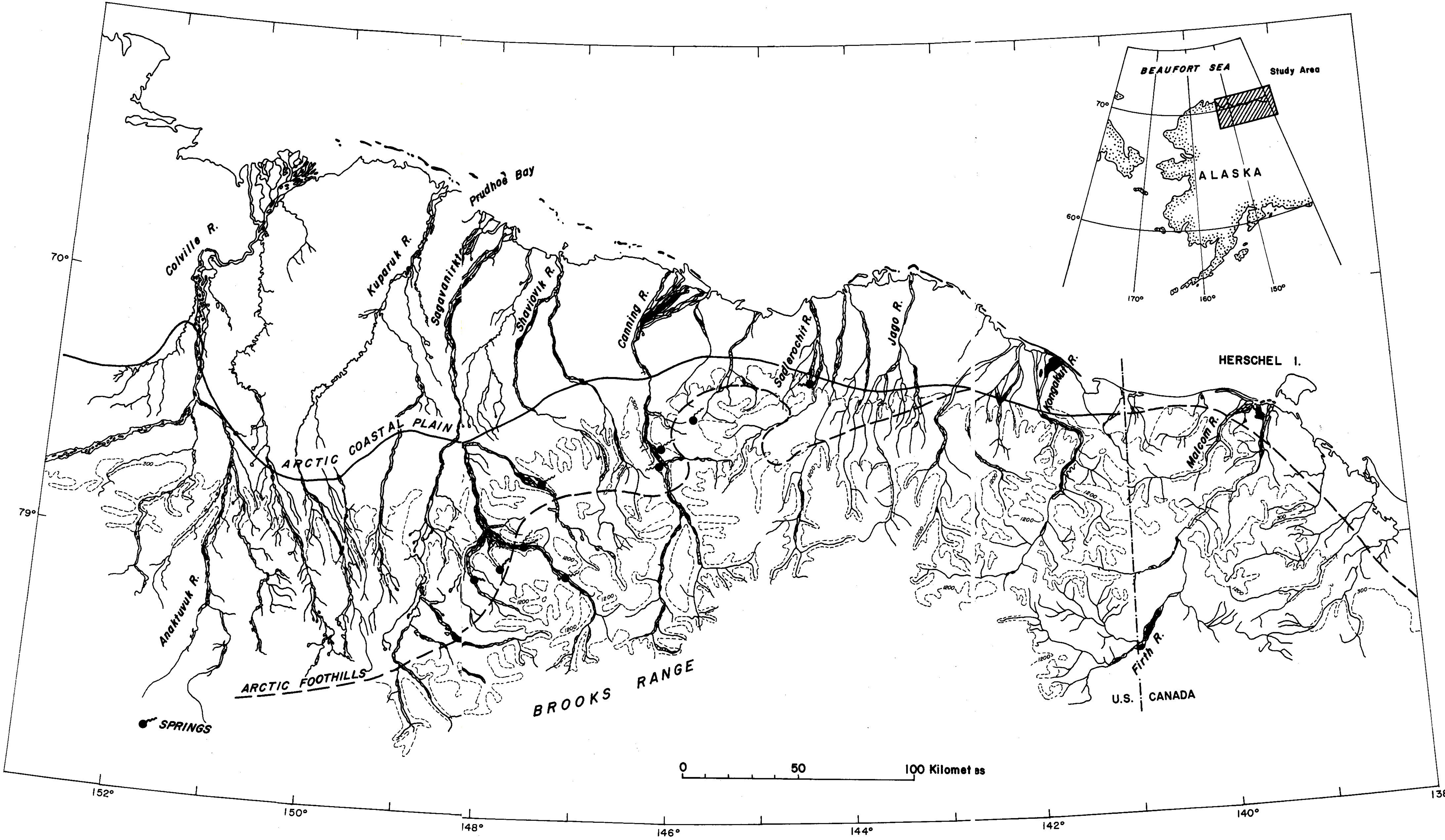


FIG. 3. **Naled on Kongakut River delta,** 2 August 1973 (photograph by courtesy of Andrew Short, Louisiana State University, Institute of Coastal Studies), with map of surrounding area. Scattered sea ice is present seaward of the barrier beach. Note the channels cut by the river through the naled, which apparently did not deflect the major river flow around its boundaries.



BEAUFORT SEA
Study Area
ALASKA
70°
60°
170°
160°
150°
Prudhoe Bay
Colville R.
Kuparuk R.
Sagavanirktok
Shaviovik R.
Canning R.
Sadlerochit R.
Jago R.
Kongakut R.
HERSCHEL I.
Malcom R.
Firth R.
ARCTIC COASTAL PLAIN
ARCTIC FOOTHILLS
BROOKS RANGE
Anaktuvuk R.
SPRINGS
U.S.
CANADA
0
50
100 Kilomet ers
70°
79°
152°
150°
148°
146°
144°
142°
140°
138°

of most of the larger naleds were visible. They were considerably less extensive than the winter naleds, and some undoubtedly melted before autumn freeze-up. Remnants of the largest naleds of the previous winter, such as on the Kongakut, Sagavanirktok and Canning Rivers, still existed in September.

It is probable that large naleds persist for more than one season under favourable conditions. Naleds also influence the ground temperature, permafrost, and channel form in such a way as to favour the continued development of naleds at the same locations. During the long summer days, when ground temperatures are raised and the surficial thaw layer is formed, much of the incoming solar energy is reflected from the naled surface. Therefore, ground temperatures would be lower, and the active layer above the permafrost thinner, in the immediate vicinity of naleds. This in turn would enhance icing in the same area during the following freeze season.

NALEDS ON THE KONGAKUT RIVER

Naleds on the Kongakut River (Kangikat on some charts) are particularly large and long-lived. The ice which builds up in the delta commonly extends into the lagoon seaward of the delta front and out to Icy Reef, a barrier beach (Figs. 1, 3 and 4). Such an interaction of river icing with a marine environment and delta front is unique along the Alaskan coastline.

Icy Reef was so named in August 1826, when numbers of the expedition under Sir John Franklin exploring the district encountered heavy ice outside the reef and had to drag their boats over the mudflats at the mouth of the Kongakut River to the lagoon (Leffingwell 1919). This circumstance apparently indicates that the name did not result because naleds extended into the lagoon at the time.

Naleds were present on the delta throughout the year of the present study (see Figs. 1 and 4). They increased in size over the period extending from sometime after September 1972 through March 1973 (Figs. 4c, d). During April and May, cloudy conditions prevailed during periods of satellite coverage. Beginning with the start of the thaw season in late May 1973, and continuing until mid-August, the naleds shrank to cover only about one tenth of their former extent (Figs. 1c, d; 4e, f, g, h). The delta naled apparently remained unchanged from mid-August to mid-September 1973 (Figs. 4a, b, h, i).

During the early months of 1973, the naled extended into the lagoon in front of the delta (Figs. 1b; 4c, d). An image obtained about two weeks after the initiation of river flow (Figs. 1c and 4e) in spring indicates that this naled remained in the lagoon through the flooding period. Field observations made during August 1972 and September 1973, as well as the images shown in Figs. 1a, d and 4g, h, i, indicate that no ice was present in the lagoon during these periods. However, images taken at low altitude in early August 1973 (Fig. 3) show naled ice on the delta front abutting the lagoon. In late August 1971, one of the present authors noted that there was ice in the lagoon behind Icy Reef, and according to another report (C.G.S. 1964), ice is commonly present in the lagoon behind Icy Reef throughout the summer.

A comparison of images obtained in mid-August and early September of 1972

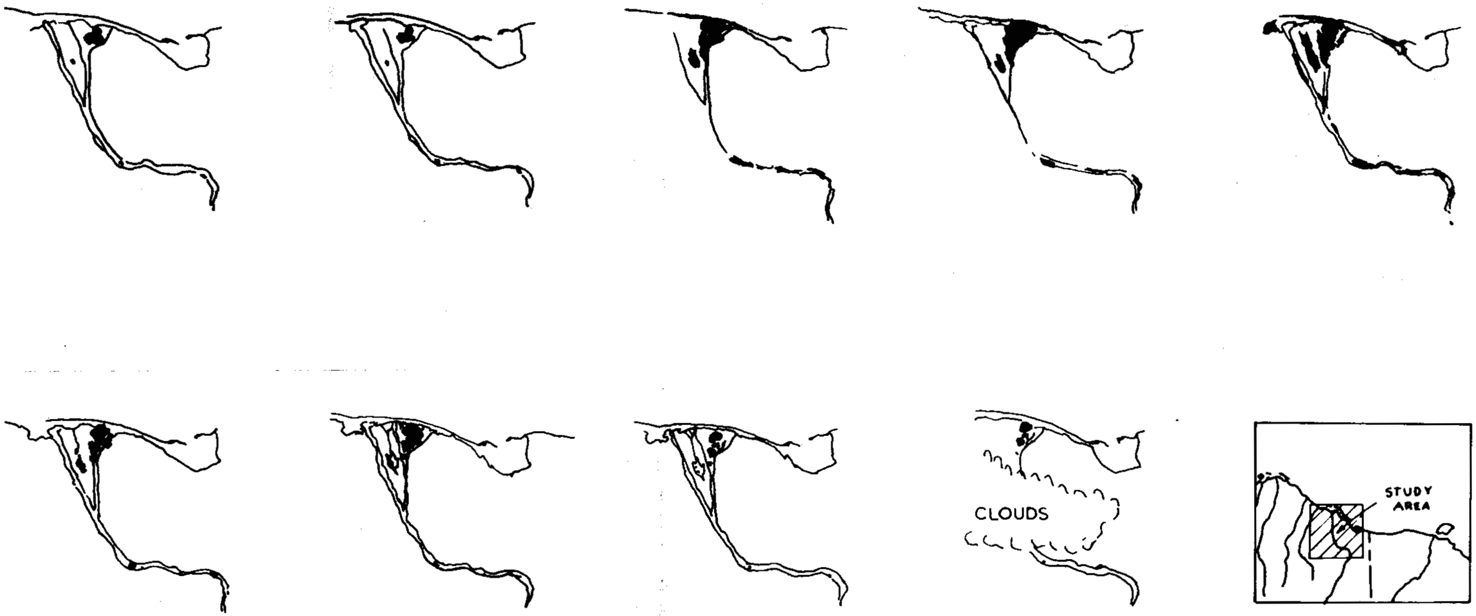


FIG. 4. Development and decay of the delta and lagoon naled on the Kongakut River delta. Landsat-1 images (top left to right) nos (a) 1308-20424 (22 Aug. 1972), (b) 1050-20541 (11 Sept. 1972), (c) 1228-20435 (8 Mar. 1973), (d) 2147-20493 (27 Mar. 1973), (e) 1318-20426 (6 June 1973); (bottom, left to right) nos. (f) 1356-20542 (14 July 1973), (g) 1374-20541 (1 Aug. 1973), (h) 1390-20434 (17 Aug. 1973), (i) 1409-20475 (5 Sept. 1973).

and 1973 reveals little difference in the size of the Kongakut River naled, although channel patterns on it differ somewhat (Figs. 1a, d; 4a, b, h, i). In years following extensive icing, the lagoon in front of the delta apparently remains ice-covered through the summer. The fact that naleds on the delta last through the summer also favours their development there during the succeeding winter.

Seeking a possible explanation for the presence of ice in the lagoon in summer, the present authors investigated the possibility that the coastline may have retreated very recently in the area of the Kongakut River, and that permafrost may be near the surface of the lagoon, thereby causing a lowering of the water temperature in it. A comparison of Leffingwell's (1919) map of the coastline, which is quite accurate in most areas, with modern maps suggests that such a retreat of the coastline may have occurred over a period of about thirty-five years. However, from a detailed examination of aerial photographs taken during the past twenty years, it seems that the early maps were erroneous and that the coastline is in fact rather stable.

It is apparent from the study of Landsat-1 images that river icing has an important influence on marine processes along the delta front of the Kongakut River. The naled which forms in the lagoon as winter proceeds would depress the floating lagoon ice which formed during the fall freeze-up until it rests on the lagoon bottom. The resulting ice mound (Fig. 4c) would form a barrier during spring flooding, when most of the water and sediment would be transported past the delta and lagoon over the ice mound to a point beyond Icy Reef. Since most of the stream sediment load is transported at this time (Walker 1974), the naleds have a significant impact on the sedimentation regime in the delta and lagoon.

CLIMATIC FACTORS

In order to assess the effect of weather conditions on the size of naleds, an analysis was made of data of monthly rainfall and snow accumulation for 1971, 1972 and 1973, as recorded at the weather station on Barter Island, located approximately 10 km west of Jago River (N.O.A.A. 1971-1973). Heavy summer precipitation would tend to promote icing during the following winter by creating an abundant groundwater supply. In contrast, the insulating effect of heavy snowfall during the early winter would decrease the growth rate of river ice cover, thus producing conditions unfavourable to icing. Heavy snow cover late in the winter may extend the period of icing by preserving lower temperatures in the ground; but according to Carey (1973), this insulating effect is less important than the incidence of rain and snow during the preceding summer and early winter.

During the two seasons studied, the influence of summer precipitation was apparently counterbalanced by the effects of snowfall. Precipitation was much greater than average during the summer of 1971, and below average the following summer season, and so groundwater conditions would have been more favourable for naled development during the winter of 1971-72 than in the following winter. On the other hand, snowfall was heavier during the early winter of 1971 than during the same period in 1972, and so the degree of ground insulation would have been less favourable to naled development in 1971-72 than in 1972-73. Finally, snowfall during late winter was greater in 1972 than in 1973, and so the period of icing would have tended to last longer in the former year.

Because of the contrasting and balancing climatic influences present during 1971-73, it is not possible to evaluate the impact of climate on naled growth on the basis of present information. There appears to have been no significant difference in the area of naleds remaining in the summer of 1973 as compared with that of 1972 (Figs. 1a, d; 4b, i). In order to assess the effects of the variability in climatic conditions, data for several more seasons would have to be studied. Furthermore, considering the abundance of springs in the Arctic, the influence of seasonal variation in precipitation patterns on spring and groundwater flow needs to be evaluated. Spring discharge may be relatively constant from season to season and from year to year because of reservoir storage. Furthermore, there may be a considerable time lag between recharge of the reservoir and its discharge in springs.

OTHER ASPECTS

Application of naled distribution map

The folded map of naleds is also a map of potentially useful freshwater sources. It may also serve as a guide in the planning of future construction projects, which might interact with the hydrologic regime to create problems. Naled areas indicate nearby springs that are overwintering sites for some fish species (Childers *et al.* 1973) and are therefore important in the biological regime of the Arctic.

The absence of naleds on the Colville River suggests that there may be continuous flow to the sea along the channel under the ice or within the river-bed. The work of Walker and others (Arnborg *et al.* 1966; Walker 1974) has indicated that the delta channels are below sea level and connected to the sea, even at the maximum ice growth. Walker's work also shows that saline water extends upstream for 60 km below the ice cover. This would suggest either that there is no continuous source of water in the drainage basin of this large system, or that the river flow is so greatly reduced in volume and force that it can be accommodated in a thin layer between the ice and an intruding salt water wedge. Measurements at three locations along the lower Colville above the delta showed no flow in April 1975 (Joe Childers, U.S. Geological Survey, personal communication, 1975). This lack of flow and the apparent absence of springs along the river suggest that there may be virtually no winter freshwater flow in the Colville River system. This would be significant in any search for a year-round water supply.

Pumping from a river with little or no winter recharge can also result in salt water intrusion, or in the depletion of stagnant freshwater pools. Pumping down of freshwater pools in March 1976 for the Prudhoe Bay oil field complex from the Sagavanirktok and Kuparuk Rivers has already forced overwintering fish to retreat to isolated pockets within the river-bed (Terry Bendock, Alaska Department of Fish and Game, personal communication, 1976). Thus, although the Sagavanirktok River has numerous naleds suggestive of year-round water recharge, the water depletion rate by pumping near Prudhoe Bay suggests that little or no flow reaches this far downstream late in winter.

Naled conditions during glacial episodes

During glacial episodes along the Arctic coast of Alaska, the climate was colder and drier (Hopkins 1967). Thus, it may be presumed that less surface water would have been available, the flow season would have been shorter, and the depth of winter freeze greater. The latitudinal depression of isotherms suggests that naleds of the type found in the Arctic today would probably have been more widespread at lower latitudes. Naleds along the Arctic coast would have been relatively unaffected by climatic change in areas where thermal springs exist. In general, naled development would probably have been enhanced by the shorter thaw season and the greater probability that naleds would last from one year to the next, but hindered by the lesser amounts of precipitation.

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