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ANALYSIS OF THE ORIGIN OF AUFEIS FEED-WATER ON THE EASTERN ARCTIC SLOPE OF ALASKA

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Charles Roswell†

ABSTRACT

In this paper, the origin of water feeding large aufeis fields (overflow river ice) on the Arctic Slope of Alaska is analyzed. Field measurements of two large aufeis fields on the eastern Arctic Slope were taken during July of 1978 and 1979. Measurements of aufeis extent and distribution were made using Landsat Multispectral Scanner Subsystem (MSS) satellite data from 1973 through 1979. In addition, ice cores were analyzed in the laboratory. Results of the field and laboratory studies indicate that the water derived from aufeis melt-water has a chemical composition different from the adjacent upstream river water. Large aufeis fields are found in association with springs and faults thus indicating a subterranean origin of the feed-water. In addition, the maximum extent of large aufeis fields was not found to follow meteorological patterns which would only be extected if the origin of the feed-water were local. It is concluded that extent of large aufeis in a given river channel on the Arctic Slope is controlled by discharge from reservoirs of groundwater. It seems probable that precipitation passes into limestone aquifers in the Brooks

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Range, through an interconnecting system of subterranean fractures in calcareous rocks and ultimately discharges into alluvial sediments on the coastal plain to form aufeis. It is speculated that only small (perhaps beaded) aufeis patches are affected by local meteorological parameters in the months just prior to aufeis formation.

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ANALYSIS OF THE ORIGIN OF AUFEIS FEED-WATER ON THE EASTERN ARCTIC SLOPE OF ALASKA

Dorothy K. Hall*
Charles Roswell†

Aufeis occurs in many rivers in the continuous permafrost region of the Arctic Slope of Alaska. Also known as icings and naleds, aufeis can form either in a stream channel or on the tundra. Aufeis is formed by ground or river water which continues to flow after the fall freeze-up period. The origin of the water which forms aufeis is the subject of this paper.

Stream aufeis is a unique type of river ice which forms in a portion of the channel which freezes deeply enough to restrict continued channel flow (Figure 1). Hydraulic pressure builds up at that point as the river ice and permafrost thicken during the freeze-up period. Water is forced upward through cracks in the river ice and freezes upon exposure to the cold air. The thickness of each layer depends upon the rate of flow of water through the cracks, and upon the air temperature (Kreitner, 1969). This process continues in successive overflows until the source of water is exhausted.

The geological situation must be suitable in order for aufeis to form. A barrier of impermeable bedrock, permafrost or seasonally frozen ground must be overlain by pervious alluvium to allow water from an aquifer to flow to the surface or into a river channel. Meteorological factors are also reported to influence aufeis formation. According to the literature, aufeis will be more extensive during very cold winters because rivers freeze more deeply leaving less room for the flow of water in the channel (Nevskiy and Nekrasov, 1973 and Carey, 1973). Additionally, when only a small

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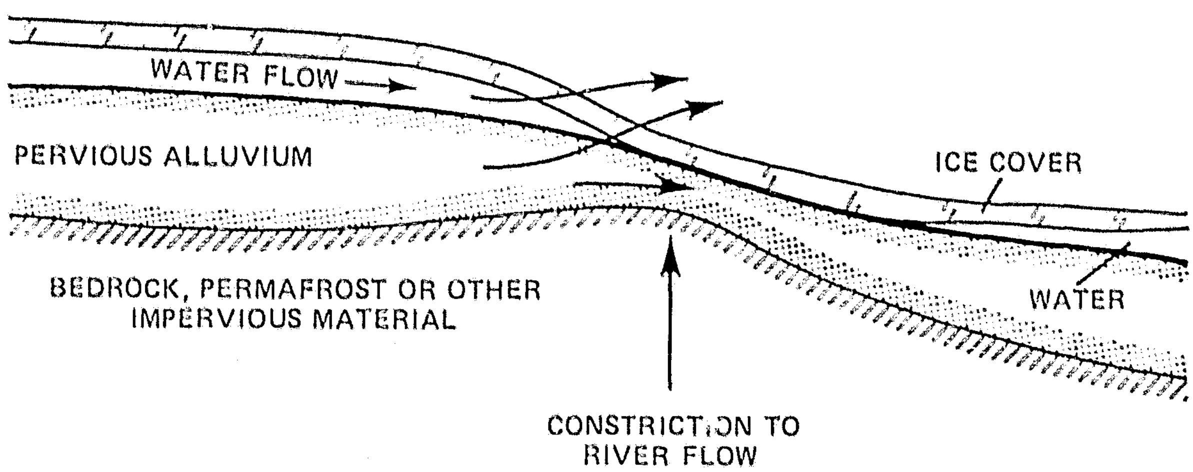

Figure 1. Formation of Stream Aufeis (after Carey, 1973).

amount of snow is present on the ground, the insulative properties of the snow are low permitting even deeper, freezing of river ice.

The objective of this study was to analyze the origin of aufeis feed-water for the eastern Arctic Slope of Alaska (Figure 2) using ground, aircraft and satellite measurements as well as available geologic and topographic maps. The source water is either local (from streamflow) or from groundwater flowing from great distances, or a combination. If the source water is local, the aufeis extent should be influenced by meteorological parameters. If the source water is deep groundwater, the aufeis extent would not be expected to vary greatly with meteorological parameters. This paper tests the above hypotheses through analysis of water chemistry, regional geology and regional meteorology of the eastern Arctic Slope of Alaska.

Significance of Aufeis

Aufeis, on the Arctic Slope of Alaska, is the surface manifestation of the interrelationships among geologic, geomorphic and meteorological conditions. Study of the origin of aufeis water for large aufeis fields requires an understanding of the physical processes which operate within continuous permafrost. Knowledge of aufeis dynamics is important to human activity in the arctic because aufeis can cause damage to structures and towns, and create problems during construction. Furthermore, aufeis can inadvertantly be caused by man's activities and disrupt construction resulting in loss of time and money.

Study Area

Three physiographic provinces comprise the Arctic Slope of Alaska: the Arctic Coastal Plain, the Arctic Foothills and the Arctic Mountains (Wahraftig, 1965). The Arctic Coastal Plain has very little relief. The surface is characterized by polygonal features, low shrubby vegetation and an abundance of standing water including thousands of lakes formed from the thawing of ground ice.

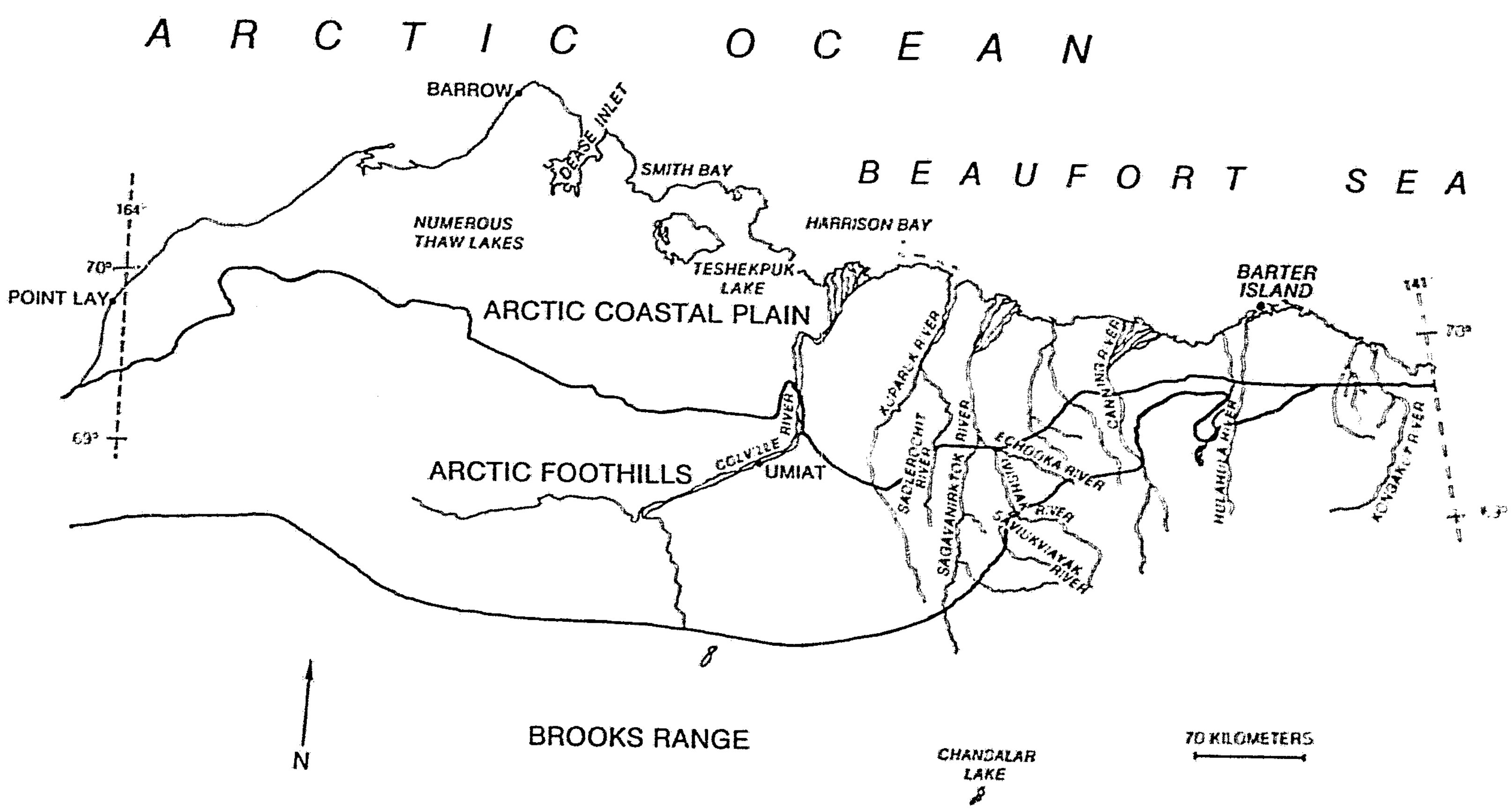

Figure 2. Location Map.

These 'oriented lakes' and their associated drained lake basins dominate the tundra surface covering up to 90% of the land surface in some locations (Holmquist, 1975). Oriented lakes are more prevalent west of the Colville River.

The Arctic Foothills, just to the south of the coastal plain, rise to an elevation of 900-1000 m and contain evidence of former glaciation. The Arctic Mountain Province, or Brooks Range, is an extension of the Rocky Mountain system and has mountain peaks up to 3000 m in elevation (Holmgren and others, 1975). A few small valley glaciers exist in the eastern part of the mountain range, however evidence of former, more extensive glaciers is present.

Permafrost is defined as any surface or ground material that maintains a temperature of 0°C or less for two or more consecutive years. Three zones of permafrost have been recognized: continuous, discontinuous and sporadic. In the continuous zone, the entire area is underlain by permafrost requiring an average annual temperature of -5.0°C or less (Black, 1976). In the discontinuous zone, areas without permafrost are found. In the zone of sporadic permafrost, permafrost is often only found where local factors such as exposure, snowcover and vegetation allow a thermal regime conducive to the perpetuation of permafrost. All of the aufeis fields which are examined in this study are within the continuous permafrost region. Continuous permafrost underlies the Arctic Coastal Plain to depths of up to 650 m (Pewe, 1975), however considerable variations in the thickness of permafrost exist. Along the Arctic Ocean Coast, thicknesses of $\leq$250 m are common because the influence of the ocean moderates the climate and inhibits permafrost development (Holmquist, 1975).

Even in areas of continuous permafrost, zones of unfrozen ground may exist. These are known as taliks and often exist beneath deep lakes and rivers (Price, 1972). Permafrost is overlain by a zone of seasonally thawed ground, the active layer, which varies in thickness depending upon local conditions but is generally <0.5 m in thickness (Lewellen, 1979) and attains a maximum thickness of ~ 1.2 m (Kane and Carson, 1973) on the coastal plain of northern Alaska. Soils composed of peat and organic matter are common in this area and have shallower active layers than those composed of sands and gravels. Infiltration of water and transfer of heat is facilitated through pore spaces in sand and gravel sediments allowing greater depths of thaw.

Ground ice can exist as various features representing various modes of formation. Pore ice exists in coarse sand and gravel sediments whereas segregated ice is typically found in fine-grained organic soils. Foliated or vein ice develops in thermal contraction cracks over thousands of years. Pingo ice can form either by upwelling of ground in a shallow lake basin or by updoming of the surface as groundwater under hydraulic pressure is forced to the surface. All of these features develop in areas of continuous permafrost.

For most of its geologic history, the Arctic Slope of Alaska was under water. On the north, it was bordered by a landmass and on the south by a geosyncline (Walker, 1973). Clastic sediments from the northern landmass filled the geosyncline between the middle Paleozoic and middle Mesozoic Eras. During the late Mesozoic, the coastal region of northern Alaska separated from the northern landmass and drifted south thus eliminating the northern sediment source. Beginning in the late Mesozoic and continuing to the present, uplift of the Brooks Range occurred thus creating a southern source of sediments for the Arctic Coastal Plain (Walker, 1973). This uplift caused the rivers to flow northward with continued infilling of the geosyncline. During the late Mesozoic and early Cenozoic, the Brooks Range was subjected to intense folding and faulting and the northern foothills underwent gentle folding. Most of the rocks in the Brooks Range are middle Paleozoic limestones, sandstones and shales. On the Arctic Coastal Plain, undeformed Mesozoic sediments underlie up to 50 m of unconsolidated silt, sand and gravel of Quaternary Age (the Gubik

Formation). East of the Colville River, deposits from the tertiery (of the Cenozoic Era) are also found according to Walker (1973).

There are differences between the eastern and western parts of the Arctic Coastal Plain. The coastal plain is wider in the western part of the Arctic Slope and contains thousands of oriented lakes formed by the thawing of ice wedges in ice-rich permafrost. Lakes are smaller and less numerous to the east of the Colville River and are not as well oriented. Faults are more numerous and located farther north in the eastern part of the Arctic Coastal Plain than in the western part (Beikman and Lathram, 1976). West of the Colville River, stream channels are meandering, but east of the Colville, the rivers are braided and are building deltas at their mouths (Walker, 1973).

Precipitation is very low on the Arctic Slope, from 13 – 25 cm per year according to Kane and Carlson (1973). Most of the precipitation occurs as snowfall between June and October. Precipitation can be in the form of snow in any season but is generally rain during the short summer. A snowpack with a maximum thickness of 30 – 40 cm develops by April each year (Holmgren and others, 1975) and is constantly redistributed and hardpacked by the wind. In the Brooks Range a thicker snowpack of ~85 cm develops each year (Brown, 1966).

The mean annual temperature and precipitation for Barrows is −12.2°C and 11.5 cm respectively, and for Anaktuvuk Pass, in the Brooks Range, −10.6°C and 28.4 cm (Holmquist, 1975). The climate of the Arctic Slope allows the perpetuation of continuous permafrost, i.e. a mean annual temperature of ≤ -5°C.

<u>Previous Work</u>

The earliest available report of aufeis distribution on the Arctic Slope of Alaska was written by Leffingwell (1919). He travelled in northern Alaska studying the geology and water resources of

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the area. Leffingwell reported extensive aufeis on the Canning River, a small aufeis field on the Okpilak River and aufeis on the Sadlerochit River.

More recently, the distribution of aufeis on the Arctic Slope of Alaska has been studied by Holmgren and others (1974), Harden and others (1977) and Hall (1980a) using Landsat Multispectral Scanner Subsystem (MSS) visible and near-infrared imagery to locate existing aufeis fields and to monitor changes in aufeis using repetitive Landsat images. Holmgren and others (1974) found a predominance of aufeis in the northern foothills of the Brooks Range at the transition between the high mountains and the upper foothills where the Sagavanirktok, Echooka and Ivishak Rivers flow together. Harden and others (1977) show that aufeis is prevalent east of the Colville River where it occurs on most of the larger streams between the Anaktuvuk and Firth Rivers. Lewis (1962) observed that near the mountain front, the change from a single, deep channel to braided channels is conducive to aufeis development.

Prior to the advent of satellite imagery, areas of aufeis were mapped on the Arctic Slope of Alaska using aerial and ground reconnaissance techniques (Alaska Water District, 1969). The discharge and chemistry of spring waters were also measured at various placed, e.g. on the Colville, Sagavanirktok and Kuparuk Rivers. Childers and others (1973) performed a hydrological reconnaissance of streams and springs in the eastern Brooks Range, Alaska in July of 1972, and another more extensive reconnaissance in the same area during April, August and November of 1975 (Childers and others, 1977). They reported that many of the large aufeis fields are related to springs upstream from the aufeis.

Aufeis is also extensive in the U.S.S.R. and its distribution has been studied in Siberia. Osokin (1978) studied the distribution of aufeis in the Trans-Baykal region of Siberia. He reported that aufeis is most common in the mountainous regions where taliks, tectonic faults and fissured rocks are prevalent. Aufeis development was the weakest in the arid steppe and forest steppe regions where only seasonal freezing occurs. Distribution of aufeis in the central Trans-Baykal region of Siberia was also discussed by Nevskiy and Nekrasov (1973). They noted that the aufeis in the central Trans-Baykal region was small (0.1 to 0.5 km^2) compared to aufeis in other parts of Siberia.

Nekrasov (1973) noted that aufeis occurring at higher elevations in the eastern part of the Stanovoye Upland, a part of the Trans-Baykal region of the northeastern U S.S.R., could last throughout the summer whereas aufeis at lower elevations generally melted by mid-August. This was attributed to the prolonged winter weather in the higher elevations.

North American and Russian authors have related aufeis genesis to groundwater emanating from springs. Childers and others (1973 and 1977) chemically analyzed melted aufeis water, and water emanating from springs upstream from the aufeis. They concluded that recharge of aquifers occurs into permeable limestone bedrock and associated talus and alluvial deposits and that consequent springs feed the aufeis. Childers and others (1973 and 1977) also speculated that streamflow ceases in late winter in all streams except in local areas of groundwater discharge where aufeis was found downstream. They further noted that the aufeis on the Kongakut River on the Arctic Ocean coast is the largest known in Alaska and is formed as a result of several large springs emerging from an alluvial fan surface.

Alekseyev (1973) stated that precipitation seeps freely into karsted dolomites and limestones, exposing and draining carbonate deposits in southern Yakutia and that these groundwaters feed aufeis. Bukayev (1973) performed chemical analyses of aufeis water in order to determine the source of water. He determined that the source of water for aufeis in the Kolyma River in the northeastern U.S.S.R. emanated from outflow of water at depth, or a spring following a fault line. "Floury salts" found on surrounding pebbles were cited as proof of the deep water supply.

Bondarev and Gorbunov (1973) discussed the process of aufeis formation in the Tyan'-Shan' area of Siberia. They observed that the locations of aufeis fields correlate with tectonic faults and that continuous taliks are confined to tectonic faults. Water travelling through these fault zones feeds the aufeis. Tolstikhin and Sokolov (1972) show that within these fault zones, aufeis waters gravitate toward regions comprised of carbonate rocks.

Nekrasov (1973) estimated that the variations in the area of aufeis between years did not exceed 6–7% in the eastern part of the Stanovoye Upland in northeastern Russia where the total area of aufeis was 76.6 km^2. Variations in aufeis extent between years have largely been attributed to meteorological factors in the literature. It has been generally accepted that the most extensive aufeis will develop during a year in which the temperatures are below normal, there is little snow on the ground and greater than normal precipitation, particularly in the late summer (Carey, 1973).

There has been much previous work by Russian scientists dealing with the distribution, extent and genesis of aufeis in Siberia. However, causes for aufeis variability and water origin remain controversial. This is true in the North American literature as well. With the advent of satellite imagery, e.g. Landsat with its 80 m resolution, the distribution of aufeis has been mapped and its variation in extent between years is now amenable to study.

TECHNIQUES

Landsat data from 1973 through 1979 were used to locate and measure aufeis on seven rivers in the eastern part of the Arctic Coastal Plain. Imagery from the Landsat Multispectral Scanner Subsystem (MSS) provides repetitive coverage of the same place on the earth at least once every 18 days with a spatial resolution of 80 m. The MSS, on-board the Landsat-1, -2 and -3 satellites, provides imagery in four spectral bands. Band 4 (0.5 – 0.6 μm) and Band 5 (0.6 – 0.7 μm) sense in the visible part of the spectrum; and Band 6 (0.7 – 0.8 μm) and Band 7 (0.8 – 1.1 μm) sense in the near-infrared range. Each Landsat image covers an area on the earth which is 185 km on a side. Landsat data have been collected since 1972 and are useful for interannual comparison of aufeis location and extent.

Landsat images were selected after perusal of candidate scenes. Black and white Band 5 images were then obtained. Using a Zoom Transfer Scope, the outline of each aufeis field was drawn onto the appropriate 1:250,000 scale U.S. Geological Survey topographic map and measured using a dot grid.

The main aufeis fields on the Canning, Echooka, Hulahula, Kongakut, Sadlerochit, Saviukviaya and Shaviovik Rivers were measured from June Landsat imagery for each year from 1973 through 1979 and measurements are shown in Table 1. It was not possible to measure aufeis extent each year for each river due to cloud conditions. In fact, in June 1976, none of the seven aufeis fields under study was visible due to clouds. And in June 1978 only the Kongakut River aufeis was measured. Most of the Landsat images in the other years were obtained in the mid- to latter part

Table 1. Landsat-Derived Measurements of June Aufeis Extent (km^2) from Selected Arctic Slope Rivers (1973 1979)

	Canning	Echooka	Hulahula	Kongakut	Sadlerochit	Saviukviayak	Shaviovik
1973	16.69	18.31	2.94	26.69	5.06	12.88	3.13
1974	4.44	23.63	3.69	27.31	8.31	16.00	3.81
1975	10.44	26.69	2.25	19.69	7.69	18.81	2.44
1976	No Data Available For 1976						
1977	21.81	19.63	3.50	16.56	5.50	--	1.19
1978	No Data			29.00	No Data		
1979	26.00	22.88			6.88	15.94	4.25

of the month of June after some melting of the aufeis had inevitably occurred. This introduces unavoidable error in the measurements of aufeis extent.

The extent of an aufeis field can best be measured using visible Landsat imagery (Figure 3) (Holmgren and others, 1974). Only June imagery was used for the analysis because June imagery allows the best possible measurement of the maximum extent. Band 5 was chosen because it was found to be best for discerning the aufeis extent. With Band 5 imagery, good contrast is achieved between the ice and surrounding tundra. Prior to snowmelt, the aufeis cannot be accurately discriminated from the surrounding snowcovered terrain in the visible bands, so the optimum time for measuring aufeis extent from Landsat imagery is as soon after breakup as possible. Band 7 (near-infrared) can be used for locating aufeis when the ground is snowcovered, because the aufeis appears darker in the near-infrared bands, however, aufeis is not delineated clearly enough after breakup for accurate measurement of extent.

Geologic and topographic maps of portions of the eastern Arctic Slope were examined. These show age of rock units (Bickman and Lathram, 1976) surficial and bedrock geology (Yeend, 1973) and lithologic facies (Detterman, 1974), type and extent of surficial sediments and topography (U.S.G.S. Topographic Series 1:250,000 and 1:63,360 scale) as well as composition and thickness of the bedrock in the areas at and upstream from the aufeis.

Field Measurements

Field work was conducted on both the Canning and Shaviovik River aufeis fields in July of 1978, and on the Canning River only in July of 1979. The 1978 field work was performed in conjunction with a NASA Convair 990 aircraft overflight. Objectives of the field work included determination of the thickness and density of the ice comprising the aufeis, identification of springs which feed the aufeis and analysis of the chemical characteristics of the aufeis water. During the

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Figure 3. Landsat Image (I.D. #30467-20542 Band 5) Acquired 15 June 1979.

1979 season bad weather conditions delayed the field work until early July although the intent was to perform the field work just after snowmelt in June during maximum aufeis thickness and extent.

The Canning and Shaviovik River aufeis fields were selected for field study largely because of their relative accessibility by plane. In addition, the aufeis was known to form at approximately the same place in each river every year as determined from Landsat imagery.

Aerial photography of the Canning and Shaviovik River aufeis was obtained from a July 12, 1978 NASA aircraft overflight (Figures 4 and 5). The field party was unable to begin field measurements until July 15, 1978 due to weather problems. The Shaviovik River aufeis was studied on July 15 and at that time thickness and density measurements were taken from 3 cores drilled with an ice auger.

Field work was performed on the Canning River aufeis from July 18-21, 1978. Fourteen cores were taken. The ice cores showed a distinct banded structure, each individual layer representing a discrete overflow. Typically, layers of clear ice alternate with layers of white, bubbly ice of varying thicknesses. Individual layers may contain impurities such as wind blown silt as seen in the core shown in Figure 6. Clear ice exists beneath much of the aufeis as determined from the cores. The clear ice is the river ice over which the aufeis forms during the fall and is easily distinguishable from the overlying, layered aufeis. River ice overlain by aufeis was frozen solidly to the riverbed in most areas from which cores were taken. Also observed during the field study on the Canning River aufeis were areas of 'old' or perennial aufeis found beneath rocks and sediment. Perennial aufeis is ice which has lasted throughout at least the previous summer and was covered over by sediment from the shifting stream channels. More aufeis subsequently formed on top of it.

On July 3-5, 1979, only the Canning River aufeis was studied in the field. The location of the aufeis had changed from that of the previous year. The northern part of the aufeis field was farther to the east in the river channel than it was in 1978. The southern portion of the aufeis was in the

Figure 4. Convair 990 Air Photo of Canning River Aufeis
Acquired July 12, 1978.

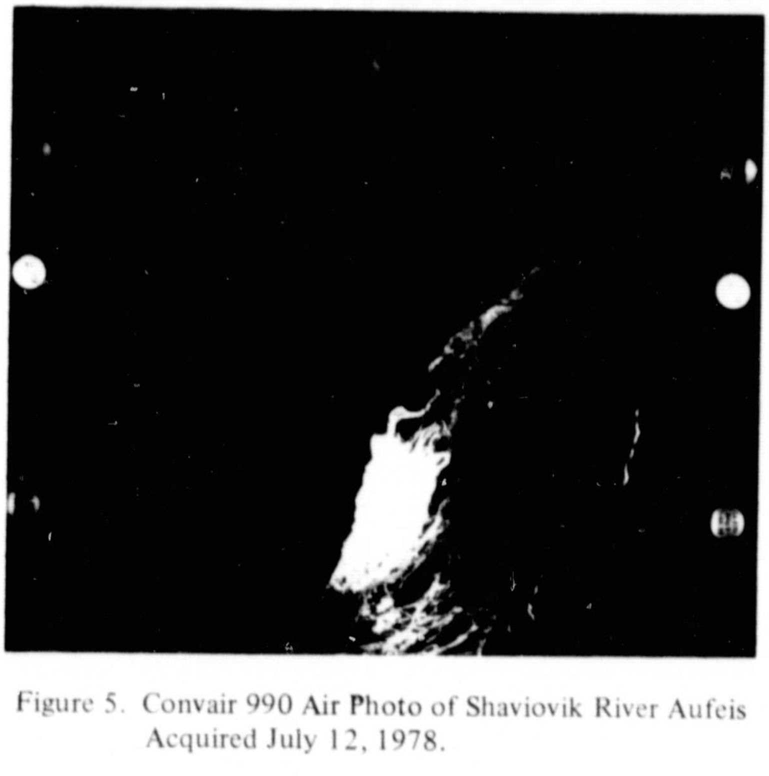

Figure 5. Convair 990 Air Photo of Shaviovik River Aufeis
Acquired July 12, 1978.

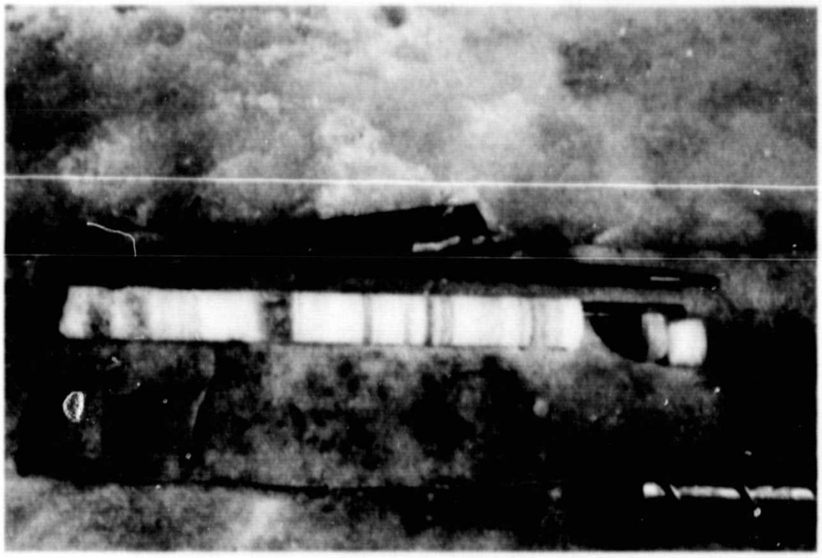

Figure 6. An Aufeis Core Taken from the Shaviovik River Aufeis July 15, 1978.

same location as in 1978. Powdered calcium carbonate patches were found on the surface and were generally 1-2 cm in thickness. Calcium carbonate was found in conjunction with ice mounds in two instances, but was generally found on the flat ice surface.

Samples of water melted from the top and bottom of the ice cores were collected for analysis in July 1979 from the Canning River aufeis. When the 1979 field season was planned, the intent was to obtain ice cores during maximum aufeis extent and thickness. Comparison of the chemical composition of the top and bottom sections of the ice cores would have been meaningful in that case. Measurements could not be taken until later in the melt season due to bad weather, so the distinction between the water sample at the top and bottom of the core is not significant because there was a considerable amount of downward ablation of the aufeis prior to the time of the field work. The original top layers of the ice were melted by the time that the ice cores were obtained. All of the samples probably represent ice from the bottom half of the aufeis, or layers which were deposited early in the freeze-up period.

CHEMICAL COMPOSITION OF AUFEIS WATER

Comparison of the chemical composition of the aufeis meltwater with the adjacent upstream river water can give very important information regarding the origin of the aufeis water. Eight cores of aufeis were drilled on the Canning River aufeis in July of 1979, and a sample of river water was collected. All samples were analyzed for amount of dissolved solids, calcium as $CaCO_3$ and presence or organic matter. Results showed distinct differences in the characteristics of the aufeis meltwater and river water.

Laboratory Analysis of Ice Cores

Two laboratory samples were taken of each core with the exception of core 8 (only one sample was taken of core 8). Samples are referred to as T1 (top – core 1), B1 (bottom – core 1), T2, B2 . . . . T8 and R (river sample). Water samples were obtained by melting portions of the ice cores and mixing each individually.

In the laboratory, the samples were evaporated on a steam bath and the residue weighed. Samples were divided into two categories according to weight of the solid material. Light samples contained less than 200 mg/l of solid material and heavy samples contained greater than 200 mg/l (Table 2). Hydrochloric acid (0.2 N) was added to each sample to dissolve the solids. Insoluble organic matter was found in the heaviest samples. Samples were then titrated to a pH of 8.5 with a 0.2 N solution of sodium hydroxide in order to determine the carbonate content of the samples as calcium carbonate equivalent. The weight of the $CaCO_3$ was calculated and percent of total was determined for the six heavy samples and the river sample (Table 3).

Table 2. Residue Upon Evaporation of Aufeis and River Water Samples

Sample	Concentration (mg/l)	Sample	Concentration (mg/l)
T1	60.6	T5	148.0
B1	127.3	B5	61.7
T2	112.0	T6	251.0
B2	153.0	B6	68.0
T3	600.0	T7	2460.0
B3	675.0	B7	942.0
T4	132.0	T8	801.0
B4	208.0	R	174.0

Table 3. Carbonate as $CaCO_3$ in Heaviest Samples and River Samples

Sample	% of Total Solids
T3	66.6
B3	68.5
T6	91.2
T7	89.3
B7	85.9
T8	71.4
R	72.8

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The heavy samples and the river samples were filtered, and the filtrate (insoluble material) was weighed. The percent of insolubles to the total solids was then calculated (Table 4). The water from those samples was then tested for calcium (Brown and others, 1970). Each sample was titrated with disodium dihydrogen ethylenediamine tetraacetate to (indicator) endpoint. The amount of calcium in each of the seven samples is given in Table 5.

Table 4. Insolubles in Heaviest Aufeis Samples and River Water Sample

Sample	Concentration (mg/l)	% Total Sample
T3	53.2	8.9
B3	82.9	12.3
T6	5.5	2.2
T7	51.6	2.1
B7	39.1	4.2
T8	142.2	17.8
R	0.01	7.0

Table 5. Calcium as $CaCO_3$ in Heaviest Aufeis Samples and River Water Sample

Sample	Concentration (mg/l)	% Total Solids
T3	148.2	24.7
B3	469.6	69.6
T6	79.3	31.6
T7	715.0	29.0
B7	288.3	30.6
T8	229.3	28.6
R	44.7	5.6

Analysis of the eight water samples obtained from cores drilled from various portions of the aufeis showed a large variation among the samples in the amount of total solids (suspended and dissolved) as seen in Tables 2 and 4. There was also a large variability in the amount of calcium found in the samples analyzed. The variability in the amount of calcium indicates that some of the cores contained river ice as well as aufeis, since the samples were probably derived from the bottom half of the original thickness of aufeis which is often composed of ice frozen from river water.

The control or river sample, R, had a low amount of calcium compared to the other cores analyzed with only 44.7 mg/l calcium (Table 5). This can be contrasted with sample B3 of which 469.6 mg/l of the total solids was composed of calcium.

Results of the Laboratory Analysis

Water which is associated with granitic or siliceous sand usually contains less than 10 mg/l of calcium, whereas water from limestone areas may contain 30 to 100 mg/l (Brown and others, 1970). Results from the aufeis water samples show a range of 79.3 to 715 mg of calcium per liter of water. Values this high clearly indicate that the water has been associated with calcareous rock.

No surficial limestone rock is present on the Arctic Coastal Plain. In the vicinity of the Shaviovik River aufeis, limestone bedrock begins 238 m below the surface and 116 m below the surface in the vicinity of the Kongakut River aufeis farther to the east. Approximately 122 m beneath the Shaviovik and Hulahula Rivers, very thin limestone layers (~3 m thick) are present (Detterman, 1974). Surficial calcareous rocks are numerous in the Brooks Range and foothills as determined from geologic maps compiled by Reiser (1971 and 1974) and Yeend (1973). Limestone aquifers in the foothills and mountains apparently collect water from precipitation and snowmelt and direct it into a system of interconnecting faults forming through-taliks which have surface expression in the form of lineaments and springs. Aufeis forms at the points of outflow (Figure 7).

The calcium content of the aufeis meltwater as compared to the river water is indicative of a different origin of the waters (Hall, 1980b). The calcium from the aufeis meltwater must be derived from the calcareous rock in the Brooks Range or from some depth beneath the coastal plain.

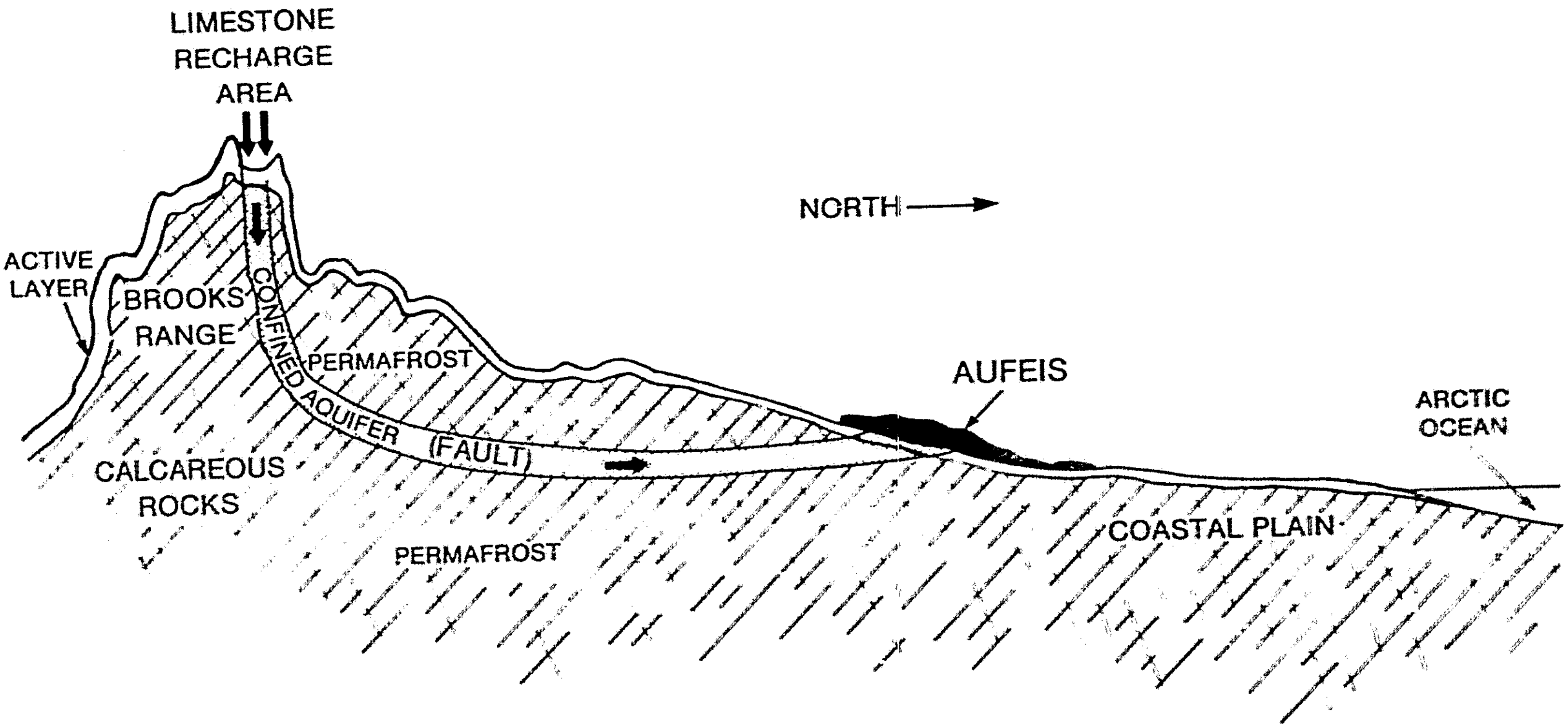

Figure 7. Probable Path of Aufeis Feed-Water from the Brooks Range to the Arctic Coastal Plain.

AUFEIS DISTRIBUTION ON THE ARCTIC SLOPE

Precise interpretation and classification of large aufeis fields, and analysis of the location of aufeis with respect to geomorphic and geologic features is relevant in the analysis of aufeis source water. Hence, aufeis is discussed in terms of topographic setting, characteristics of the streams in which it is located, and proximity to springs and faults.

The location of stream aufeis in the Arctic Foothills and Arctic Coastal Plain Provinces was determined from analysis of several years of Landsat imagery. Aufeis is found in stream channels predominately to the east of the Colville River as shown in Figure 8. Although small aufeis fields may develop to the west of the Colville River, they are not large enough to be seen on Landsat imagery.

Stream aufeis occurs either in the form of beaded patches or as discrete aufeis fields. Beaded aufeis often occurs along stretches of a river channel and is located in the Canning, Ivishak, Kavik, Kongakut and Sagavanirktok Rivers. Beaded aufeis occurs upstream from large discrete aufeis fields on the Canning, Ivishak and Kongakut Rivers.

The origin of the water for beaded and discrete aufeis fields may be different. Discrete aufeis fields may form from a stationary groundwater source while beaded aufeis may form from water in open-channel flow. The non-stationary source of water for beaded aufeis would account for its shifting in location within a stream channel between years.

Topographic Setting

Three types of stream aufeis can be classified according to their topographic setting on the Arctic Slope: deltaic, foothills and coastal plain aufeis (Table 6). Deltaic aufeis occurs on large river deltas on the Arctic Ocean coast, in the Canning, Clarence and Kongakut Rivers. The foothills type

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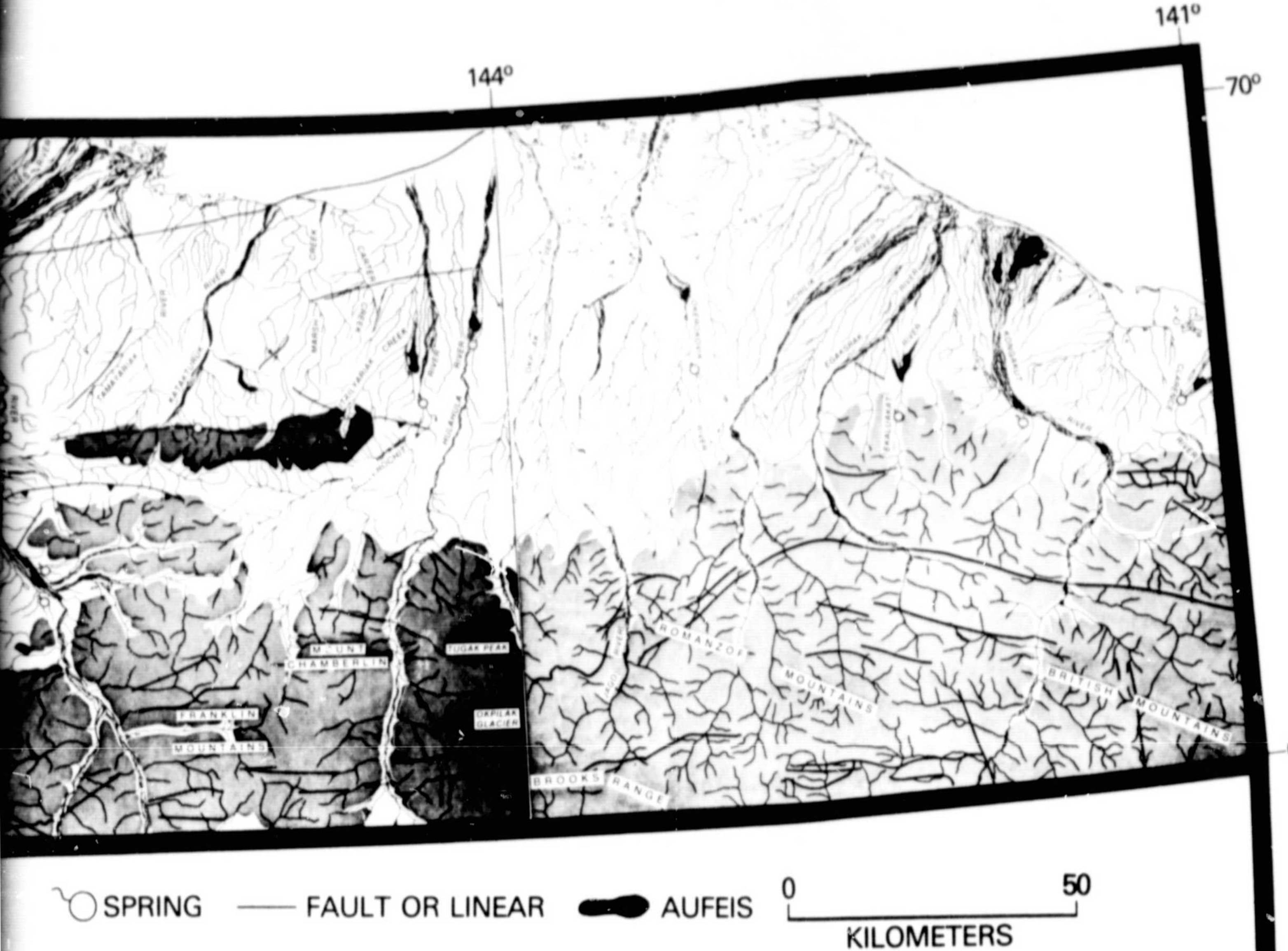

DISTRIBUTION OF STREAM AUFEIS ON THE EASTERN ARCTIC SLOPE OF ALASKA WITH RESPECT TO MAPPED SPRINGS AND FAULTS

Locations of aufeis were obtained from measurements of June aufeis extent from Landsat imagery (1973-1979). Locations of springs were obtained from Childers et al. (1973 and 1977) and U.S.G.S. (1969). Locations of faults and linears were obtained from maps compiled by Reiser et al. (1970), Beikman and Lathram (1976) and Albert (1978). Base map is from U.S.G.S. 1:250,000 series.

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Table 6. Classification of Aufeis Fields by Topographic Setting

Foothills	Coastal Plain	Deltaic
Hulahula	Aichilik	Canning (Lower)
Kuparuk	Canning (Upper)	Clarence
Itkilyariak	Echooka	Kongakut (Lower)
Okerokovik	Egaksrak	
Sadlerochit	Ivishak	
Tamayariak	Katakakturuk	
Toolik	Kavik	
	Kongakut (Upper)	
	Saviukviayak	
	Shaviovik	

occurs at the base of the mountains where the single river channels in the mountains become shallow and braided as they lose their capacity to carry material on the flat coastal plain. Examples of this type are in the Ivishak, Echooka and Saviukviayak Rivers as seen in Figure 8. Aufeis also occurs on the coastal plain often in alluvial fans of the rivers on the flat tundra such as in the Hulahula River (Figure 8).

The Canning, Clarence and Kongakut Rivers have aufeis in their deltas near the Arctic Ocean (Figure 8). The water which forms the deltaic aufeis is able to travel great distances along the flat delta between channels after flowing to the surface and before freezing, and the aufeis shifts position in the delta between years as determined from analysis of several years of June Landsat imagery.

Aufeis can form in alluvial sediments on the coastal plain as well as in the foothills. Childers and others (1977) show that there are aufeis fields, for example in the Kongakut River delta, on the eastern Arctic Slope which have no apparent relationship to channel constriction or change in slope, bedrock outcrops or structure. They speculate that such aufeis fields are fed by water from buried bedrock.

Channel Braiding

Most of the widest portions of river channels as seen on Landsat imagery and topographic maps contain aufeis for much of the year. Controversy exists as to whether aufeis is the cause or the result of braiding. If aufeis were the result of braiding, then an open-channel source of aufeis feedwater would be indicated, while a groundwater source is indicated otherwise.

Harden and others (1977) state that spring flood waters are forced to flow around the aufeis patches thus diverting stream channels and causing increased channel braiding. This appears to enhance braiding as determined from the aufeis in the Sadlerochit River. The aufeis in the Sadlerochit River is not located in a well-defined braided stream basin as are most discrete aufeis fields. There is a widened area of the Sadlerochit River flood plain, approximately 5 km to the northeast of the main aufeis field, which has the surficial characteristics of an aufeis area but contains only a small patch of aufeis in comparison to the width of the river basin at that point. That widened portion of the Sadlerochit River alluvial fan contains only a small aufeis patch. That point of outflow may have become blocked and diverted to the west to discharge into the alluvium of the small creek which now contains the aufeis. Enhanced braiding at the new site of aufeis will undoubtedly ensue as a result of the presence of the aufeis.

The active layer of permafrost is insulated (by the ice) from significant thawing underneath the aufeis in the summer. The overlying ice maintains the thermal regime of the frozen ground making the formation of aufeis in that particular location less likely in the following year by blocking the flow of water through the frozen material. Bukayev (1973) states that the active layer beneath aufeis does not thaw. Water is then forced to follow a path through permeable material (an adjacent thawed portion of the active layer) elsewhere in the channel in the following year. This may account for some of the shifting of the position of the aufeis within a channel, especially if the aufeis remained throughout most of the summer thus not permitting significant thawing below. In addition, water is diverted around the aufeis forming new stream channels each year (braiding) and thus a new route through which water can flow is created. This process would be most likely to occur on deltaic aufeis. For example, the aufeis in the Canning River appears to shift from one channel in one year to another channel in the next year.

Evidence suggests that changes in the relative position of the aufeis between years is the result of the presence of the aufeis. This supports the hypothesis that aufeis causes enhanced braiding of a stream channel.

Streamflow and Spring Characteristics

Most of the streams on the coastal plain of Alaska derive their source water from snowmelt emanating in the Brooks Range. Some derive part of their flow from glaciers. The Canning River derives part of its flow from glacier meltwater originating in the foothills and two large lakes: Lake Shrader and Lake Peters. The large Kongakut River derives its above-ground flow from runoff in the mountains and is not associated with glaciers. Continuous streamflow data for the seven selected basins under intensive study are not available.

Childers and others (1973 and 1977) measured the discharge of eighteen springs on the eastern Arctic Slope. Most of these springs were associated with aufeis just downstream. Table 7 shows the comparison between calculated average aufeis volume in the years studied from Landsat data on aufeis extent, and average estimated spring discharge (from Childers and others, 1973 and 1977) for five rivers on which aufeis is located downstream. Aufeis volume was calculated using a formula derived by Sokolov (1978) in which the related aufeis extent to volume, where V is aufeis volume in m^3 and F is aufeis area in m^2:

$$V = (0.96)(F^{1.09})$$

Table 7. Estimated Mean Annual Volume of Spring Discharge Derived from Childers and others (1973 and 1977) and Average June Aufeis Volume (m^3)

River	Spring Discharge	Aufeis Volume
Echooka	57,292,334	97,821,710
Hulahula	5,313,942	11,424,981
Kongakut	123,605,352	105,616,938
Sadlerochit	33,074,452	26,423,218
Saviukviayak	74,395,316	67,934,711

A rough measure of average spring discharge was determined by taking an average of the spring discharge values reported in Childers and others (1973 and 1977).

The discharge from springs feeding the Kongakut, Sadlerochit and Saviukviayak Rivers exceeds the aufeis volume. But on the Echooka and Hulahula Rivers, the estimated average volume of aufeis exceeds the average spring discharge volume. Figure 9 graphically illustrates the relationship between spring discharge and aufeis extent from Table 7 above. Note that the spring discharge volume for the Echooka River does not compare with the Echooka River aufeis volume as is the case for the other rivers. There may be unmapped springs contributing to the aufeis formation in the case of the large Echooka River aufeis field.

There is other evidence of active groundwater activity in the area besides the presence of the springs. Five pingos were found on aerial photography of the region near the Shaviovik River aufeis. These pingos were seen to the west of the aufeis and are not shown on the U.S.G.S. 1:63,360 scale topographic map of the area (Sagavanirktok (D-2) Alaska). Aufeis formation and pingo formation can be related. Strong springs produce aufeis by causing water to break through to the surface, and weak springs can produce pingos where water pressure causes more gradual updoming of surface sediments (Muller, 1959).

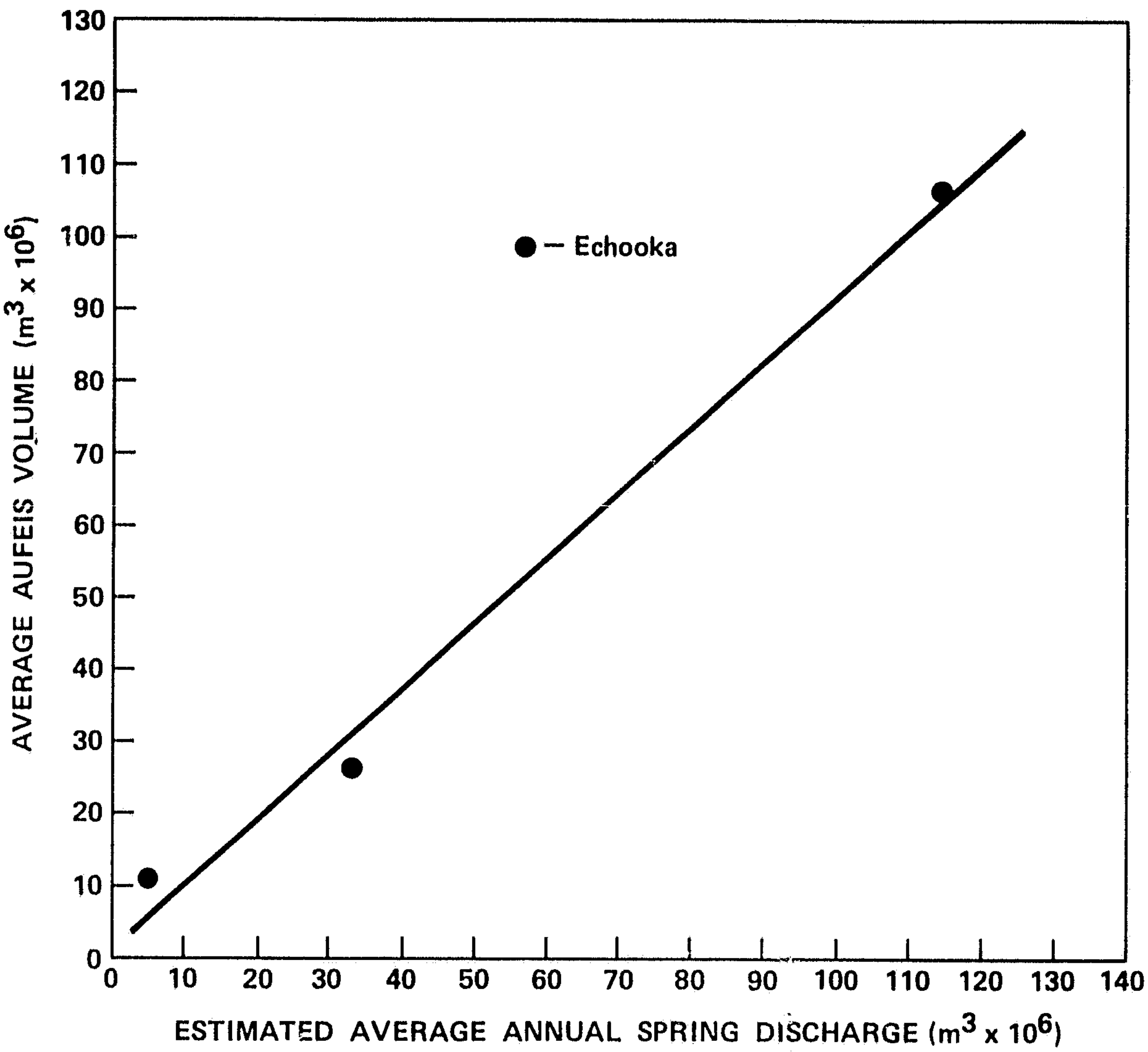

Figure 9. Relationship of Estimated Spring Discharge (from Childers and thers, 1973 and 1977) to Calculated Aufeis Volume (derived from 1973 – 1979 Landsat Measurements of Areal Extent).

Most pingos on the Arctic Coastal Plain of Alaska are considered to be the closed-system type (Brown, 1968). Closed-system pingos were discussed in the Introduction and are formed due to aggredation of permafrost in a talik following drainage of a deep (>2 m) lake. However, based on the juxtaposition of the pingos and aufeis, it seems logical that these pingos may be the open-system type having formed from artesian water. The formation of pingos and aufeis is probably related in the Shaviovik River aufeis area. Not many deep lakes are present in that location from which the closed-system type of pingo could have developed.

Known springs occur upstream from the aufeis in all of the seven rivers studied intensively as determined through analysis of maps compiled by U.S. Geological Survey (1969) and Childers and others (1973 and 1977), as seen in Figure 8. The presence of springs upstream from aufeis and the magnitude of their discharge clearly supports a groundwater origin of aufeis feed-water.

Tectonic Faults

The locations of faults and linears on the Arctic Slope with respect to aufeis fields, are shown in Figure 8. The locations of known faults were determined from maps compiled by Reiser and others (1970), and Beikman and Lathram (1976), and the locations of linears were derived from a Landsat mosaic compiled by Albert (1978). Faults are more numerous and they occur closer to the coastline in the eastern Arctic Slope as compared to the western Arctic Slope.

From the Clarence to the Kuparuk Rivers, faults actually cross aufeis fields in only two cases: in the Saviukviayak and Tamayariak Rivers. Out of 19 rivers studied, faults cross upstream of the river or tributary in 10 cases, and faults parallel rivers containing aufeis in 4 cases as shown in Table 8. No mapped faults are closely associated with aufeis in 3 of the rivers studied.

Russian investigators have recognized the correspondence between the location of faults and aufeis (Osokin, 1973) and in particular, recent tectonic activity and aufeis development (Alekseyev,

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Table 8. Locations of Faults and Linears with Respect to Aufeis on the Arctic Slope

Rivers or Tributaries on Which Faults Cross Upstream From Main Aufeis Field	Distance (km)	Rivers on Which Faults Parallel Aufeis	Distance (km)
Aichilik	23.6	Canning	3.3
Clarence	29.7	Echooka	3.3
Egaksrak	12.4	Ivishak	2.8
Ekaluakat	14.2	Kavik	1.5
Hulahula	43.1		
Katakakturuk	5.1		
Kongakut	50.4		
Sadlerochit	10.9		
Sagavanirktok	81.8		
Shaviovik	18.2		

Rivers on Which Faults Cross the Aufeis Field	Rivers on Which No Mapped Faults Cross Upstream, or Parallel the Main Aufeis Field
Saviukviayak	Kuparuk
Tamayariak	Okerokovik
	Toolik

1973). Kazimirov and Simov (1973) discuss groundwater flow through interconnecting faults which qre known as continuous taliks or through-taliks. This type of groundwater flow leads to aufeis development in alluvial sediments where groundwater flows to the surface in the form of a spring.

In the basin of the Khubsugul Lake, Pisarskiy and others (1978) report that through-taliks are linked to zones of tectonic disturbances and carbonate rocks. In the continuous permafrost region of northern Alaska and Siberia, water movement could only exist in taliks controlled by geologic structure because no other areas remain free of permafrost (except directly beneath deep lakes and rivers).

The preponderance of aufeis east of the Colville River is probably related to the number of faults east of the Colville creating an easy passageway for groundwater to flow. The dearth of faults to the west of the Colville River on the coastal plain, may explain why aufeis there is rare. A steady source of groundwater flowing through taliks (in this case faults) must be present in order for large aufeis fields to form if they are being fed by groundwater. The proximity of the aufeis to faults is indicative of a groundwater source of aufeis feed-water because faults represent a passageway through which groundwater can flow. Only proximity of aufeis to faults is necessary; the fault does not have to cross the aufeis field because water can move downstream through the alluvium beneath the stream channel until it reaches a channel constriction.

INTERANNUAL VARIATIONS IN AUFEIS EXTENT

Many authors have stated that three meteorological factors: amount of snow-on-the-ground, severity of freezing, and amount of late summer precipitation strongly influence the magnitude of aufeis growth in a particular winter (Carey, 1970 and 1973; Osokin, 1973 and Nevskiy and Nekrasov, 1973). Patterns of the aforementioned meteorological data from continuously operating stations at Barter Island and Chandalar Lake, Alaska were compared with patterns of June aufeis extent for the years in which Landsat data are available in order to determine the extent which meteorological factors govern the extent of aufeis growth in a given year in Hall (1980a).

Correspondence (if any) between interannual variation of aufeis extent and meteorological variables for the months prior to aufeis development was found to be much weaker than suggested in previous literature (Hall, 1980a). This further indicates that the aufeis water is of subterranean origin and is not from precipitation which occurred during the months just prior to aufeis development. In fact, according to Harden and others (1977) there may be a considerable time lag between groundwater recharge into the aquifer and discharge into the springs. If this is the case, amount of rainfall in a given year should not be amenable to direct correlation with aufeis extent for spring-fed aufeis fields. The size of the groundwater reservoir will affect the residence time of the water so that the correspondence between precipitation and maximum aufeis extent is inherently weak without better knowledge of the size and occurrence of the reservoirs from which the spring water emanates.

CONCLUSIONS

Results of this study strongly corroborate existing theories which indicate a deep groundwater origin of aufeis feed-water. And a mechanism is proposed by which precipitation, falling in the Brooks Range, flows through an interconnecting system of fractures through calcareous rock to the surface of the coastal plain to form aufeis. Evidence for this follows:

1. Springs are present upstream of all seven aufeis fields studied intensively.
2. Volume of springs measured upstream of discrete aufeis fields is of comparable magnitude to the calculated volume of aufeis.
3. Discrete aufeis fields form at the same place in a river channel each year indicating a stationary source of groundwater (i.e. a spring).
4. Faults are common in the areas of aufeis on the eastern Arctic Slope, but rare west of the Colville River which is devoid of aufeis.
5. Faults parallel and cross tributaries and main channels of most aufeis-prone streams studied.
6. The calcium content of the water melted from Canning River aufeis cores was high compared to the calcium content of adjacent upstream river water.
7. Although no surficial calcareous rock exists on the Arctic Coastal Plain, it is prevalent in the foothills and Brooks Range and is presumed to be the source for the $CaCO_3$ found in the aufeis.
8. Patterns of interannual variability of aufeis field extent did not necessarily correspond indicating that the aufeis field are probably not supplied by a common source of water.
9. Pingos found in the vicinity of aufeis fields may be the open-system type which are fed by artesian water.

Recommendations for Future Work

The theory that meteorological variables control aufeis extent is prevalent in the literature. As more data are amassed on aufeis extent, statistical correlations could then be performed on the relationship of interannual aufeis extent variations to meteorological variables. With the advent of better resolution satellite imagery, smaller aufeis fields can also be measured, perhaps some beaded aufeis, and compared statistically to meteorological patterns. This might result in quantitative distinction between the origin of beaded versus discrete aufeis patches. It will also be interesting to compare variations in precipitation in the Brooks Range, with more years of Landsat-derived data on aufeis extent. A time lag between precipitation and aufeis variations could possibly be found and quantified if such a relationship exists.

More work should be done to refine the work of Sokolov (1978) in which he formulated a relationship between aufeis area and aufeis volume for Alaskan and Siberian aufeis. This would require field measurements of the thickness of various aufeis fields and aircraft and satellite measurements of the extent.

More chemical analysis of water melted from aufeis cores should be performed in order to trace the source of water in various aufeis fields on the Arctic Slope. Chemistry of various spring waters and water melted from pingo cores could be compared with aufeis meltwater to determine if the chemical composition is similar. Dating techniques could be used to date material found in aufeis meltwater to infer the residence time of the water in the ground between recharge of aquifers in the Brooks Range and discharge to form aufeis. This would give an indication of the distance which the water must flow to reach the point of discharge. Chemical analysis of the meltwater from pingo cores would give information on the source of the pingo water. This would help to determine if there were open-system (spring-fed) pingos in the area of aufeis which are supplied with the same water which feeds large aufeis fields.

The characteristic layering (banding) of aufeis is not completely understood. Aufeis forms in discrete overflows and the banding is probably related to the water being temporarily stored before it is discharged. This is an interesting problem to investigate further because it may give information on the storage capacity beneath aufeis-prone rivers.

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