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PERIGLACIAL LANDFORMS AND PROCESSES IN THE SOUTHERN KENAI MOUNTAINS, ALASKA

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The distribution and characteristics of periglacial landforms in the southern Kenai Mountains, Alaska, were investigated during the summer of 1979. The principal area of study was a 1300-metre high mountain mass which stood as a nunatak during the last general glaciation. Periglacial features in the area include gelifluction lobes, nivation hollows, cryoplanation terraces, tors, a string bog, and various forms of patterned ground such as sorted circles, sorted polygons, earth hummocks, sorted steps, sorted stripes, and small ice-wedge polygons.

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Ground temperature measurements indicate that permafrost recently existed in the area but is no longer present. The sorted polygons, cryoplanation terraces, and nivation hollows are relic features which have been inactive for a considerable time. The turf-banked sorted steps and large gelifluction lobes were active until the very recent thawing of permafrost. Cryofraction and frost sorting still are vigorous active processes.

Finely jointed bedrock, a previous colder environment, and long exposure in the absence of glacial ice has allowed periglacial processes to be the dominant surface agents both in the principal study area and in similar areas along the western side of the Kenai Mountains.

PERIGLACIAL LANDFORMS AND PROCESSES IN THE SOUTHERN KENAI MOUNTAINS, ALASKA

by
Palmer K. Bailey

Bachelor of Science, University of North Dakota, 1970

A Thesis

Submitted to the Graduate Faculty

of the

University of North Dakota

in partial fulfillment of the requirements

for the degree of

Master of Science

Grand Forks, North Dakota

May
1980

This thesis submitted by Palmer K. Bailey in partial fulfillment of the requirements for the Degree of Master of Science from the University of North Dakota is hereby approved by the Faculty Advisory Committee under whom the work has been done.

(Chairman)

This thesis meets the standards for appearance and conforms to the style and format requirements of the Graduate School of the University of North Dakota, and is hereby approved.

Dean of the Graduate School

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Title PERIGLACIAL LANDFORMS AND PROCESSES IN THE SOUTHERN KENAI MOUNTAINS, ALASKA

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ABSTRACT

The distribution and characteristics of periglacial landforms in the southern Kenai Mountains, Alaska, were investigated during the summer of 1979. The principal area of study was a 1300-metre high mountain mass which stood as a nunatak during the last general glaciation. Periglacial features in the area include gelifluction lobes, nivation hollows, cryoplanation terraces, tors, a string bog, and various forms of patterned ground such as sorted circles, sorted polygons, earth hummocks, sorted steps, sorted stripes, and small ice-wedge polygons.

Ground temperature measurements indicate that permafrost recently existed in the area but is no longer present. The sorted polygons, cryoplanation terraces, and nivation hollows are relic features which have been inactive for a considerable time. The turf-banked sorted steps and large gelifluction lobes probably were active until the very recent thawing of permafrost. Cryofraction and frost sorting still are vigorous active processes.

Finely jointed bedrock, a previous colder environment, and long exposure in the absence of glacial ice has allowed periglacial processes to be the dominant surface agents both in the principal study area and in similar areas along the western side of the Kenai Mountains.

INTRODUCTION

Purpose of Study

The purpose of this study is to describe the periglacial features and processes in the southern Kenai Mountains, Alaska. This investigation extends scientific knowledge into a region not previously studied from a periglacial point of view. It is also anticipated that this study will provide useful information to the Alaska District of the U.S. Army Corps of Engineers in their evaluation of Bradley Lake as a potential hydropower site.

Area of Study

Kenai Peninsula

The south coast of Alaska from the 141st meridian to Cook Inlet is bordered by a broad belt of rugged mountains which rise abruptly from the sea. In the east they are known as the Chugach Mountains. Southwest of Turnagain Arm and Passage Canal they are the Kenai Peninsula. Structurally and geologically the two mountain masses are continuous (Capps 1940, p. 24). They are composed primarily of sedimentary rocks of Mesozoic age which have been highly deformed and, in many areas, slightly to moderately metamorphosed (Soward 1962, p. 50). On the Kenai Peninsula they are rugged peaks which rise 1200 to 2000 m.

The dominant surface forms are the result of extensive glacial erosion (Capps 1940, p. 24). Two large icefields still exist; the

Sargent icefield, in the extreme eastern portion of the peninsula, and the Harding icefield, west of the village of Seward. Numerous glaciers descend from these icefields; additional alpine glaciers occur along the crestline of the range southwest of the Harding icefield (Soward 1962, p. 24).

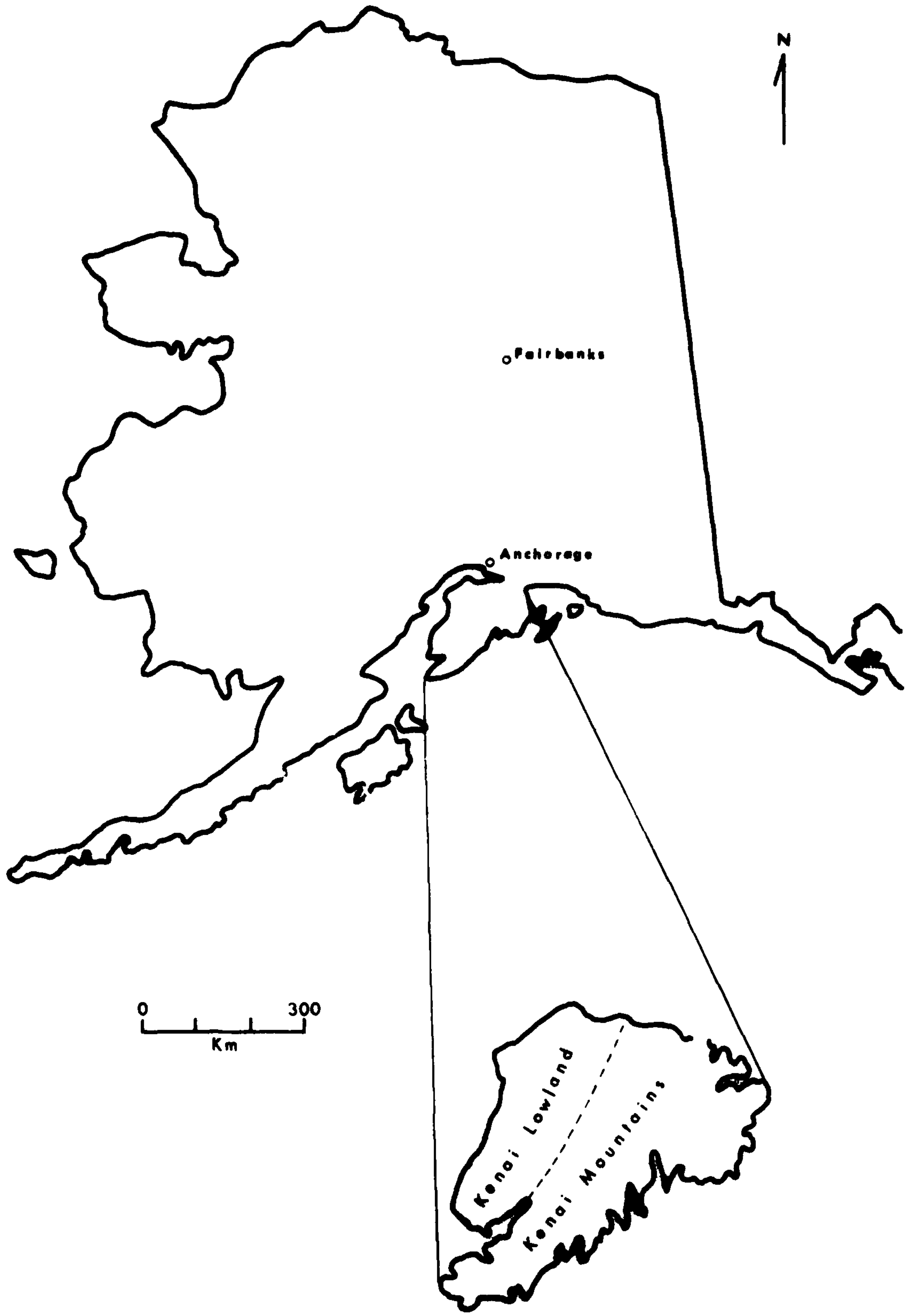
The Kenai lowland lies to the west of the mountains and comprises the remaining one-third of the peninsula. In the north it consists of a low plain covered by innumerable shallow lakes and bogs (Karlstrom 1955a, p. 133). The topography there seldom exceeds 50 m in altitude (Soward 1962, p. 49). In the south it becomes a broad rolling upland reaching a maximum elevation of over 700 m at Caribou Hills, 10 km north of Kachemak Bay (Barnes and Cobb 1959, p. 221). The entire lowland is underlain by the loosely consolidated Eocene beds of the Kenai Formation. Soward (1962, p. 51) describes these beds as consisting of partly indurated sand, silt, clay, a few thin lenses of conglomerate, and many beds of subbituminous coal. The stratigraphic thickness of this formation probably exceeds 1500 m (Barnes and Cobb 1959, p. 225). The Kenai lowland and the valley bottoms in the mountainous areas are generally covered by till, glacial outwash, or alluvium (Soward 1912, p. 51).

The location of the Kenai Peninsula is shown in Figure 1. The total area of the peninsula is about 24,600 square km, comparable in size to the states of Vermont or New Hampshire, or about twice the size of Connecticut (Karlstrom 1955a, p. 133).

Bradley Lake Area

Bradley Lake is a 6.6 square km glacial lake 5.7 km east of the head of Kachemak Bay and 42 km east-northeast of Homer on the

Fig. 1. Location of the Kenai Peninsula, Alaska.

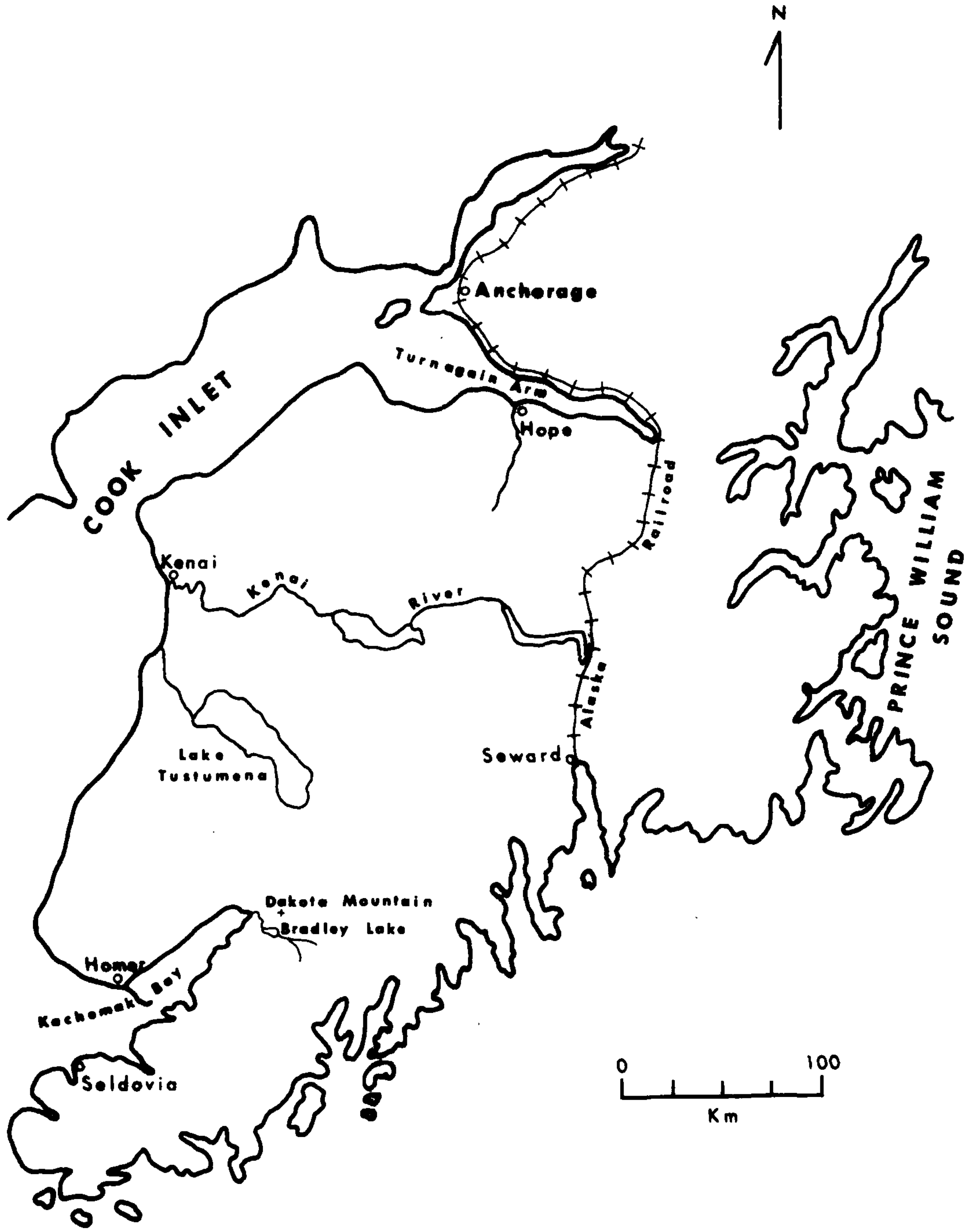

N
Fairbanks
Anchorage
0
300
Km
Kenai Lowland
Kenai Mountains

Kenai Peninsula, Alaska (Figure 2). Its surface is at an elevation of 332 m (1090 feet). The lake water is derived principally from the Kachemak and Nuka Glaciers in the valleys to the east and southeast respectively. The valley walls north and south of the lake rise sharply as a series of exposed rock faces and steep alder-covered slopes. The east end of the lake is dominated by a large delta which grades into a broad outwash plain formed by the braided meltwater streams from the glaciers. The west end of the lake is enclosed by a barrier of glacially sculptured bedrock hills rising 150 m above lake level. The Bradley River flows 8 km from the northwest corner of the lake through a steep gorge to the mud flats at the head of Kachemak Bay. The region to the east and the south of the lake is sharply dissected alpine topography with many active glaciers. The highest peaks in the region reach an elevation of 1700 m.

The bedrock of the Bradley Lake area is slightly to moderately metamorphosed greywacke, in places grading to arsillite and slate. In general the rock is highly jointed. On a single outcome it is often possible to observe dozens of well defined cleavage and joint planes. The fragments derived from physical weathering are generally blades, rods, or prisms, with blades being the most common. Evidence of both large and small scale structural control of the topography is abundant. The area overlies an active crustal subduction zone at the boundary of the North American and Pacific Ocean plates (Anthony and Tunley 1976, p. 178). Numerous faults are evident in the region. A belt of active volcanoes is situated about 130 km to the west.

During the last major glacial episode all but the highest mountains in the region were covered by glacial ice (Soward 1962, p. 49).

Fig. 2. Map of the Kenai Peninsula, Alaska, and the adjacent area.


N
Anchorage
Turnagain Arm
Hope
COOK INLET
Alaska Railroad
Kenai
Kenai River
PRINCE WILLIAM SOUND
Lake Tustumena
Seward
Dakota Mountain
Bradley Lake
Homer
Kachemak Bay
Seldovia
0
100
Km

There are few areas in the region which do not show distinct evidence of glacial erosion. Valleys are steep sided, U-shaped, and straight. The divides separating drainages are typically sharp arêtes. Cirques and horns are also common. Many cirque glaciers and a number of larger valley glaciers are present. At lower elevations many outcrops have been striated, grooved, or polished by glacial abrasion.

Five kilometres northeast of Bradley Lake is an area of about 2.3 square km lying between 1000 and 1300 m elevation which exhibits rounded topography and subdued peaks in distinct contrast with the angular glacially carved terrain nearby. The steep sides of this mountain descend into glacial valleys in all directions. A large glacial cirque 300 m deep and 800 m across is cut into the north end of the mountain. The bedrock of this mountain mass is essentially all slightly metamorphosed greywacke consisting of plagioclase with smaller amounts of potassium feldspar, quartz, lithic fragments, micas, pyroxene, and other mafic minerals. In a few areas the bedrock grades to a metaconglomerate. This mountain was selected, using remote imagery, as a probable site of periglacial surface morphology and was the principal area of study for this investigation.

Geographic Names

Two geographic place names are used for the first time in this report. The name Dakota Mountain has been formally submitted to the U.S. Department of the Interior, Board on Geographic Names, to designate the mountain mass extending from 150°46'27" west longitude, 59°46'46" north latitude to 150°43'23" west longitude, 59°48'17" north latitude. This mountain is the one described in the preceding paragraph and was studied from the ground in this research project. The name was chosen both in honor of the University of North Dakota and because of its literal meaning. The Indian tribes of the northern Great Plains known as the Sioux Nation use the word "Dakota" to describe their affiliation with each other. Literally translated it means an alliance or agreement of cooperation. The field work accomplished on Dakota Mountain was possible because of the cooperation of the U.S. Army Cold Regions Research and Engineering Laboratory, the University of North Dakota, and four other government agencies. The name "Dakota" is indicative of the spirit of cooperation which made this research project possible.

The highest camp occupied during fieldwork on Dakota Mountain was established in an east-west trending valley located between 150°45'48" west longitude, 59°47'28" north latitude and 150°44'26" west longitude, 59°47'28" north latitude. Many of the features described in this document are located in or adjacent to this valley. The informal name Camp Valley is used to designate this feature.

Previous Work

Economic Geology

Most of the early geologic investigations on the Kenai Peninsula were studies of the gold and coal resources of the region. The first recorded visit by a geologist was that of W. H. Dall, who investigated the coal beds of the Kenai Formation on the west side of the peninsula in 1880 and 1895 (Dall and Harris 1892, p. 237; Dall 1896, p. 763). In 1904 T. W. Stanton, G. C. Martin, and R. W. Stone spent a month on the Kenai Peninsula and produced a report on the coalfields near Kachemak

Bay (Stone 1906). The same year F. H. Moffit investigated the mineral deposits of the peninsula, primarily describing the gold lode and placer mining areas in the north but also briefly mentioning a mining works in gold-bearing quartz veins at Aurora on the south shore of the upper Kachemak Bay (Moffit 1906, p. 47). In 1906 W. W. Atwood investigated some of the mineral resources of the region, including the coal beds of the Kenai Formation (Atwood 1909, p. 109). U. S. Grant and D. F. Higgins studied deposits along the Prince William Sound and the eastern and southern Kenai Peninsula in 1908 and 1909 (Grant and Higgins 1909, p. 98; 1910a, p. 4; 1910b, p. 166-178). In 1911 G. C. Martin led an expedition which expanded upon earlier studies and resulted in a report which incorporated all of the previous investigations (Martin, Johnson and Grant 1915, p. 19). During the same year B. L. Johnson compiled a detailed report on the gold mining areas of the northern part of the peninsula (Johnson 1912, p. 131).

Construction of the Alaska Railroad from Seward on the eastern shore of the Kenai Peninsula to Fairbanks, 750 km to the north, began about this time. Most of the geologic interest in Alaska was subsequently directed to the "railbelt" region. In 1923, the year the railroad was completed, S. R. Capps made an extensive regional study of the route, touching briefly on the mineral resources of the Kenai Peninsula (Capps 1924, p. 116). In 1931 Ralph Tuck continued the investigations of northern gold mining areas (Tuck 1933). The next year E. R. Pilgrim studied the small lode-gold mines on Nuka Bay, only a few kilometres from Bradley Lake on the south coast of the peninsula (Pilgrim 1933). With the increase in Alaska's population following World War II, interest in the territorial energy resources was revived. In 1950 and 1951

E. H. Cobb and F. F. Barnes made a detailed examination of the Kenai Formation coal deposits which had not been studied seriously since 1911 (Barnes 1951; Barnes and Cobb 1959). These coal resources were never fully developed, however, because of the discovery a few years later of oil and natural gas in the upper Cook Inlet region. Very little gold mining has been done on the Kenai Peninsula during the last several decades. A study by D. H. Richter (1970), however, resulted in a brief renewal of activity in the Nuka Bay area.

Bedrock Geology

The earliest geologic investigations of the Kenai Peninsula were generally confined to those coastal areas accessible by boat. In 1898 W. C. Mendenhall conducted a reconnaissance of the eastern portion of the peninsula (Mendenhall 1900, p. 425). Emerson, a member of the Harriman Alaska Expedition, described spheroidal diabase and chert deposits near Halibut Cove on the southeast shore of Kachemak Bay (Martin 1926, p. 46). About 1903 T. W. Stanton and G. C. Martin briefly investigated the chert layers near Seldovia, also on the south shore of Kachemak Bay, and correlated them with chert beds of Late Triassic age on the Alaskan Peninsula (Stanton and Martin 1905, p. 393). While investigating mineral deposits on the south shore of upper Kachemak Bay in 1904, F. H. Moffit observed what he termed ellipsoidal lavas. Sidney Paige and U. S. Grant made some brief studies on the east coast of the Kenai Peninsula in 1905 (Capps 1940, p. 14). The investigations by G. C. Martin in 1911 contributed to the knowledge of the bedrock of the Kenai lowland (Martin, Johnson and Grant 1915, p. 19). In 1926 Martin compiled an analysis of the

Mesozoic stratigraphy of all of Alaska. He considered the lava, chert, limestone, and tuff exposed on the south shore of the Kachemak Bay to be of Late Triassic age and concluded that they are underlain by a mass of greywacke and slate which comprises the bulk of the Kenai Mountains (Martin 1926, p. 45). In 1939 P. S. Smith published a volume on the areal geology of Alaska. The following year S. R. Capps produced a much enlarged and revised update of his 1924 regional study of the railbelt. Both authors included sections on the geology of the Kenai Peninsula (Smith 1939, p. 67; Capps 1940, p. 24).

Hydropower Resources

In 1913 C. E. Ellsworth and R. W. Davenport (1915, p. 110-140) investigated the potential for hydroelectric power in the northern and eastern portion of the Kenai Peninsula. At that time a small private hydroelectric plant was already in operation, supplying power to the village of Seward. No further development was undertaken in the region until the early 1950's when the Cooper Lake and Eklutna Lake powerplants were constructed. The U.S. Army Corps of Engineers and the U.S. Geological Survey also studied the Bradley Lake basin as a potential power source. Reports on water resources and site geology were prepared and a hydropower project recommended to the Congress (U.S. Army Corps of Engineers 1955; Johnson 1961; Soward 1962). At that time, however, cheap natural gas became available in the Cook Inlet region and the project was dropped. Rising energy costs have since revived the proposal and the Corps of Engineers has issued a reanalysis of the project (1978). The Alaska District of the Corps of Engineers is now studying in detail the environmental and engineering problems associated with the proposal (Vern Thompson, verbal communication, February 1980).

Geomorphology

The glaciers of the Kenai Mountains drew the attention of the earliest geologists in the region. W. H. Dall visited the Grewinsk Glacier on the south side of Kachemak Bay in 1880, 1892, and 1895. In 1899 he again visited the glacier, this time accompanied by G. K. Gilbert of the Harriman Alaska Expedition who described it in detail (Grant and Higgins 1913, p. 1). In 1908 and 1909 U. S. Grant and D. F. Higgins studied the glaciers of the northeastern part of the peninsula. Late in the summer of 1909 these same men conducted a 64-day boat trip around the south end of the peninsula, mapping topography and studying the glaciers near the coastline (Brooks 1910, p. 13; Grant and Higgins 1913, p. 2). Several years later R. S. Tarr and Lawrence Martin (1914, p. 370-380) published their classic volume of Alaskan glacier studies. Their work extended only to the northeastern portion of the Kenai Peninsula. In 1913 S. R. Capps published a summary of glacial history of Alaska in which he concluded that the entire Kenai Peninsula and Cook Inlet were covered by Wisconsin glaciers (Capps 1931, plate 1). Not until twenty years later was a serious study of Alaskan glacial history undertaken. T. N. V. Karlstrom (1952, p. 1269), in examining the upper Cook Inlet region, recognized four major Quaternary glaciations. He only briefly described evidence from the Kenai Peninsula but implied that the same four episodes extended to that region. In 1953 T. L. Péwé compiled a number of regional studies into a progress report covering most of Alaska. D. B. Krinsley's chapter in that report dealt specifically with the southwest Kenai Peninsula. He recognized evidence for three major glaciations in that area. Ice of the oldest glaciation, which he named the Caribou Hills, covered the entire Kenai lowland. He implied that in that area all evidence of Karlstrom's older Mount Susitna glaciation was destroyed by the Caribou Hills episode. Two younger glaciations were identified as the Swan Lake and the Naptowne (Krinsley 1952, p. 1272; 1953, p. 5). He also found evidence of another glacial advance, the Nikolai Creek glaciation, but was not certain if it occurred during a part of the Naptowne glaciation or was a separate younger event (Krinsley 1953, p. 6). In his summary Péwé correlated the Naptowne and Nikolai Creek advances as late Wisconsin, concluding that the Naptowne occurred between 8,000 and 14,000 years B. P. He considered the Swan Lake glaciation to be early Wisconsin, of an age greater than 18,000 years, and the Caribou Hills and Mount Susitna advances to be pre-Wisconsin (Péwé and others 1953, p. 13). Karlstrom continued to refine the understanding of the regional glacial history and published several documents on the subject (Karlstrom 1955b, 1956, and 1957). In 1964 he published a comprehensive work encompassing the Quaternary geology and history of the Cook Inlet and surrounding regions. He revised Krinsley's interpretations to include five major ice advances, discarding the Swan Lake glaciation and replacing it by two separate glaciations, the Knik and Eklutna. He also dropped the term Nikolai Creek and divided the late Naptowne glaciation into four individual advances. The glacial history of the most recent few thousand years was referred to as the Alaskan glaciation. A summary of his interpretations are tabulated in table 1. On his

TABLE 1

GLACIAL CHRONOLOGY OF THE COOK INLET REGION AND KENAI PENINSULA, ALASKA
Compiled from Karlstrom (1964, p. 63)

Name of Episode	Maximum Advance (Years B.P.)	Approximate End of Episode (Years B.P.)
Mount Susitna	217,000 ± 15,000	200,000
Caribou Hills	175,000 ± 18,000	155,000
Eklutna	102,000 ± 10,000	90,000
Knik	60,000 ± 8,000	45,000
Naptowne	19,000 ± 3,000	5,500
Alaskan	4,000 ± 500	continuing

map of the extent of the glaciations he designated over thirty small areas on the west side of the southern Kenai Mountains as not having been covered by ice since the Eklutna glaciation. These areas would have thus stood as nunataks during subsequent glaciations. (Dakota Mountain and most of the other periglacial surfaces mapped during this present investigation are located in these areas). Karlstrom also studied permafrost, groundwater, and other aspects of surficial geology in parts of the Kenai lowland but not in any of the upland areas of the Kenai Mountains (Karlstrom 1955a and 1958).

I was unable to find any reference to periglacial phenomena in the Kenai Mountains. Wahrhaftig (1950, p. 1532) did mention periglacial processes as a landform modifier in the coastal mountains of Alaska but did not include specific locations or processes. Karlstrom (1955a, p. 133) mapped the entire Kenai Peninsula as part of the "no permafrost" zone, but J. R. Williams and R. M. Waller (1965, p. 160) and Warren George (1965, p. 221) included the southern Kenai Mountains within the region of possible permafrost. Péwé (1965, figure 3) plotted the limit of spradic permafrost directly through the Bradley Lake area. At this time the most accurate statement on the occurrence of permafrost and associated features is that of Wahrhaftig (1965, p. 40) who states that the extent of permafrost in the Kenai-Chugach Mountains is unknown.

Field Methods

field study for this investigation consisted primarily of photographing, mapping, measuring, and excavating periglacial features on Dakota Mountain. About 150 black and white photographs and numerous color slides were taken on or near the mountain. Dominant features were observed on the ground and mapped onto a 1:15,840 scale base map of Dakota Mountain derived from the 1:63,360 USGS topographic quadrangle maps of the area. Other periglacial surfaces in the region were mapped from a high point on Dakota Mountain and from low level aerial reconnaissance in a light airplane.

Surface features were measured using a Brunton compass and a steel tape. These were also used to install movement pins on several features. Soil temperatures were measured using a dial thermometer calibrated in degrees Celsius. Soil colors were identified using standard Munsell soil colors. Excavations on Dakota Mountain were made using only light tools which had been backpacked from Bradley Lake.

These excavations were:

a. A trench 3 m long and 1 m deep through three sorted steps.

b. A 2.1 m deep pit through a snow patch into a northfacing slope.

c. Five shallow trenches through sorted circles.

d. Three trenches up to 0.9 m deep and 2 m long through non-sorted polygons.

e. One excavation of a hummock in a hillside hollow.

f. A large trench 1.7 m deep and 2 m long through the front of a prominent gelifluction lobe.

Laboratory Methods

Sediment Samples

Twenty five samples of unconsolidated material were collected from Dakota Mountain and brought to the University of North Dakota for analysis. Each sample was air dried at room temperature and sizes separated using a RoTap machine and standard sieves at one-quarter-Phi intervals. Large samples were mechanically split after removal of gravel size particles. The fraction from each sieve was weighed and microscopically examined for aggregations. Fractions were statistically adjusted for aggregate content of less than 25 percent (Folk 1974, p. 34). Those exceeding this limit were disaggregated using a rubber-tipped pestle and the sieving process repeated. Pipette analysis of the fraction smaller than 4.0 Phi was performed according to the procedures outlined by Galehouse (1971, p. 79). A one percent concentration of Calgon was used as a dispersing agent. Pipette samples were taken at whole Phi intervals from 4 to 12 Phi. A Fortran computer program written by T. A. Cross (1974) was extensively modified in order to analyze the sieve and pipette data. Output for each sample consisted of statistical parameters and grain size distribution in the form of a histogram, a table, and a cumulative curve.

A sample of the well sorted fine sand from Site K (Figure 3) was stirred into a clear epoxy resin, poured into a plastic form, and cured to proper hardness. The resulting block was cut, polished, mounted on a glass slide and ground to optical thickness. The thin section was studied under a petrographic microscope to determine general mineral composition and grain characteristics. Another small sample of the same sand was studied using the scanning electron microscope and microprobe. The surface morphology and elemental composition of some twenty grains of various mineralogy were observed. Preparation was according to Krinsley and Doornkamp (1973, p. 7).

Rock Samples

Thin sections of four rock samples were prepared and examined under a petrographic microscope. Two of the samples were typical country rock, one was a small banded erratic, and one was a polished faceted erratic cobble. A small piece of the polished surface of the cobble was examined under the scanning electron microscope.

Radiocarbon Samples

Four samples of buried organic soil were obtained from excavations in Camp Valley for the purpose of establishing radiocarbon dates of key events in the history of that area. Unfortunately, modern roots extended into each sample and if allowed to remain would drastically bias the radiocarbon results. Attempts to hand-pick all modern root hairs from the samples under a binocular microscope proved ineffective, time consuming, and frustrating. A system of sieving and floatation was devised to facilitate the removal of the root hairs. The procedure is described in appendix C. The samples were sent to the U.S. Army Cold Regions Research and Engineering Laboratory. They have since been submitted by CRREL to a radiocarbon dating laboratory but no results are available at this time.

OBSERVATIONS

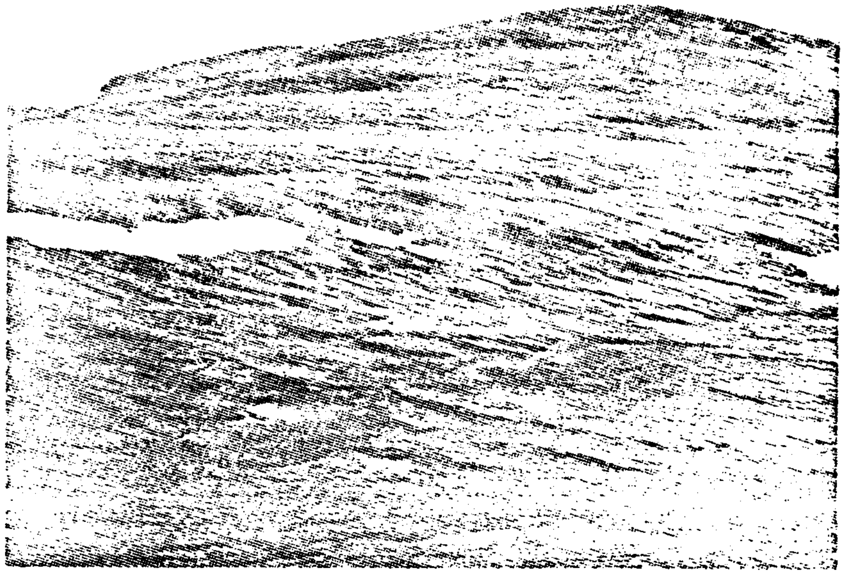
Many different types of geomorphic features of various scales are present on Dakota Mountain. This section is a description of the features observed and summarizes other data collected in the study area. Other than the periglacial implication of the term gelifluction, interpretations of process and environment are deferred to the next section.

Gelifluction Lobes

Large linguoid-shape gelifluction lobes are common on Dakota Mountain, particularly on south-facing slopes of 10° to 20°. The largest concentration of these features is on the north side of Camp Valley (Figures 3 and 4). They are typically 10 to 20 m long, 4 to 8 m wide, and stand from 0.2 to 1.1 m high at the lobe front. Their long axis seldom is aligned precisely downhill; it may deviate as much as 45° to the right or left. All of the lobes on south-facing slopes tend to deviate to the east in an en echelon arrangement. The entire lobe is covered by alpine tundra vegetation, but it is most dense at the lobe front. There is little evidence of frost heaving or sorting associated with these features with the exception of a sorted stripe of coarse rock fragments on the center line of several lobes. Few sorted circles and no prominent vertical stones were observed. Two samples of sediment were collected from within a lobe at Site K at the base of the north side of Camp Valley

Fig. 3. Gelifluction lobes on the north side of Camp Valley. The tent below the snow patch at left indicates scale.

Fig. 4. Gelifluction lobes on Dakota Mountain. Lobe fronts are approximately 500 mm high.



(Figure 5). Grain size analysis revealed 85% gravel, 14% sand, 1% silt, and negligible amounts of clay. This distribution corresponds well with that of samples from a steep north-facing slope at Site B and from beneath an apparently active sorted circle at Site I (Plate 1).

Hollows and Platforms

Other prominent features on Dakota Mountain are cirque-shape hollows with an associated platform of debris (Figures 6 and 7). Single cirque-shape hollows are from 100 to 100 m across. Some are elongated across the hillslope to form a terrace-like feature up to several hundred metres long (Figure 10). They occur most commonly on hillslopes of 10° to 15°. Although they were observed on slopes of every direction, the best developed examples face southwest. The headwall of each hollow typically is inclined 25° at the steepest point and grades into the nearly horizontal floor of the hollow. Both the floor and the lower portion of the headwall have a luxuriant assemblage of flora growing on usually well developed hummocks. The distal end of the hollow is a platform of accumulated debris. The platform is about equal in volume to the amount apparently excavated to form the hollow. The slope of the top of the platform in many cases is a few degrees opposite that of the hillslope. For this reason some hollows have internal drainage. Many more drain to the side rather than over the platform. The fronts of some platforms display a steep, lobate shape similar to the terminus of a gelifluction lobe such as described above; the platform fronts are wider and usually much higher, however, often exceeding 2 m. The coarsest surface material and the sparsest vegetation occur at the crest of the platform. While most of the study area was clear

Fig. 5. Profile through gelifluction lobe at Site K (Plate 1). Samples collected at numbered locations are described in table 2.

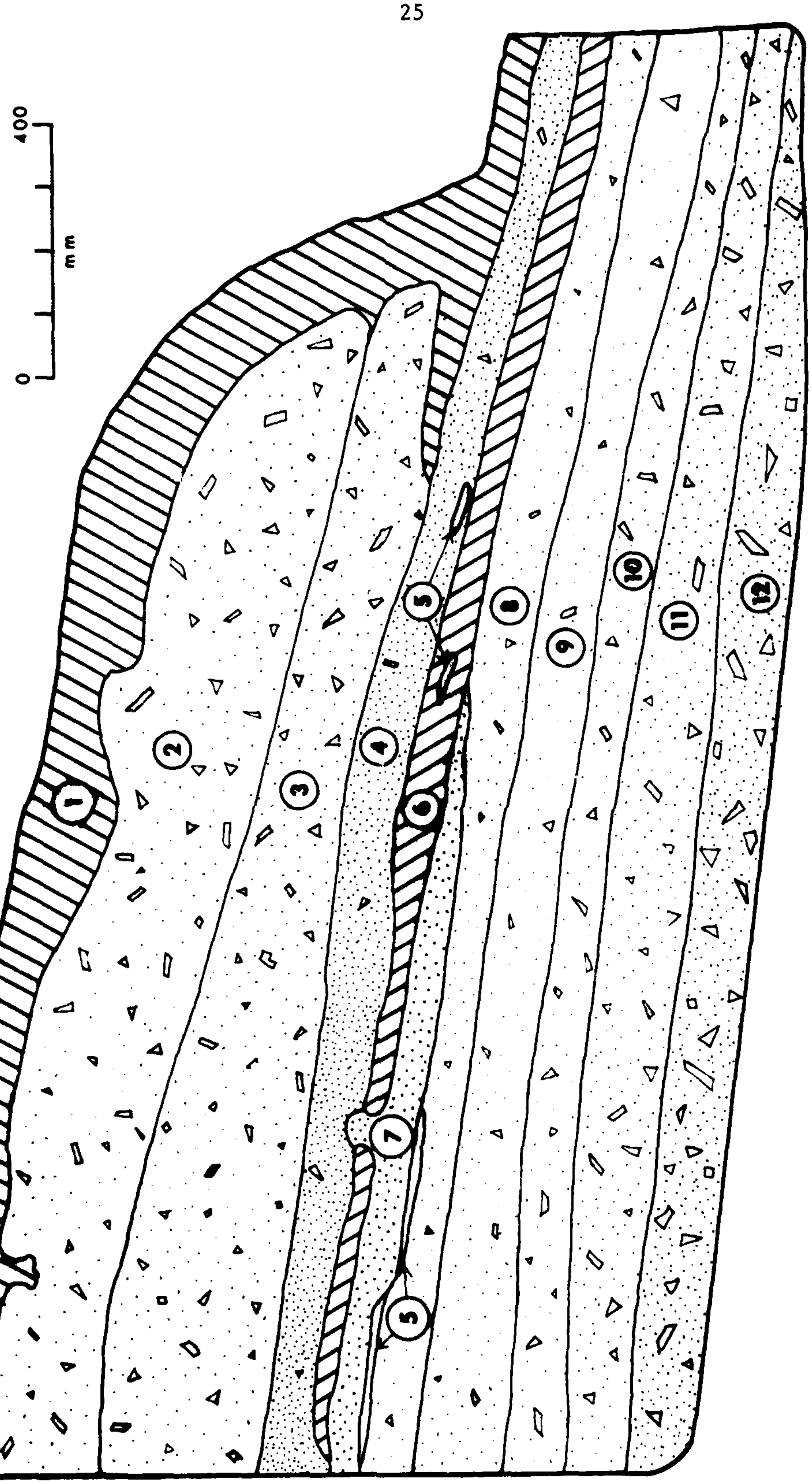

0
400
mm
1
2
3
4
5
6
7
8
9
10
11
12

TABLE 2

PHYSICAL CHARACTERISTICS OF SAMPLES FROM THE GELIFLUCTION LOBE AT SITE K.
(Sample locations are shown in Figure 5)

Sample Number	Munsell Color Name	Munsell Color No.	Mean Grain Size (mm)	Weight Percent Gravel	Sand	Silt	Clay	Description
1	Dark brown	7.5YR 3/2	-	-	-	-	-	Organic mat of roots.
2	Olive brown	2.5Y 4/4	4.51	84.5	13.9	1.7	0.01	Particles up to 40 mm, many roots.
3	Dark grayish brown	10YR 4/2	5.74	84.8	14.2	0.9	0.03	Some cobbles, many roots.
4	Dark grayish brown	10YR 4/2	.77	33.3	61.0	5.5	0.12	Few large particles.
5	Yellowish brown	10YR 5/4	.18	.6	92.3	7.0	0.09	Thin well sorted sand lenses.
6	Dark yellowish brown	10YR 3/4	.22	2.8	90.0	7.3	0.03	Sandy layer, darker under lobe.
7	Brown	10YR 4/3	.28	12.1	75.0	12.6	0.21	Discontinuous sandy layer.
8	Dark brown	10YR 3/3	.35	15.6	73.8	10.6	0.09	Sandy layer with some pebbles.
9	Dark brown	10YR 3/3	.79	34.3	59.7	6.0	0.03	All sizes. Contains reddish streaks.
10	Dark brown	7.5YR 3/2	3.37	70.9	26.7	2.4	0.01	Large particles. Some roots.
11	Olive brown	2.5Y 4/4	3.73	77.9	20.2	1.9	0.06	Gradational boundary.
12	Dark grayish brown	2.5Y 4/2	-	-	-	-	-	Particles up to 400 mm.

Fig. 6. Hollow containing a snow patch. The 450 mm long mattock on the snow indicates scale.

Fig. 7. Hollow and associated platform of debris. The person is standing near the crest of the platform.

of snow early in June, nearly all of the hollows still retained snowbanks; some hollows supported snow patches well into July. The only evidence of frost sorting on these features was near the crests of the platforms.

Terraces

There is a distinct terraced effect on several of the hillslopes on Dakota Mountain (Figures 8 and 9). A good example of this occurs on the southwest slope of the hill just north of the east end of Camp Valley. The upper convex portion of the slope inclines at 11°, then descends for 25 m at 18°, levels to 6° for 52 m and continues downslope at 14°. Level surfaces similar to the treads of terraces occur on each hilltop and along several divides on the mountain. There is no apparent preferred orientation of the terraces, but those on the southerly facing slopes seem better developed.

String Bog

A small but well developed string bog (Troll 1944, p. 72) occurs at the west end of Camp Valley (Figure 11). It is about 90 by 130 m and is at the base of a large snowbank. The snowbank is sufficiently large to provide a continuous flow of melt water day and night during the entire melting season. The water flows through the bog and exits Camp Valley to the north under a yet larger perennial snowbank. The vegetation-covered "strings" are oriented in a northwest and southeast direction, parallel to water flow.

Fig. 8. Terrace on a southwest-facing slope of Dakota Mountain.

Fig. 9. Terrace on a north-facing slope of Dakota Mountain.

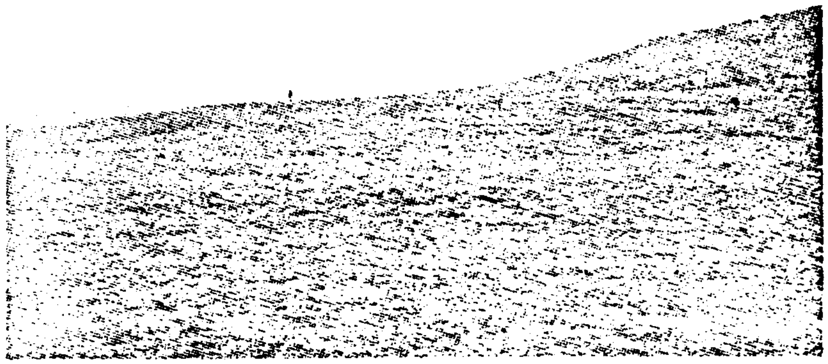


Fig. 10. Cirque-shape and elongated hollows on Dakota Mountain.

Fig. 11. String bog in Camp Valley. The bog is 130 m long from the base of the snowbank to the outlet.

Lineations

Both large and small scale surface lineations are present on Dakota Mountain. The southern Kenai Peninsula exhibits widespread regions of prominent structurally controlled lineations. The area near the Bradley River, 6 km west of Dakota Mountain, displays a well developed rectangular (lineation-controlled) drainage pattern. On aerial photographs of Dakota Mountain there are two distinct east- and west-trending lines 130 m apart located 350 m north of and parallel to Camp Valley (Figure 12). A strip of darker colored surface material lies between the lines. These lines were not observed from the ground. The lines and Camp Valley itself are parallel to a prominent set of structurally controlled lineations displayed elsewhere in the region.

On the eastern portion of Dakota Mountain smaller scale lineations were observed on the ground. They were visible as unobtrusive alignments of pebbles, edges of angular cobbles, and surface lichen patterns. The alignment was strikingly obvious when viewed along the lineation but invisible from any other direction. A number of these subtle lines is found near the rim of the large cirque at the extreme north end of the mountain. They are perfectly straight and may extend for up to 100 m or more. There is no apparent pattern to their orientation. In some cases they intersect one another. Two lineations were traced to exposed bedrock outcrops at the top of the cirque wall and found to coincide with the orientation of two prominent joint sets.

Much smaller scale lineations were observed in the fine surface material of the centers of some sorted circles. These lineations

Fig. 12. Photographic stereogram of Dakota Mountain area taken July 4, 1951. Part of Bradley Lake is in the southwest corner. Photographs provided by the U.S. Army Cold Regions Research and Engineering Laboratory. Scale: 1:43,000.

consist of narrow parallel ridges of sand and silt not more than 5 mm high and 10 mm apart. The ridges are often capped by granules or small pebbles. The presence of the lineations was not noted until the day following two days of snow and freezing ground temperatures. They were observed only in Camp Valley and the north-south trending saddle to the north of Camp Valley. Both of these features serve as wind funnels which topographically control wind direction. The small scale lineations are oriented parallel to the wind directions.

Patterned Ground

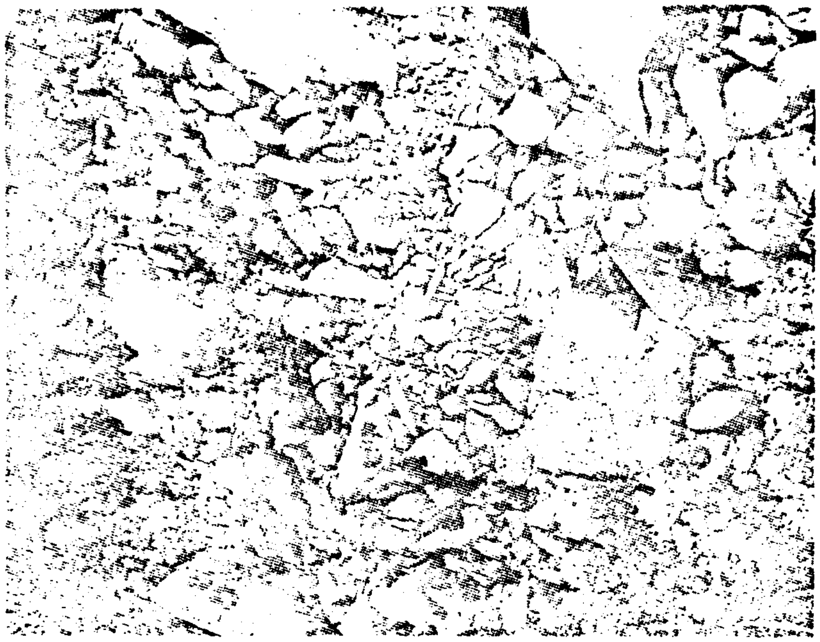
In describing the patterned ground found on Dakota Mountain the non-generic nomenclature proposed by Washburn (1956, p. 826) is used. Patterned ground is polygenetic and similar forms may result from different processes (Washburn 1973, p. 137; Embleton and King 1975, p. 68). Interpretation of the processes of formation of the features are discussed later.

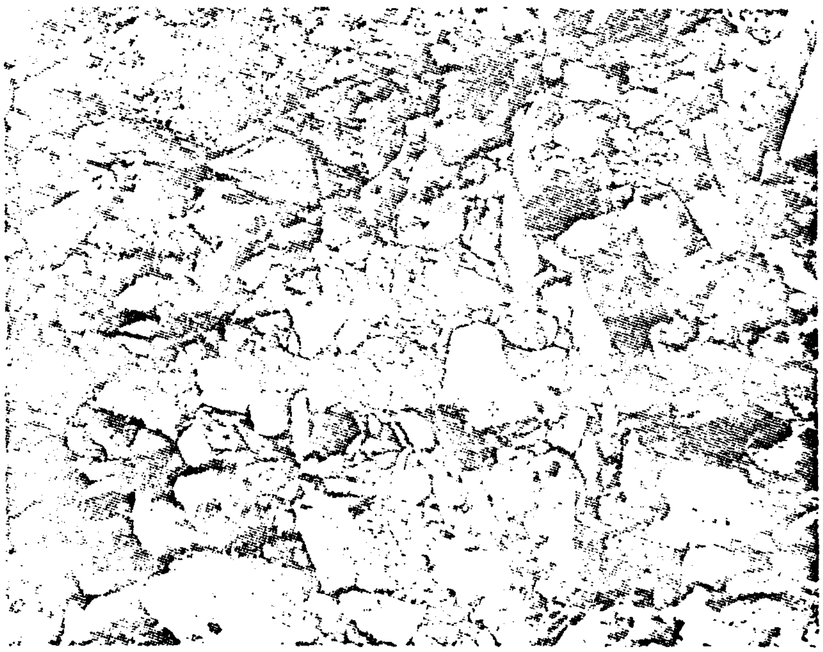
Sorted Circles

Sorted circles are found on nearly every part of Dakota Mountain. In many cases they are not perfectly circular in outline but have been distorted by local conditions. Those on hillsides tend to be elongated in the down slope direction. Typical circles are 0.5 m in diameter and consist of a center of finer particles up to 40 mm in length surrounded by a margin of coarser rock fragments (Figures 13 and 14). Small areas within the centers often exhibit a packing of particles oriented with their long axis radial and their intermediate axis vertical. Some of the centers consisted of an exposed core of sand and silt with only

Fig. 13. Sorted circle on Dakota Mountain. Note the stone packing in the center. The 90 mm long knife indicates scale.

Fig. 14. Sorted circle on Dakota Mountain. Note the black lichens on more stable particles surrounding the circle.





scattered granules and pebbles at the surface (Figures 15 and 16). Excavations of sorted circles were made at Sites C, D, G, H and I (Plate 1). It was discovered from these excavations that the sorting effect is very shallow. The sand and silt centers extended to a depth of about 30 mm. Centers containing larger particles were not obvious in damp material below a depth of 90 mm. In one excavation which had been allowed to dry, however, a preferential orientation of particles was apparent below the center to a depth of about 140 mm.

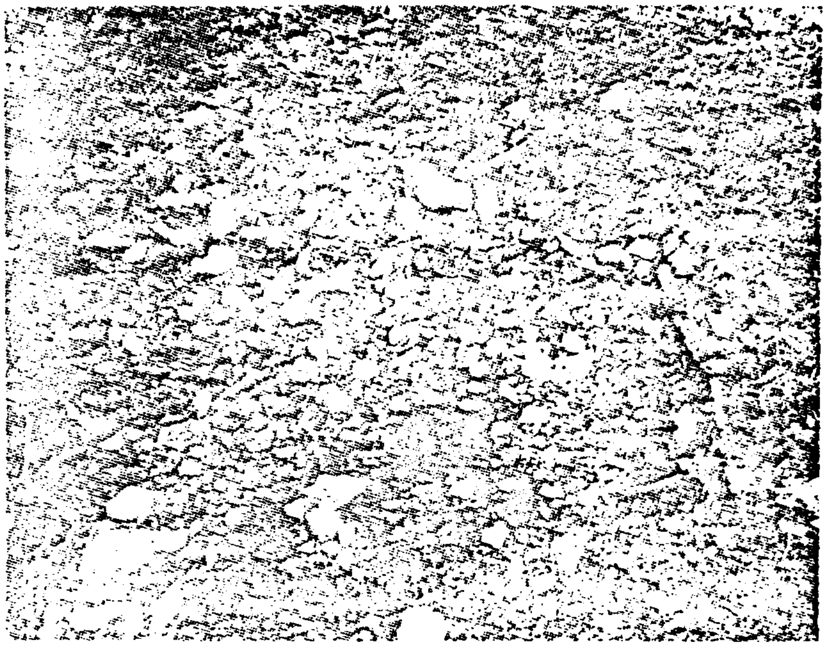
The circles are found on level hilltops, gently sloping valley sides, and the treads of sorted steps. On the hilltops, where much of the surface may be covered by black crustaceous and foliaceous lichens, the stone centers have a striking appearance of freshly exposed light-colored rock. In some circles sorting is not apparent; the centers are identified only because of the stone packing and the distinct lack of lichen cover.

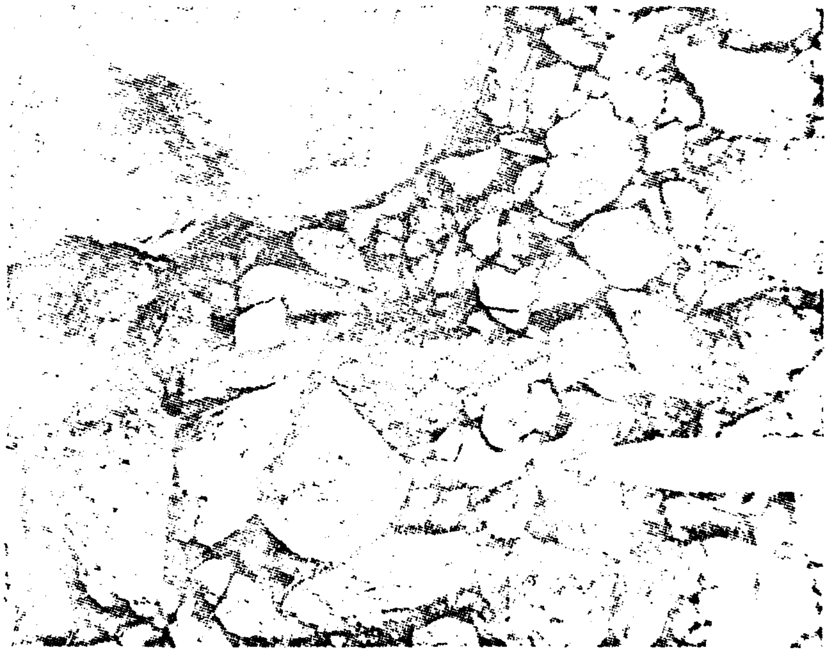
Nonsorted Nets

Well developed earth hummocks comprising nonsorted nets are found within the hollows described above (Figure 17). They support an assemblage of thick and continuous flora which contrasts with the patchy dry tundra flora elsewhere on the slopes. Individual hummocks are typically 0.3 m high and one metre in diameter. The largest was 0.4 m high and 1.6 m across. This corresponds well with those described by Sharp (1942, p. 282). The hummocks occur on the floor and lower portion of the back wall of the hollow, but do not extend onto the associated platform. Their extent appears to correspond approximately to the maximum limit of the snow patch in the hollow.

Fig. 15. Sorted circle on Dakota Mountain. Note the exposed fine-grained center. The 90 mm long knife indicates scale.

Fig. 16. Small scale sorted circle on Dakota Mountain.





On June 30th an excavation of a typical hummock was made at Site E (Figure 18). The hummock was 1.4 m in diameter and 0.33 m high. The surface consisted of a mat of humus, roots, moss, and other tundra plants, which varied from 130 mm thick at the edge to 210 mm at the crest of the hummock. This mat covered a solidly frozen core consisting of a few large angular cobbles and pebbles intermixed in a fine matrix. The afternoon temperature 100 mm deep in the center of the mat was 2.4°C. The temperature 40 mm into the frozen core was -0.1°C. An excavation to 450 mm and additional probing to a depth of 640 mm between hummocks revealed no frozen ground. When the site was reexamined 16 days later no frozen ground could be found even under the largest hummocks.

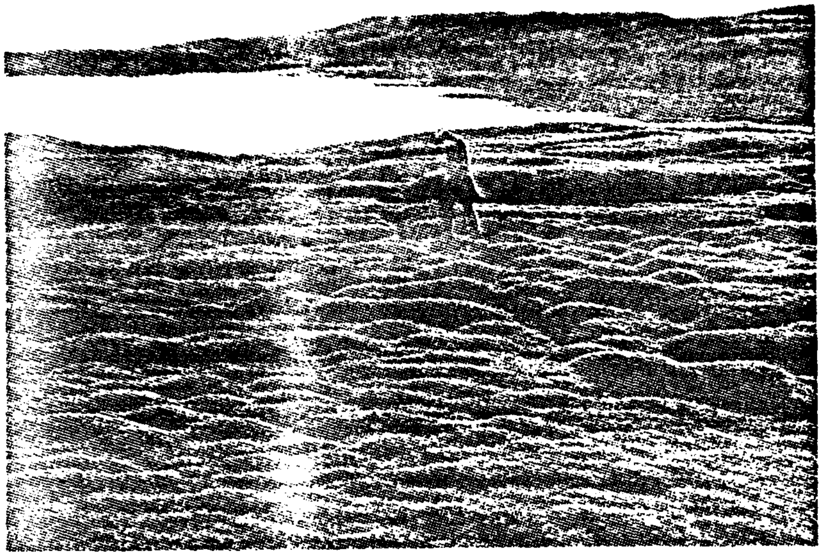
Sorted Polygons

Sorted polygons from 0.9 to 3.1 m across are found on the high level areas of Dakota Mountain (Figures 19 and 20). The borders are typically 500 mm wide and contain coarse angular particles up to 300 mm long. The centers of the polygons are turf-covered and not obviously higher or lower than the margins. Apparently active sorted circles are common at the polygon borders and have obscured the original shape of the polygonal patterns. Except for particles in the centers of sorted circles, the stones of the polygon borders generally support a well developed growth of black lichens. Vertical stones up to 300 mm tall are also common.

Small scale sorted polygons were observed in several small areas within the string bog. The polygons are approximately 200 mm across and cover the mud bottoms of drained pools one-half to four metres in

Fig. 17. Earth hummocks on Dakota Mountain.

Fig. 18. Excavation of an earth hummock at Site E (Plate 1). The material beneath the knife is frozen.



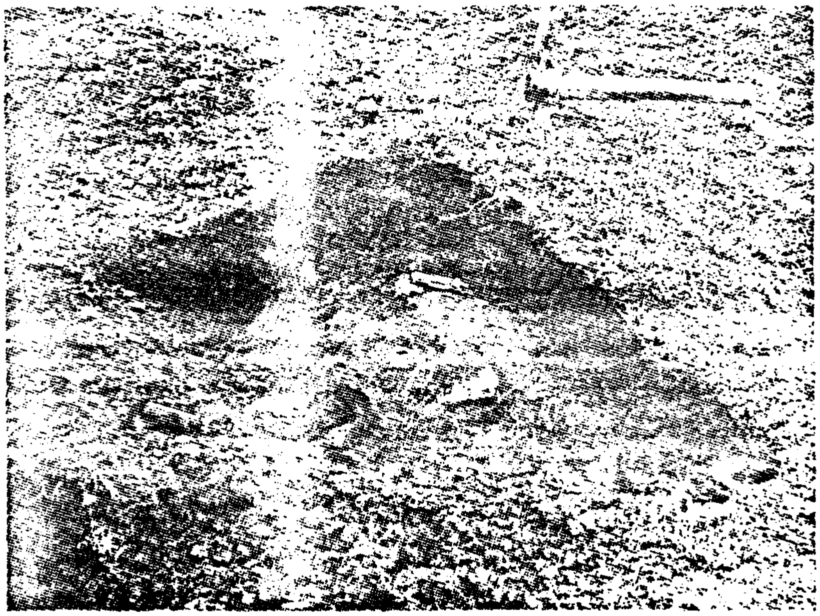
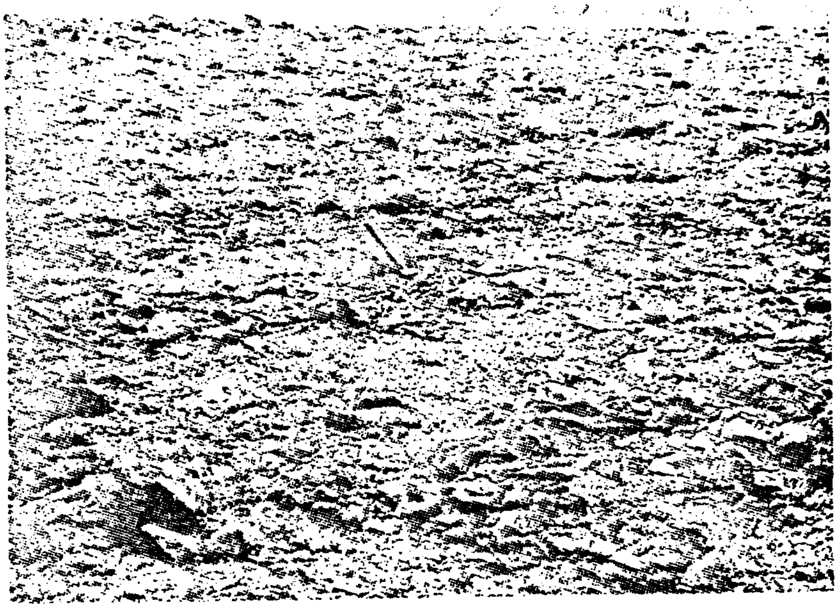
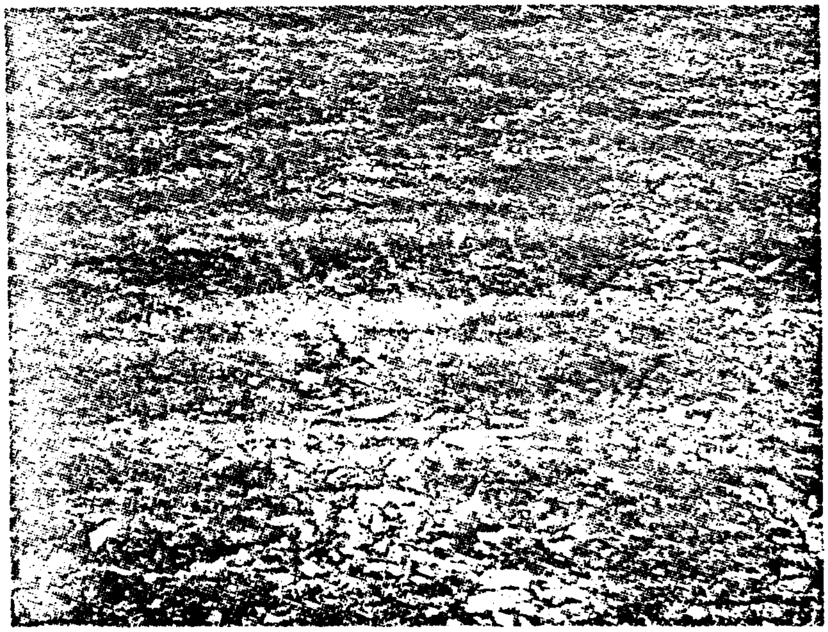


Fig. 19. Sorted polygons and vertical stones on a hilltop on Dakota Mountain.

Fig. 20. Sorted polygons on Dakota Mountain. The 450 mm long mattock indicates scale.





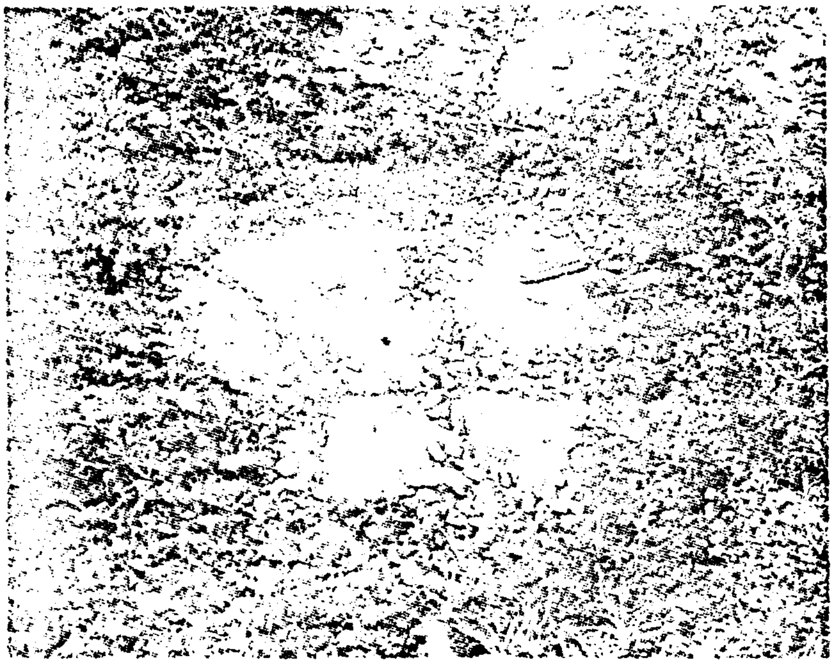
diameter (Figures 21 and 22). The borders of the polygons consist of narrow cracks in the mud surface in which pebbles from 6 to 10 mm in diameter are lodged. Some cracks are nearly devoid of pebbles, others are filled for their entire length. Pebbles are more numerous in the cracks toward the lower or outlet end of each pool becoming sparser toward the inlet. In each pool there is an accumulation of pebbles along the lower end of the pool.

Nonsorted Polygons

An area approximately 80 m wide by 90 m long in that part of Camp Valley some 300 m east of the string bog is covered by nonsorted polygons. The features are 0.6 to 1.5 m in diameter and are delineated by shallow vegetated troughs about 100 mm deep and 300 mm wide. Such polygons were excavated at Sites F, J, and L (Figures 23 and 24). It was found that a very dark grayish-brown layer rich in organic matter covered the features to a depth of about 100 mm in the centers of the polygons and extended to a maximum depth of 420 mm beneath the troughs. This layer was underlain by inorganic olive-brown sediment composed of 85% gravel, 14% sand, and 1% silt. In each excavation this material was near saturation. At Site F the local water table was encountered at a depth of only 920 mm. The contact between the two zones was marked in places by a concentration of large angular pebbles. Distorted layers and irregular masses of dark organic-rich material were discovered within the olive-brown zones in two of the three excavations as well as under a nearby sorted circle at Site G. At Site L the most distinct of these layers was from 20 to 90 mm thick and could be traced for 1.1 m. It dipped 36° to the southwest and

Fig. 21. Sorted polygons in a small drained pool of the string bog. The 90 mm long knife indicates scale.

Fig. 22. Sorted polygons in a larger drained pool of the string bog.



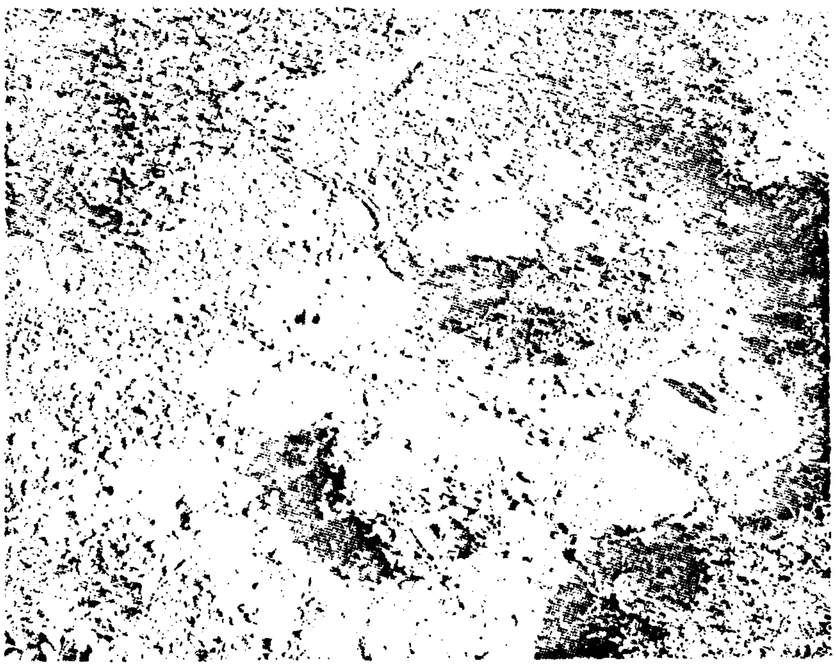
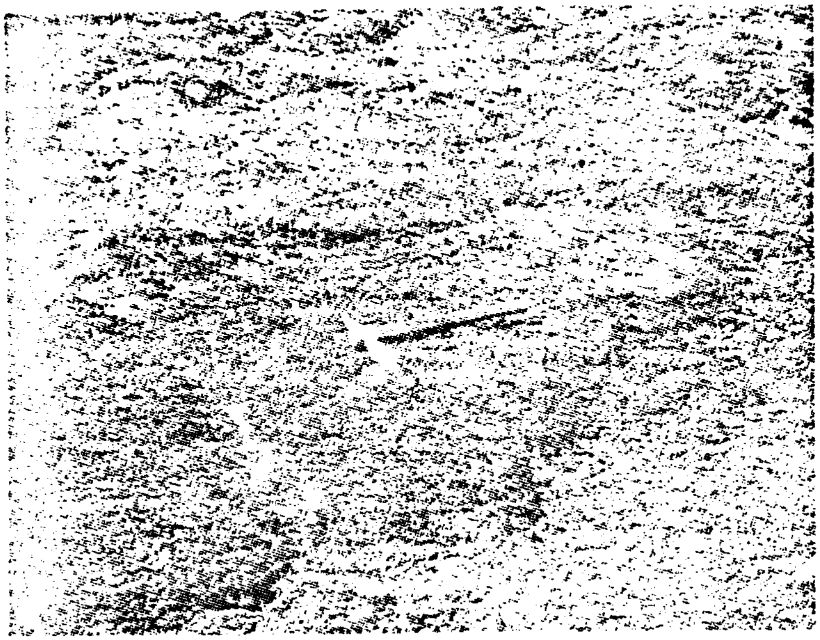


Fig. 23. Nonsorted polygon at Site J (Plate 1).

Fig. 24. Excavation through nonsorted polygon at Site J (Plate 1). The thickness of the organic zone is approximately 150 mm.



corresponded in both strike and dip to the face of a 0.4 m scarp several metres to the southwest. Part of Site L is sketched in Figure 25.

Sorted Steps

Small regular sorted steps with turf-banked risers and rock-covered treads are present on most of the south- to southwest-facing slopes of Dakota Mountain (Figures 26 through 29). They are in general parallel to the contours but many exhibit a longitudinal slope of up to 10°. The vertical rise between steps is less than 0.5 m and the horizontal spacing is typically one to three metres. The tread surfaces usually dip a few degrees into the hillslope. The treads are typically covered by angular rock fragments with little vegetation. The sediment forming the surface of one representative tread was 92.7% gravel, 6.8% sand, 0.5% silt and 0.0% clay. Although vertical stones are not often observed on these features, widespread evidence of frost heaving and sorting is present on the treads. Sorted circles with oriented rock particles are ubiquitous. The steps are often associated with hollows and platforms.

Sorted Stripes

Short sorted stripes are associated with the sorted steps described above where the slope exceeds about 15°. The composition of the surface sediment of the stripes is similar to that of the step treads. Most stripes typically are in the form of a branch of a step tread and descend at some angle to the local slope to the next lower step. As the slope steepens, the orientation of the stripes become more closely aligned to the slope direction. On the upper slope of the southwest end of Dakota Mountain, where the slope locally exceeds

Fig. 25. Nonsorted polygon at Site L (Plate 1). A composite view of the north walls of an "L"-shape excavation is shown.

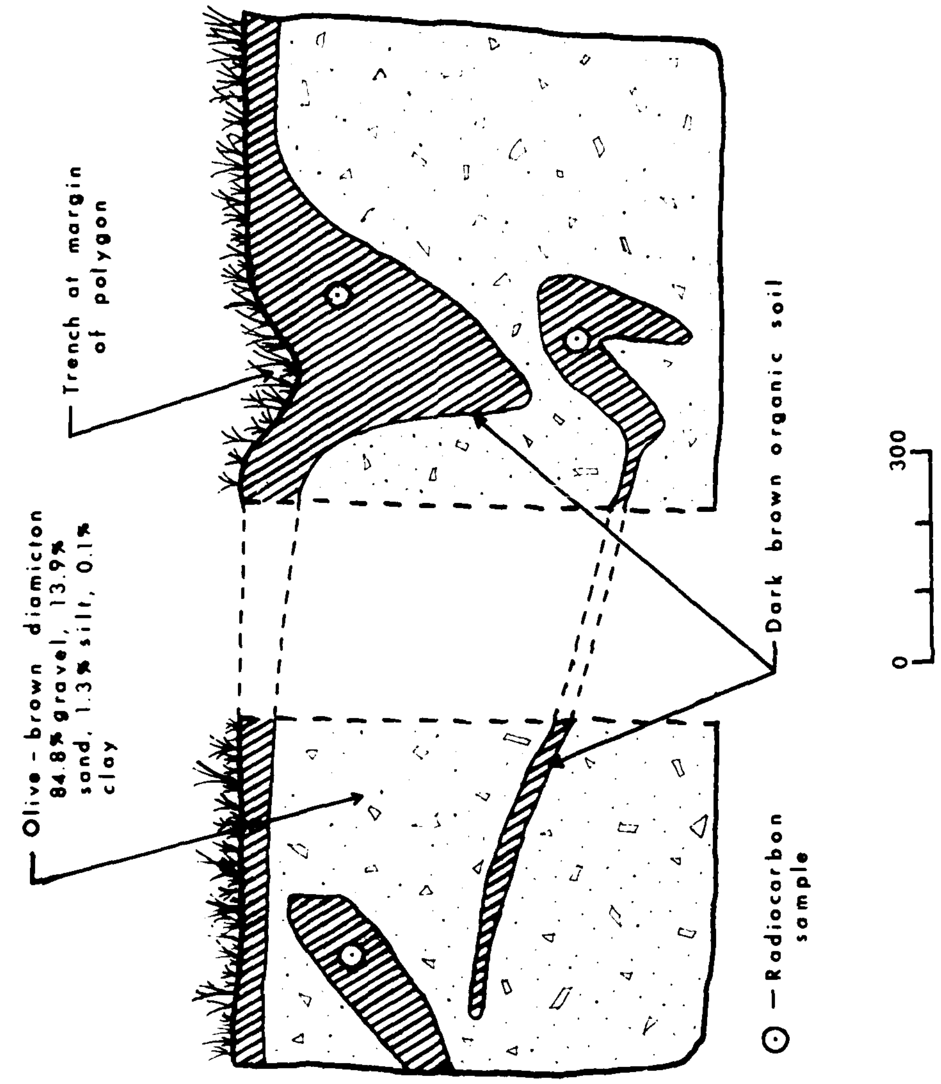

Trench at margin of polygon
Olive - brown diamicton 84.8% gravel, 13.9% sand, 1.3% silt, 0.1% clay
Dark brown organic soil
0
300
mm
— Radiocarbon sample

Fig. 26. Sorted steps at the west end of Camp Valley. The distance between steps is approximately 1.5 m.

Fig. 27. Turf-banked sorted steps on a southwest-facing slope of Dakota Mountain. The 300 mm long hammer indicates scale.

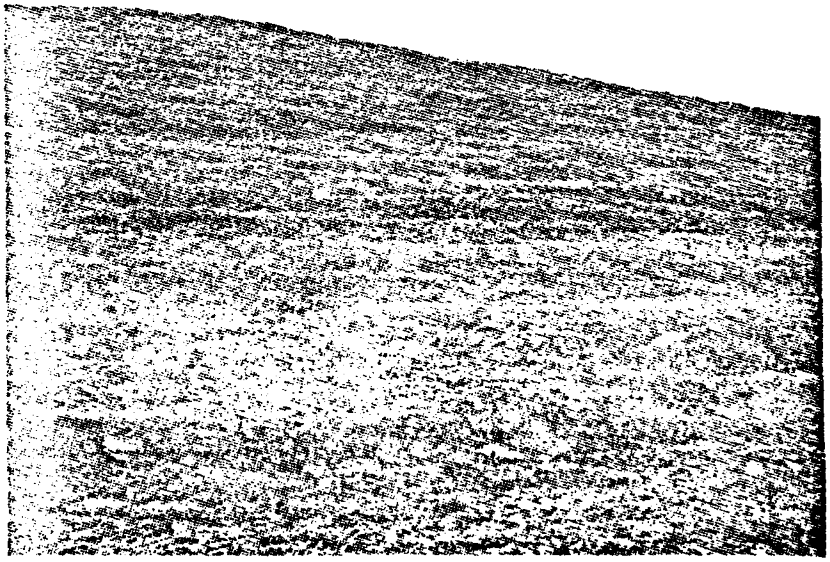
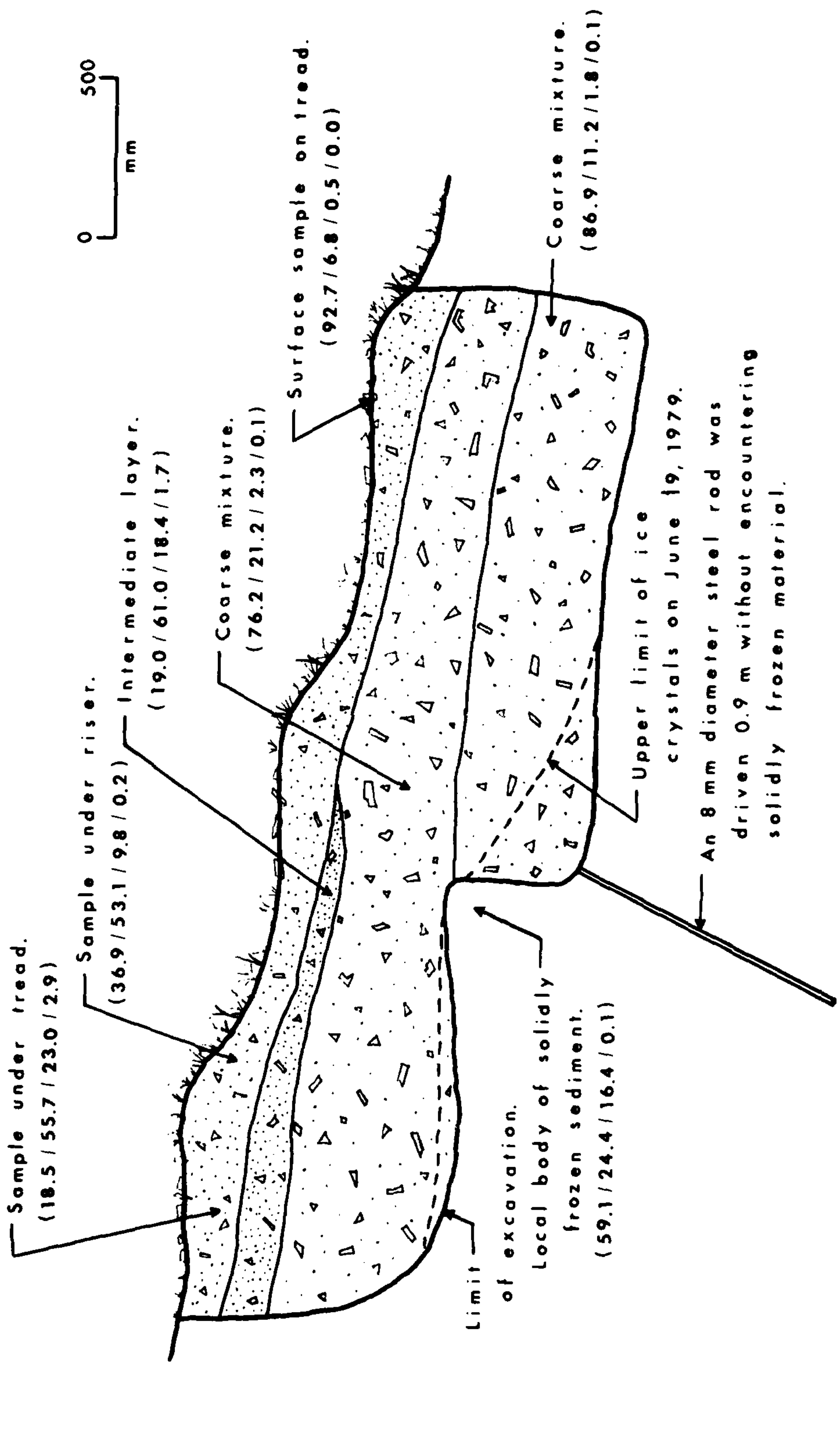


Fig. 28. Turf-banked sorted steps at Site A (Plate 1). The particle size distribution is shown for each sample. Numbers indicate weight percent of gravel / sand / silt / clay.


0
mm
500
Sample under tread.
(18.5 / 55.7 / 23.0 / 2.9)
Sample under riser.
(36.9 / 53.1 / 9.8 / 0.2)
Intermediate layer.
(19.0 / 61.0 / 18.4 / 1.7)
Coarse mixture.
(76.2 / 21.2 / 2.3 / 0.1)
Surface sample on tread.
(92.7 / 6.8 / 0.5 / 0.0)
Coarse mixture.
(86.9 / 11.2 / 1.8 / 0.1)
Upper limit of ice crystals on June 19, 1979.
An 8 mm diameter steel rod was driven 0.9 m without encountering solidly frozen material.
Limit of excavation.
Local body of solidly frozen sediment.
(59.1 / 24.4 / 16.4 / 0.1)

30°, the stripes are 0.5 to 1.2 m wide, composed of angular fragments up to 140 mm long, and oriented directly down slope. The stripes are usually truncated at the next lower step and seldom reach a length exceeding 3 m.

About 1100 m east of the string bog a series of curved sorted stripes was found at the margin of a late melting snow patch. The stripes consist of alternating one metre wide zones of alpine vegetation and exposed rock particles. The vegetated zones are raised 150 to 300 mm above the adjacent unvegetated zones. The rock particles seldom exceed 100 mm in length; the average is less than 40 mm. The stripes descend to the south into a saddle between the main mountain mass to the north and a smaller hill to the south. Within the saddle the stripes divide, one-half curving east, the other half curving west. Surprisingly, the two sets of stripes do not separate at the crest of the saddle; the actual divide is over 100 m to the east. Thus, those stripes which curve east actually trend upslope for a distance before cresting the divide and continuing downslope.

Long narrow sorted stripes about 100 mm apart were sometimes observed in unvegetated areas just downslope from melting snowbanks (Figure 30). Sorting is present but not distinct. The darker stripes are often slightly entrenched and consist of particles coarser than those in the spaces between stripes.

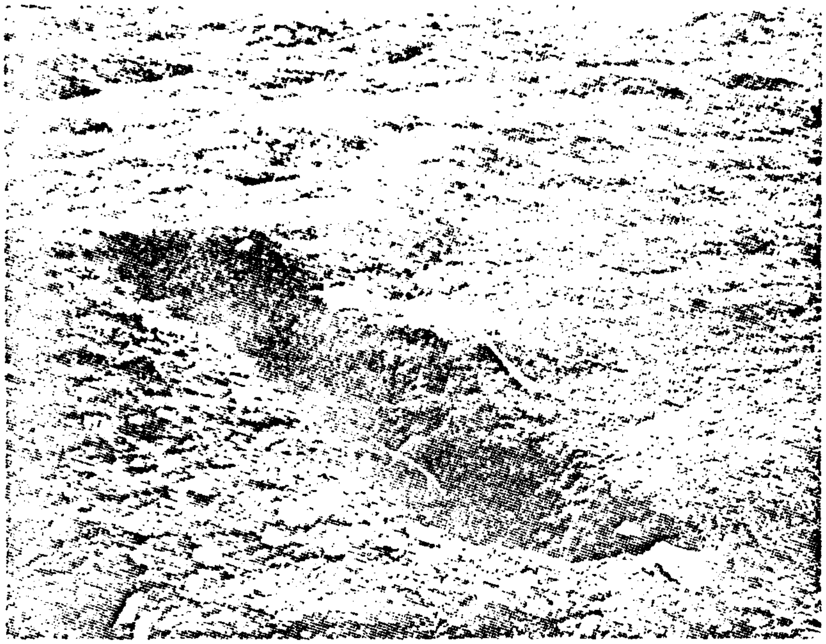
Other Observations

Organic Spheres

During microscopic examination of soil from Site L (Figure 25) a large number of small black spheres was discovered in several samples.

Fig. 29. Excavation through turf-banked sorted steps at Site A (Plate 1).

Fig. 30. Small scale sorted stripes at the margin of a melting snow patch. The 90 mm long knife in the center of the photograph indicates scale.



Further investigation revealed their presence in each and every sample of surficial sediment collected on Dakota Mountain as well as from the several buried organic layers in Sites J and L.

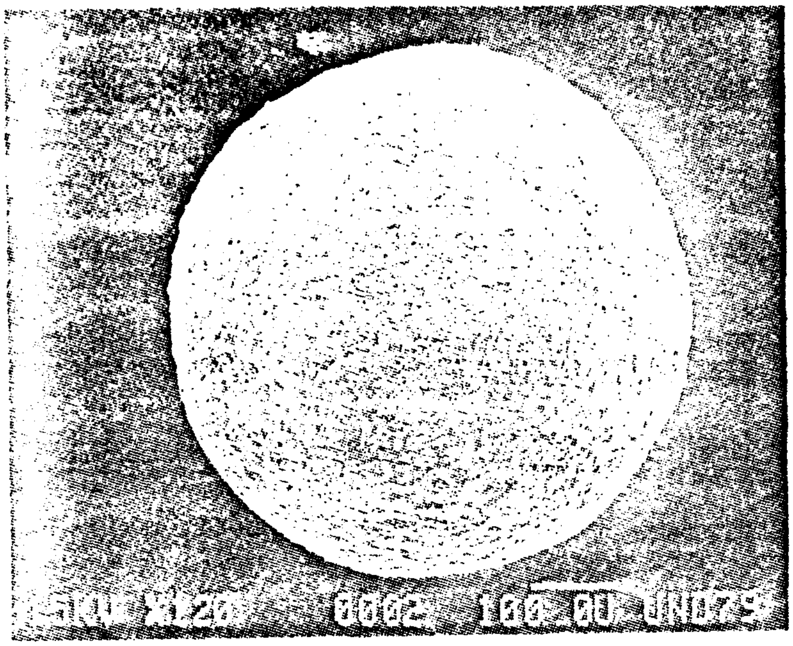
The largest of the spheres observed was 1.40 mm in diameter, the smallest 0.20 mm, and the average about 0.4 mm. Whole spheres usually float in water whereas most fragments of crushed spheres slowly sink. They have a vesicular interior structure with a distinct thickened rind (Figures 31 and 32). The color of the interior grades from black at the exterior to a reddish brown in the center of large specimens. Some very large spheres are hollow with the inside dimensions being about one-third the outside diameter. In some samples only perfect spheres were observed. In other samples some spheres were elongated to a length of up to two diameters. In a cold mixture of acetic acid and hydrogen peroxide the spheres were unaffected. However, when the mixture was heated, they dissolved completely with little residue. Scanning electron microscope photos reveal a complex internal structure (Figures 33 and 34).

Erratics

Two rocks were discovered on Dakota Mountain which appeared to be erratics. The first was collected 200 m south of Site A at an elevation of about 1115 m (3660 feet). This cobble, approximately 70 mm in diameter, displays alternating dark and light bands about 6 mm wide. In cross section five distinct reverse microfaults are apparent. Examination of a thin section from this rock revealed that the dark bands are primarily the result of iron oxide staining. The rock has a very high content of microcrystalline quartz and is the result of low grade

Fig. 31. Scanning electron microscope photograph of a typical organic sphere from Site L (Plate 1). Magnification is x 120. The 100 micron bar indicates scale.

Fig. 32. Internal structure of an organic sphere from Site L (Plate 1). Magnification is x 180. The 100 micron bar indicates scale.


15KV X120 0002 100.0U UND79

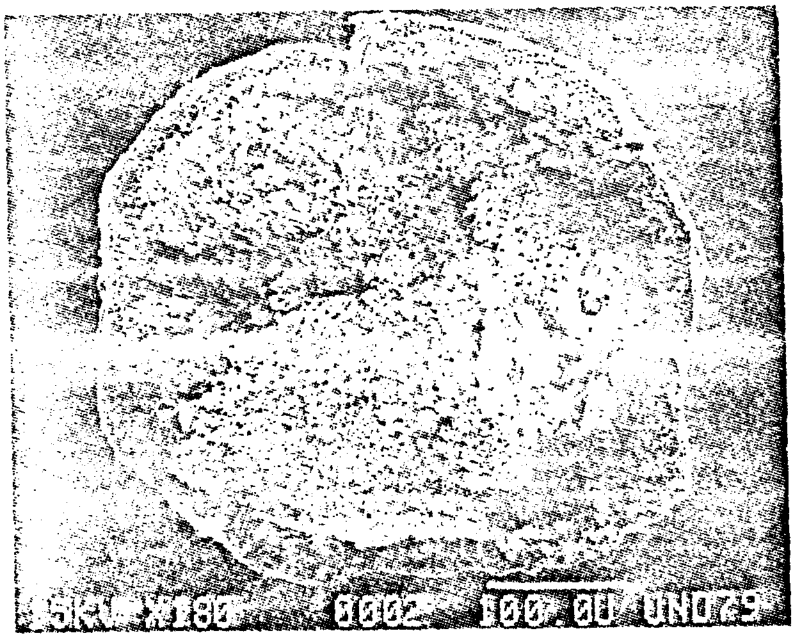
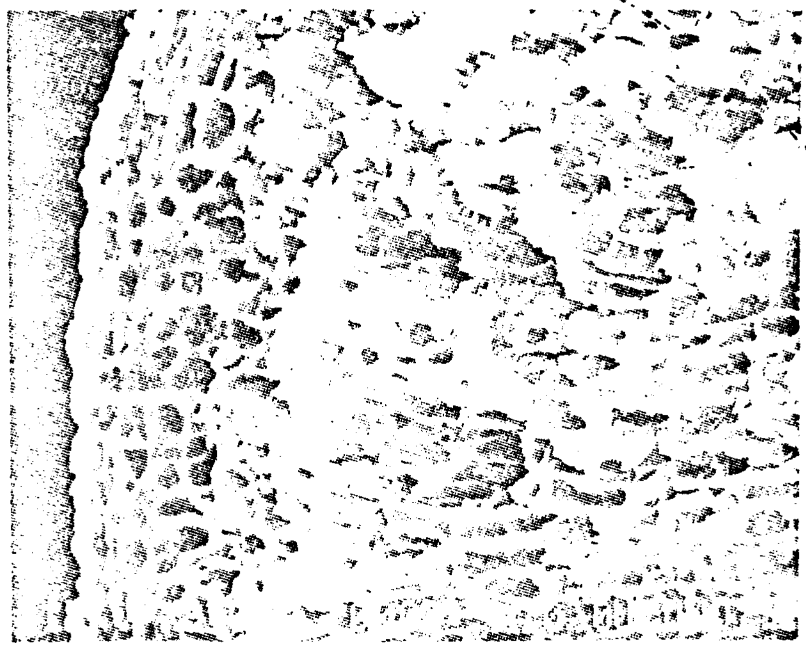

15KV X180 0002 100.0U UND79

Fig. 33. Scanning electron microscope photograph of the internal detail of an organic sphere from Site L (Plate 1). Magnification is x 940. The 10 micron bar indicates scale.

Fig. 34. Section of the rind of an organic sphere from Site L (Plate 1). Magnification is x 3600. The 10 micron bar indicates scale.



metamorphism of a layered rock, probably of extrusive igneous origin.

A second cobble 260 mm long was discovered on the side of Camp Valley at an elevation of 1065 m (3495 feet), 100 m northeast of the string bog (Plate 1). The composition of the rock is a complex mixture of metamorphosed lithic fragments rich in quartz. One fragment 100 m long is discernable. One surface of the cobble forms a perfect plane which has been polished to an exceedingly smooth finish (Figure 35). It is so well polished that no scratches or striations are visible even using a hand lens. Upon examination using the scanning electron microscope, however, a number of subparallel striations and crescentic fractures were observed (Figure 36).

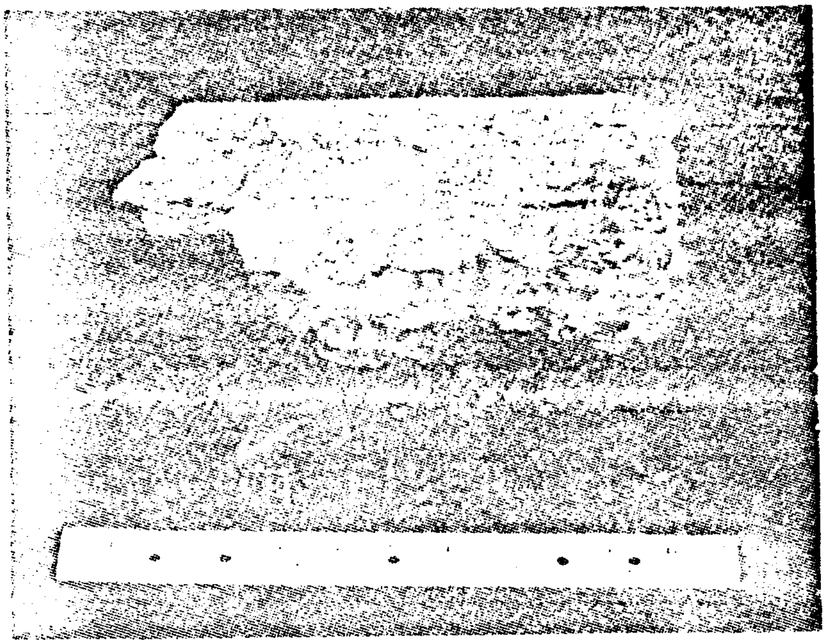
Soil Temperatures

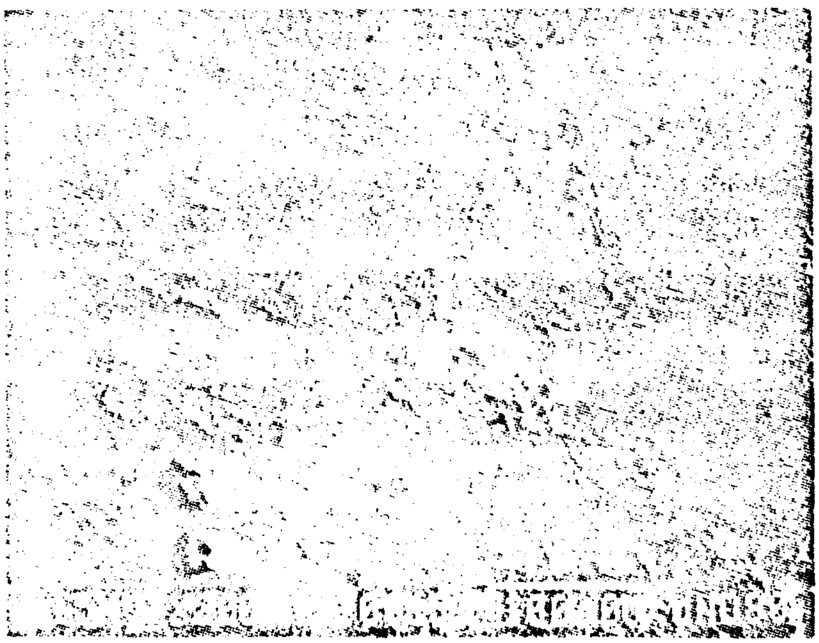
Soil temperatures were recorded from nine excavations on Dakota Mountain using a dial thermometer. The thermometer calibration was checked periodically in an ice water bath and necessary corrections applied to the data.

The excavation at Site B was made for the sole purpose of observing the soil temperature profile in a location likely to be underlain by permafrost. The site is on a north-northeast-facing slope about 20 m above the floor of Camp Valley. The area has a general slope of 23° and is overlain by a persistent snow patch during part of the year. There was 360 mm of snow at the site on June 27th when the excavation was begun. The snow had melted at the site by July 13th. Beneath the snow the ground was thawed to a depth of 250 mm. The next 350 mm contained a large amount of solid ice. Below that level the material was at 0.0°C and contained

Fig. 35. Polished faceted cobble from Camp Valley.

Fig. 36. Scanning electron microscope photograph of the polished surface of the cobble in Figure 35. Note the striations and crescentic fractures. Magnification is x 200. The 100 micron bar indicates scale.





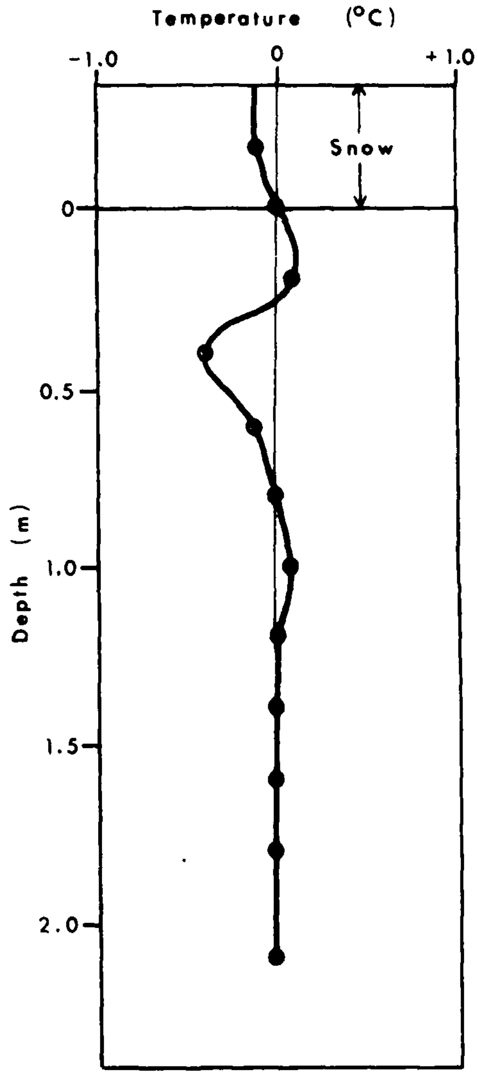
much less water (Figure 37). Ice crystals up to 10 mm in diameter were discovered in the material, usually in protected positions on the underside of angular cobbles and large pebbles. The apparently stable mixture of ice crystals in damp regolith continued to the full depth of the excavation. Excavation was abandoned at a depth of 2.1 m because of danger from the frequent collapse of the thawing upper walls of the pit.

The only other excavation in which ice crystals were discovered was Site A where they occurred below a depth of from 400 to 810 mm (Figure 28).

Meteorological Data

Meteorological data were collected from two sites in the Bradley Lake area, Alaska, during June and July, 1979. Daniel Lawson, U.S. Army Cold Regions Research and Engineering Laboratory, installed a 31-day drum recording thermograph on June 6th near the U.S. Geological Survey water resource data station cabin on the north shore of Bradley Lake, about 1400 m from the lake outlet, 59°45'17" north latitude, 150°49'32" west longitude. The thermograph was calibrated with a dial thermometer at the beginning and end of each chart. It was enclosed in a standard instrument shelter placed on top of a small wooden crate. The crate was located on a gravel beach ridge approximately 15 m from water's edge and about one metre above the surface level of the lake. The shelter was shaded on all but the south side by alder thicket. Approximately 6 m to the northwest of the shelter a 4-inch diameter plastic rain gauge was mounted on the top of a wooden tower, about 3 m above ground level. The surrounding alder thicket was low enough so as to offer no obstruction to accurate rainfall collection. Corrected

Fig. 37. Profile of ground temperatures at Site B (Plate 1) on June 27, 1979.


Temperature (°C)
-1.0
0
+1.0
Snow
Depth (m)
0
0.5
1.0
1.5
2.0

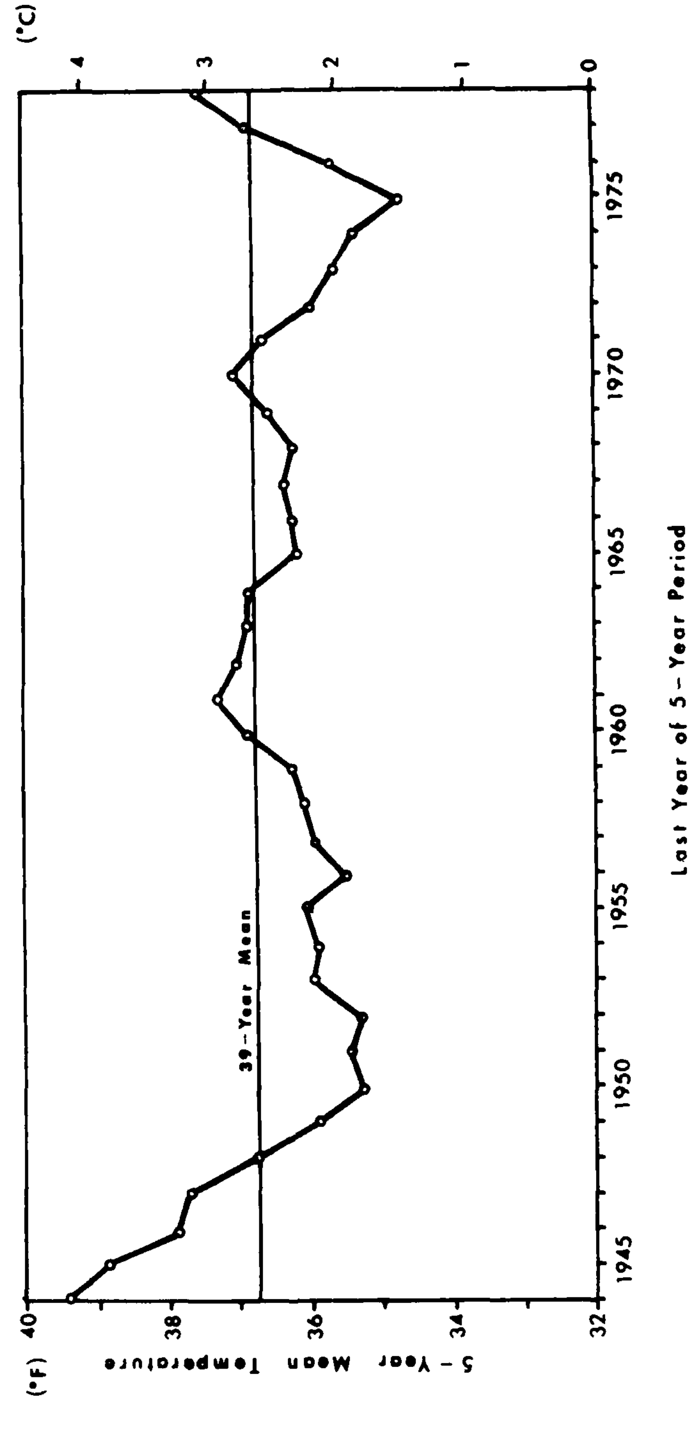
temperatures were derived from the charts using the dial thermometer and a formula supplied by the U.S. Army Cold Regions Research and Engineering Laboratory.

On June 14, 1979, a disk recording 7-day "Temprascribe" thermograph was installed near the camp on Dakota Mountain at 59°47'22" north latitude, 150°45'27" west longitude. The site is approximately 4.3 km north-northeast of Bradley Lake at an elevation of 1085 m (3560 feet). The instrument was sheltered according to standard practice in a loosely stacked rock cairn. The site is on the south-facing slope of a 50 m deep valley. On June 26, 1979, a digital rain gauge was installed about 20 m east of the thermograph cairn. All instruments were removed on July 21, 1979. Temperature and precipitation data are tabulated in appendix A.

Two other meteorological instruments were found in the area. The U.S. Weather Service built a wooden tower and installed a recording precipitation gauge about 1970 on the north shore of Bradley Lake. Several years of data were recorded. There were numerous technical problems with the instrument, however, and it was abandoned some years ago. The data tapes were sent to the National Climate Center, Ashville, North Carolina, and have never been published. The station name is listed as "Bradley Lake"; the station number is 50-0935-N. Approximately 500 m north of the center of the lake at an elevation of about 560 m (1850 feet) the Anchorage District Office, U.S. Geological Survey, Water Resources Division, installed a cumulative precipitation gauge. That gauge was never read and now appears abandoned.

The published temperature data from all stations on the Kenai Peninsula were studied in order to identify any long-term climatic trend. Unfortunately, the meteorological records available from the first seventy years of the Territory of Alaska are either nonexistent or incomplete. The only station near Dakota Mountain is Homer WSO, which has essentially continuous data only since 1940. The five-year moving mean annual temperature from this station is depicted in Figure 38.

Fig. 38. Five-year moving mean temperature at Homer, Alaska.


(°C)
4
3
2
1
0
39-Year Mean
1945
1950
1955
1960
1965
1970
1975
Last Year of 5-Year Period
(°F)
40
38
36
34
32
5-Year Mean Temperature

DISCUSSION OF PERIGLACIAL PHENOMENA

Permafrost

No conclusive evidence of existing permafrost was found on Dakota Mountain. The steep angular fronts of the gelifluction lobes and the sharp, distinct sorted steps seem to imply either that permafrost is present or recently has underlain much of the mountain. Excavations in the area, however, always bottomed in thawed sediment. The excavation at Site B was made for the sole purpose of determining the presence of permafrost and was positioned at the most likely location one might expect to find it. Figure 37 depicts the soil temperature data obtained at that site. The profile indicates that the overlying snow is slightly below the freezing point, as might be expected. A thin layer below the soil-snow interface was thawed and wet from the percolation of melt water under the snow. The next 600 mm represented the remaining annual frost layer, frozen the previous winter. It was necessary to break through this solidly frozen layer with a mattock. As it thawed during excavation, the matrix of the poorly sorted sediment formed a mud which flowed down the sides of the excavation. Below this annual frost layer the temperature profile stabilized exactly at the freezing point. Ice crystals a few millimetres across were found intermixed in the wet sediment between the frozen layer and the bottom of the excavation. Most of the crystals occurred beneath large pebbles and cobbles. Similar crystals were encountered near the bottom of the excavation at Site A. It is concluded that these crystals are relics of a recently deteriorated permafrost and reflect a warming trend in the local climate. As the ground temperature increased, remnant crystals of ice might have persisted as the thawing level moved downward. The bottoms of larger particles are more protected from the effects of downward percolating water and may serve as a shelter for the underlying ice particles. It would be impossible to develop crystals in such sites during climatic cooling. In that situation the annual frost layer would exceed the depth of thaw and the resulting permafrost base would move downward with no means of freezing ice crystals any distance beneath the freezing front. The average geothermal heat flow provides energy sufficient to thaw only about 6 mm of ice per year (Paterson 1969, p. 126). It is thus impossible for the observed conditions to result from upward thawing of an annual frost layer. It is conceivable that the ice developed during an abnormally cold winter and is thawing over a period of more than one year. Such ice, however, is by definition permafrost (Muller 1947, p. 3, in Fairbridge 1968, p. 833). If the climatic warming takes place over many years, the subsurface temperature profile will remain nearly vertical. The permafrost will gradually warm until it reaches 0°C. The heat from further increase in temperature at the surface will then be used to melt the material at the permafrost table. As this thawing proceeds deeper, there will be a tendency for a circulation of water to occur if the soil is saturated. As water nearer the surface is warmed slightly above the freezing point it will become more dense and tend to move downward to displace colder less dense water. At the thawing front the water will cool as it gives up heat to thaw more ice. Even in a well-drained side hill location such as Site B, downward percolating water would provide an important means of transferring energy from the surface to the thawing front. When all of the permafrost has thawed or even when the permafrost table has migrated downward enough to make thermal communication with the surface materials insufficient to absorb the excess energy at the surface, the layers below the zone of annual temperature variation will begin to warm, eventually bringing the temperature profile into equilibrium with the warmer climate. At the same time as the permafrost is melting downward from the surface, it would also be melting upward from the base of the permafrost zone due to geothermal heat flow. The present conditions on Dakota Mountain indicate that any existing permafrost is being thawed from top and bottom. It is unknown if the excavated ice crystals are the very last vestiges of regional permafrost or if there is yet a mass of permafrost at some depth below the surface. In either case, it appears that permafrost has recently ceased to be an effective element in the geomorphology of the area. Although no evidence is available upon which to base absolute ages, the most logical suggestion is that permafrost was a dominant factor in landform development on Dakota Mountain during the "Little Ice Age," but has degenerated during the last century or so.

This conclusion is supported by the presence of the string bog in Camp Valley. Schenk (1965, p. 158) believes that string bogs are a clear indicator of previous but not present permafrost. He observed that they do not occur in the continuous permafrost zone. He developed a hypothesis to explain their formation as part of the degeneration of permafrost in an area. His views, however, are not universally accepted (Washburn 1973, p. 151).

Published climatic data from the region is available for only the last forty years and proved of no value in detecting a long-term climatic trend. Some short-term trends can be observed in Figure 38, but it is doubtful if they are of any real significance in the longer-term development or destruction of permafrost. The mean temperature for the last forty years at Homer is 2.63°C (36.74°F). Transposition of this temperature from Homer, elevation 30 m, to Camp Valley, elevation 1070 m, using the theoretical minimum adiabatic lapse rate of 5.5°C per 1000 m (Schulz 1974, p. 106), reveals that the mean air temperature in Camp Valley during the last forty years could not have exceeded -3.1°C (26.5°F). Although the mean ground temperatures must have been slightly warmer than the mean air temperatures (Embleton and King 1975, p. 6), it is clear that the thermal regime must have been at least very near that necessary for the development or preservation of permafrost.

Gelifluction Features

The term solifluction was proposed by Anderson (1906, p. 95) to describe the slow flowing from higher to lower ground of masses of waste saturated with water. This definition does not limit solifluction to a specific environment. Common usage of the term, however, often implies that the process is characteristic of a periglacial (Anderson's subglacial) environment. It is not always clear in publications if the term solifluction is being used in a general sense or if an implication of cold environment or even permafrost is being made. In some cases the differentiation between soil creep and solifluction may be

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arbitrary. Implying that solifluction is a cold environment process, Sharpe (1938, p. 35) states that the material involved in solifluction is comparable to that of the soil creep of warmer climates. Washburn (1947, p. 88) explains that there is little or no difference between completely saturated soil creep and solifluction. Several authors suggested changes in nomenclature to resolve this ambiguity (Dylik 1967, p. 170). Baulig (1957, p. 926) defined gelifluction as solifluction associated with frozen ground. Use of the term solifluction may be ambiguous; gelifluction is unequivocally periglacial (Washburn 1973, p. 173). This more specific term is used throughout this discussion.

Gelifluction is a complex interaction of unconsolidated sediment, ice, water and slope. Permanent or seasonally frozen ground prevents water derived from melting snow, melting ground ice, or rain from percolating downward. As a result, thawed surface layers may become saturated and flow downslope under their own weight (Embleton and King 1975, p. 97). Gelifluction is possible on gradients as low as 1° (St.-Onge 1965, p. 40, in Washburn 1973, p. 173). Gelifluction should be differentiated from mudflows, which are rapid and usually of short duration, as well as from frost creep, which is downslope movement of individual particles resulting from the expansion and contraction of ground subject to alternations of freezing and thawing (Washburn 1973, p. 170). Gelifluction is an important secondary agent in the formation of many of the features attributed to nivation and frost action. It is the dominant formative process, however, in the development of gelifluction lobes and turf-banked steps.

Gelifluction Lobes

Gelifluction lobes are the dominant landform in some areas on Dakota Mountain. The vertical fronts and sharp angular contact between lobes and underlying material indicate that they are currently active or at least very young relic features. Little apparent modification of the steep edges of the lobes has taken place other than the trails and holes excavated by ubiquitous voles. Some of the thicker lobes apparently are compound features formed by several layers of gelifluction movement, one on top of the other. The preferential distribution of better developed lobes on southerly facing slopes may be explained by at least two hypotheses. The south-facing slopes are subject to the most rapid thawing by solar radiation. The sun would tend to melt more of the snow cover as well as the surface ground layers in a shorter period of time, thus increasing the chances of saturation and promoting greater rates and amounts of gelifluction. The snow melt and ground thaw in areas receiving less direct solar radiation would tend to be spread over a longer time period, mitigating the saturating effect. The second hypothesis does not depend as much on intensity of gelifluction as on the shape of features developed. Because of their aspect, the near-vertical fronts of south-facing lobes receive the maximum possible radiation from the low angle Alaskan sun. Also, because of the steepness, the material exposed at the fronts will tend to drain freely, increasing the local effective stress (grain-to-grain pressure) and the competency of the material. Water in the saturated layers which flow over the frozen subsurface strata toward the edge of the lobe front tends to drain away through or over the drier material when the flow approaches the front. This decreases the liquidity and increases the strength of the flowing material, thus tending to form a retaining wall of unsaturated material to contain the upstream gelifluction debris. This hypothesis explains the greater thickness of the downslope portions of the lobes. It also explains the eastward deflection of most southerly moving lobes. The southwest face of a lobe will be subject to more effective afternoon solar radiation than the southeast face which has direct exposure only during the cooler morning hours. The west face thaws more quickly, drains more thoroughly, and forms a more effective deflecting wall than the east face. For an expanding gelifluction lobe on a south-facing slope the path of least resistance is therefore to the southeast.

Permafrost is helpful but not necessary for gelifluction. An annual frost layer is adequate to allow gelifluction, provided it is sufficiently deep and impervious. Data from Dakota Mountain are insufficient to define the thermal regime or rates of movement of the lobes found there. For descriptions of rates of flow of other gelifluction lobes, the reader is referred to articles such as those by Benedict (1970), Washburn (1947 and 1967), or Williams (1959).

Turf-Banked Sorted Steps

These steps are dependent upon several interacting processes for their formation. Frost sorting is obvious on the treads of many steps and certainly plays some role in distributing sediment within the steps. Gelifluction is no doubt the chief agent of downslope movement of step material. Only scale differentiates individual steps from larger terraces attributed to gelifluction. The turf tends to restrain gelifluction and modify the features developed (Embleton and King 1975, p. 117). Figure 39 shows the effect of slope on turf-banked forms observed in England by Hollingworth (1934, in Embleton and King 1975, p. 119). The entire gradation from near-horizontal forms on hilltops to the steep step and stripe pattern is present on Dakota Mountain. Most of the steps observed are similar to those in Sketch B of Figure 39; the diagonal descending stripes on Dakota Mountain are usually less prominent and farther apart, however. The most striking characteristic of the Dakota Mountain steps is their precise spacing. The distance between adjacent steps ranges from less than one to more than three metres at some locations on the mountain, but those in a single area usually do not vary by more than ten percent. To account for this regularity there must be some controlling mechanism. No theory concerning the mechanism of step spacing was found in the literature. Therefore, the following hypothesis is presented to provide a basis for future study.

The first part of a step to be thawed each spring will be the upper portion of the riser and the exposed portion of the higher adjacent tread. The last part to be thawed is the concave intersection of the back of a tread and the bottom of the next riser. The resulting thaw pattern will produce an arcuate profile in the permafrost or annual frost zone under each step (Figure 40). As the thawed material is saturated by the melting snow on the step and farther upslope, gelifluction will tend to steepen the riser and move the mass of the step downslope, lengthening the tread above and shortening the tread below. As long as the steps each move at the same yearly rate, the step spacing and equilibrium of the process is maintained. The distribution

Fig. 39. Effects of turf on patterned ground (after Hollingworth 1934). The diagrams illustrate the patterns formed by moving debris on partially turfed slopes of various inclinations in the Lake District of England. The same patterns exist on Dakota Mountain.

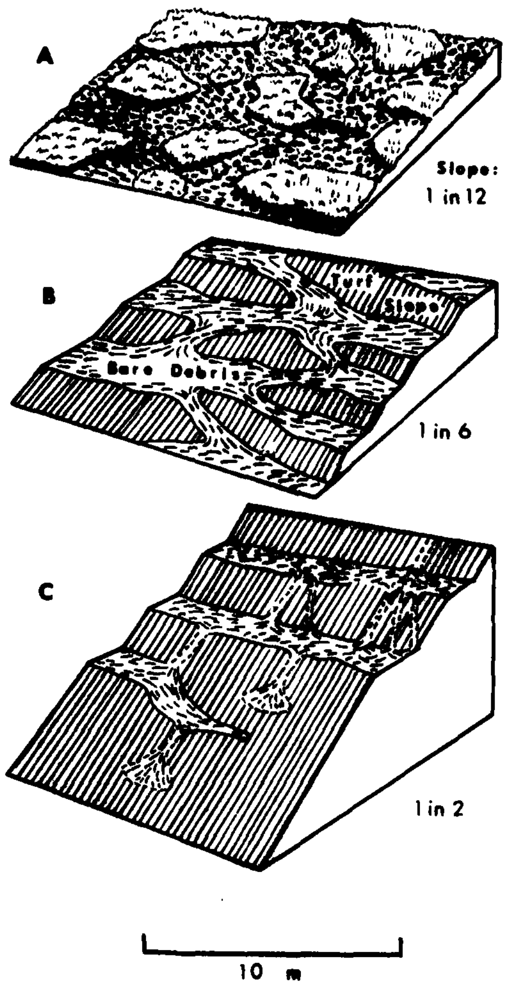
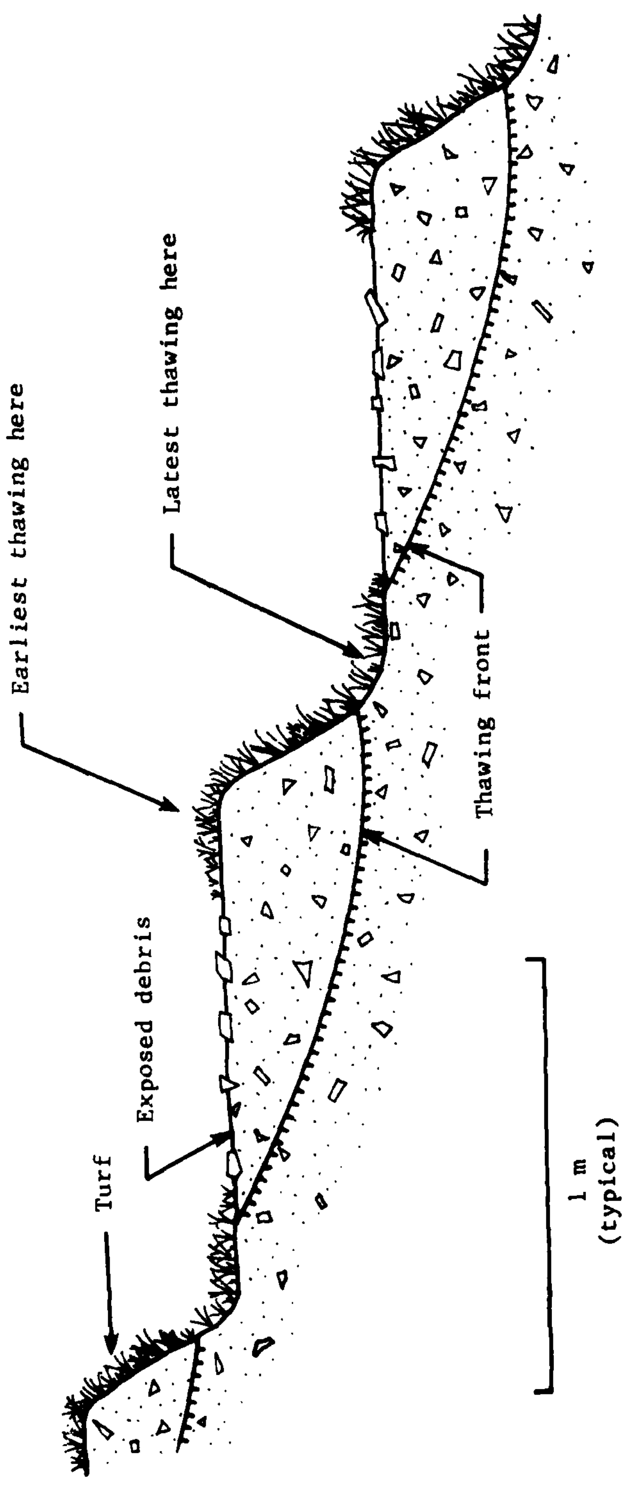

A
Slope:
1 in 12
B
Turf
Slope
Bare Debris
1 in 6
C
1 in 2
10 m

Fig. 40. Thawing profile of regularly spaced turf-banked sorted steps.



Earliest thawing here
Latest thawing here
Thawing front
Exposed debris
Turf
1 m
(typical)

of snow is probably controlled almost entirely by wind. The concave angle of each step provides a wind shelter to trap a small accumulation of snow while the exposed convex portion of each step is swept bare. If adjacent steps are unequally spaced, as depicted in Figure 41, the shorter steps will tend to attain a greater degree of saturation during thawing due to their smaller volume. The longer steps will be provided with the same amount of moisture from about the same amount of melting snow. The greater bulk of the step above the thawing front, however, will result in the average moisture content being less. Each year the wetter smaller steps will move farther than the less moist longer steps, thus tending to equalize the step size.

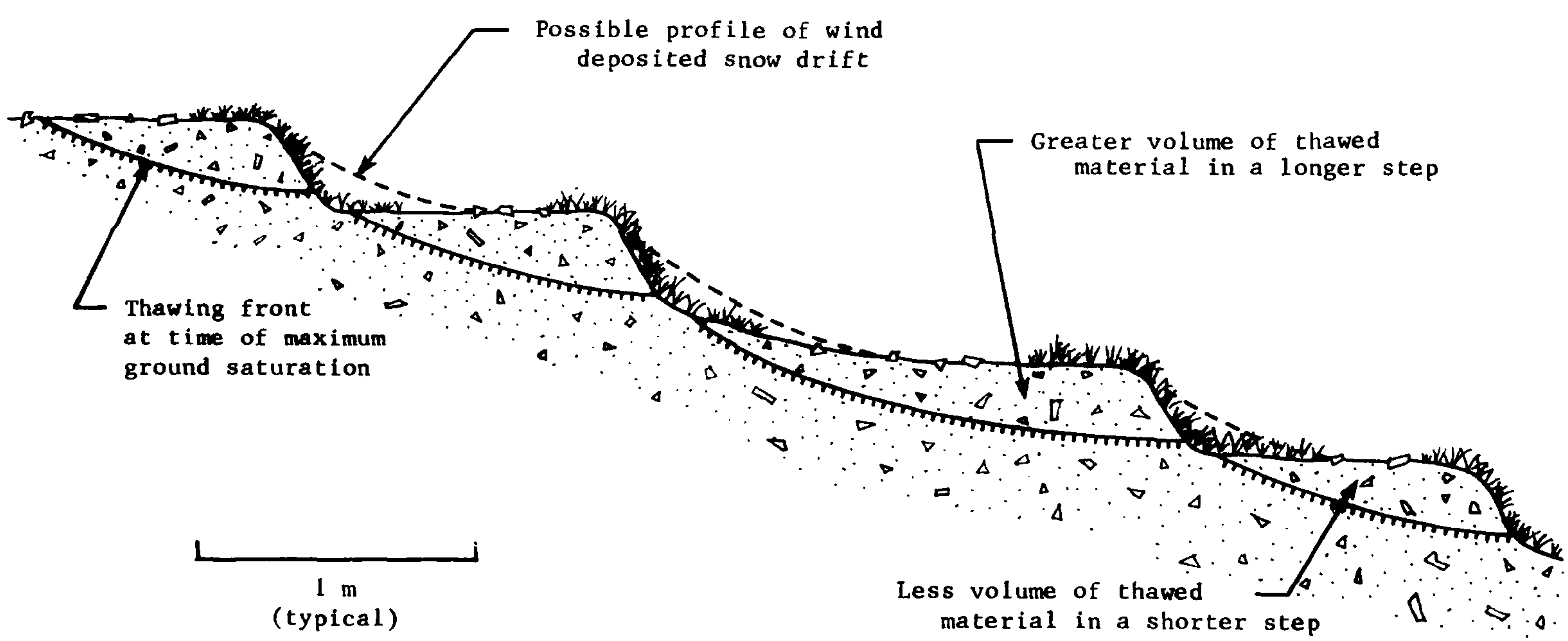
It is apparent that the above ideas cannot be substantiated with the presently available data. No one has ever recorded the winter snow distribution on Dakota Mountain. Nothing is known of the current rate of movement, if any, of the steps. The uncertain effects of running water and frost action are not addressed. The hypothesis is speculative and is presented in that spirit.

Nivation Features

Cryoplanation Terraces

Matthes (1900, p. 177) introduced the term nivation to describe the erosive effects associated with immobile snow patches. The process is as yet poorly understood, but recent studies such as those by Thorn (1974, 1975, 1976a, 1976b) have provided new insights and have refuted some long-held assumptions. There are two components to the nivation process: a weathering mechanism and a transportation mechanism. It

Fig. 41. Thawing profile of irregularly spaced turf-banked sorted steps.


Possible profile of wind deposited snow drift
Greater volume of thawed material in a longer step
Thawing front at time of maximum ground saturation
1 m (typical)
Less volume of thawed material in a shorter step

is commonly believed that the weathering mechanism is principally frost action (Embleton and King 1975, p. 130). In some cases the edges of melting snow patches are subjected to a greater number of freeze-thaw cycles than either the surface beneath the snow or the exposed area some distance from the edge (Gardner 1969, p. 119). Thorn (1976a, p. 1171), however, found no significant difference in annual freeze-thaw-cycle frequency between snow-patch and snow-free sites. In either case, the melting snow does provide the water required for frost action to attack the rock. Williams (1949, p. 135) observed high concentrations of carbon dioxide beneath snow drifts and suggested that chemical weathering by carbon dioxide-rich melt water may be an important aspect of nivation. Thorn (1976a, p. 1176) found that chemical weathering is two to four times as great beneath a snow patch as in adjacent snow-free areas.

The transportation mechanism of nivation is also a matter of debate. The earliest investigators generally considered gelifluction to be the primary movement agent (Embleton and King 1975, p. 133). Others (Lewis 1939, p. 155; McCabe 1939, p. 449; Nichols 1963, p. 477) have concluded that running water is most important. In his quantitative studies in the Colorado Front Range, Thorn (1976a, p. 1176) found running water to be most important within nivation hollows and gelifluction more dominant downslope from the snow patches. Some authors regard snow creep and sliding to be significant agents of transportation (Costin and others 1964, p. 222). Others (Russell 1933, p. 932) consider snow movement to have no role in nivation. It is probable that the effectiveness of snow creep is greatest over exposed bedrock and least over surfaces of unconsolidated debris (Thorn 1976a, p. 1173).

A wide variety of features has been attributed to the effects of nivation (Washburn 1973, p. 204). The largest of these are cryoplanation terraces. Extensive distinct terraces with flat treads and steep headwalls are present in many mountainous areas of the north such as Alaska, the Ural Mountains, central and eastern Siberia, northern Greenland, and the Alps (Ekblaw 1918, p. 292; Washburn 1973, 207-210). The earlier investigators considered them to be fluvial terraces or remnants of old erosion surfaces (Prindle 1913, p. 17). Eakin (1916, p. 77-82) recognized them to be associated with cold climates and named them altiplanation terraces. They are now accepted to be the result of erosion and transportation processes in a rigorous periglacial environment and are usually described by the more appropriate term cryoplanation terrace (Péwé 1970, p. 360). Several hypotheses as to the mechanism of their formation have been proposed. Eakin (1916, p. 82) considered the terraces to evolve through the lowering of the tread by frost heaving and shattering and subsequent removal of debris by gelifluction. Most other researchers believe that terrace development proceeds not by vertical tread reduction, but by horizontal retreat of headwall scarps (Péwé and Reger 1968, p. 41). Waters (1962) suggested that scarp retreat is facilitated by melting snow and springs emerging from the scarp providing moisture for basal sapping. Many other writers consider nivation to be the most important aspect of cryoplanation. Boch (1946, appendix C, figure 1, in Péwé and Reger 1968, p. 42) believed that such terraces resulted from intensive frost attack on the scarp headwalls and subsequent removal of debris by an "under-the-snow" movement mechanism. According to his hypothesis, the ground beneath a persisting snow bank is nearly entirely thawed while the sediment beyond the lower edge of the snow bank is frozen. Although there is some evidence to support an under snow nivation movement process (Dyson 1937, p. 550, 554; Costin and others 1964, p. 222), Péwé and Reger (1968, p. 42) did not find support for Boch's ideas of thawed ground under snowbanks. On Dakota Mountain the ground under persisting snow patches was also generally frozen long after nearby exposed surfaces had thawed. Occasionally, however, the uppermost few centimetres of sediment was found to be thawed in specific locations beneath the snow. As the snow patches receded, the frozen ground thawed soon after it was exposed. The ground exactly at the lower margin of snow was nearly always frozen solidly; one metre away from the snow it was always thawed. It may be, however, that extremely large snow patches might protect underlying thawed material from freezing temperatures. Péwé and Reger (1968, p. 43) were also skeptical of an "under-the-snow" movement hypothesis. They instead agreed with the ideas of Lyubimov (1967).

> Lyubimov advocated that the seasonal frost layer is preserved beneath the snowbank by the insulating characteristics of that body, except at very localized and shallow depths (Lyubimov 1967, appendix C, figure 2). The position of the upper boundary of this frozen zone comprises a temporary primary base level of nivation for this snow patch. This level gradually lowers. In contrast the headwall of the nivation hollow thaws quickly and close to the snowbank becomes saturated with meltwater. Lyubimov considered the zone of maximum frost shattering to be at the base of the headwall in a zone of intensive meltwater infiltration. This zone of maximum frost shattering is the result of maximum penetration by meltwater and atmospheric temperature fluctuations. Here intensive frost shattering degrades the bedrock surface and during periodic thaws the resulting rubble is washed or shifts and tumbles as "nival landslides" to the base of the headwall where further comminution occurs. By meltwater washing and solifluction down to the "primary nivation base level" this material is redistributed so that the hollow headwall becomes over-steepened, the gradient beneath the snowbank is essentially retained, and the gradient about the toe of the snowbank is decreased. Scarp

retreat along the "primary base level of nivation" by transverse snow patches results in the development of altiplanation (cryoplanation) terraces (Péwé and Reger 1968, p. 43-44).

There is evidence that cryoplanation once may have been an active geomorphic process on Dakota Mountain. The many leveled areas and hillside terraces are best explained as relic cryoplanation surfaces. They are of the scale and slope expected of such features (Péwé 1970, p. 359) and are regionally situated where they, no doubt, were subjected to a rigorous periglacial environment during later glaciations. There is, however, no present information by which to determine if this environment was as cold as that necessary to promote cryoplanation (Reger and Péwé 1976, p. 108). I visited Reger's Mount Hayes A-5 study site and observed his Boundary site from a light aircraft (Péwé and Reger 1968, p. 1). Both sites are hundreds of kilometres inland from the Gulf of Alaska and exposed to very cold winter temperatures. The cryoplanation terraces at these locations are much more distinct and well developed than the features on Dakota Mountain. At the inland sites, the breaks in slope are abrupt and there is an obvious distinction between tread and headwall. On Dakota Mountain the changes of slope are rounded and the headwalls are covered with the same sort of sediment as on the tread. Reger (verbal communication, August, 1979) expressed the belief that the Dakota Mountain features are probably relic cryoplanation terraces, provided they are in fact cut into the bedrock of the mountain. It was impossible to conclusively verify that condition. The tors exposed near the top of the headwall and at the toe of the tread of several features do tend to support that supposition, however. It is therefore concluded that the terraces and leveled hilltops on Dakota Mountain are relic cryoplanation terraces which have been modified and obscured by subsequent slope processes, primarily gelifluction.

Nivation Hollows

The hollows and associated platforms on Dakota Mountain also may be attributed primarily to nivation. The hollows serve as collection basins for snow on the wind-swept slopes of the mountain. The snow patches in the hollows remain long after the thin snow cover on the more exposed areas of the mountain has been melted. Some of these snowbanks persist until August and some years may never disappear completely. Most of them, however, are melted by the first part of July. The several very large perennial snow patches on northwest-facing slopes of Dakota Mountain are deposited by orographically-controlled winds; they do not completely melt during a typical year, and are not associated with hollows and platforms. As the snowbanks in the hollows melt, they provide abundant water to the area just downslope from their lower margin. The floors of the hollows and the upslope portion of the associated platforms often were found to be completely saturated. This condition, together with a near surface permafrost table, would provide ideal conditions for gelifluction; however, other evidence seems to indicate that nivation and gelifluction may not be the principal processes in the development of the hollows and platforms. The bottoms of nivation hollows which I observed in the interior mountains of Alaska are devoid of any appreciable vegetation and contrast conspicuously with the surrounding areas where substantial growths of lichens and low tundra plants are present. This same situation is reported by numerous authors including Matthes (1900, p. 178), Lewis (1939, p. 154), and Embleton and King (1975, p. 135) who state that vegetation ceases abruptly at the edge of the nivation hollow. On Dakota Mountain the bottoms of hollows support the most luxuriant vegetation in the area. In interior Alaska the debris platforms downslope from the hollows invariably sloped directly downhill, as would be expected of a gelifluction lobe. On Dakota Mountain the platforms are generally close to horizontal and in many cases actually exhibit a slope opposite the general hillslope. This slope reversal is characteristic of a rotational slump. Figures 42 and 43 depict such slumping as a possible primary mechanism in hollow development or as a secondary event in the expansion of an already existing nivation hollow. Several hollows on one hill are aligned precisely along a large-scale lineation observed on air photos. It is probable that this lineation, as well as the location of the hollows, is structurally controlled. The bedrock of Dakota Mountain is highly jointed and fractured. Low angle joints are likely zones of weakness along which failure might occur, especially if they are lubricated from melting snow in an overlying nivation hollow. Reger (verbal communication, August, 1979) suggested, however, that it is possible for a platform to develop a reverse slope solely by gelifluction. As the associated hollow migrates into the hillslope, the slope over which the debris are transported becomes longer and less steep. Reger explained that as the platform grows sediment will cease to be moved over the front and instead will be evacuated laterally to the sides. The front of the platform becomes relatively inactive as the surface nearer the source area is depleted laterally, thus developing a reverse slope. Reger observed sorted stripes on a reverse slope cryoplanation terrace which were parallel

Fig. 42. Schematic sequence showing primary development of hollows by slumping.

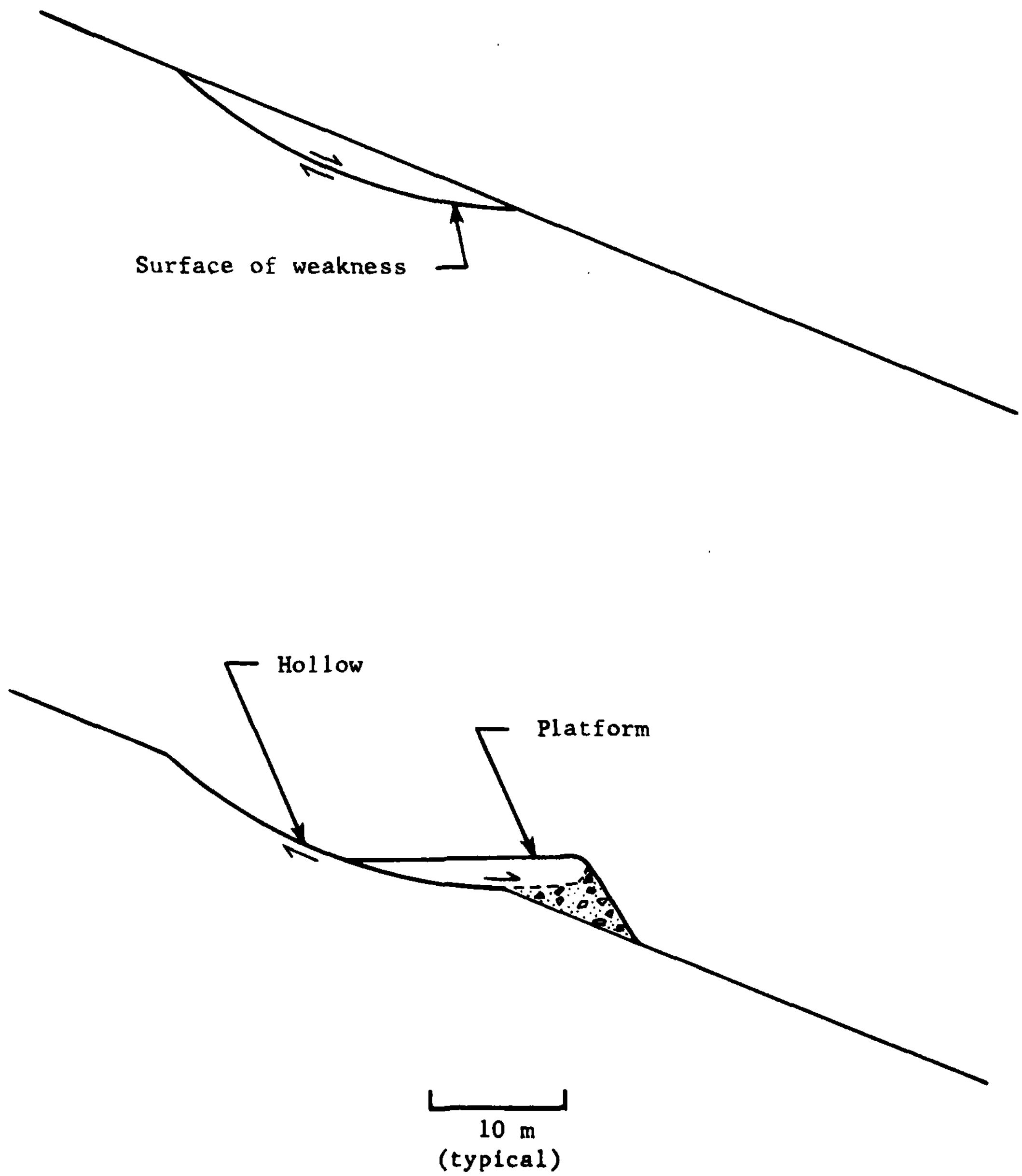
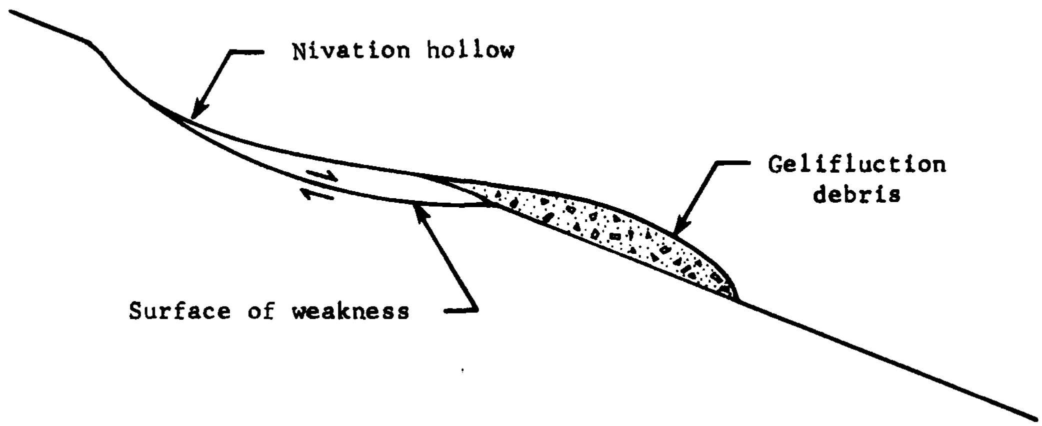
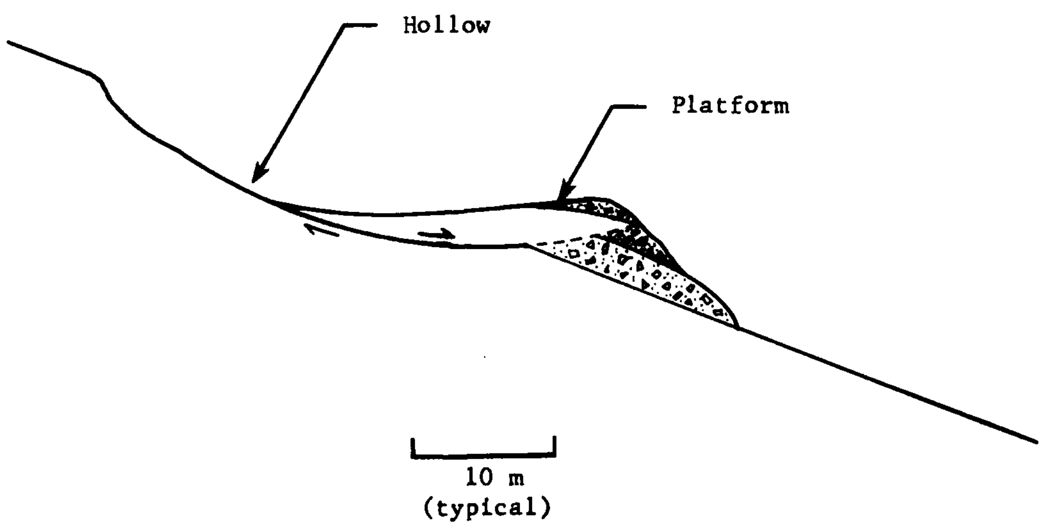

Surface of weakness
Hollow
Platform
10 m
(typical)

Fig. 43. Schematic sequence showing secondary expansion of nivation hollows by slumping.


Nivation hollow
Gelifluction
debris
Surface of weakness


Hollow
Platform
10 m
(typical)

to the headwall, indicating lateral transportation of material from the terrace. On a cryoplanation terrace just south of the Amphitheater Mountains, 200 kilometres southeast of Fairbanks, Alaska, I observed lateral elongation of ground patterns, also indicating evacuation of debris from near the headwall to the side of the terrace. The form of the hollows and platforms on Dakota Mountain are conformable to this hypothesis. The meltwater drainage path of most of the features is, in fact, over the side of the platform. Many hollows and platforms appear to be elongated laterally at a moderate slope along the hillside. This elongation could be attributed to the expansion of the platform caused by lateral gelifluction movement.

There is other evidence from Dakota Mountain that tends to discredit the hypothesis of hollow formation through slumping. Under a given load the shear stress on a surface of potential failure is proportional to the sine of the slope angle of that surface. Because the average slope of the surface on which a slump moves must equal the hillslope, one would expect slumping to be most common on the steepest slopes. The features on Victoria Island which Washburn (1947, p. 85) attributed to slumping were on slopes as steep as 34°. On Dakota Mountain, however, the hollows are generally limited to slopes of 8° to 14°, whereas gelifluction lobes without well-developed hollows occur on steeper slopes. It is difficult to accept the idea that the distribution of suitable joints is such as to limit slumping to the shallower slopes and at the same time attribute the wide-spread areal distribution of hollows to the ubiquitous existence of such joints. Slumps in mountainous terrain often result in corollary mass movement downslope from the slump. There is no example of this on Dakota Mountain. If slumping is responsible for the dozens of hollows on the mountain, it is difficult to understand why there is no evidence of additional rapid mass movement downslope from at least some of these hollows. If one assumes that all such evidence has been obliterated by subsequent slope processes, it is equally difficult to explain why the distinct crests of some headwalls and the steep fronts of many platforms have not likewise been subdued. Although it is certainly possible that some of the hollows on Dakota Mountain have been formed at least in part by slumps, it is doubtful that slumping is the primary hollow forming process.

It is concluded that the hollows and platforms on Dakota Mountain are primarily nivation features. It is suggested that the laterally-elongated hollows developed from the movement of debris to the side of the platform. The accumulation of debris in that position provides a notch where snow may accumulate, enlarge the snow patch, and thus expand the nivation hollow. If this process is perpetuated, a "transverse hollow" may develop (Lewis 1939, p. 153; Cook 1962, p. 79). This hypothesis is speculative and cannot be conclusively supported by present observations.

It is probable that warming of the climate on Dakota Mountain has reduced the length of time necessary to melt the snow in the hollows each summer. Rather than late summer snow covering the bottom of the hollows and preventing vegetative colonization, there is now enough time each year between the melting of the snow and the onset of autumn snowfall to permit a variety of plants to become established. The snow also both provides protection from the cold abrasive winds which sweep over the slopes during winter and furnishes abundant soil moisture during melting. These factors have allowed a rich flora, especially mosses, sedges, and grasses, to develop.

These same conditions promoted formation of the turf-covered earth hummocks on the bottom of the hollows. Many authors have suggested mechanisms such as frost heaving (Taber 1952, p. 713), local patches of freezing ground (Sharp 1942, p. 298), and erosion (Beschel 1965, p. 14) to explain hummock development. They are probably of diverse origin (Washburn 1973, p. 146; Beschel 1965, p. 16) and no refinement of any hypothesis is possible from the observations made during this study. These hollows may be similar to those in Quebec which Henderson (1956, p. 616) interpreted to have formed during the "Little Ice Age" and been subsequently stabilized, probably during the first half of the nineteenth century.

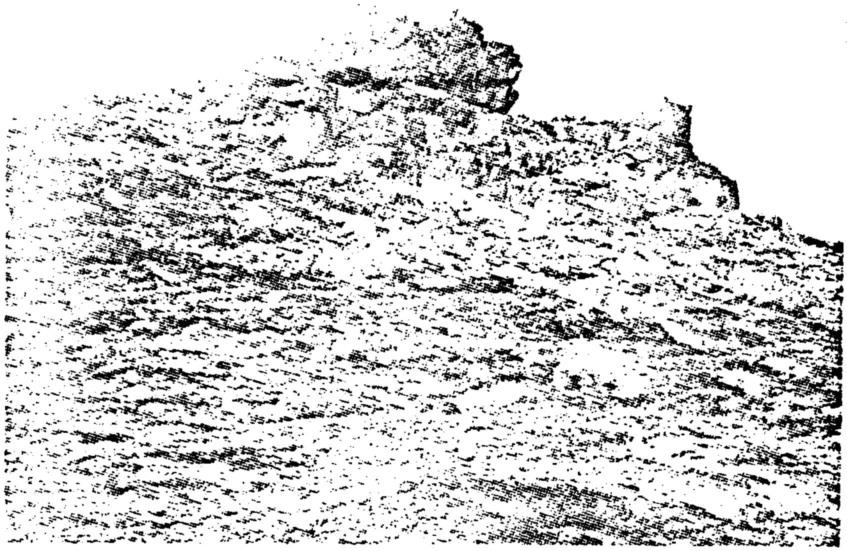
Frost Action Features

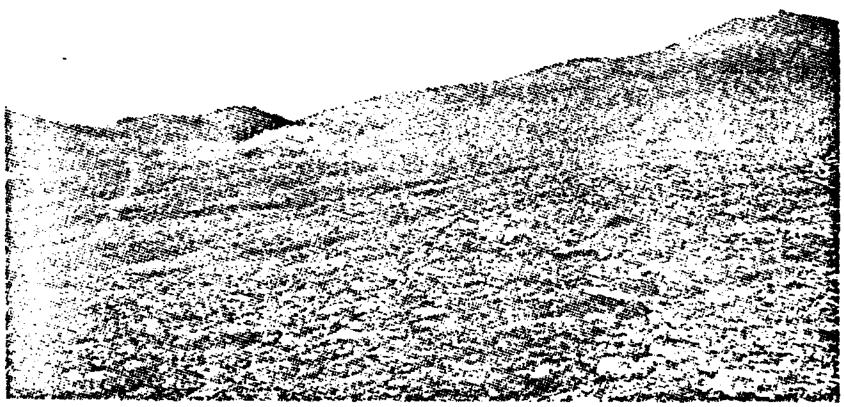
Frost action is a prominent agent in the surficial development of Dakota Mountain. Much of the surface is covered with a scattering of coarse particles, mostly angular pebbles and cobbles. Such particles are a major constituent of essentially all the surficial material on Dakota Mountain. Their angular shape and the relative lack of chemical weathering products indicate that cryofraction is a primary process in the formation of regolith in the area. The depth of unconsolidated surface materials on the mountain is unknown. Excavations to a depth of more than two metres at several locations on the mountain, however, revealed no evidence that bedrock was near. The level areas covered with coarse angular particles have the appearance of block fields or felsenmeer (Washburn 1973, p. 191). The size of the particles, however, is much smaller than that found in blockfields which I have observed elsewhere in Alaska. It is suggested that this is the result of differences in source material rather than process; the closely jointed rocks on Dakota Mountain tend to produce smaller blocks (St.-Onge 1969, p. 3). The only exposures of bedrock in the area are the precipitous glacially excavated sides of the mountain and isolated tors (Linton 1955, p. 476) on the upper surfaces. The tors range in size from one to tens of metres in extent. They are usually located on a local prominence or at the crest of a convex break in slope (Figures 44 and 45). The particle size of the surface stones near the tors is invariably larger than that of more distant particles. The areas around the tors are usually thickly covered by black crustaceous and foliaceous lichens. The extent of lichen growth in areas away from the tors is much less. These relationships indicate that the rock fragments surrounding the tors are derived by frost action from the tors and are gradually reduced in size by further cryofraction as they are moved away by slope processes. The more abundant lichen growth near the tor indicates the relative stability of the area due to larger particle size and more gentle slope. The rock exposed in the tors is well jointed, usually in several directions, thus providing easy access for moisture to penetrate into cracks, freeze, and expand them. Tors have been often associated with the development of cryoplanation terraces (Péwé and Reger 1968, p. 119).

The most ubiquitous frost features on Dakota Mountain are the sorted circles. They occur on all but the steepest slopes of the mountain. They form by the processes of primary frost sorting and differential frost heaving (Washburn 1973, p. 138). The frost sorting raises coarser particles to the surface (Corte 1961, p. 10) and

Fig. 44. Large tor on the south end of Dakota Mountain. The man at the base of the tor indicates scale.

Fig. 45. Terraces and a small tor at the top of the hill northwest of Camp Valley. View looking west.





separates them radially from concentrations of fine particles (Corte 1962, p. 9). Local differential frost heaving can cause a blister-like expansion of the ground which may start sorted patterns (Washburn 1973, p. 196; Taber 1943, p. 1454). Pressure forces associated with uneven freezing of heterogeneous sediment may also contribute to the formation of sorted circles (Embleton and King 1975, p. 84). Stones near the centers of the sorted circles tend to have their long axis radial and their intermediate axis vertical. The net result is a stone packing or "stone rose" (Troll 1944, p. 43) of closely spaced coarse particles standing on edge (Figure 13). In some circles a fine-grained center is exposed free from particles larger than coarse sand. In such cases the centers are often moist which the surrounding coarser sediment is much drier. The symmetry of the circles is affected by individual large cobbles or boulders and especially by the slope of the surface. On steep slopes the ligher-colored less weathered particles uplifted in the circles may form small subcircular terraces with a miniature talus slope on the downslope side.

There can be little doubt that frost sorting is a currently active process on Dakota Mountain. The complete lack of lichens on the centers of most circles, even in areas where crustaceous lichens form a nearly continuous covering on nearby rocks, testifies to the modern activity of the process (Figure 14). Fresh debris from a sorted circle at Site D has buried a mat of vegetative matter. The site is on a hillslope of 14° and particles up to 160 mm long are spilling over the lower edge of the 600 mm diameter circle. One live plant of the genus Dryas was found buried under 100 mm of debris and yet had an intact system of stems and leaves. A few of the leaves extended beyond the edge of the overlying debris some 150 mm away and apparently were allowing the plant to survive its recent burial. The common vertical stones, some precariously erect, also indicate the contemporaneity of frost action here.

The depth of sorting on Dakota Mountain is quite shallow. The deepest observed preferential orientation of particles was 140 mm. The implication of this shallow limit is uncertain. The limit of sorting might reflect a warm climate with a shallow depth of annual freezing below which frost action does not occur. The same result can be explained by the presence of a shallow permafrost table in a very cold environment. Because frost sorting requires an alternation of freezing and thawing, it does not occur below the depth of annual thawing and is limited to the active zone in permafrost regions. In light of the presence of the many permafrost-associated features on Dakota Mountain, it seems reasonable to conclude that the depth of frost action has been limited by permafrost.

Unlike the features discussed above, the sorted polygons on the level upland regions of the mountain are probably relic patterns from a previously more rigorous climate. The central portions of the polygons have well-established patches of turf. The stone margins themselves are, in some cases, almost completely covered by crustaceous lichens. The only freshly exposed rocks are in the sorted circles which appear to be superimposed on the margins of some polygons. In many cases the margins have been breached by the turf patches. The pattern is so obscure in places that it is not readily discernable from a helicopter even though it is apparent from the ground. Never was the polygonal pattern seen to merge into sorted stripes, as might be expected where the slope is increased. In such locations the polygons simply ceased to exist or were replaced by turf-banked sorted steps of a smaller scale. It is concluded that the processes which produced these obscure polygons have not been active for a considerable time. Any associated patterned ground which had existed on adjacent slopes has been obliterated by more recent slope processes. The patterns have been preserved only on the more stable hilltops.

In many periglacial areas long parallel sorted stripes are a distinctive surface pattern. This is not the case on Dakota Mountain. It is possible that the vegetative cover on much of the mountain inhibits stripe development. The closely jointed feldspathic bedrock of Dakota Mountain produces a regolith of finer particles than that in many other regions of similar climate. A speculative hypothesis might be that finer particle sizes promotes development of mass movement features such as turf-banked steps and gelifluction lobes rather than those features more dependent on sorting, such as garlands and stripes. The short sorted stripes on the steep southwest slope of the mountain are associated with the sorted steps previously discussed. The narrow stripes seen emerging from some melting snowbanks are due principally to rillwork by meltwater (Embleton and King 1975, p. 78; Washburn 1973, p. 146). In areas where vegetation is present to deflect and disrupt the downslope movement of meltwater these stripes are not present. The unique case of the large scale sorted stripes at the east end of Camp Valley is discussed later as part of the historical interpretation of that area.

The very small-scale soil lineations were observed only where the wind is directed and accelerated by a topographic wind funnel (p. 34). The wind velocities in the western end of the bottom of Camp Valley were often nearly twice that estimated at the campsite not more than 20 m higher on the north valley wall. The saddle north of Camp Valley also served as a wind gap and tended to direct the wind in a north-south direction. The lineations were, without exception, oriented precisely parallel to the wind direction dictated by the terrain. It is thus probable that wind is a principal agent in their formation. These features were observed only subsequent to a two-day period of snowfall and freezing or near-freezing ground temperatures. When first observed they were distinct and well defined. Those observed days or weeks later appeared to have deteriorated to some degree and were less well defined. It is suggested that needle ice was formed on the exposed fine sediment during the cool period and that strong winds during freezing and melting resulted in a striped alignment of the particles moved by the fine ice crystals. Troll (1944, p. 30) observed this phenomenon in the Drakensberg of South Africa in June, 1934. Schubert (1973, p. 463) reports a similar occurrence in the South American Andes. Because needle ice, also known as piprake (Embleton and King 1975, p. 101), grows by drawing water from the moist underlying sediments, it is expected to be present on areas of fine sediment dampened by wet snow and absent in areas covered by coarser material. Although needle ice was not observed at any time on Dakota Mountain, it is the only plausible answer to the origin of these small lineations.

Small polygons of the same scale as those found in the drained pools of the string bog (p. 48) have been attributed to shallow frost sorting (Troll 1944, p. 53) or needle ice (Troll 1944, p. 32). The features on Dakota Mountain, however, are unrelated to frost action. Numerous small pools in the string bog are subjected to draining, rapid flooding, desiccation, and refilling as the source snowbank warms, cools, and recedes in response to solar radiation and air temperature. When the pools dry completely, the fine mud bottoms undergo desiccation cracking. During rapid flooding foreign matter may be flushed into the cracks, thus providing a more distinct "memory" of the crack position. During the next drying episode the same polygonal cracks will form at the same points of weakness. The pool also acts as a trap to collect pebbles which are carried into the pools by the small rapid meltwater streams. Some of the pebbles become lodged in the well-established desiccation cracks; most are carried to the lower end of the pool where they accumulate, while finer particles are flushed downstream. The resulting sorted polygons are solely the result of desiccation and intermittent flowing water. No frost related process would develop the accumulation of pebbles near the pool outlet or dispose of all sand size particles. There is no obvious direct relationship of these features to any present or past periglacial environment.

INTERPRETATIONS

Geomorphic History of Camp Valley

Buried Soil

Evidence found in the central portion of Camp Valley indicates that the geomorphic history there is quite complex. Five excavations were made in the area; one through the front of a large gelifluction lobe in Site K, one through a sorted circle at Site G, and three in the nonsorted polygons at Sites F, J, and L (Plate 1).

At Sites G, J, and L irregular inclusions of dark-colored soil similar to the present organic surface material were discovered as deep as 500 mm. At Site G the inclusions were dark streaks inclined upward and toward the center of the sorted circle. At Site J the very dark grayish-brown surface material extends to a maximum depth of 400 mm below a trough marking the margin of a polygon. Elsewhere in the excavation similar soil in irregular masses is buried. Near one trough three thin darker layers about 50 mm thick and 50 to 110 mm apart curve downward and toward the center of the polygon. At Site L the dark layers are more continuous and distinct than elsewhere. Two layers can be identified clearly.

All of this dark organic material probably developed near the surface as part of an "A" soil horizon. This assumption is supported by the presence of organic spheres (p. 60) in the samples. Other than in these buried organic masses, they were found only in near-surface sediment. Their origin, environmental significance, or value for more specific correlation is unknown. Thomas Freeman, Professor of Botany at North Dakota State University, tentatively identified them as plant seeds.

The coarse poorly sorted sediment which encloses the soil is similar to the gelifluction debris in nearby lobes. The conformity of the distinct organic layer in Site L with the nearby gelifluction scarp tends to indicate that gelifluction has had a role in the burial process. The wide level valley bottom beginning 200 m east of the string bog may be the result of filling by gelifluction debris. Valley fills several tens of metres deep have been reported elsewhere (Embleton and King 1975, p. 106). The irregular character of the organic inclusions is probably the result of cryoturbation (frost stirring). The upward inclination of the buried soil masses at Site G probably resulted from the upward frost heaving in the center of the sorted circle.

Nonsorted Polygons

The origin of the nonsorted polygons themselves is problematic. A number of mechanisms can be eliminated. For example, there is no associated pronounced heaving or collapse as would be expected if the polygons were the result of dilation cracking (Washburn 1973, p. 141). There is no evidence of the salt concentration needed for salt cracking. The apparently great depth of unconsolidated debris precludes development of surface polygons by frost action along bedrock joints. Neither is there any evidence that seasonal frost cracking can result in cracks as wide and well defined as those in Camp Valley (Washburn 1973, p. 142). Sand wedging can be disregarded simply because of the lack of sand fillings. The remaining alternatives are ice-wedge or desiccation polygons. The width and depth of individual cracks tends to support the ice-wedge mechanism. The upturning of strata adjacent to the polygon border, as at Site J, has been observed commonly in ice-wedge polygons (Lachenbruch 1962, p. 4). The size of the polygons, however, is smaller than expected from ice-wedging. Péwé (1965, p. 77) indicates that ice-wedge polygons are typically from 3 to 30 m or more in diameter. Lachenbruch (1965, p. 63) states that they vary from a few metres to more than 100 m. Black (1952, p. 120) indicates that ice-wedge polygons may be less than a metre in diameter when they result from subdivision of larger ice-wedge polygons. No such subdivision is apparent on Dakota Mountain, yet the polygons there are from 1.5 to only 0.6 m in diameter. This size approaches the largest which can be expected from desiccation cracking. Washburn (1973, p. 139) indicates that desiccation is important in formation of polygons having a diameter less than one metre, but he does not exclude larger forms. Washburn (1973, p. 14) quotes Tricart (1967, p. 176-201) as concluding that nonsorted polygons up to 0.5 m in diameter are probably due to air drying and those with diameters of 0.6 to 3 m are likely desiccation features due to freeze drying. A qualitative laboratory analysis of desiccation cracking from air drying was carried out by Corte and Higashi (1964). The largest polygons which they produced in the laboratory were about 0.3 m in diameter. The various materials used to form the bottoms of the test containers had a profound effect on polygon size, as did the depth of the soil sample. Deep soil on a sand bottom produced the largest forms. Soil with a smaller content of silt and clay produced larger polygons than finer soil under similar conditions. These relationships indicate that the Camp Valley polygons are probably within the size range of possible desiccation polygons. In some unusual playas of the American Great Basin there are desiccation polygons up to 300 m in diameter (Neal and others 1968, p. 70).

Two unanswered questions cast doubt on the hypothesis of desiccation, however. It is doubtful that it is possible for sediment with only 1.35% silt and clay to develop distinct desiccation cracks. The sample from Site F is 84.77% gravel, 13.89% sand, 1.27% silt, and only 0.08% clay. The sand-silt-clay ratio of the matrix is 91.1 - 8.3 - 0.5 and the silt-clay ratio is 94.1 to 5.9. The coarsest sample studied by Corte and Higashi (1964, p. 67) was 19% gravel, 51% sand, 22% silt, and 8% clay and had a sand-silt-clay ratio of 63 - 27 - 10 and a silt-clay ratio of 73 to 27. Although the true quantitative significance of such size distribution to desiccation cracking is unknown, it appears that the Camp Valley sediment certainly approaches or exceeds the coarse limit of soils subject to desiccation cracking. The second problem is the width of crack fillings and the overlying troughs. Ice-wedges grow by water freezing in small cracks during many cycles of expansion and contraction. When they melt they may then be replaced by surface sediment that slumps into the vacant space. In the case of desiccation, however, the surface material must repeatedly fill each small crack in order to develop the filling. Filling, therefore, must be nearly contemporary with the desiccation. It is difficult to explain how a 300 mm wide filling of organic-rich material could develop in an environment subject to such intense repeated drying. At Site F there was a concentration of stones up to 100 mm in diameter along the sides and bottom of one filling. It is not difficult to conclude that they dropped into a wide crack vacated by a thawing ice-wedge; it is more difficult to explain their occurrence if incremental filling of narrow desiccation cracks is the source of the overlying material.

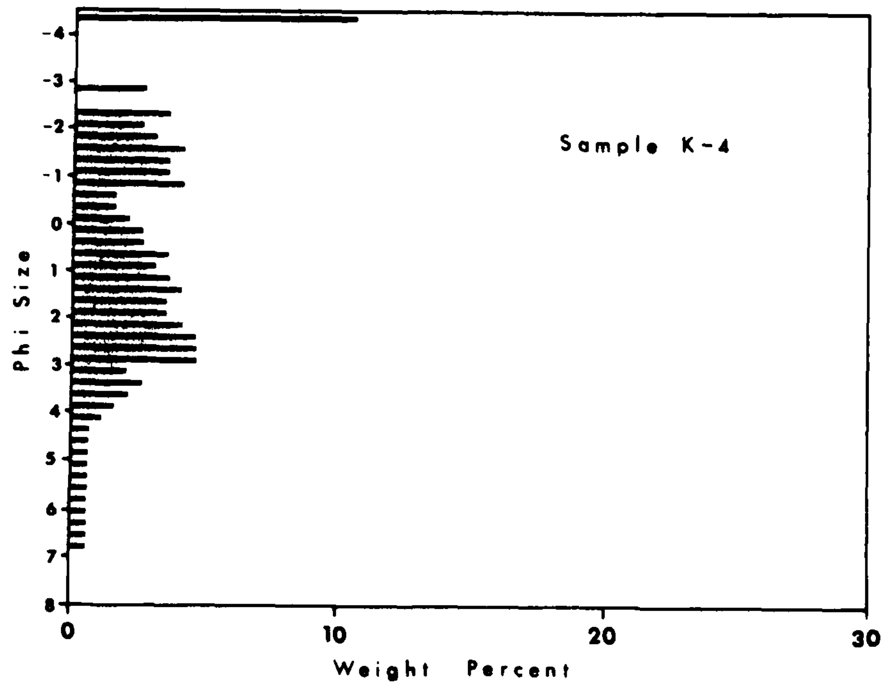
It is tentatively concluded that the nonsorted polygons in Camp Valley are small ice-wedge polygons. The possibility that they are the result of desiccation should not be discarded, however.

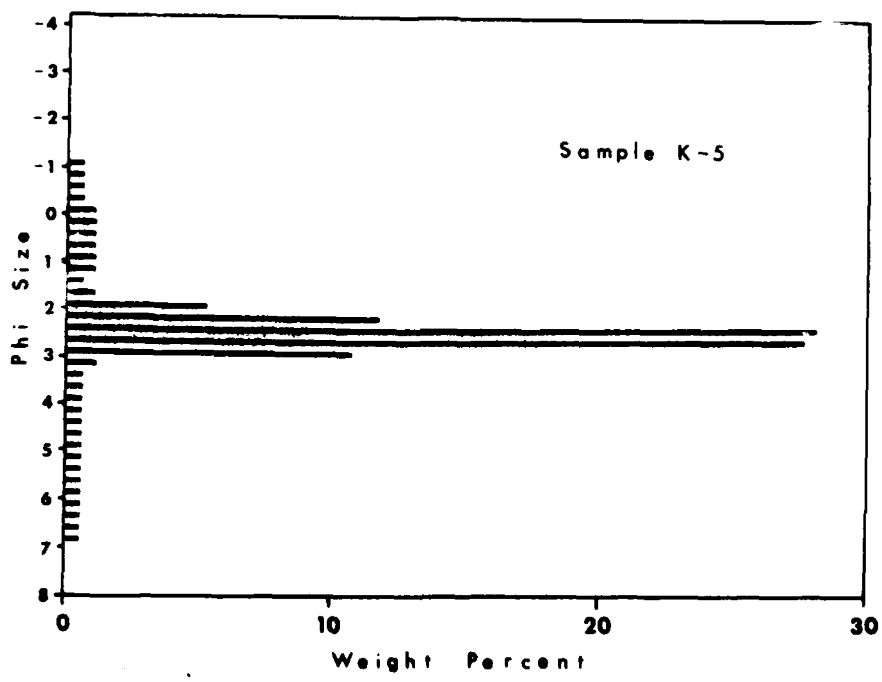
Sand Lenses

Several thin discontinuous masses of well-sorted yellowish-brown fine sand were found in the soil profile buried beneath the gelifluction lobe at Site K (Figure 5). These sand lenses were from 4 to 12 mm thick and were located about 50 mm below the original surface, now covered by the lobe. Grain size distribution of the sand is compared with other samples from Dakota Mountain in Figure 46. The thin deposits exhibited no crossbedding or other structure which might give a clue as to their origin. Optical microscopy of the sample in thin section and analysis by microprobe revealed an overwhelming concentration of plagioclase. Potassium feldspar, pyroxene, and small lithic fragments are present along with minor amounts of quartz and a few fragments of glass. The particles are irregular with sharp unweathered cleavage and fracture. Very little rounding of grains is evident.

The original impression that the sand is tephra was easily discarded because of the lack of an appreciable amount of volcanic glass. Fluvial origin is unlikely because of the location on the side of the valley away from any natural drainage path. Marine-related processes clearly can be eliminated due to the high altitude

Fig. 46. Particle size distribution of samples from Site K (Plate 1). Sample K-4 is gelifluction debris. Sample K-5 is from thin lenses of fine sand.


Sample K-4
Phi Size
Weight Percent

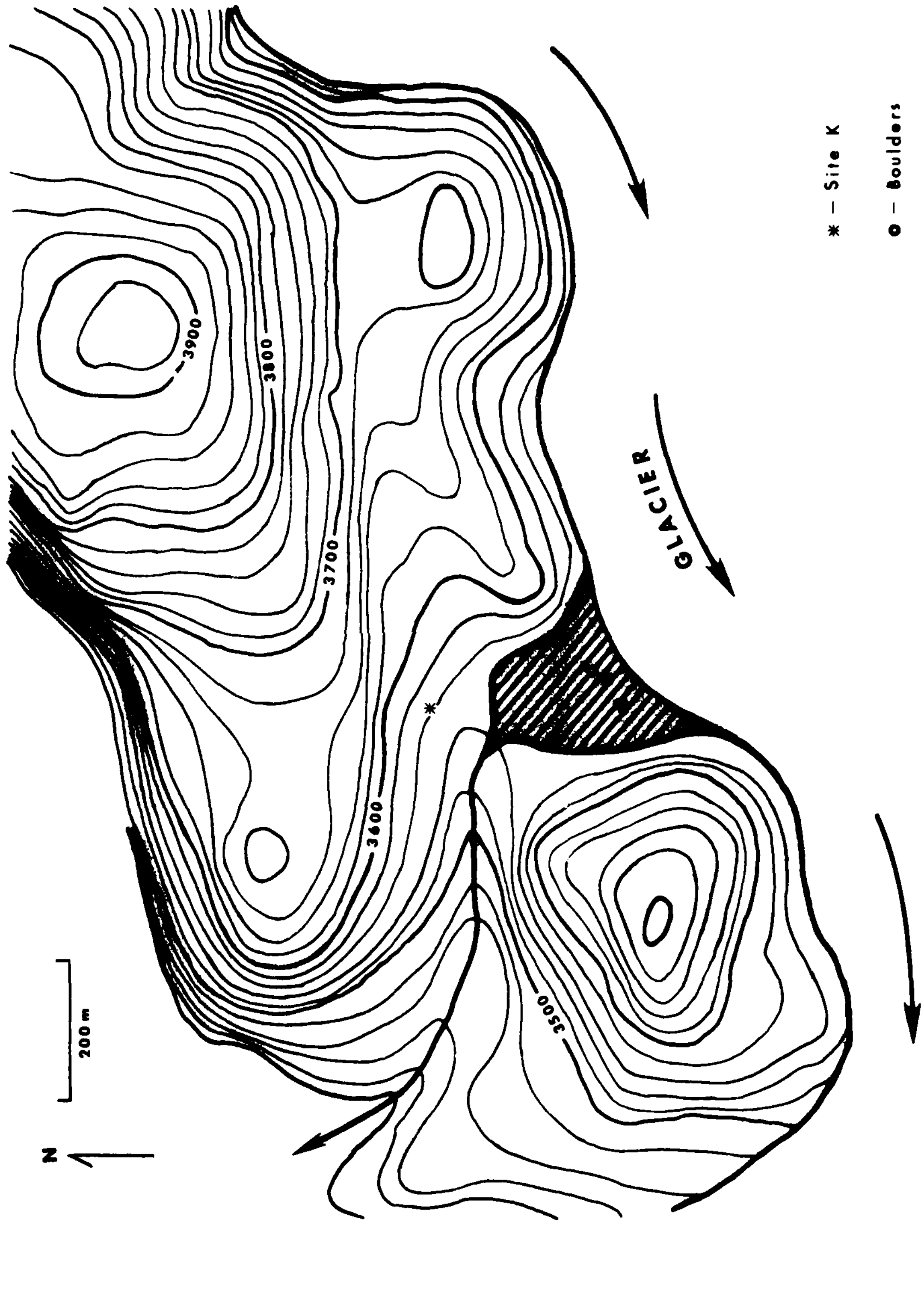

Sample K-5
Phi Size
Weight Percent

and total lack of any other marine evidence. The remaining possibilities are those of eolian and lacustrine environments. The surface morphology of grains of the sample were studied under the scanning electron microscope. Characteristic surface features of quartz grains from various environments are well known (Krinsley and Doornkamp 1973). Unfortunately, the few quartz grains found in the sample were freshly fractured and showed no diagnostic surface morphology. The surface textures did reveal that the particles had not been subject to much abrasion and were probably very near the source area.

An eolian origin of the sand deposits is the least complex and thus most likely explanation. The mean grain size of the sand, 0.18 mm, corresponds to the most common grain size of modern wind-blown sands (Troll 1944, p. 23). Wind transported sediment is often associated with dry periglacial environments (Embleton and King 1975, p. 180).

Although the probability of encountering lacustrine deposits in such a steep well-drained area as Dakota Mountain seems remote, the topography of Camp Valley does support this possibility. The central part of the valley now drains in two directions. The portion of the valley including the string bog is part of the drainage to the northwest. The eastern portion drains to the southeast into the valley of the North Fork of Bradley River. The broad divide between these drainages now lies at about the location of the sorted polygons. If glacial ice were to fill the valley of the North Fork of Bradley River to an elevation of about 1100 m (3600 feet), the drainage to the southeast would be blocked. With a supply of surface water a small proglacial lake would develop against the side of the glacier and extend into a part of Camp Valley as shown in Figure 47. The several large boulders

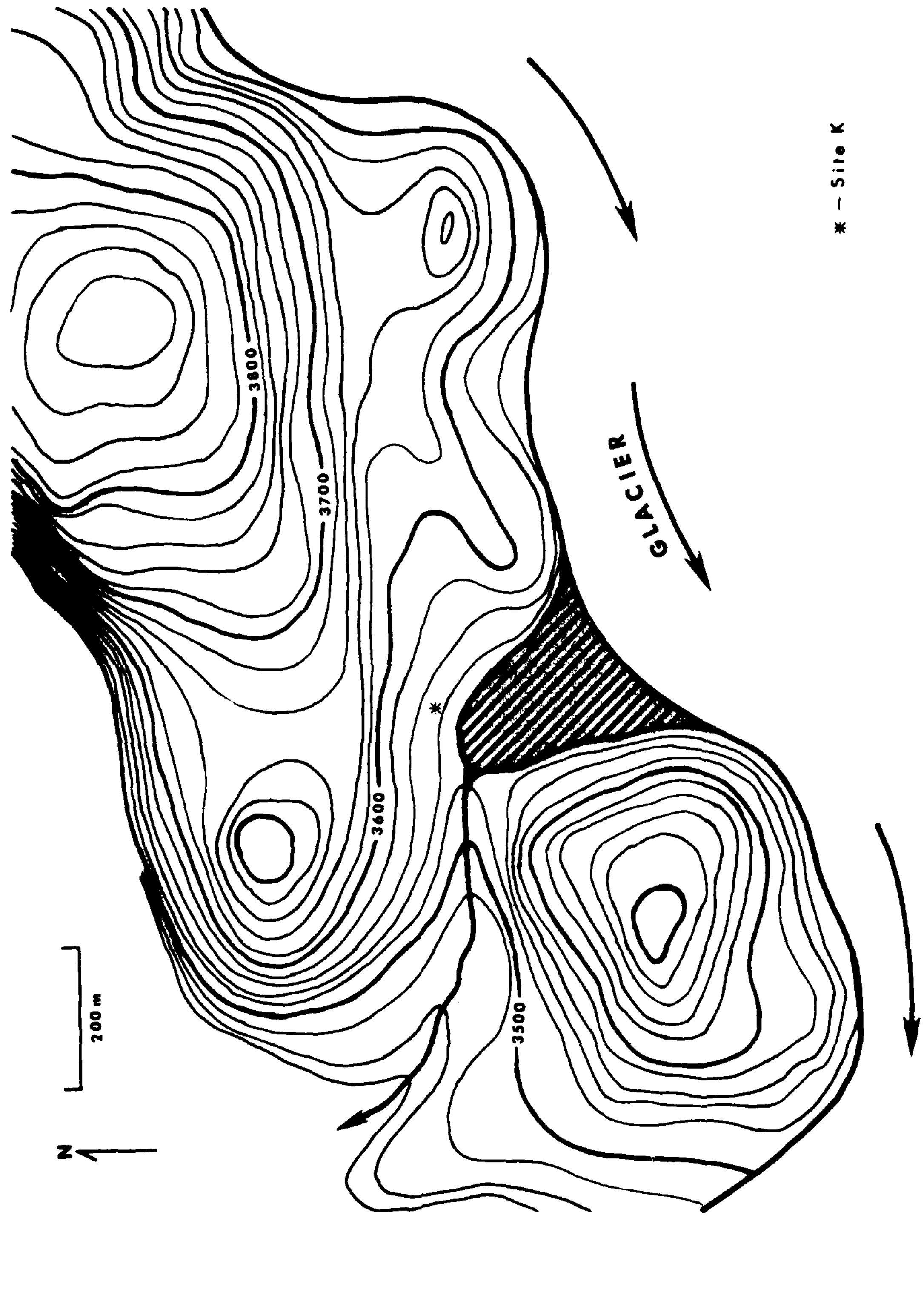
Fig. 47. Map of Camp Valley area showing the relationship of the sand lenses at Site K to a hypothetical proglacial lake, based on existing topography.


3900
3800
3700
3600
3500
GLACIER
200 m
N
* — Site K
o — Boulders

marked on that figure near the ice face may have rolled or slid onto the ice some distance to the east and later been dropped off of the side of the glacier to their present position. In order for this lake to have extended to the location of the sand deposit, the drainage divide to the west would have to have been relatively higher than at present. This difference in elevation may have existed during the past either because of the presence of a higher spillway which has since been eroded away or because of a relative change in elevation resulting from isostatic tilting toward the east. Calculations of the maximum tilting which could be expected to result from the weight of glacial ice in the region are developed in appendix B. The map in Figure 48 was mathematically derived from the map in Figure 47 by applying a 1° tilt toward the east. The shore of the hypothetical lake on the tilted mountain would come very near the present location of the sand deposit. The local sharp break in slope about 150 m east of the string bog could well be the limit of headward stream erosion into the spillway of such a lake. Figure 49 is a subjective modification of Figure 48 which shows the possible topography before the down-cutting of the divide by overflowing lake water. The sand deposit corresponds to the characteristics and location expected of shore deposits of the supposed lake in that setting.

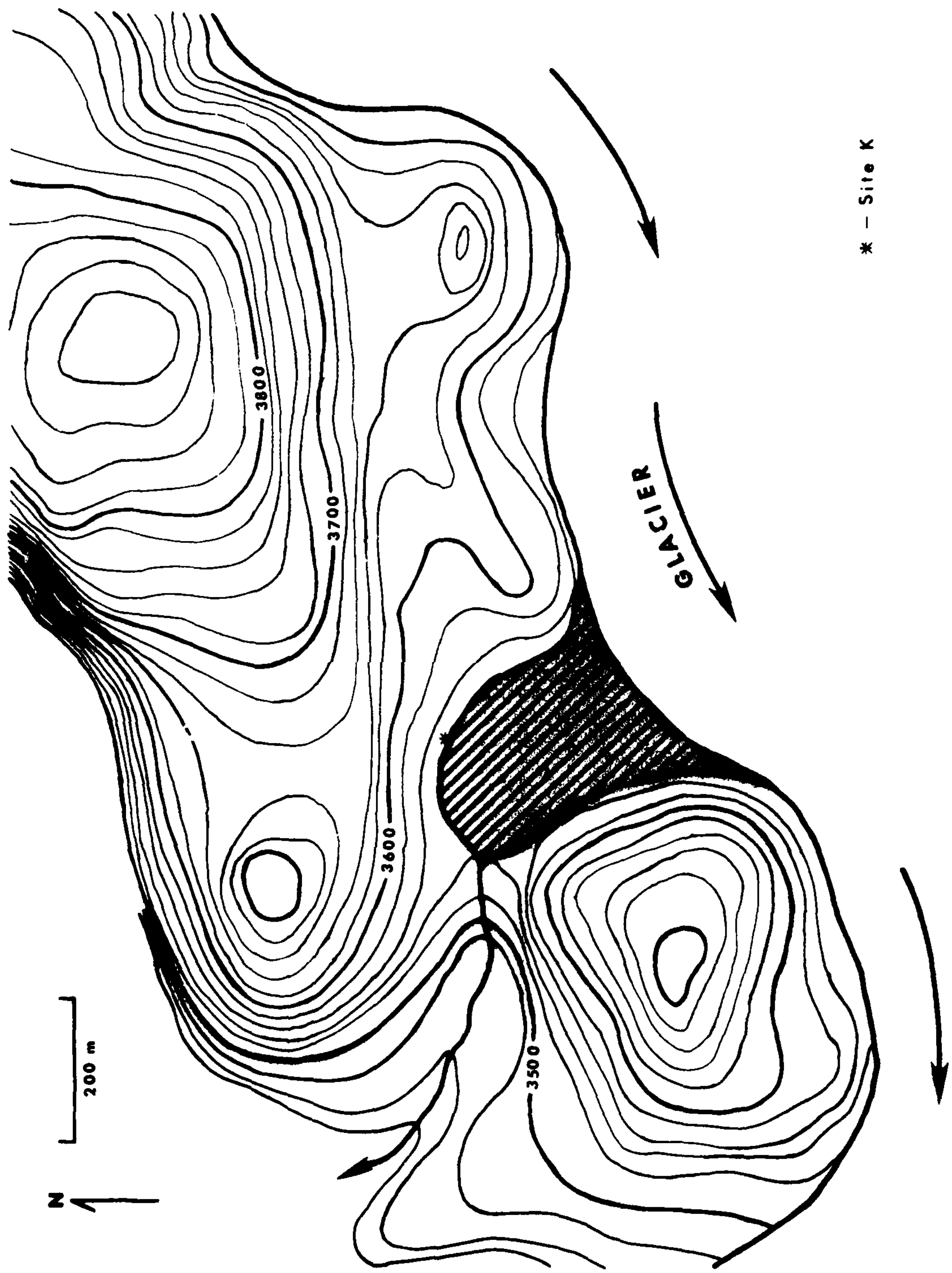
Additional data from Camp Valley is needed before firm conclusions concerning the hypothetical proglacial lake can be drawn. No other sand deposits have been observed at other probable shoreline sites; however, they may have been buried or obscured by subsequent gelifluction. No lake bottom deposits are apparent. The surveying instruments and methods used were too inaccurate to define precisely

Fig. 48. Reconstructed map of the Camp Valley area showing the effect of a 1° tilt to the east on the location of Site K with respect to the lake. Compare with Figure 47.



3800
3700
3600
3500
GLACIER
* — Site K
200 m
N

Fig. 49. Reconstructed map of the Camp Valley area showing the effect of a 3 m higher spillway on the hypothetical proglacial lake in Figure 48.



3800
3700
3600
3500
GLACIER
200 m
N
* — Site K

the positions and elevations of the drainage divides or the deposits in question. Until further data is accumulated, any conclusion is little more than speculation.

Nonconformable Sorted Stripes

The sorted stripes at the extreme east end of Camp Valley are an unusual case of bifurcating striped patterned ground. The pattern is well defined but there is no evidence of currently active sorting. The stripes are probably relic patterns that have been preserved by differential vegetation growth. Sorted stripes are by definition oriented down the steepest available slope (Hamelin and Cook 1967, p. 157). A situation such as this case where one branch of the pattern turns upslope to the east is truly remarkable. No mechanism has been found that explains their formation in their present position and attitude. If the mountain, however, were tilted downward slightly to the east as discussed above, the gently sloping divide of the saddle would be moved to the west. A tilt of one to two degrees would position the divide directly where the stripes separate from each other. This would allow the stripes to descend from the north onto the crest of the broad north-south trending saddle, bifurcate, and continue downslope to both the east and the west. Subsequent tilt toward the west, as from the isostatic adjustment to glacial unloading, would move the crest of the saddle eastward, but leave the stripes to be preserved in their seemingly illogical position.

It is concluded that these unusual stripes are evidence of isostatic tilt from glacial loading in the Kenai Mountains to the east.

Glacial History of Dakota Mountain

Dakota Mountain was selected as a study area because of its lack of glacial erosion features. Its smooth rounded summits distinctly contrast with the sharp angular adjacent topography. The deep glacial valleys on both sides of the mountain and the large cirque cut into its northern end clearly indicate that it stood as a nunatak amid the ice when those features were last fully occupied by glaciers. A similar situation exists today near the margins of both the Antarctic and Greenland ice sheets where mountainous nunataks are common (Sugden and John 1976, p. 97). Only during the last few days of fieldwork was any evidence of previous glaciations discovered on the mountain. The composition of the two small erratics and especially the microscopic striations and crescentic gouges on the polished surface conclusively indicate that the mountain was at some time covered by glacial ice. It is remotely possible for the larger erratic to have been transported into Camp Valley by ice rafting or fluvial action resulting from complex drainage across the mountain by glacial meltwater from a large glacier. The high position in which the smaller erratic was found eliminates all natural processes other than transportation by a glacier.

Karlstrom (1964, plate 1) maps a small area including Dakota Mountain as last being covered by ice of Eklutna age, but shows that the surrounding region was buried beneath two later glaciations, the Knik and Naptowne. His chronology thus implies that Dakota Mountain has been free of glacial ice about 90,000 years and that the adjacent area was deglacierized 14,000 to 9,000 B.P. (Karlstrom 1964, p. 63). He does not explain the criteria he used in mapping the upland areas;

his principal area of concern was the Kenai lowlands. His conclusions, however, are compatible with the evidence discovered during this investigation. Péwé and Reger (1968, p. 56) concluded that the cryoplanation terraces at their Mt. Hayes A-5 site formed during 50,000 to 70,000 years of periglacial attack. If that length of time was required to develop those terraces, it is probably impossible for the ones on Dakota Mountain to have developed during only the 45,000 years since the end of the Knik glaciation (Karlstrom 1964, p. 63).

Regional Correlations

Many areas, both large and small, along the western side of the southern Kenai Mountains display the same surface morphology as Dakota Mountain. These areas were mapped from a low level aircraft on 1:50,000 scale topographic base maps. They are depicted on Plate 2. The identification of these periglacial areas was based on their smooth rounded surface, a distinct differentiation from adjacent glacial topography, such as steep valley sides or cirque headwalls cutting into the area, or the presence of periglacial features, usually gelifluction lobes or steps. South of Tustumena Lake (Plate 2) they are distinct and generally easy to define. As far north as the Kenai River some areas could be identified; they were more difficult to separate from the less sharply dissected topography of that region, however. No attempt was made to map areas north of the Kenai River and Kenai Lake or east of the Alaska Railroad. No periglacial surfaces were found on the southeast side of the Kenai Mountains; however, clouds precluded careful examination of a portion of that region just southwest of Seward. On the southwest end of the mountain range only a small area on Red Mountain, 10 km south of

Jakolof Bay near Seldovia, was identified. Some of the areas display extraordinarily large gelifluction lobes, others have distinct systems of steps and small lobes. All have the subdued topography typified by Dakota Mountain. To have developed such similar surface morphology, they must have been subject to similar processes for about the same period of time. It is thus concluded that they, like Dakota Mountain, were not glaciated during the Knik or Naptowne glaciations.

SUMMARY OF CONCLUSIONS

The surface morphology of Dakota Mountain is the product of a periglacial environment. Although geologic structure has had an effect on topographic development, the periglacial processes of cryoplanation, nivation, cryoturbation, cryofraction, and gelifluction have been the principal agents of landform modifications.

Ground temperature measurements indicate that permafrost has existed on Dakota Mountain in the recent past; however, no permafrost presently exists which is shallow enough to affect surface processes. The conclusion that permafrost recently existed is also supported by the distinct gelifluction features, the presence of a string bog, and the low mean annual air temperature.

Three general groupings of features may be made. The first group consists of features which are products of a previous colder environment. Included are the cryoplanation terraces, the sorted polygons on hilltops, and the nonsorted polygons in Camp Valley. Each of these features shows evidence of modification by subsequent processes. The second group includes the recently active gelifluction lobes and turf-banked steps. They are sharp unmodified forms with a fresh appearance. Because of the lack of permafrost, however, it is doubtful that they are currently active. They are probably relic forms which ceased developing at the time the near-surface permafrost thawed. The third group includes only those features which are being formed or modified presently. Part of this group are features that result from the currently active processes of cryofraction and frost sorting, such as tors, vertical stones, and sorted circles. Three small-scale patterned ground forms not related to periglacial processes should also be included in this group. They are the sorted stripes formed by rillwork, lineations resulting from needle ice and wind, and sorted polygons developed by desiccation and flowing water.

Sand found beneath a gelifluction lobe in Camp Valley probably was deposited by eolian action; it may, however, be a beach sand deposited at the shore of a small proglacial lake. Such a lake could have existed had a glacier blocked the southeast outlet of Camp Valley and the mountain been slightly tilted to the east by isostatic adjustment to glacier loading. Glacier mass estimates indicate that such tilting is realistically possible. The alignment of a bifurcated set of sorted stripes tends to support the hypothesis that the mountain was tilted.

Topography on and around Dakota Mountain indicates that the mountain stood as a nunatak during the last general glaciation of the region. Two erratics discovered on the mountain, however, are evidence that the area has been glaciated. The degree of development of the periglacial features suggests that the mountain has been free of glacial ice since the Eklutna glaciation which ended about 90,000 years B.P.

The finely jointed bedrock, a previous colder environment, and long exposure in the absence of glacial ice has allowed periglacial processes to be the dominant surface agent on Dakota Mountain. Numerous other areas on the west edge of the Kenai Mountains display characteristics and features similar to those on Dakota Mountain. They are also interpreted to be the result of periglacial activity and probably share a similar history.

APPENDICES

APPENDIX A

METEOROLOGICAL DATA FOR BRADLEY LAKE AND DAKOTA MOUNTAIN

Air Temperatures, Bradley Lake, 1979

Date		High °C	High °F	Low °C	Low °F	Range °C	Range °F
June	6	15.4	60	Installed			
	7	15.7	60	5.1	41	10.6	19
	8	15.7	60	6.1	43	9.6	17
	9	24.0	75	5.0	41	19.0	34
	10	17.5	64	6.4	44	11.1	20
	11	17.2	63	8.6	47	8.6	15
	12	21.1	70	6.9	44	14.2	26
	13	17.5	64	7.1	45	10.4	19
	14	22.3	72	6.9	44	15.4	28
	15	16.4	62	4.7	40	11.7	21
	16	10.7	51	7.6	46	3.1	6
	17	12.7	55	8.6	47	4.1	7
	18	18.0	64	6.1	43	11.9	21
	19	17.8	64	7.8	46	10.0	18
	20	14.9	59	9.2	49	5.7	10
	21	17.8	64	8.2	47	9.6	17
	22	24.0	75	5.6	42	18.4	33
	23	24.0	75	5.9	43	18.1	33
	24	11.6	53	9.5	49	2.1	4
	25	9.4	49	8.2	47	1.2	2
	26	11.9	53	6.8	44	5.1	9
	27	11.4	53	5.0	41	6.4	12
	28	11.7	53	4.8	41	6.9	12
	29	21.5	71	4.4	40	17.1	31
	30	16.9	62	4.1	39	12.8	23
July	1	19.0	66	8.9	48	10.1	18
	2	25.2	77	10.1	50	15.1	27
	3	27.7	82	12.9	55	14.8	27
	4	20.6	69	11.7	53	8.9	16
	5	14.4	58	10.3	50	4.1	7
	6	18.8	66	9.6	49	9.2	17
	7	19.2	67	8.9	48	10.3	19
	8	16.1	61	10.1	50	6.0	11
	9	19.2	67	9.8	50	9.4	17
	10	20.9	70	8.2	47	12.7	33
	11	16.0	61	9.0	48	7.0	13
	12	16.1	61	10.1	50	6.0	11
	13	20.9	70	9.0	48	11.9	21
	14	14.7	58	11.2	52	3.5	6
	15	14.7	58	9.8	50	4.9	9
	16	15.1	59	7.0	45	8.1	15
	17	24.3	76	11.3	52	13.0	23
	18	20.0	68	12.0	54	8.0	14
	19	18.9	66	12.3	54	6.6	12
	20	28.0	82	10.9	52	17.1	31
	21	Removed		12.0	54		

Summary, Bradley Lake, 1979

		June 6-30 °C	June 6-30 °F	July 1-21 °C	July 1-21 °F	June 6-July 21 °C	June 6-July 21 °F
Average	high	16.7	62.0	19.5	67.1	17.9	64.3
	low	6.6	43.9	10.2	50.4	8.3	46.9
	range	10.1	18.2	9.3	16.8	9.8	17.6
Maximum	high	22.3	72	28.0	82	28.0	82
	low	9.5	49	12.9	55	12.9	55
	range	19.0	34	17.1	31	19.0	34
Minimum	high	10.7	51	14.7	58	10.7	58
	low	4.1	39	7.0	45	4.1	39
	range	1.2	2	3.5	6	1.2	2

	Dates	Inches	mm
Precipitation:	June 6 to June 15	0.39	9.9
	June 16 to June 24	0.06	1.5
	June 25	0.57	14.5
	June 26 to July 12	0.99	25.1
	July 13 to July 18	0.53	13.5
	July 19 to July 21	0.00	0.0
		2.54	64.5

Air Temperatures, Dakota Mountain, 1979

Date	High °C	High °F	Low °C	Low °F	Range °C	Range °F
June 19	7.8	46	5.0	41	2.8	5
20	8.9	48	4.4	40	4.4	8
21	11.1	52	3.3	38	7.8	14
22	16.1	61	3.3	38	12.8	23
23	17.8	64	5.6	42	12.2	22
24	12.2	54	8.3	47	3.9	7
25	6.7	44	5.0	41	1.7	3
26	7.2	45	1.1	34	6.1	11
27	5.6	42	1.7	35	3.9	7
28	5.0	41	1.7	35	3.3	6
29	13.3	56	1.7	35	11.7	21
30	13.3	59	4.4	40	8.9	16
July 1	15.0	59	5.0	41	10.0	18
2	17.8	64	6.7	44	11.1	20
3	21.7	71	10.6	51	11.1	20
4	13.3	56	10.0	50	3.3	6
5	11.7	53	7.8	46	3.9	7
6	7.8	46	3.9	39	3.9	7
7	14.4	58	5.0	41	9.4	17
8	11.7	53	7.2	45	4.4	8
9	12.2	54	6.1	43	6.1	11
10	15.0	59	6.7	44	8.3	15
11	17.2	63	7.8	46	9.4	17
12	12.8	55	7.8	46	5.0	9
13	13.9	57	4.4	40	9.4	17
14	12.8	55	8.3	47	4.4	8
15	10.6	51	6.7	44	3.9	7
16	8.3	47	5.0	41	3.3	6
17	16.7	62	6.1	43	10.6	19
18	13.3	56	10.0	50	3.3	6
19	11.1	52	8.9	48	2.2	4
20	18.3	65	6.1	43	12.2	22
21	14.4	58	7.2	45	7.2	13

Summary, Dakota Mountain, 1979

		June 19-30		July 1-21		June 19-July 21	
		°C	°F	°C	°F	°C	°F
Average	high	10.4	50.8	13.8	56.9	12.6	54.6
	low	3.8	38.8	7.0	44.6	5.8	42.5
	range	6.6	11.9	6.8	12.2	6.7	12.1
Maximum	high	17.8	64	21.7	71	21.7	71
	low	8.3	47	10.6	51	10.6	51
	range	12.8	23	12.2	22	12.8	23
Minimum	high	5.0	41	7.8	46	5.0	41
	low	1.1	34	3.9	39	1.1	34
	range	1.7	3	2.2	4	1.7	3

Precipitation:

Date	Time	Inches		mm	
June 27	0900 to 1200	0.06		1.5	
	1200 to 1800	0.08		2.0	
	1800 to 2200	0.29		7.4	
	Day total		0.43		10.9
June 28	0001 to 0600	0.06		1.5	
	0600 to 0900	0.05		1.3	
	0930 to 1230	0.03		0.8	
	1230 to 1400	0.08		2.0	
	1400 to 1930	0.03		0.8	
	Day total		0.25		6.4
June 30	1715 to 1900	0.02		0.5	
	1900 to 2000	0.01		0.3	
	Day total		0.03		0.8
July 4 to July 12			0.67		17.0
July 14	0001 to 0700	0.04		1.0	
	0700 to 0800	0.07		1.8	
	0800 to 0900	0.02		0.5	
	0900 to 1000	0.01		0.3	
	1000 to 1100	0.03		0.8	
	Day total		0.17		4.3
July 15	0001 to 0700	0.18		4.6	
	0700 to 0800	0.02		0.5	
	Day total		0.20		5.1
July 18	0001 to 0600		0.02		0.5
July 19 to July 21			0.01		0.3
			1.78		45.2

APPENDIX B

ISOSTATIC ADJUSTMENT ESTIMATES

Derivation of Equations

During work on this project there arose the need for a simple method of estimating the isostatic adjustment of the earth's crust due to glacial loading and unloading. The following formulae were derived for this purpose.

In these calculations, it was assumed that the crust of the earth behaves as if it were floating on a fluid which has a specific density of 3.2 and that the area in question responds to loading according to Archimede's Principle of buoyancy. Complicating factors, such as time rate of movement and interference from adjacent areas of the crust, were not included. If the depth of ice which previously covered an area is known, the amount of isostatic adjustment should have been proportional to that depth.

Let T = average thickness of glacial ice

A = amount of isostatic adjustment

If glacial ice is assumed to have a uniform specific density of 0.9, the specific weight of the ice per unit area is 0.9 x T. The specific weight of the mantle fluid displaced per unit area is A x 3.2. By Archimede's Principle, these quantities most be equal.

$$0.9 \times T = 3.2 \times A$$

$$A = 0.28 \times T$$

In many cases, however, the thickness of the ice which covered a now deglacierized area is not known, yet an estimate of its former surface elevation might be possible.

Let I = mean surface elevation of the ice

Z = present mean land surface elevation

$$T = I - (Z - A)$$

$$A = 0.28\ (I - Z + A)$$

$$0.72 \times A = 0.28\ (I - Z)$$

$$A = 0.39\ (I - Z)$$

Let A' equal the relative adjustment between two points b and c.

$$A' = A_b - A_c$$

$$A' = 0.39\ (I_b - Z_b) - 0.39\ (I_c - Z_c)$$

$$A' = 0.39\ [(I_b - I_c) - (Z_b - Z_c)]$$

$$A' = 0.39\ (I' - Z')$$

where I' is the difference in elevation of the ice surface at the two points during glaciation and Z' is the difference in ground elevations during the absence of glacier ice.

If both sides of the last equation are divided by d, the horizontal distance between the points, we obtain

$$A'/d = 0.39\ (Z'/d - Z'/d)$$

$$S = 0.39\ (SI - SZ)$$

where S is the change in average ground slope due to isostatic adjustment, SI is the average surface slope of the glacier between the points, and SZ is the average ground slope without the ice.

Calculations

In order for a glacier to have blocked drainage to the south from Camp Valley, it is necessary for the ice to have stood at the present position of the 3600-foot contour. Therefore, the ice in the glacial valley south of Dakota Mountain would have been at least 335 m (1100 feet) thick. Having this information and a basic understanding of ice flow dynamics, it seems logical that one should be able to determine something of the extent of glacierization upstream and downstream from this area. Various formulae based on Glen's law of ice flow have been proposed to describe the surface of a theoretical ice sheet (Nye 1952, p. 529; Nye 1959, p. 494; Haefeli 1961, p. 1142; Weertman 1961, p. 958). Although these formulae can depict an unconstrained ice sheet quite accurately, if applied to conditions in the Cook Inlet region they appear faulty. They predict that the location of glacier termini would be much closer to the source areas than is indicated by the geological evidence reported by Karlstrom (1964, plate 1). There has been no formula developed which is sufficiently complex to incorporate the vast number of variables introduced by tributary glaciers, variable bed characteristics, and the complex restraining and constraining effects of topography present in alpine glaciation. Nevertheless, an estimate of the limiting condition of isostatic tilt of Dakota Mountain can be calculated. Such an estimate was made by applying Nye's formula of ice profile south of Camp Valley and calculating as if the topography were horizontal and the glacier unconstrained. It was found that the ice 4 km to the west would be at least 170 m thick. This value was accepted as a minimum; the effect of tributary ice flow and ground slope would tend to increase the thickness of the ice. The ice thickness used in the subsequent calculations was assumed to decrease in a linear fashion between the two points. The same linear thickness profile was continued upstream to establish an ice thickness except where sharply rising topography dictated a subjective reevaluation. By using a linear profile, the ice thickness obtained should be a minimum for the downstream area and a maximum for the upstream area. The average ground elevation and ice thickness were then calculated for each 500 m square within an area 2 km north and south and 4 km east and west from Camp Valley. The average thickness of ice in each square and its isostatic effect were calculated. It was found that the area to the west was covered by an average of 132 m of ice and would have been depressed at least 37 m. The ice to the east of Camp Valley averaged 157 m in thickness and would have caused no more than 44 m of depression. These results indicate that the local distribution of ice caused very little tilting of the area. When viewed on a slightly larger scale, however, the isostatic effect of glacierization could have been of real significance. By using the downstream ice thickness derived above and extending that elevation to the valley of Sheep Creek, which enters the Kachemak trough 8000 m north of Bradley River, it is estimated that the depth of ice at the mouth of that valley was at least 600 m. Thirteen kilometres upstream from that location at a point less than 3 km east of Dakota Mountain, cirques in the valley wall indicate that the maximum depth of the main glacier was about 840 m. This value is compatible with the thickness estimated at the valley mouth. A glacier of that size would have filled the valley to a width of 4600 m and had an average depth of 540 m. Such a mass of ice would have tended to depress the valley by 150 m. The exact manner in which the crust of the earth adjusts to isostatic forces is, no doubt, extremely complex and to a large extent yet unknown. If we make an arbitrary assumption that no adjustment occurred by faulting, that the area from Dakota Mountain to Sheep Creek behaved as a single rigid block, and that effective hinge lines were located in Sheep Creek Valley and just west of Dakota Mountain, it can be calculated that the block including Dakota Mountain would have been inclined 1.1° to the east. If the calculation were to be expanded to include the icecap that covered the central crest of the Kenai Mountains, it would also be necessary to include the ice that filled the less distant Kachemak trough. It is presently impossible to determine accurately the thickness of ice in both of these areas at a single time. Ice masses in these areas, however, would tend to have a cancelling effect on each other with respect to the isostatic tilt of Dakota Mountain. It is reasonable, therefore, to conclude that the maximum eastward tilt that can be attributed to general isostatic adjustment to glacial loading is about 1.1°.

APPENDIX C

RADIOCARBON SAMPLE PREPARATION

The soil samples collected on Dakota Mountain were badly contaminated with modern roots and root hairs. In order to obtain accurate radiocarbon ages, such modern carbon must be removed. A system of floatation and filtration was developed to eliminate most of the contamination. Each sample was processed in batches of about 25 grams. Each batch was soaked and strained through a 2 mm fiberglass screen into a 800 ml flask. More distilled water was added and the flask vigorously agitated to break up aggregations of particles on root hairs. The mixture was permitted to settle for ten minutes and the root hairs and other buoyant matter allowed to float to the surface. The flask was inclined over a filter funnel and more water added to the bottom of the flask using a 100 ml pipette. The water in the neck of the flask, together with any floating matter, spilled into the funnel and through the filter into a catchment beaker. The pipette was used to recycle water from the beaker back into the flask. The tip of the pipette was held very near the sediment in the bottom of the flask and considerable force was used in expelling water from the pipette in order to maximize the washing action. Determination of the material to be used as a filter in the funnel was a subject of some difficulty. Filter paper or cotton cloth could not be used because of the possibility of introducing fibers containing modern carbon into the sample. The weave of "rip-stop" parachute nylon proved too close to allow water to pass freely. Excellent results were finally obtained using several layers of a fine polyester knit fabric. Water was recycled into the flask until no visible floating matter was being flushed into the funnel. The flask was allowed to stand for one half hour to let microscopic root hair fragments float to the surface. The top one-third of the clear liquid was then decanted and discarded. The sample and remaining fluid was poured into a sample jar and allowed to stand for 48 hours. The accumulated clear water was carefully removed using a pipette. The open sample jar was then covered with a piece of polyester fabric to prevent contamination and the sample allowed to dry at room temperature. Examination of the processed samples revealed essentially complete removal of modern macroscopic root fragments and far better separation of microscopic root hairs than was possible using hand methods. Dr. Minze Stuiver (verbal communication, October, 1979) of the Quaternary Research Center, University of Washington, believes that minimal removal of ancient carbon and no additional modern carbon contamination results from this procedure when carefully performed. It should be recognized that this procedure is useful for only limited types of soil samples.

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FEATURES AND EXCAVA
ON DAKOTA MOUNTAI

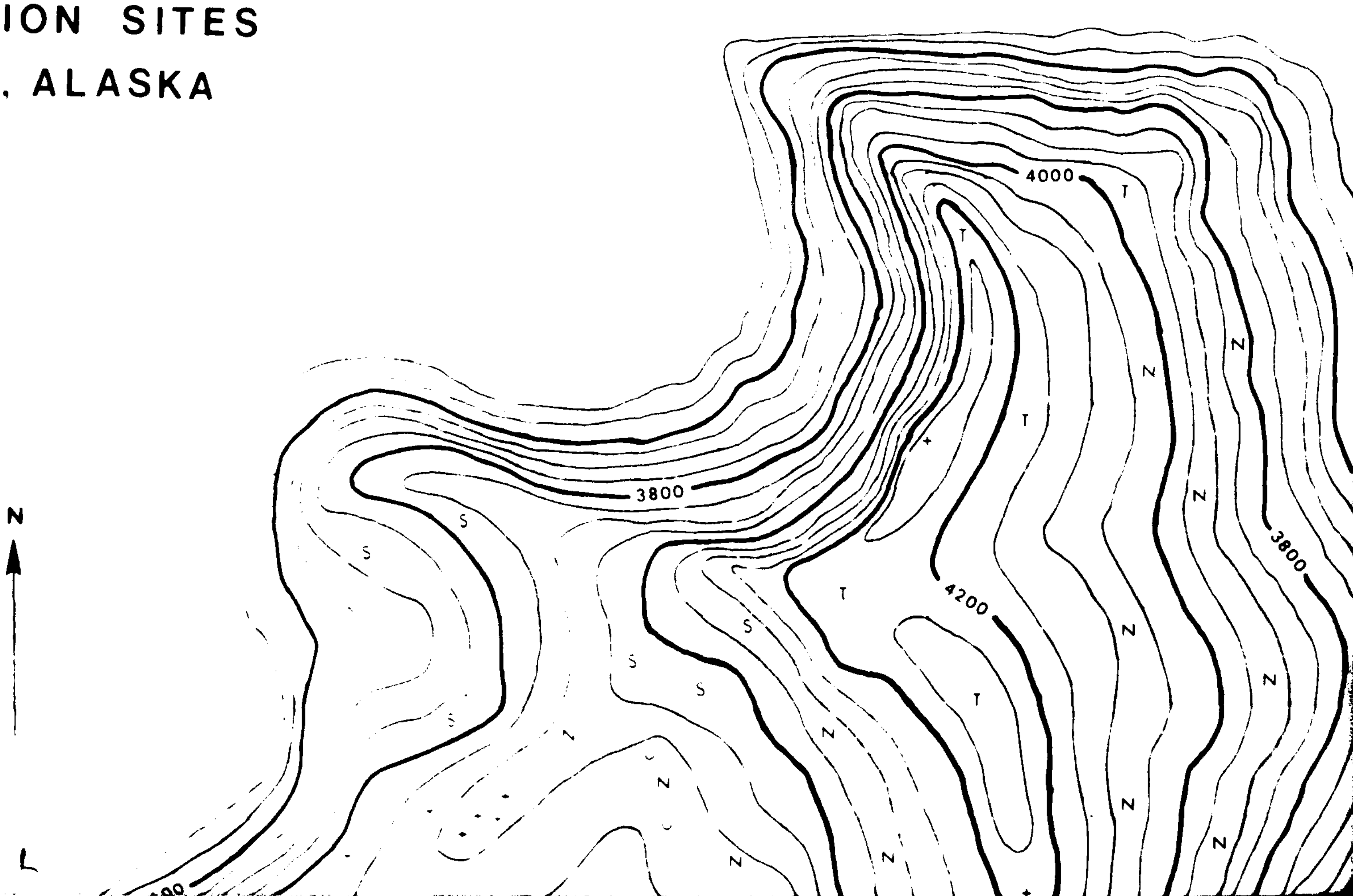
LEGEND

Ⓐ - Excavation Site
o - Meteorology Site
+ - Tor

DOMINANT FEATURES

N Nivation Hollows
S Turf Banked Steps
T Terrace Treads and Flat Hilltops
U Gelifluction Lobes

ATION SITES
IN, ALASKA



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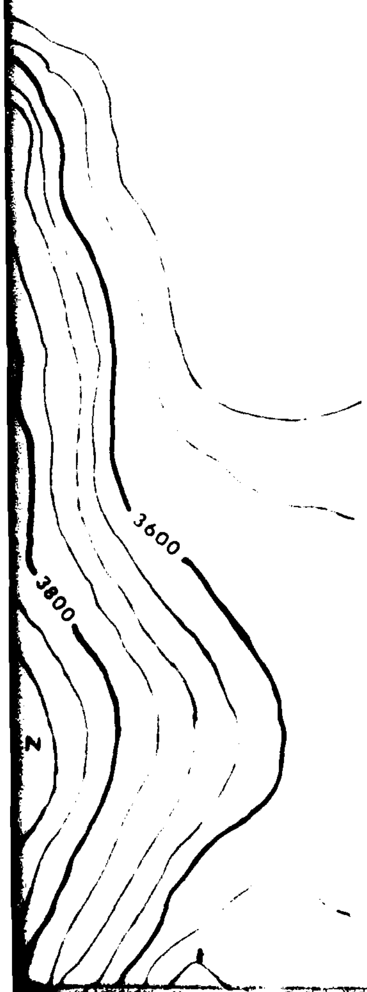

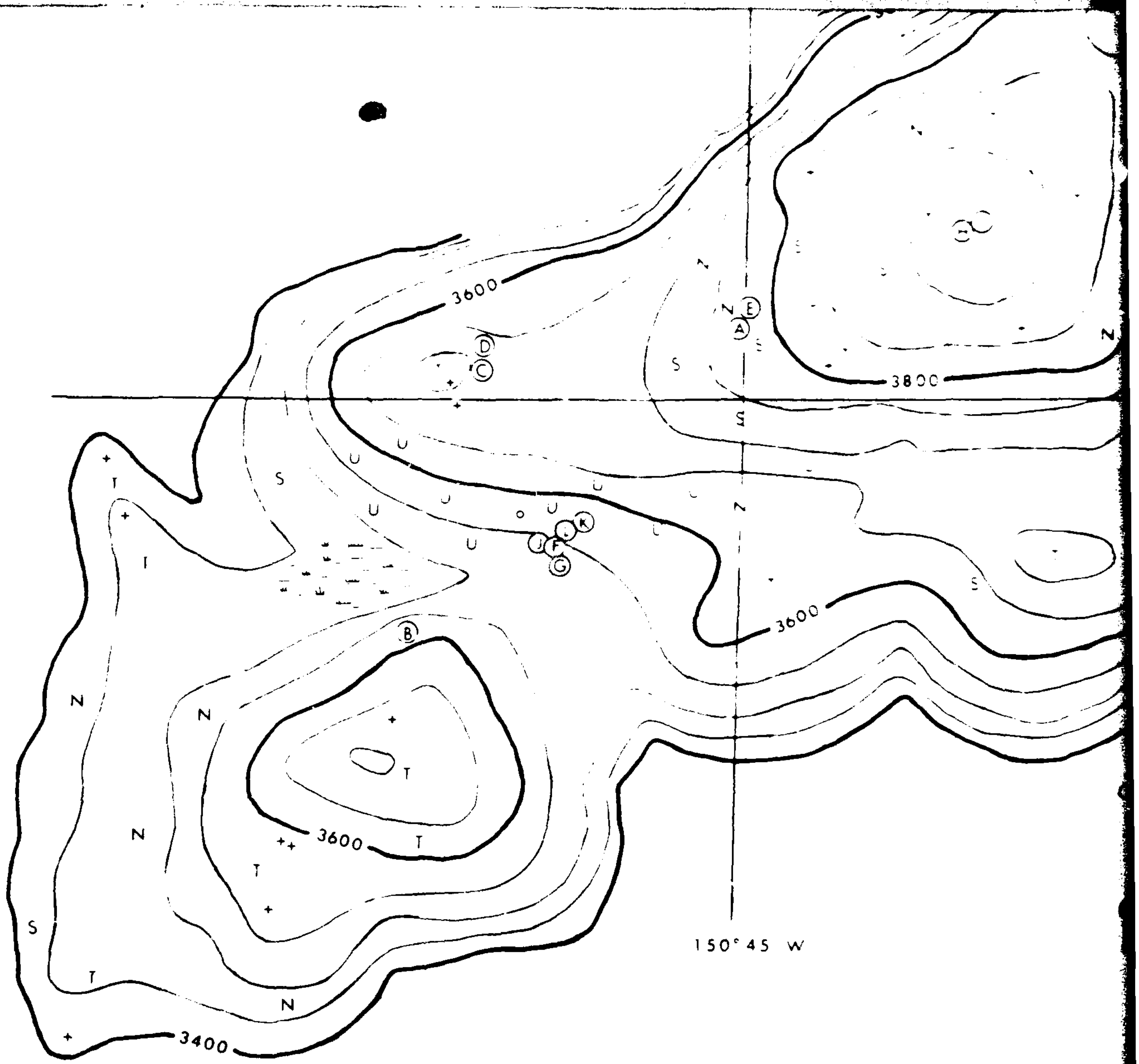

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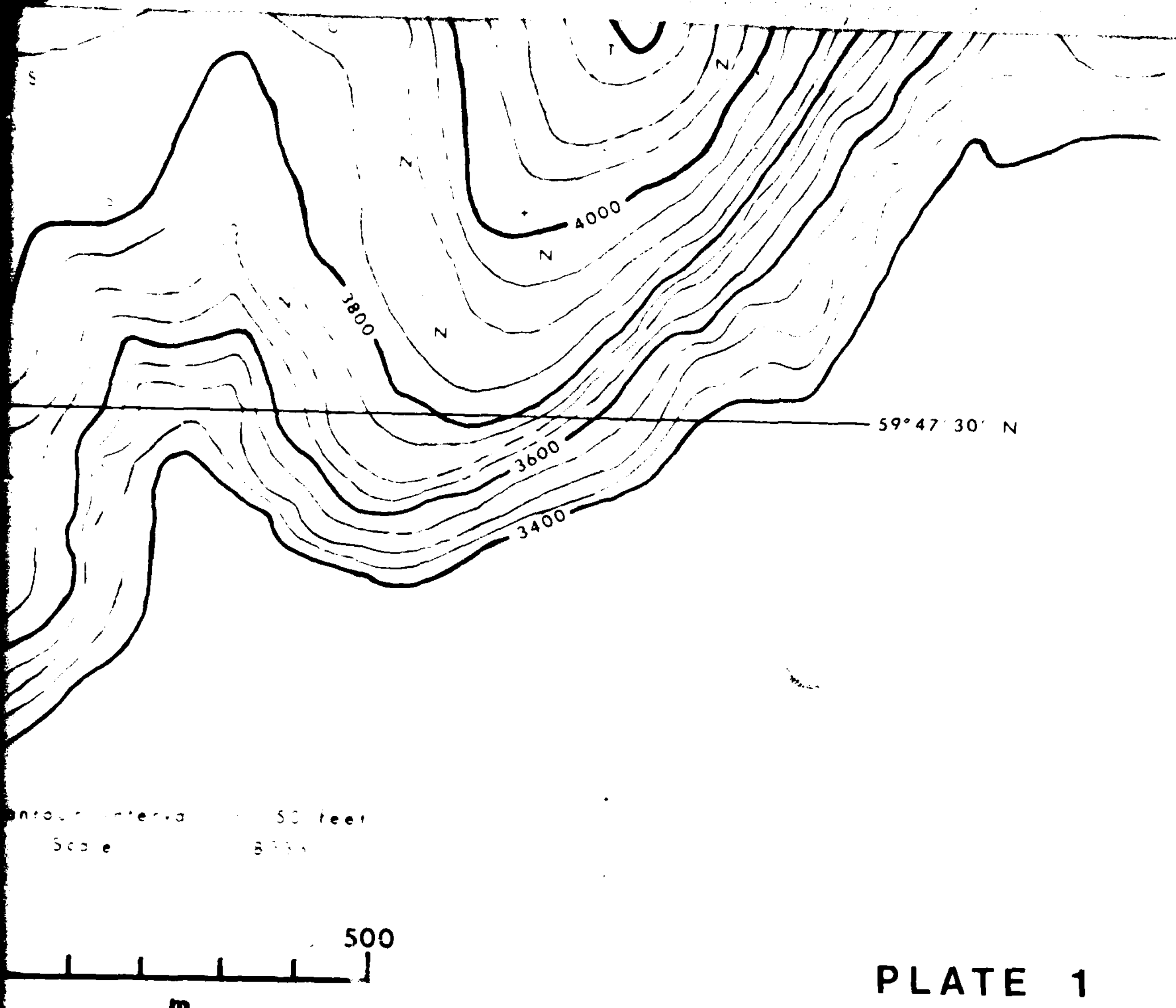


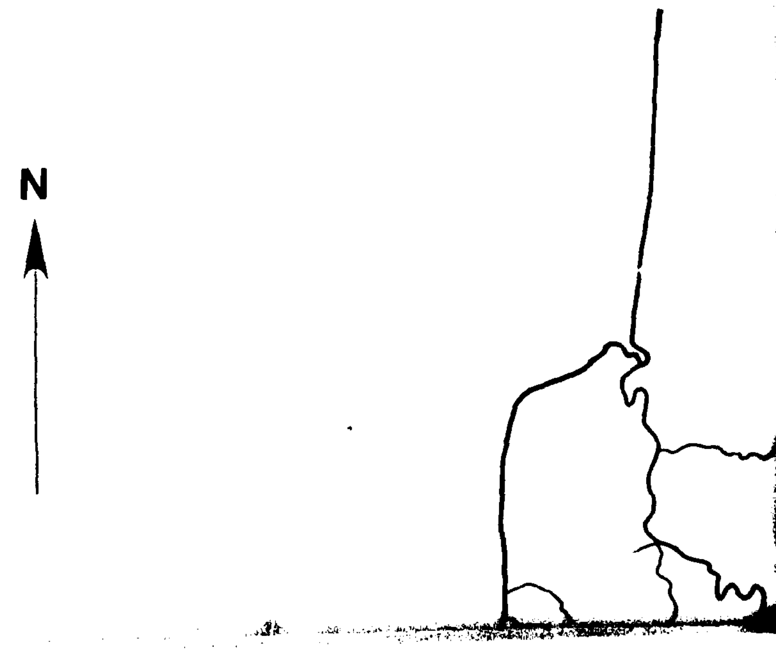
PLATE 1

Bailey, 1980

5

PERIGLACIAL SURFA

KENAI MOU



2

FACES IN THE SOUTHERN

OUNTAINS, ALASKA

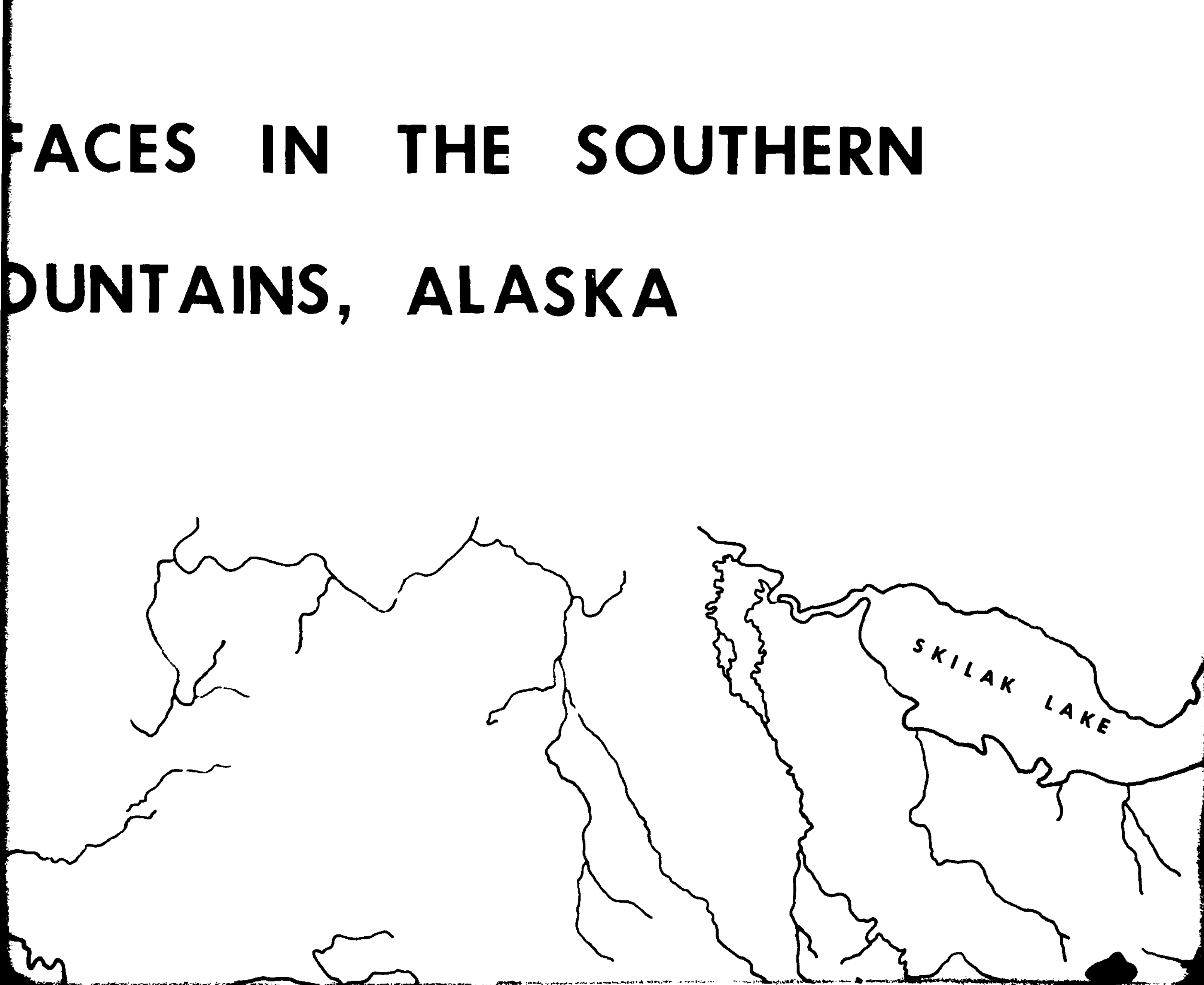


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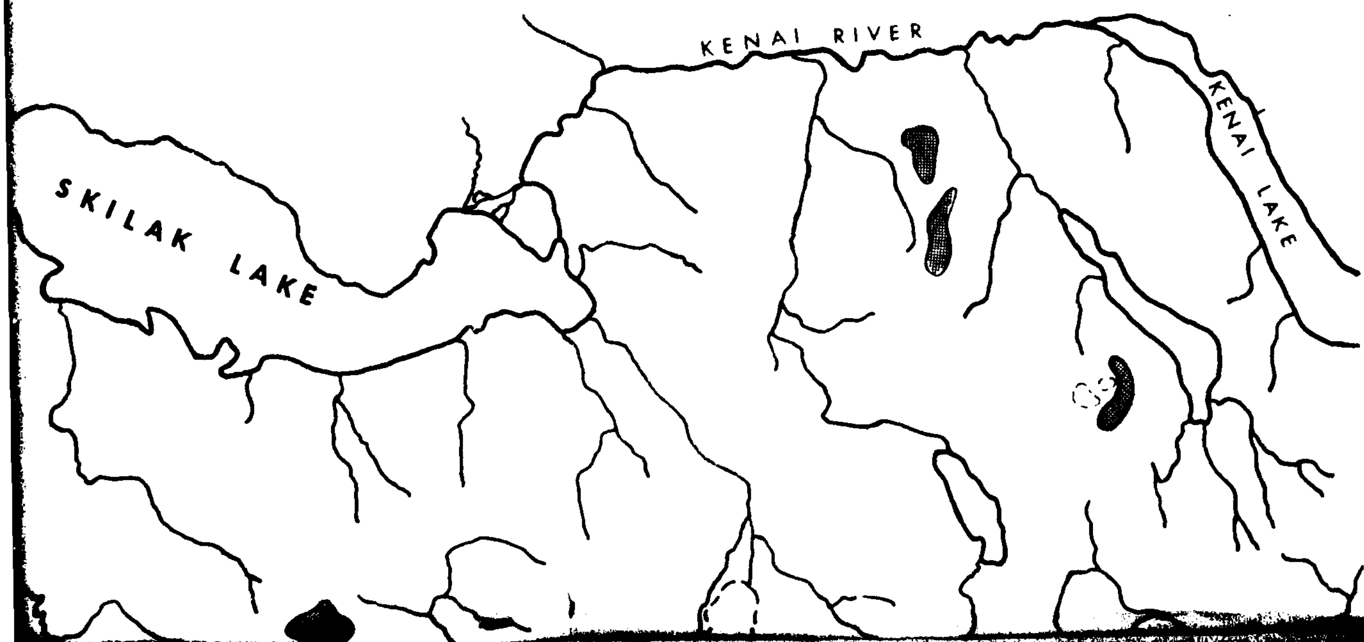
PLATE 2

Bailey, 1980



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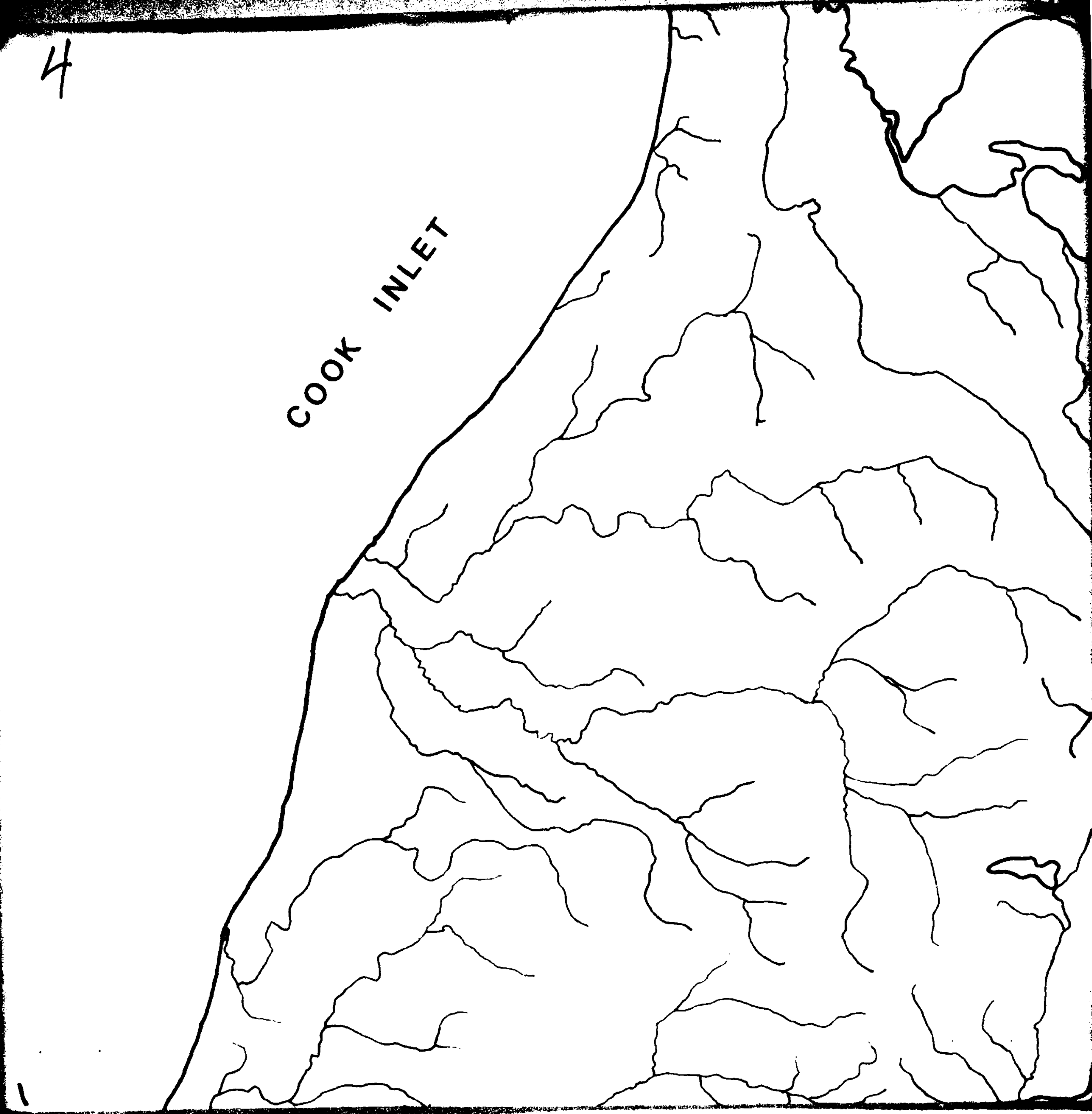
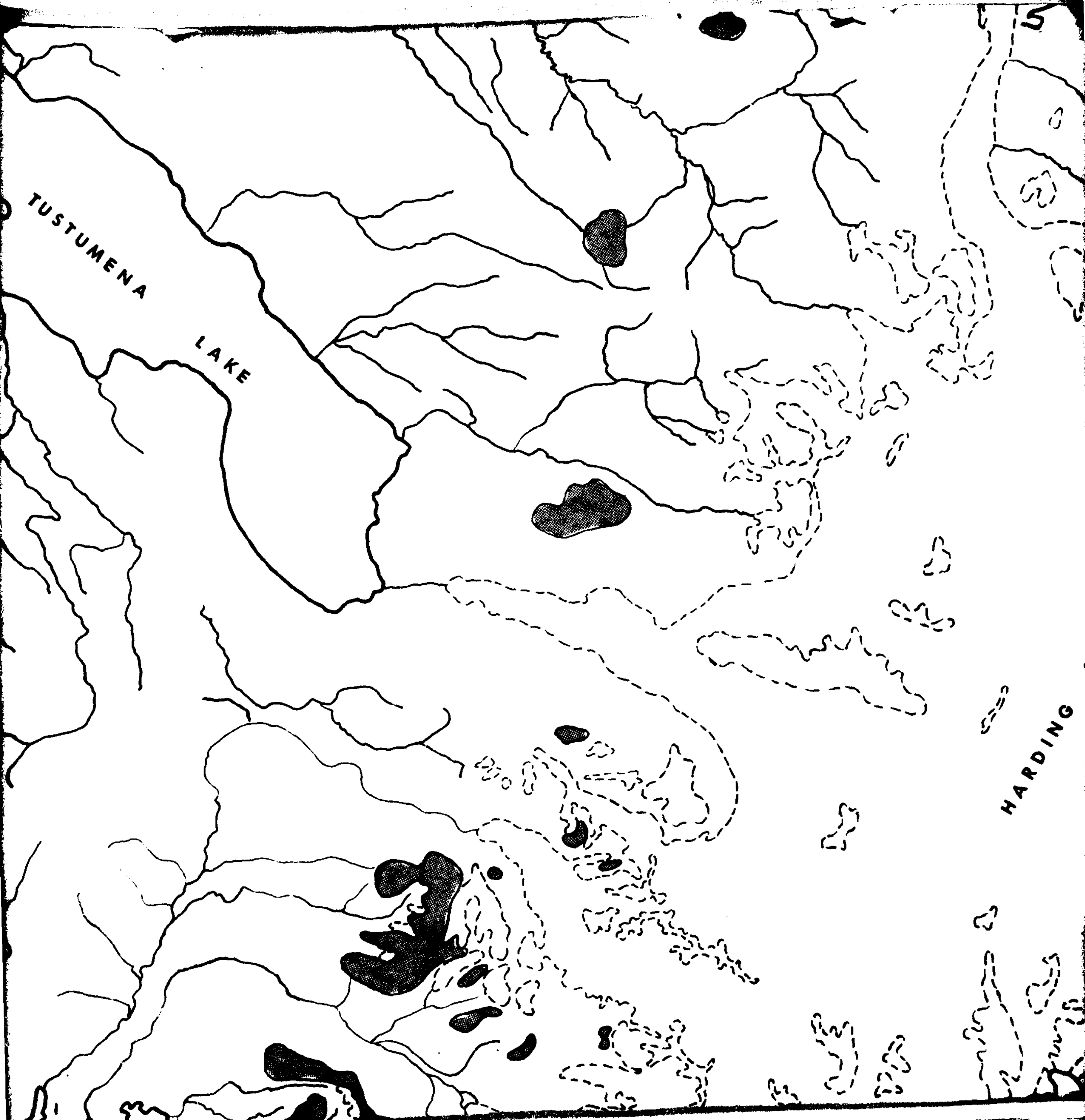
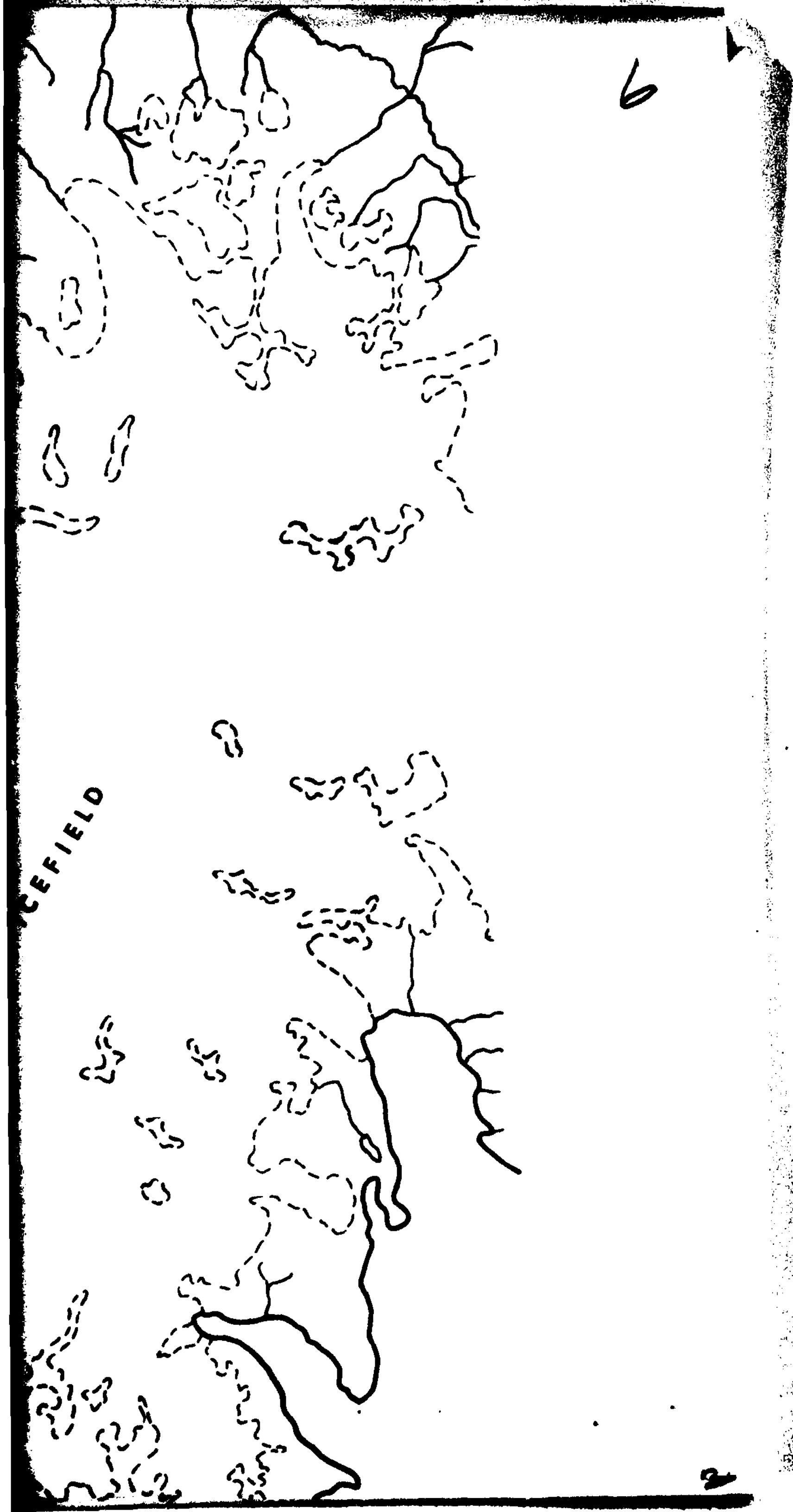



TUSTUMENA
LAKE
HARDING

6



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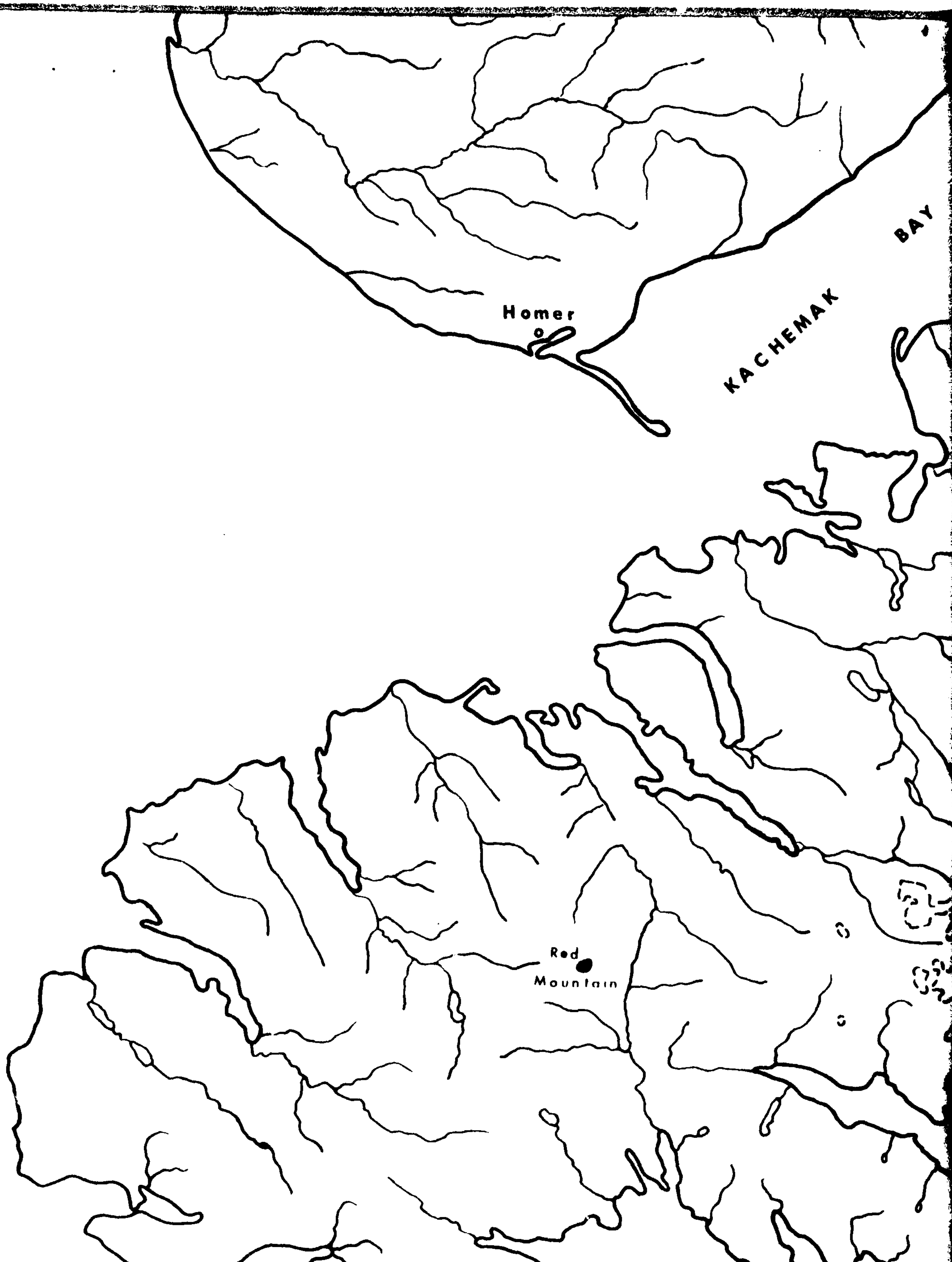

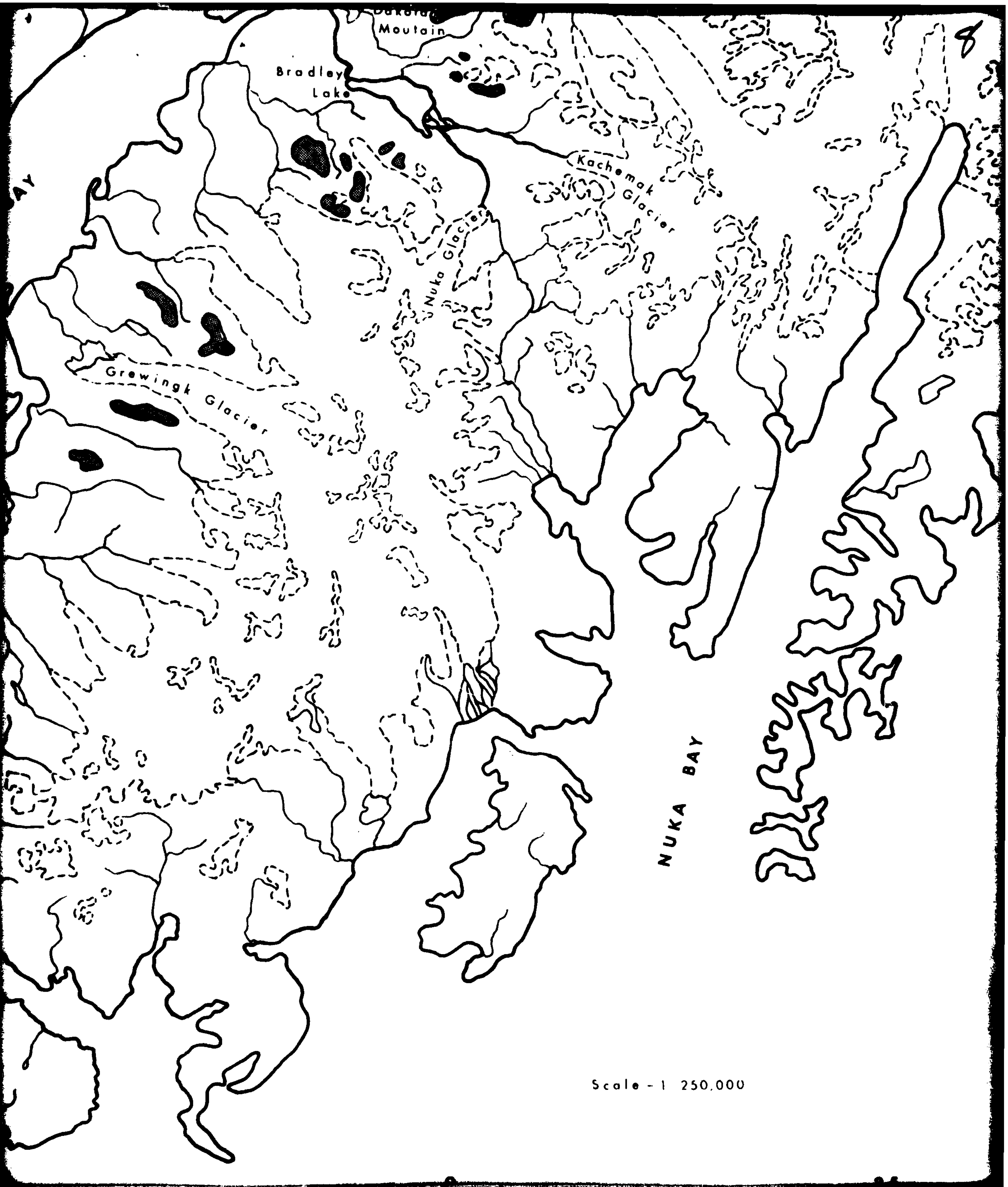
8
Dakota Moutain
Bradley Lake
Kachemak Glacier
Nuka Glacier
Grewingk Glacier
NUKA BAY
Scale - 1 250,000

LEGEND

- Periglacial Surface

Present Glacier

10

Scale - 1 250,000

0 25

km

11