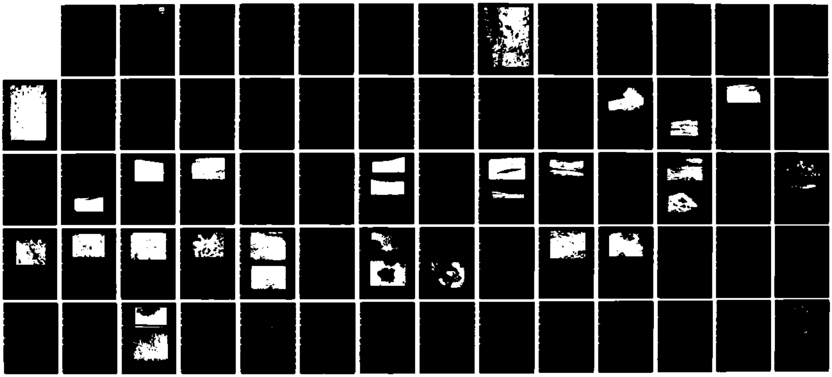
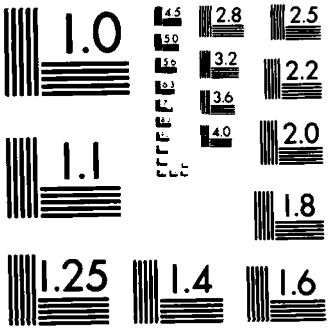
AD-A157 459 PERIGLACIAL LANDFORMS AND PROCESSES IN THE SOUTHERN KENAI MOUNTAINS ALASKA(U) COLD REGIONS RESEARCH AND ENGINEERING LAB HANOVER NH P K BAILEY APR 85 1/1

UNCLASSIFIED CRREL-SR-85-3 F/G 8/12 NL





MICROCOPY RESOLUTION TEST CHART

ARDS-1963-A

AD-A157 459

Special Report 85-3

April 1985

Periglacial landforms and processes in the southern Kenai Mountains, Alaska

Palmer K. Bailey

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE	READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER Special Report 85-3 2. GOVT ACCESSION NO. A157 459	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) PERIGLACIAL LANDFORMS AND PROCESSES IN THE SOUTHERN KENAI MOUNTAINS, ALASKA	5. TYPE OF REPORT & PERIOD COVERED 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Palmer K. Bailey	8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS U.S. Army Cold Regions Research and Engineering Laboratory Hanover, New Hampshire 03755-1290	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS U.S. Army Cold Regions Research and Engineering Laboratory Hanover, New Hampshire 03755-1290	12. REPORT DATE April 1985 13. NUMBER OF PAGES 65
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)	15. SECURITY CLASS. (of this report) Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution is unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Gelifluction
Geomorphology
Kenai Mountains
Nunatak
Patterned ground
Periglacial
Permafrost

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The distribution and characteristics of periglacial landforms in the southern Kenai Mountains, Alaska, were investigated during 1979 and 1980. The principal area of study was a 1300-m-high mountain mass that 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 such patterned ground as sorted circles, sorted polygons, earth hummocks, sorted steps, sorted stripes, and small ice-wedge polygons.

DD FORM 1473, 1 JAN 73 EDITION OF 1 NOV 65 IS OBSOLETE

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

20. Abstract (cont.d)

Ground temperature measurements indicate that permafrost exists in only isolated patches but may have recently been much more extensive. The sorted polygons, cryoplanation terraces, and nivation hollows are relict features that have been inactive for a considerable time. The turf-banked sorted steps and large gelifluction lobes probably were active until the recent thawing of permafrost. Cryofraction and frost sorting still are vigorous, active progresses. 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.

PREFACE

This study was conducted by Palmer K. Bailey, Major, U.S. Army, formerly Associate Professor, Department of Geography and Computer Science, U.S. Military Academy, West Point, New York.

The initial field work was funded by the U.S. Army Cold Regions Research and Engineering Laboratory. Subsequent field work was funded by the Alaska District, U.S. Army Corps of Engineers, and the Army Research Office through the Science Research Laboratory of the U.S. Military Academy.

The author wishes to thank J. Brown of CRREL, who made this work possible through his ideas, energy, encouragement and persistent support. J.R. Reid of the University of North Dakota provided invaluable assistance as advisor and thesis committee chairman during the first year of research. Dr. Reid and L.W. Gatto of CRREL technically reviewed the final report. Colonels G.W. Kirby and G.E. Galloway of the U.S. Military Academy generously provided time and encouragement to pursue this work. The author is grateful to Mr. and Mrs. Theo Veal of Homer, Alaska, for their gracious hospitality and valuable assistance during the seasons of field work. The author's wife, Bonnie, provided moral support and encouragement, and contributed her talents and efforts at the office, laboratory and darkroom, and in the field.

CONTENTS

ILLUSTRATIONS

Figure | Page

TABLES

Table

Frontispiece. Frost-split boulder in Alaska.

PERIGLACIAL LANDFORMS AND PROCESSES IN THE SOUTHERN KENAI MOUNTAINS, ALASKA

Palmer K. Bailey

INTRODUCTION

The purpose of this study is to describe the periglacial features and processes in the southern Kenai Mountains of Alaska. This investigation extends scientific knowledge into a region not previously studied from a periglacial point of view.

Area of Study

Kenai Peninsula

The location of the Kenai Peninsula is shown in Figure 1. The total area of the peninsula is about 24,600 km^2, comparable in size to the states of Vermont or New Hampshire, or about twice the size of Connecticut.

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

The dominant surface forms are the result of extensive glacial erosion (Capps 1940). 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).

The Kenai lowland lies to the west of the mountains and makes up 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). The land

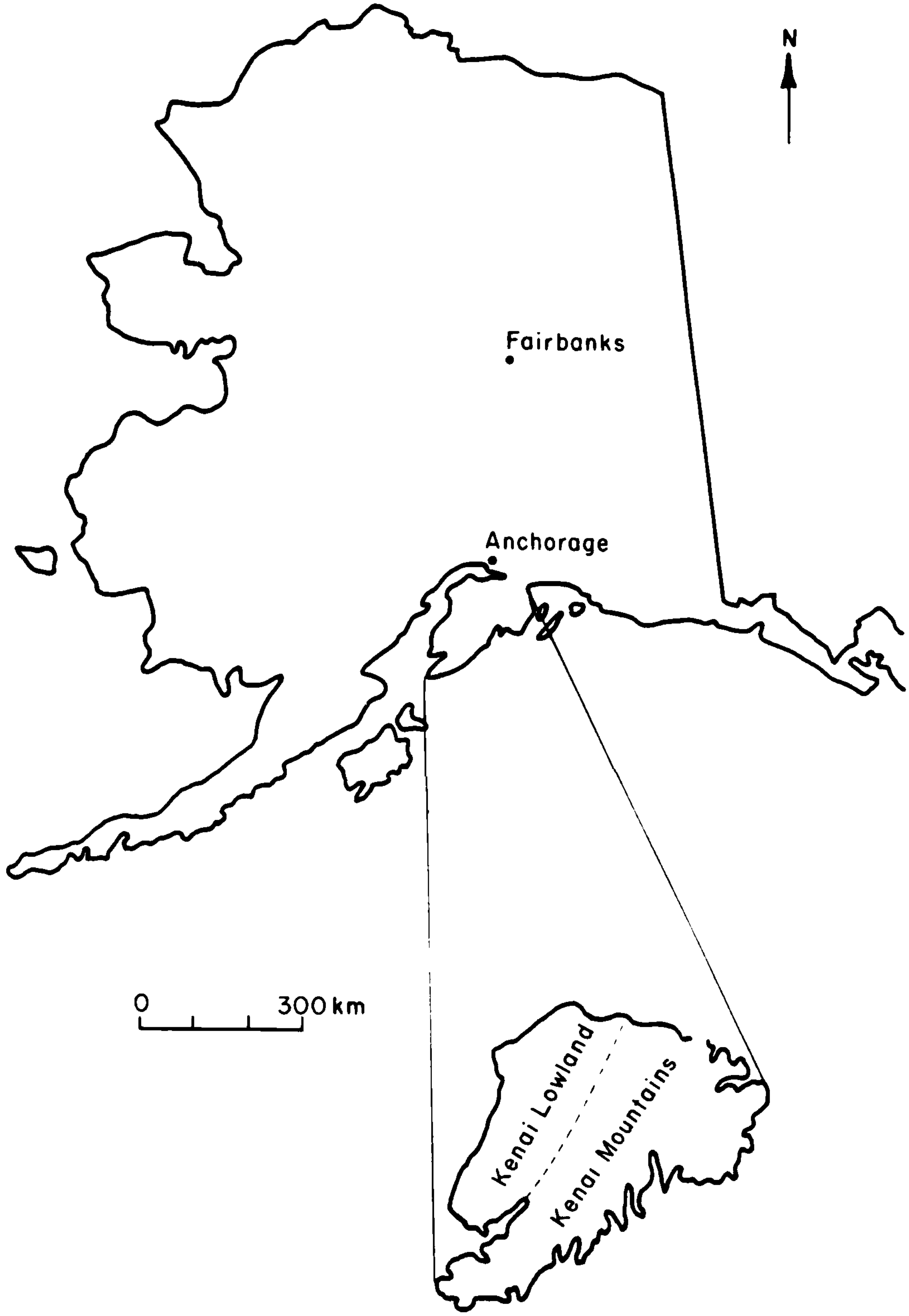


Figure 1. Location of the Kenai Peninsula, Alaska.

there seldom exceeds 50 m in altitude (Soward 1962). 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).

The entire lowland is underlain by the loosely consolidated Eocene beds of the Kenai Formation. Soward (1962) describes these beds as consisting of partly indurated sand, silt, clay, a few thin lenses of conglomerate, and many beds of sub-bituminous coal. The stratigraphic thickness of this formation probably exceeds 1500 m (Barnes and Cobb 1959). The Kenai lowland and the valley bottoms in the mountainous areas are generally covered by till, glacial outwash, or alluvium (Soward 1962).

Bradley Lake Area

Bradley Lake is a 6.6 km^2 glacial lake 5.7 km east of the head of Kachemak Bay and 42 km east-northeast of Homer on the Kenai Peninsula, Alaska (Fig. 2). Its surface is at an elevation of 332 m. The lake is recharged 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 in 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 argillite and slate. In general the rock is highly jointed. On a single outcrop it is often possible to observe dozens of well-defined 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). Numerous faults are evident in the region. A belt of active volcanoes exists about 130 km to the west across Cook Inlet.

During the last major glacial episode all but the highest mountains in the region were covered by glacial ice (Soward 1962). There are few areas in the region that do not show distinct evidence of glacial erosion. Valleys are steep-sided, U-shaped, and straight. 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 kilometers northeast of Bradley Lake is a mountain top area of about 2.3 km^2 lying between 1000 and 1300 m elevation that 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 wide is cut into the north end of the mountain. The bedrock of this mountain

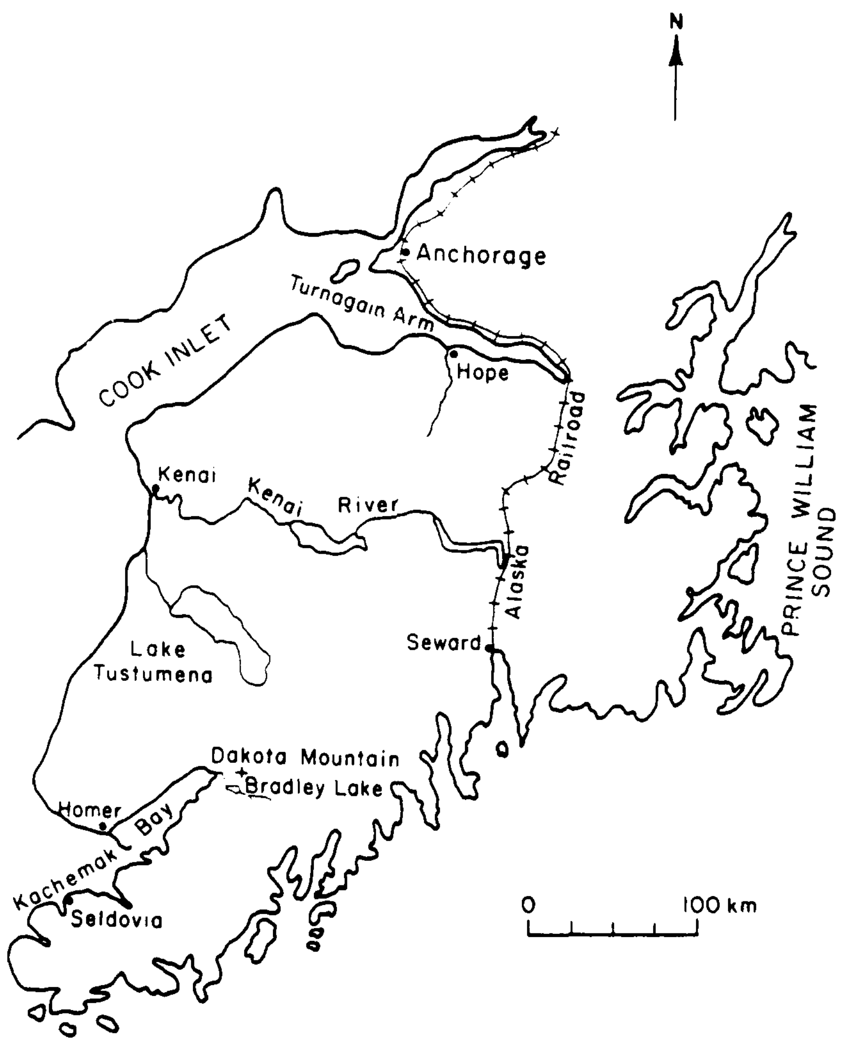


Figure 2. Map of the Kenai Peninsula and the adjacent area.

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, based on photo interpretation, as a probable site of periglacial surface morphology and was the principal area of study for this investigation (Fig. 3). The informal name Dakota Mountain is used to designate this mountain mass.

The highest camp occupied during field work was established in an east-west trending valley that transects Dakota Mountain. Many of the features described in this document are in or adjacent to this valley, which is designated informally as Camp Valley.

Past Studies

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, Dall 1896). In 1904, Stanton, Martin, and Stone spent a month on the Kenai Peninsula and reported on the coalfields near Kachemak Bay (Stone 1906). The same year, 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). In 1906, Atwood investigated some of the mineral resources of the region, including the coal beds of the Kenai Formation (Atwood 1909), and Grant and Higgins studied deposits along Prince William Sound and the eastern and southern Kenai Peninsula in 1908 and 1909 (Grant and Higgins 1909, 1910a,b). In 1911, Martin led an expedition that expanded upon earlier studies and resulted in a report that incorporated all of the previous investigations (Martin et al. 1915). During the same year, Johnson compiled a detailed report on the gold mining areas of the northern part of the peninsula (Johnson 1912).

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, Capps made

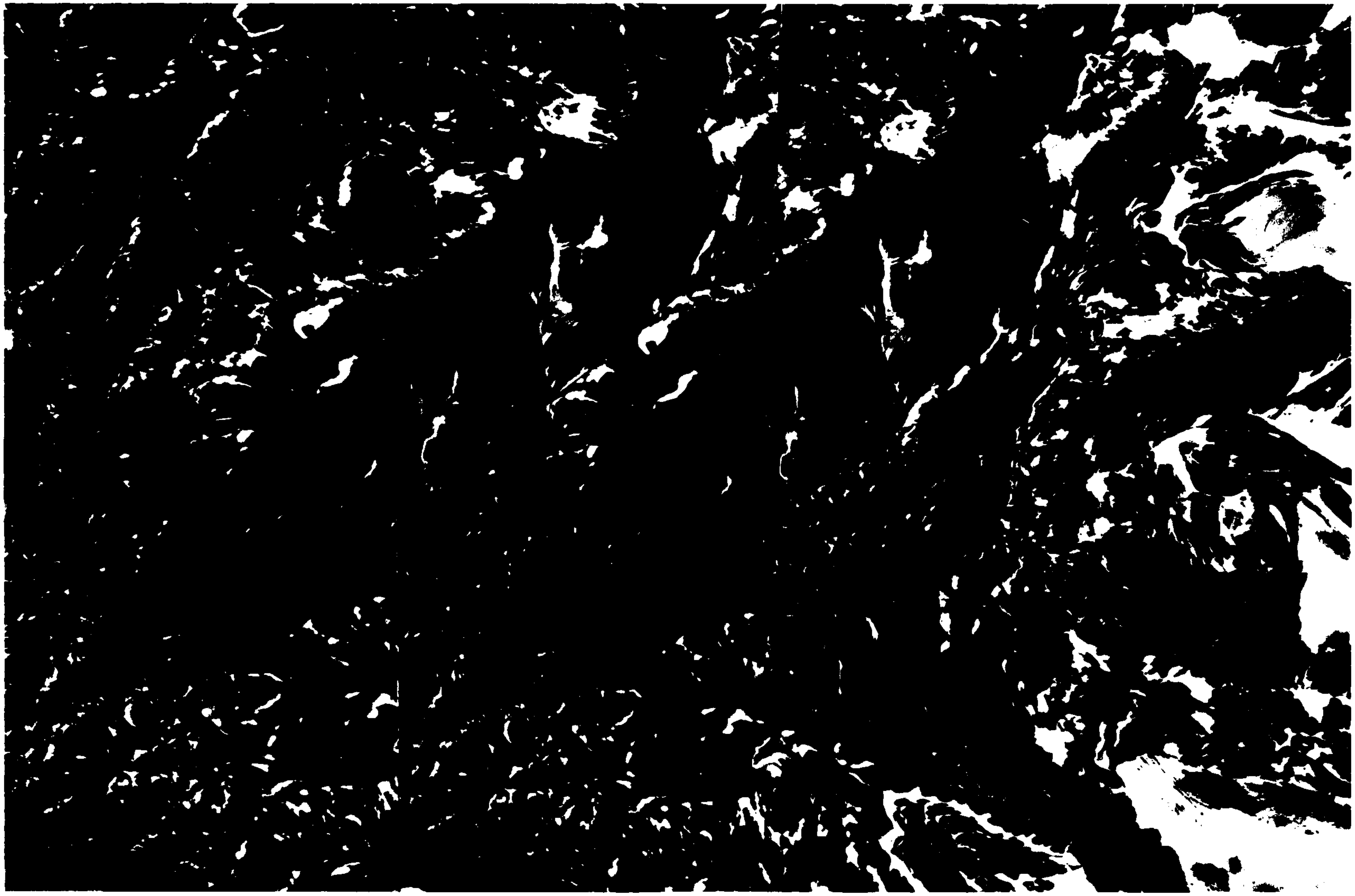


Figure 3. Photographic stereogram of Dakota Mountain area, taken 4 July 1951 (scale = 1:43,000). Part of Bradley Lake is in the southwest corner.

an extensive regional study of the route, touching briefly on the mineral resources of the Kenai Peninsula (Capps 1924). In 1931, Tuck continued the investigations of northern Kenai Peninsula gold mining areas (Tuck 1933), and the next year, Pilgrim studied the small lode-gold mines on Nuka Bay, only a few kilometers 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 revived. In 1950 and 1951, Cobb and 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 of 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, although a study by Richter (1970) promoted 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, Mendenhall reconnoitered the eastern portion of the peninsula (Mendenhall 1900). Emerson, a member of the 1899 Harriman Alaska Expedition, described spheroidal diabase and chert deposits near Halibut Cove on the southeast shore of Kachemak Bay (Martin 1926). About 1903, Stanton and 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). While investigating mineral deposits on the south shore of upper Kachemak Bay in 1904, Moffit observed what he termed ellipsoidal lavas. Paige and Grant made some brief studies on the east coast of the Kenai Peninsula in 1905 (Capps 1940).

Martin's investigations in 1911 contributed to the knowledge of the bedrock of the Kenai lowland (Martin et al. 1915), and in 1926 he 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 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).

In 1939, Smith published a volume on the areal geology of Alaska, and the following year 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, Capps 1940). A surficial geology study by Riehle (1977) included the upper Kachemak Bay, but did not extend into the Bradley Lake area.

Hydropower Resources

In 1913, Ellsworth and Davenport (1915) 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 power-plants 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, prepared reports on the water resources and site geology, and recommended a hydropower project 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).

Geomorphology

The glaciers of the Kenai Mountains drew the attention of the earliest geologists in the region. 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). In 1908 and 1909, Grant and Higgins studied the glaciers of the northeastern part of the peninsula; late in the summer of 1909, they conducted a 64-day boat trip around the south end of the peninsula, mapping topography and studying the glaciers near the coastline (Brooks 1910, Grant and Higgins 1913).

Several years later, Tarr and Martin (1914) published their classic volume of Alaskan glacier studies, but their work extended only to the northeastern portion of the Kenai Peninsula. In 1931, Capps published a summary of the glacial history of Alaska in which he concluded that the entire Kenai Peninsula and Cook Inlet had been covered by Wisconsin glaciers (Capps 1931).

Not until 20 years later was a serious study of Alaskan glacial history undertaken. Karlstrom (1952), 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, Péwé compiled a number of regional studies into a progress report covering most of Alaska; Krinsley's contribution dealt specifically with the southwest Kenai Peninsula. He recognized evidence for only 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 all evidence there 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, 1953). 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). In his summary, Péwé correlated the Naptowne and Nikolai Creek advances as late Wisconsin, concluding that the Naptowne occurred between 8000 and 14,000 B.P. He considered the Swan Lake glaciation to be early Wisconsian, of an age greater than 18,000 yr, and the Caribou Hills and Mount Susitna advances to be pre-Wisconsian (Péwé et al. 1953).

Karlstrom (1955b and 1957) continued to refine the understanding of the regional glacial history and published several documents on the subject. 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 with 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. Table 1 is a summary of his interpretations. On his map of the extent of the glacia-

Table 1. Glacial chronology of the Cook Inlet region and Kenai Peninsula, Alaska. Compiled from Karlstrom (1964).

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 ± 8000	45,000
Naptowne	19,000 ± 3000	5500
Alaskan	4000 ± 500	continuing

tion he designated over 30 small areas on the west side of the southern Kenai Mountains as having been free of 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 investigation are in these areas.

Karlstrom also studied permafrost, groundwater, and other aspects of surficial geology in parts of the Kenai lowland (Karlstrom 1955a, 1958), but no reference has been found to periglacial phenomena in the Kenai Mountains. Wahrhaftig (1950) did mention periglacial processes as a landform modifier in the coastal mountains of Alaska, but did not include specific locations or processes. Karlstrom (1955a) mapped the entire Kenai Peninsula as part of the "no permafrost" zone, but Williams and Waller (1965) and George (1965) included the southern Kenai Mountains within the region of possible permafrost. Péwé (1965) plotted the limit of sporadic permafrost right 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), who states that the extent of permafrost in the Kenai-Chugach Mountains is unknown.

METHODOLOGY

Field Methods

The 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.

Surface features were measured using a Brunton compass and a steel pipe. These were also used to install movement pins on several features. Soil temperatures were measured using a dial thermometer, and soil colors were identified using standard Munsell soil colors. Excavations on Dakota Mountain were made using only hand tools.

These excavations were:

- A trench 3 m long and 1 m deep through three sorted steps.
- Two pits, 2.1 m and 1.9 m deep, through a snow patch into a north-facing slope.
- Five shallow trenches through sorted circles.
- Three trenches up to 0.9 m deep and 2 m long through nonsorted polygons.
- One excavation of a hummock in a hillside hollow.
- A large trench 1.7 m deep and 2 m long through the front of a prominent gelifluction lobe.

Three lines of metal marker pins were installed on Dakota Mountain in July 1979. One set is positioned on a prominent gelifluction lobe, one in a nivation hollow, and one over a series of turf-banked steps. The pin locations were measured in August 1981 to determine movement rates.

Detailed mapping of small areas of Dakota Mountain was accomplished during June 1980 using plane table methods.

Laboratory Methods

Sediment Samples

To determine the characteristics of unconsolidated materials on Dakota Mountain, 25 samples were brought to the University of North Dakota for analysis. Each sample was air-dried at room temperature; sizes were 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% (Folk 1974). Those exceeding this limit were disaggregated using a rubber-tipped pestle; the sieving process was then repeated. Pipette analysis of the fraction smaller than 4.0 phi was performed according to the procedures outlined by Galehouse (1971). A Fortran computer program (Cross 1974) was extensively modified to analyze the sieve and pipette data.

A sample of the well-sorted fine sand from site K (Fig. 4) was mounted in a clear epoxy resin block. A thin section from the block was studied under a petrographic microscope to determine general mineral composition and grain characteristics related to the geomorphic history of the sand. Another

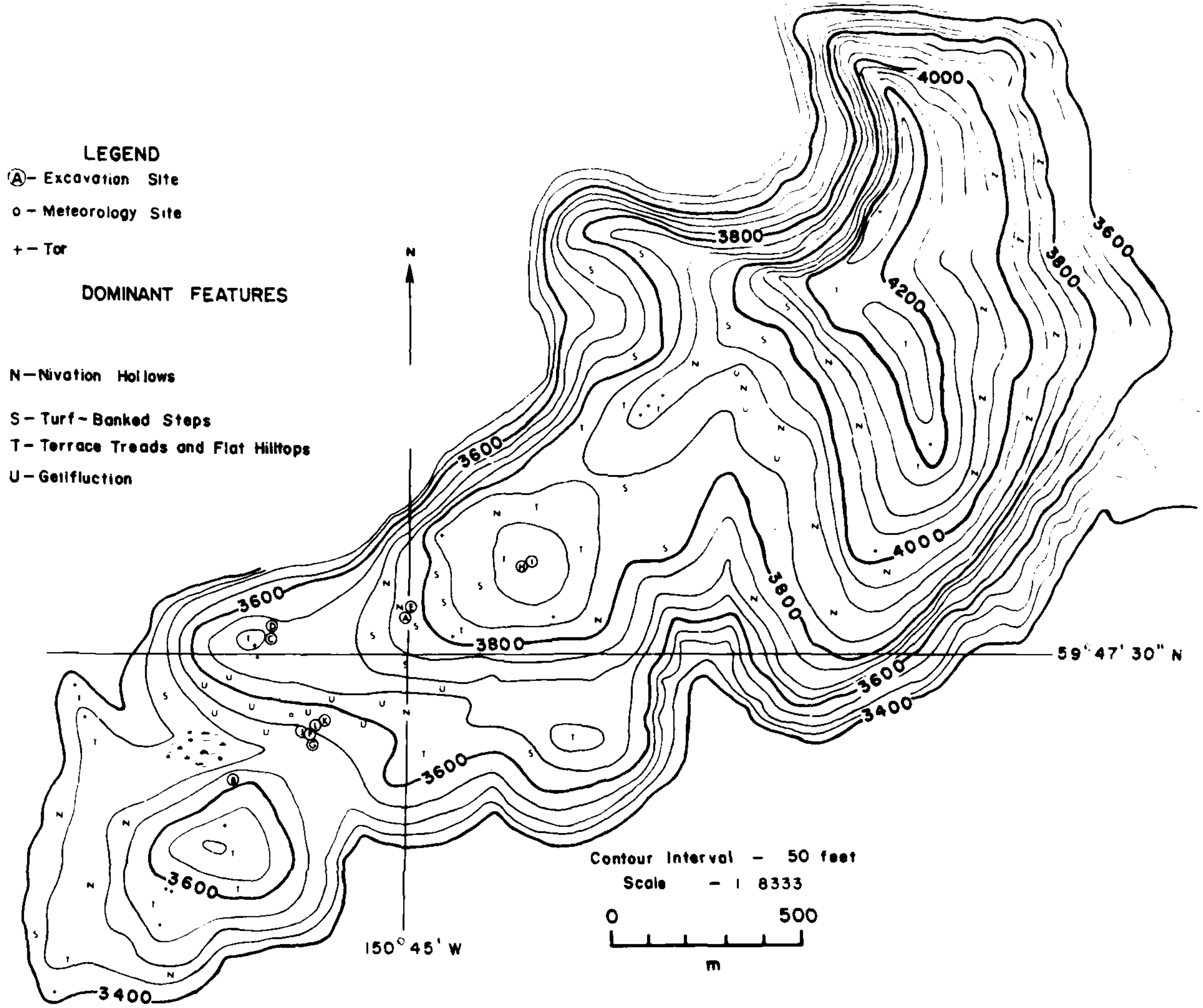


Figure 4. Features and excavation sites on Dakota Mountain, Alaska (Bailey, 1981).

small sample of the same sand was studied using the scanning electron microscope and microprobe. The surface morphology and elemental composition of some 20 grains of various mineralogy were observed. Preparation was according to Krinsley and Doornkamp (1973).

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 cobble was examined under the scanning electron microscope to determine the origin of the polished surface.

Radiocarbon Samples

Four samples of buried organic soil were collected from excavations in Camp Valley to establish radiocarbon dates of key events in the history of that area. Unfortunately, all the samples were contaminated by modern organic matter, rendering the dates useless.

Meteorological and Climatic Data

Meteorological data were collected from two sites in the Bradley Lake area during June and July 1979. Continuous temperature and periodic precipitation data were recorded from 6 June to 21 July at a water resource data station on the north shore of Bradley Lake, about 1400 m from the lake outlet (59°45'17"N, 150°49'32"W). Similar data were collected from 14 June to 21 July near the camp on Dakota Mountain (59°47'22"N, 150°45'27"W). The site is approximately 4.3 km north-northeast of Bradley Lake, at an elevation of 1085 m on the south-facing slope of a 50-m deep valley.

There were two other meteorological instruments 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 in Asheville, North Carolina, and have never been published.

Approximately 500 m north of the center of the lake, at an elevation of about 560 m, the Anchorage District Office, U.S. Geological Survey, Water Resources Division, installed a cumulative precipitation gauge. That gauge was never read and now appears to be 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 early years of the Territory of Alaska are either nonexistent or incomplete. The station nearest Dakota Mountain is Homer WSO, which has essentially continuous data only since 1940. The 5-yr moving mean annual temperature from this station is shown in Figure 5.

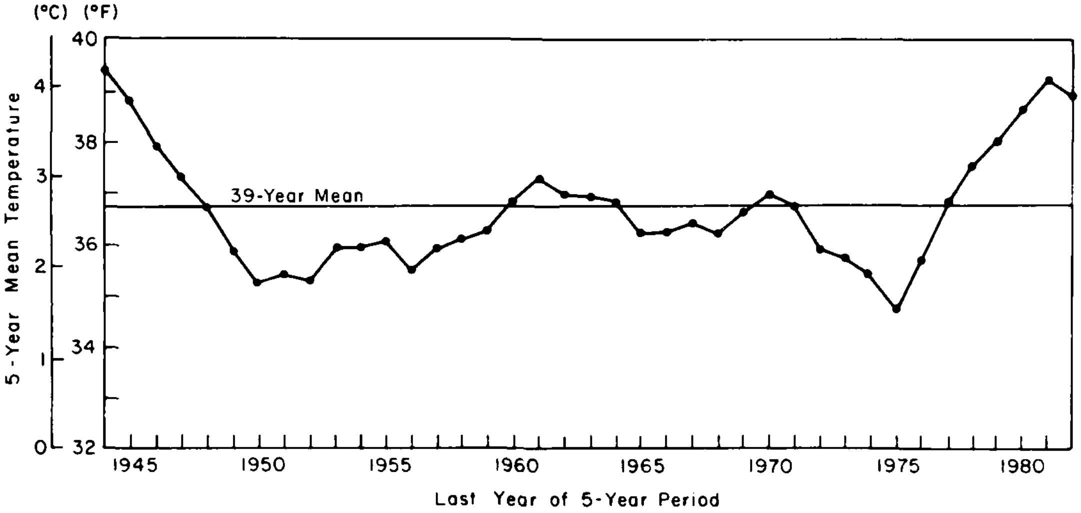


Figure 5. Five-year moving mean temperature at Homer, Alaska.

PERIGLACIAL PHENOMENA ON DAKOTA MOUNTAIN

Permafrost

On Dakota Mountain permafrost occurs only in scattered patches. The abundance and apparent freshness of some periglacial features on the mountain imply that permafrost is or was recently present, but excavations in these features always bottomed in thawed sediment. The excavations at sites B and B1 were made for the sole purpose of finding permafrost. Both sites are in a persistent snow patch on a steep north-facing slope, a most likely location for permafrost. Figure 6 shows the soil temperature data from those sites. In both cases, the overlying snow was just slightly below the freezing point.

Site B 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. The snow had melted at the site by July 13. There was 360 m of snow at the site on 27 June, 1979, when the excavation was begun. A thin layer below the soil/snow interface was thawed and wet from the percolation of meltwater under the snow. The next 600 mm represented the remaining annual frost layer, frozen the previous winter. A mattock was necessary to break through this solidly frozen layer. As the ground thawed during excavation, the matrix of the poorly sorted sediment formed a mud that flowed down the sides of the excavation. Below this annual

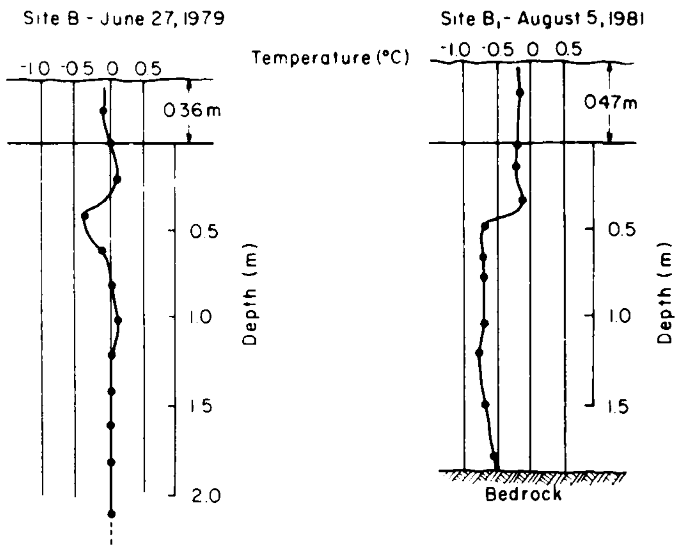


Figure 6. Temperature profiles obtained from two excavations about 30 m apart on the same north-facing slope of Dakota Mountain. Elevation is 1080 m.

frost layer, the temperature profile stabilized exactly at the freezing point. Ice crystals a few millimeters 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.

Site B1 was excavated on 4 and 5 August, 1981, about 30 m southwest of site B, in the same persistent snow patch. Total depth from the snow surface to bedrock was 2.35 m including 0.47 m of snow. The ground was frozen the entire depth of the excavation. The sharp drop in temperature at 0.5 m probably represents the limit of penetration of summer warming. Below that limit down to the bedrock surface the soil temperature was consistently at least one half degree below freezing. There is little doubt that the material remained frozen into the next winter.

Such minor isolated occurrences of very warm permafrost may be the last vestiges of regional permafrost. It is possible that there is still a considerable mass of permafrost at some depth in a wider area, but it appears that permafrost is no longer an effective element in the geomorphological processes in the region.

This conclusion is supported by the presence of a small but well-developed string bog at the west end of Camp Valley (Fig. 7). Schenk (1965) 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. Although he developed a hypothesis to explain their formation as part

Figure 7. String bog in Camp Valley. The bog is 130 m long from the base of the snowbank to the outlet.

of the degeneration of permafrost in an area, his views are not universally accepted (Washburn 1973).

Published climatic data from the region proved of no value in detecting a long-term climatic trend. Some short-term trends can be observed in Figure 5, but it is doubtful that they are of any real signifi ce in the longer-term development or destruction of permafrost. The mea.. .emperature since 1940 at Homer is 2.73°C (36.92°F). Transposition of this temperature from Homer, elevation 30 m, to Camp Valley, elevation 1070 m, using the minimum adiabatic lapse rate of 5.5°C per 1000 m (Marsh and Dozier 1981), reveals that the mean air temperature in Camp Valley during the last 40 years could not have been warmer than -3.0°C (26.6°F). Although the mean ground temperatures must be slightly warmer than the mean air temperature (Embleton and King 1975), it is clear that the thermal regime must have been at least very near that necessary for the development or preservation of permafrost. This is supported by the fact that the frozen ground at site B1 was observed in August 1981, the warmest year in four decades.

Gelifluction Features

Gelifluction is a complex interaction of unconsolidated sediment, ice, water, and slope. Permanently or seasonally frozen ground prevents water derived from melting snow, melting ground ice, or direct precipitation from percolating downward. As a result, thawed surface layers may become saturated and flow downslope under their own weight (Embleton and King 1975). Gelifluction is possible on gradients as low as 1° (St.-Onge 1965).

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). Gelifluction is an important secondary agent in the formation of many of the features attributed to nivation and frost action, but it is the dominant process in the development of gelifluction lobes and turf-banked steps.

Gelifluction Lobes

Large linguoid-shaped 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 (Fig. 8 and 9). They are typically 10 to 20 m long, 4 to 8 m wide, and from 0.2 to 1.1 m high at

Figure 8. Gelifluction lobes on the north side of Camp Valley. The tent below the snow patch at left indicates scale.

Figure 9. Gelifluction lobes on Dakota Mountain. Lobe fronts are approximately 500 mm high.

the lobe front. Their long axes are seldom aligned precisely downhill. All of the lobes on south-facing slopes tend to deviate to the east. In most cases the entire lobe is covered by alpine tundra vegetation, which 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 strip of coarse rock fragments on the center line of several lobes. Few sorted circles and no prominent vertical stones were observed on lobes. Two samples of sediment were collected from within a lobe at site K at the base of the north side of Camp Valley (Fig. 10). Grain-size analysis revealed 85% gravel, 14% sand, 1% silt, and negligible amounts of clay (Table 2). 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 (Fig. 4).

The vertical fronts and sharp angular contact between the lobes and the underlying material indicate that they are currently active or at least very young relict features. Little apparent modification of the steep edges of the lobes has taken lace other than the trails and burrows of the ubiquitous voles. Some of the thicker lobes are compound features formed by several sequences of gelifluction movement, one on top of the other. The preferential distribution and orientation of better developed lobes on south-facing slopes may be explained by the following hypothesis: Because the south-facing slopes are subject to the most rapid thawing by solar radiation, the sun

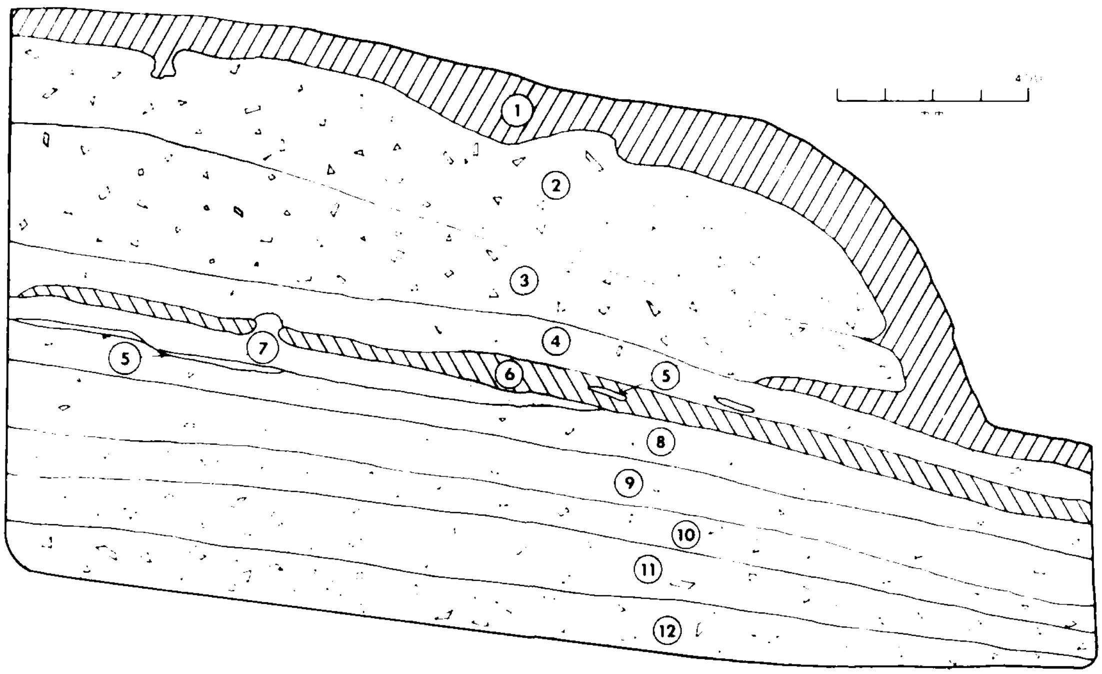


Figure 10. Cross section of a gelifluction lobe at site K (Fig. 4). Samples collected at numbered locations are described in Table 2.

tends to melt more of the snow cover and 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. Because of their aspect, the near-vertical fronts of south-facing lobes recieve the maximum possible radiation from the relatively low-angle Alaskan sun. Moreover, 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 strength of the material. Water in the saturated layers near the edge of the lobe front tends to drain away through the drier material as the saturated 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. The southwest face of a lobe is 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 less deeply thawed east face. For an expanding gelifluction lobe on a south-facing slope, therefore, the

Table 2. Physical characteristics of samples from the gelifluction lobe at site K. (Sample locations are shown in Figure 10.)

Sample	Munsell color Name	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	2.5YR	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	2.5YR	4/4	3.73	77.9	20.2	1.9	0.06	Gradational boundary.
12	Dark grayish brown	2.5YR	4/2	-	-	-	-	-	Particles up to 400 mm.

path of least resistance is to the southeast. This hypothesis explains both the greater thickness of the downslope portion of the lobes and the eastward deflection of most southerly lobes.

Permafrost is helpful to but not necessary for gelifluction. An annual frost layer is adequate to allow gelifluction, provided it is sufficiently deep and impervious. One lobe was marked with a line of metal pins in 1979; the net movement of each pin was measured during the summer of 1981. The apparent downslope movement of pins on the centerline of the lobe was from 4 to 6 mm annually. It is impossible from data available to determine what portion, if any, of that movement is the result of gelifluction and what is attributable to frost creep. For descriptions of rates of flow of other gelifluction lobes, the reader is referred to articles such as those by Alexander and Price (1980), Benedict (1970), Price (1973), Washburn (1947, 1967), or Williams (1959).

Turf-Banked 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 (Fig. 11-14). 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 1-3 m. The tread surfaces usually dip a few degrees into the hillslope.

Figure 11. Sorted steps at the west end of Camp Valley. The distance between steps is approximately 1.5 m.

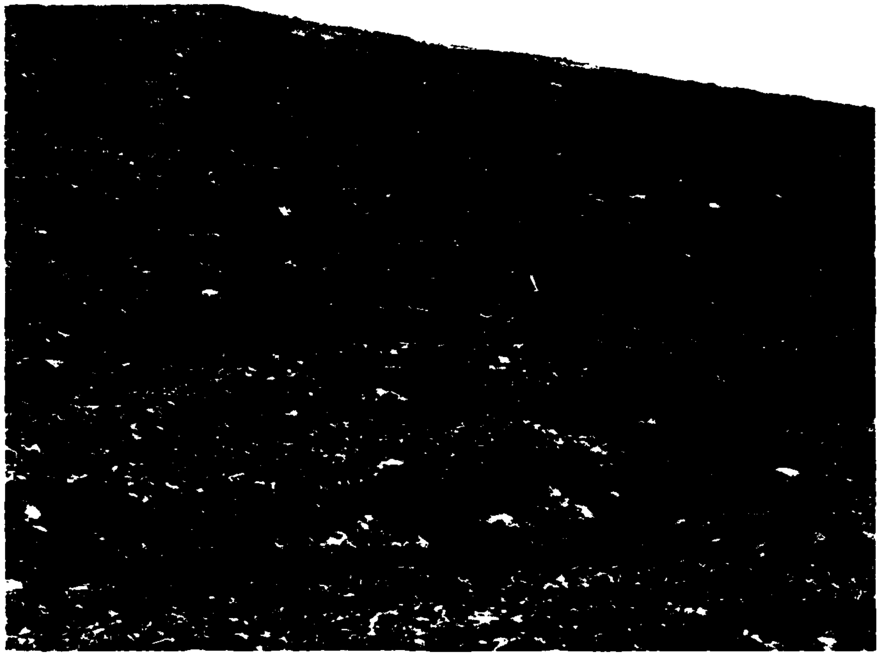


Figure 12. Turf-banked sorted steps on a southwest-facing slope of Dakota Mountain. The 300-mm-long hammer indicates scale.

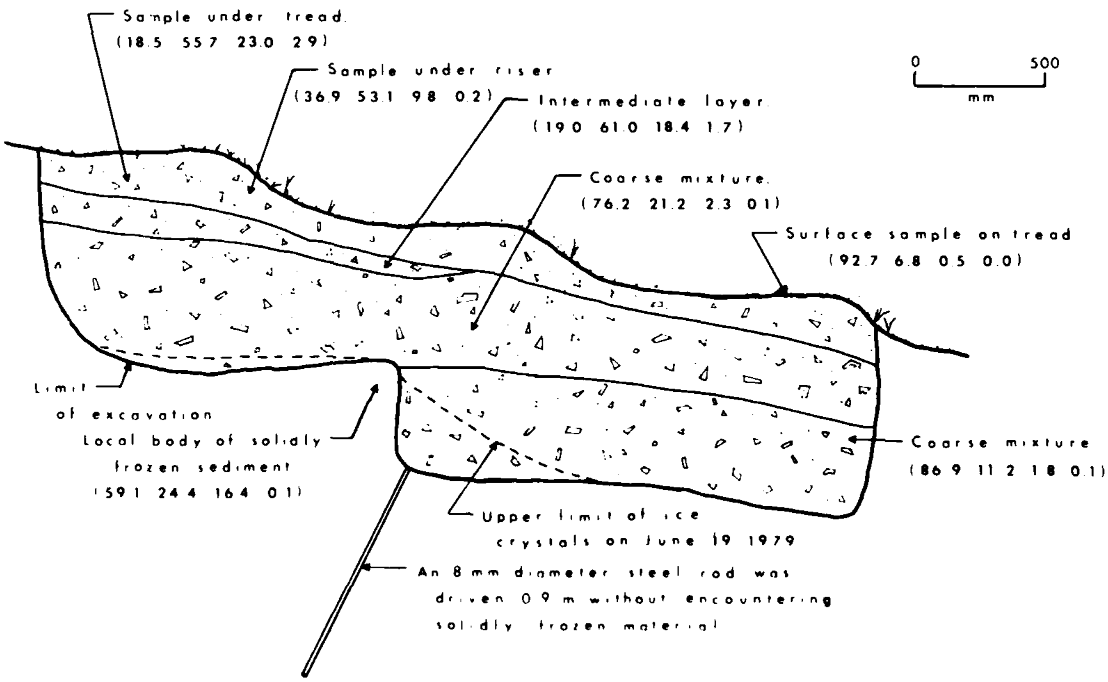


Figure 13. Turf-banked sorted steps at site A (Fig. 4). The particle size distribution is shown for each sample. Numbers indicate weight percent of gravel/sand/silt/clay.

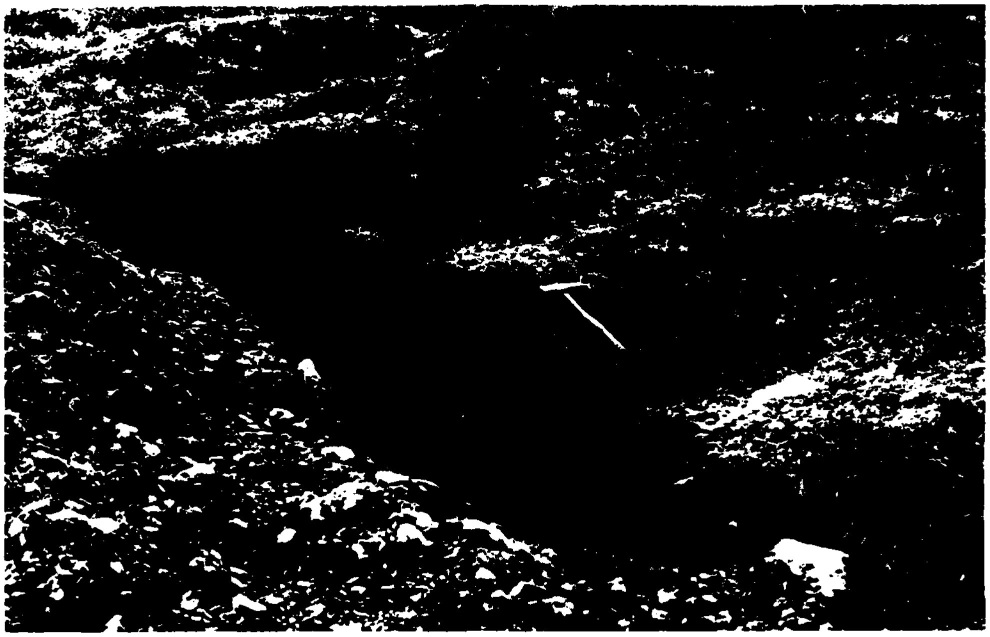


Figure 14. Excavation through turf-banked sorted steps at site A (Fig. 4).

The treads are usually covered by angular rock fragments with little vegetation. The sediment forming the surface of one typical tread was 92.7% gravel, 6.8% sand, 0.5% silt, and 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.

Turf-banked 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).

Figure 15 shows the effect of slope on turf-banked forms observed in England by Hollingworth (1934). 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 15; however, the diagonal descending stripes on Dakota Mountain are

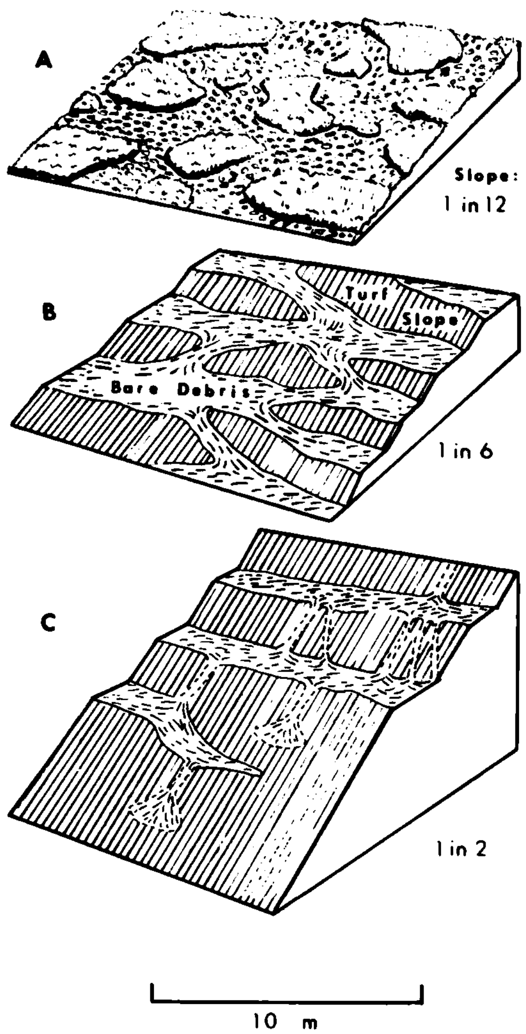


Figure 15. Effects of turf on patterned ground (after Hollingworth 1934). The diagrams illustrate the patterns formed by moving debris on partially turfed slopes of various inclinations in the Lake District of England. The same pattern exists on Dakota Mountain.

usually less prominent and farther apart. The most striking characteristic of the Dakota Mountain steps is their precise spacing. The distance between adjacent steps ranges from less than 1 to more than 3 m at some locations on the mountain, but spacing of those in a single area usually does not vary by more than 10%.

Sorted Stripes

In many periglacial areas, long parallel sorted stripes produced by frost sorting are distinctive surface features. This is not the case on Dakota Mountain. The vegetative cover on much of the mountain may inhibit 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. The finer particle size 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.

Short sorted stripes are associated with the sorted steps on Dakota Mountain where the slope exceeds about 15°. The composition of the surface sediment of the stripes is similar to that of the step treads. 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. On steeper slopes the orientation of the stripes is more closely aligned to the slope direction. On the upper slope of the southwest end of Dakota Mountain, where the slope locally exceeds 30°, the stripes are 0.5-1.2 m wide, composed of angular fragments up to 140 mm long, and oriented directly downslope. The stripes are usually truncated at the next lower step and are seldom longer than 3 m. Although these stripes are probably influenced by frost action, they appear to be principally a secondary product associated with the turf-banked steps (Fig. 15).

Nivation Features

Matthes (1900) introduced the term nivation to describe the erosive effects associated with immobile snow patches. There are two components to the nivation process: a weathering mechanism and a transportation mechanism. It is commonly believed that the weathering mechanism is principally frost action (Embleton and King 1975). 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). Thorn (1976), however, found no significant difference in annual freeze/thaw cycle frequency between snow-patch and snow-free sites. In either case, the melting snow provides the water required for frost action to attack the rock.

Williams (1949) observed high concentrations of carbon dioxide beneath snow drifts and suggested that chemical weathering by carbon dioxide-rich meltwater may be an important aspect of nivation. Thorn (1976) 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). Others (Lewis 1939, McCabe 1939, Nichols 1963) have concluded that running water is most important with-

Figure 16. Terrace on a southwest-facing slope of Dakota Mountain.

Figure 17. Terrace on a north-facing slope of Dakota Mountain.

in nivation hollows and gelifluction is more dominant downslope from the snow patches. Some authors regard snow creep and sliding to be significant agents of transportation (Costin et al. 1964), and others (Russell 1933) consider snow movement to have no role in nivation.

Cryoplanation Terraces

A wide variety of features has been attributed to the effects of nivation (Washburn 1973). 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, Washburn 1973). Early investigators considered them to be fluvial terraces or remnants of old erosion surfaces (Prindle 1913). Eakin (1916) recognized them to be associated with cold climates and called 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).

There are distinct terraces on several of the slopes on Dakota Mountain (Fig. 16 and 17). A good example 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 south-facing slopes seem better developed.

These surfaces are best explained as relict cryoplanation features. They are of the scale and slope expected of such features (Péwé 1970) and are regionally situated where they, no doubt, were subjected to a rigorous periglacial environment during later glaciations. There is, however, no present means by which to determine if this environment was as cold as that necessary to promote cryoplanation (Reger and Péwé 1976).

In central Alaska, most cryoplanation terraces 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 sediment as the tread. Reger (verbal communication, August 1979) expressed the belief that the Dakota Mountain features are probably relict cryoplanation terraces, provided they are in fact cut into the bedrock of the mountain. Although it was impossible to verify that condition conclusively, 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. It is therefore concluded that the terraces and leveled hilltops on Dakota Mountain are relict cryoplanation terraces that have been modified and obscured by subsequent slope processes, primarily gelifluction. They may be considered class II and IV terraces, according to the morphological classification of Reger (1975).

Figure 18. Hollow containing a snow patch. The 450-mm-long mattock on the snow indicates scale.

Figure 19. Hollow and associated platform of debris. The person is standing near the crest of the platform.

Nivation Hollows

Other prominent features on Dakota Mountain are cirque-shape hollows with an associated platform of debris (Fig. 18 and 19). These hollows are similar to those in Quebec, which Henderson (1956) interpreted as having formed during the "Little Ice Age" and subsequently stabilized, probably during the first half of the nineteenth century. Single cirque-shaped hollows

Figure 20. Cirque-shaped and elongated hollows on Dakota Mountain.

are from 10 to 100 m across. Some are elongated across the hillslope to form a terrace-like feature up to several hundred meters long (Fig. 20). 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 to the nearly horizontal floor of the hollow. The distal end of the hollow is a platform of accumulated debris. The platform is about equal in volume to the material apparently removed from the hollow. In many cases, the slope of the top of the platform 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 gelifluction lobes; 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.

These hollows and associated platforms may also be attributed primarily to nivation. The hollows serve as collection basins for snow from the windswept 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 melted. Some of these snowbanks persist until August, and in some years may never disappear completely. Most of them, however, are melted by the first part of July. As the snowbanks melt, abundant water is released to the area just downslope from their lowest margin. The floors of the hollows and the upslope portion of the associated platforms were often found to be completely saturated. This condition, together with a near-surface permafrost table, would provide ideal conditions for gelifluction.

The bottoms of nivation hollows that I have observed in the interior mountains of Alaska are often 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 has been reported by numerous authors, including Matthes (1900), Lewis (1939), and Embleton and King (1975), 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. It seems reasonable to assume that warming of the climate of 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 provides protection from the cold abrasive winds that sweep over the slopes during winter as well as abundant soil moisture during melting. These factors have allowed a rich flora, especially mosses, sedges, and grasses, to develop.

These same conditions have promoted the formation of well-developed turf-covered earth hummocks in the hollows (Fig. 21). 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. They support an assemblage of thick and continuous flora that contrasts with the patchy dry tundra flora elsewhere on the slopes. Individual hummocks are typically 0.3 m high and 1 m in diameter. The largest was 0.4 m high and 1.6 m across. This corresponds well with those described by Sharp (1942).

On 30 June, 1979, a typical hummock was excavated at site E (Fig. 22). 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

Figure 21. Earth hummocks on Dakota Mountain.

Figure 22. Excavation of an earth hummock at site E (Fig. 4). The material beneath the knife is frozen.

center of the mat was 2.4°C. The temperature 40 mm into the frozen core was -0.1°C. An excavation to a depth of 450 mm and additional probing to a depth of 640 mm between hummocks revealed no frozen ground. When the site was re-examined 16 days later, no frozen ground could be found even under the largest hummocks.

Many authors have suggested mechanisms such as frost heaving (Taber 1952), local patches of freezing ground (Sharp 1942), and erosion (Peschel 1965) to explain such hummock development.

Frost Action Features

Block Fields and Tors

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 2 m 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). The size of the particles, however, is much smaller than that found in block fields elsewhere in Alaska. This is the result of differences in source material rather than process; the closely jointed rocks on Dakota Mountain tend to produce smaller blocks.

The only exposures of bedrock in the area are the precipitous, glacially excavated sides of the mountain and isolated tors on the upper surfaces. The tors range in size from 1 to 10s of meters. They are usually located on a local prominence or at the crest of a convex break in slope (Fig. 23 and 24). The rock composing the tors is well jointed, usually in several directions, thus providing easy access for moisture to penetrate into cracks, freeze, and expand them. The closely jointed metamorphic rock of this area produces tors that are much smaller than those of massive igneous bedrock found elsewhere in Alaska (Bailey 1983).

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

Figure 23. Large tor on the south end of Dakota Mountain. The man at the base of the tor indicates scale.

Figure 24. Terraces and a small tor at the top of the hill northwest of Camp Valley. View looking east.

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 tors reflects the relative stability of the area due to larger particle size and more gentle slope.

Sorted Circles

The most ubiquitous frost features on Dakota Mountain are the sorted circles. They occur on all but the steepest slopes of the mountain. Typical

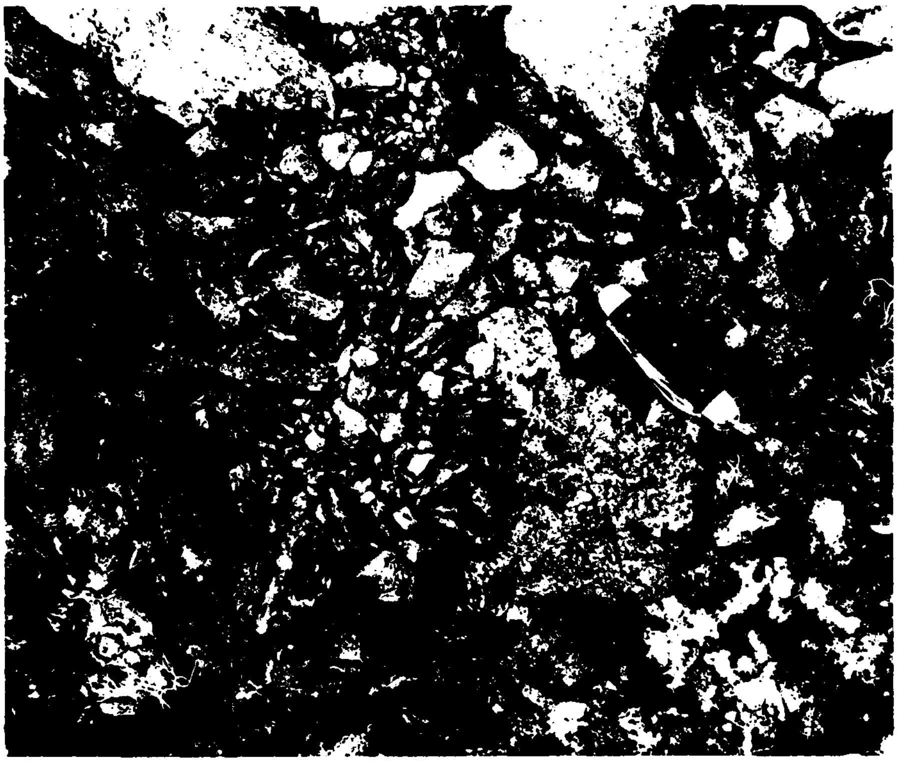


Figure 25. Sorted circle with stone packing in the center of Dakota Mountain. The 90-mm-long knife indicates scale.

circles are 0.5 m in diameter and consist of a center of fine particles surrounded by a margin of coarser rock fragments (Fig. 25 and 26). 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) of closely spaced, coarse particles standing on edge. Some of the centers consist of an exposed core of sand and silt with only scattered granules and pebbles at the surface (Fig. 27 and 28).

The symmetry of the circles is affected by individual large cobbles or boulders and especially by the slope of the surface. Those on hillsides tend to be elongated in the downslope direction. On steep slopes the lighter colored, less weathered particles uplifted in the circles may form small subcircular terraces with a miniature talus slope on the downslope side.

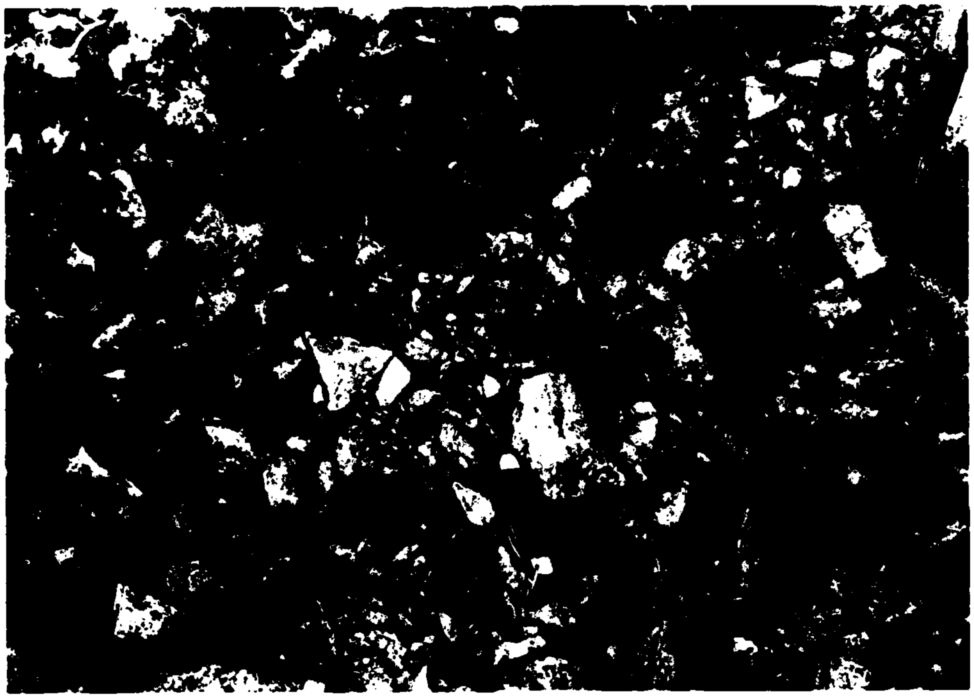


Figure 26. Sorted circle on Dakota Mountain. Note the black lichens on more stable particles surrounding the circle.

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 recent activity of the process (Fig. 26). Fresh debris from a sorted circle at site D has buried a mat of vegetative matter. This site is on a hillslope of 14°; particles up to 160 mm long are spilling over the lower edge of the 600-mm-diameter circle. One live plant of the genus <u>Dryas</u> was found buried beneath 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. Numerous vertical stones up to 300 mm high, some precariously erect, also indicate the contemporaneity of frost action here.

The depth of sorting on Dakota Mountain is quite shallow. Excavations of sorted circles were made at sites C, D, G, H, and I (Fig. 4). It was discovered from these excavations that the sorting effect is very shallow. The sand and silt centers extend to a depth of about 30 mm. Sorting in centers containing larger particles was not immediately obvious below a depth of

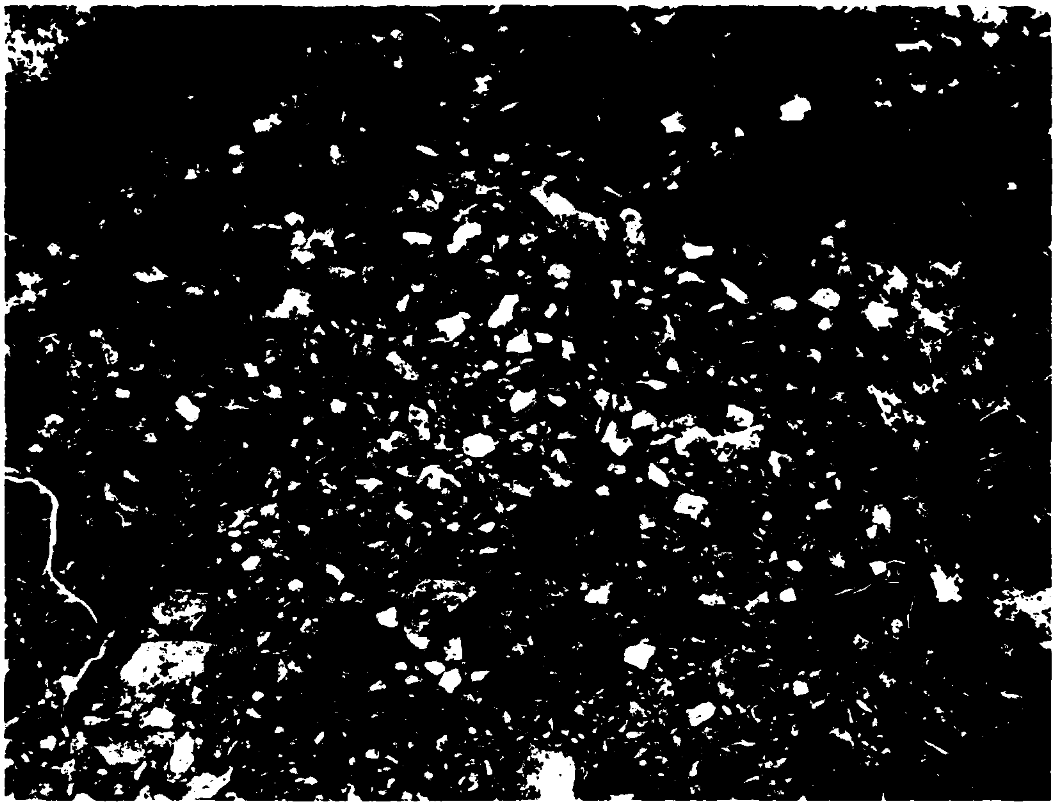


Figure 27. Sorted circle with exposed fine-grained center of Dakota Mountain. The 90-mm-long knife indicates scale.

90 mm. After several days of drying, however, a preferential orientation of particles was apparent to a maximum depth of about 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 is reasonable that the depth of frost action has been limited by permafrost. Annual frost action since the thawing of the permafrost has not yet produced perceptible sorting.

Figure 28. Small-scale circle on Dakota Mountain.

Sorted Polygons

Sorted polygons from 0.9 to 3.1 m across are found on the high level areas of Dakota Mountain (Fig. 29 and 30). The borders are typically 500 m wide and contain coarse angular particles up to 300 mm long. These polygons are probably relict frost-sorted patterns from a previously colder 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 discernible from the air, 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 cease to exist or are replaced by turf-banked sorted steps of a smaller scale.

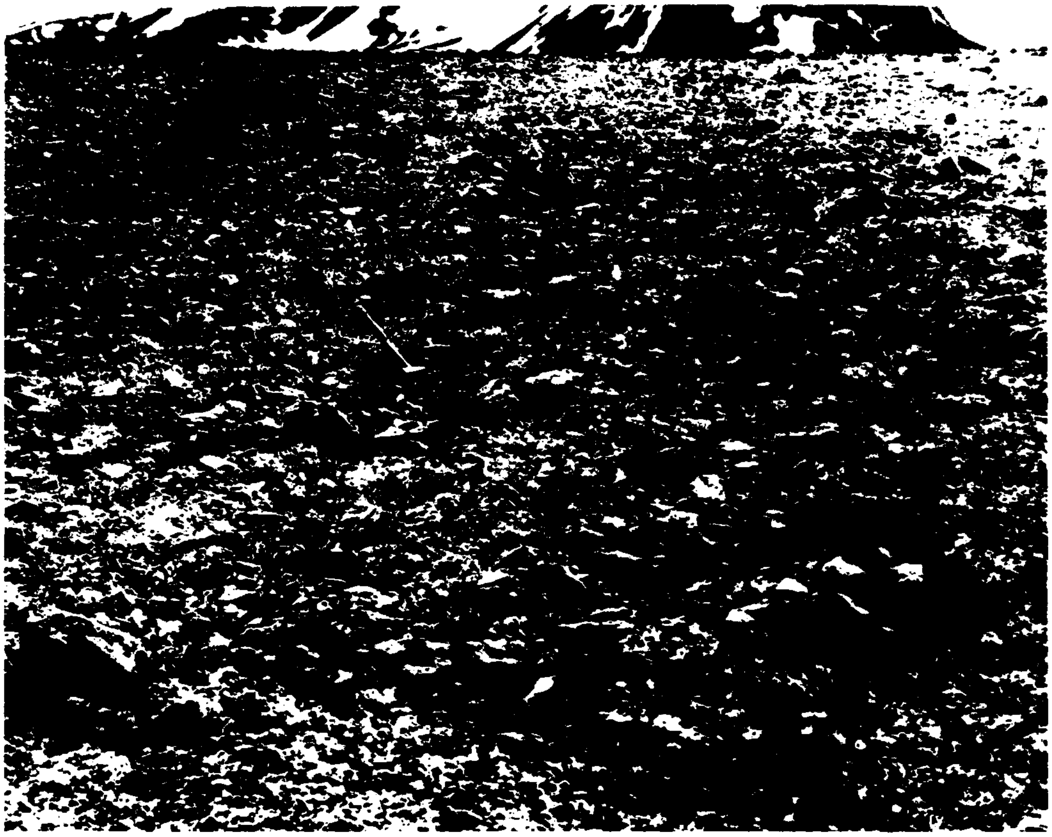


Figure 29. Sorted polygons and vertical stones on a hilltop on Dakota Mountain.

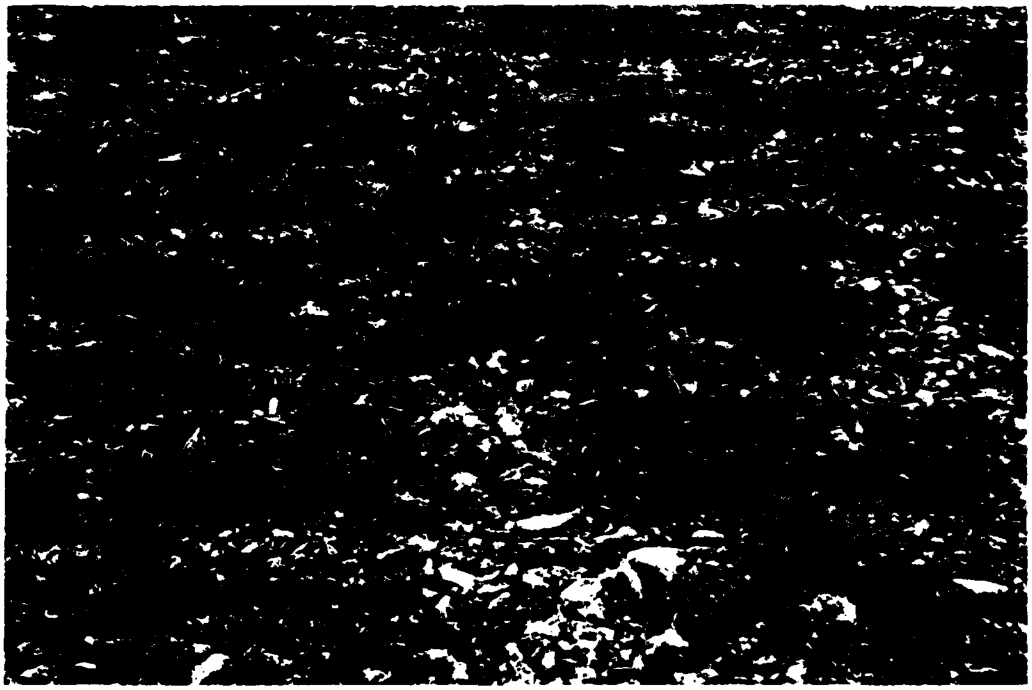


Figure 30. Sorted polygons on Dakota Mountain. The 450-mm-long mattock indicates scale.

It is concluded that the processes that produced these obscure polygons have not been active for a considerable time. Any associated patterned ground that existed on adjacent slopes has been obliterated by more recent slope processes. The patterns are preserved only on the more stable hilltops.

Soil Lineations

Very small-scale lineations were observed in the fine surface material of the centers of some sorted circles. These lineations 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. These lineations were first noted the day following two days of snow and freezing ground temperatures. Subsequently they were observed only after periods of freezing or near-freezing ground temperatures. The lineations were observed only in Camp Valley and the north-south trending saddle to the north of Camp Valley. Both of these valleys serve as wind funnels that topographically control wind direction. The lineations were, without exception, oriented precisely parallel to the wind direction dictated by the terrain. It is thus concluded that wind is a principal factor in their formation.

When first observed, the lineations were usually distinct. Those observed after days or weeks of thawing weather appeared to have deteriorated and were less well defined. It is suggested that needle ice was formed on the exposed fine sediment during cool periods and that strong winds during freezing and melting resulted in a striped alignment of the particles moved by the fine ice crystals. Troll (1944) observed this phenomenon in the Drakensberg of South Africa in June 1934. Schubert (1973) reports a similar occurrence in the South American Andes. Because needle ice, also known as piprake (Embleton and King 1975), grows by drawing water from the underlying sediments, it is reasonable to expect it to be present on areas of fine moist sediment and absent in areas covered by coarser sediment.

Features Produced by Running Water

Stripes

Long, narrow sorted stripes about 100 mm apart were sometimes observed in unvegetated areas just downslope from melting snowbanks (Fig. 31). Sorting is present but not well developed. The darker stripes are often slightly entrenched and consist of particles coarser than those between stripes. These stripes are due principally to rillwork by meltwater (Embleton and King

Figure 31. Small-scale sorted strips at the margin of a melting snow patch. The 90-mm-long knife in the center of the photograph indicates scale.

Figure 32. Sorted polygons in a small drained pool of the string bog. The 90-mm-long knife indicates scale.

1975, Washburn 1973). They do not occur in areas where vegetation is present to deflect and disrupt the downslope movement of meltwater.

Sorted Polygons

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 0.5 to 4 m in diameter (Fig. 32 and 33). The borders of the polygons consist of narrow cracks in the mud surface in which pebbles 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, and are sparser toward the inlet. In each pool there is an accumulation of pebbles along the lower end of the pool.

Small polygons of the same scale have been attributed to shallow frost sorting or needle ice (Troll 1944), but small-scale polygons on Dakota Mountain are unrelated to frost action. Numerous small pools in the string bogs are subjected to draining, rapid flooding, desiccation, and refilling as the

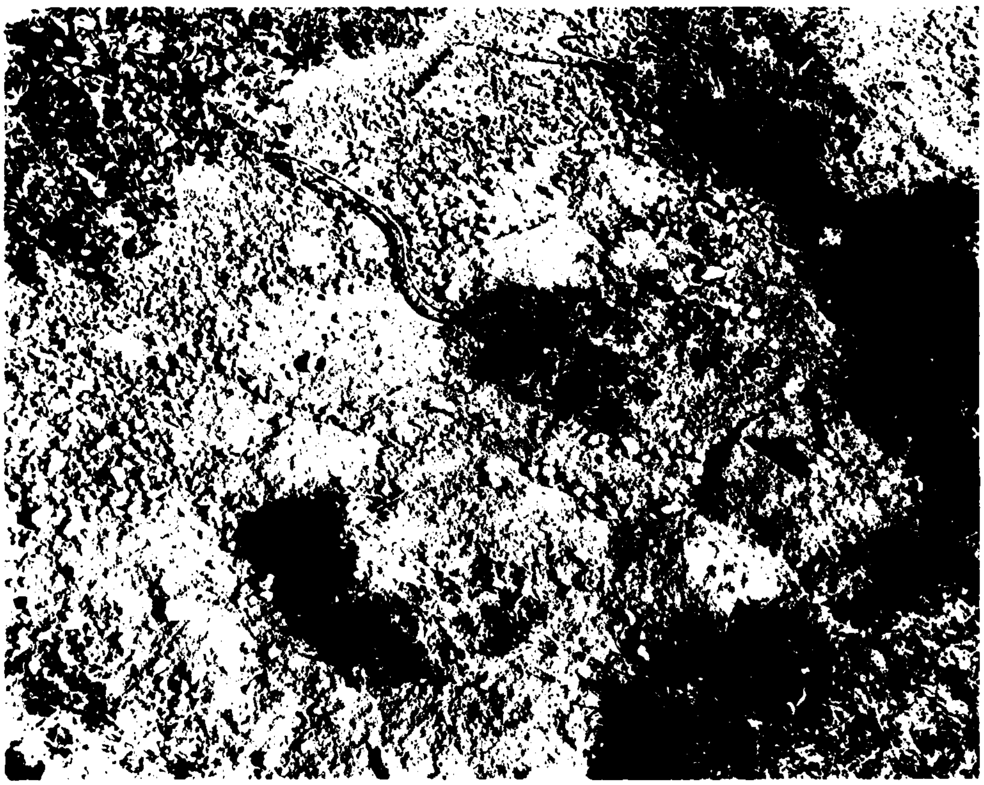


Figure 33. Sorted polygons in a larger drained pool of the string bog.

snowbank above the bog warms, cools, and recedes in response to solar radiation and air temperature. When the pools dry completely, the fine mud bottoms undergo desiccation cracking. Subsequent rapid flooding may flush coarser particles into the cracks. During the next drying episode the polygonal cracks will re-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 (Fig. 4).

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 are 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 irregular masses of soil are buried. Near one trough three thin dark 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.

The coarse, poorly sorted sediment that 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

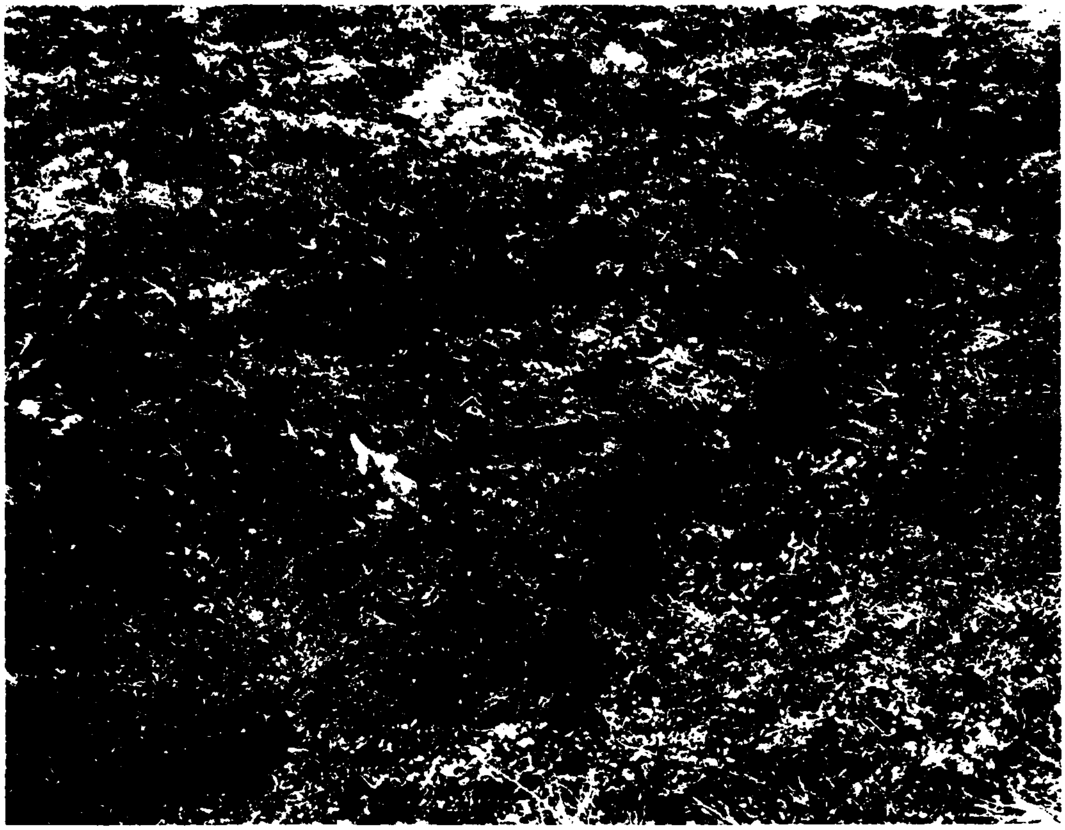


Figure 34. Nonsorted polygons at site J (Fig. 4).

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 meters deep have been reported elsewhere (Embleton and King 1975). The irregular character of the organic inclusions is probably the result of cryoturbation (frost stirring), and 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

An area approximately 80 m wide by 90 m long in the part of Camp Valley some 300 m east of the string bog is covered by nonsorted polygons. The polygons 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 (Fig. 34 and 35). Part of site L is sketched in Figure 36. 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

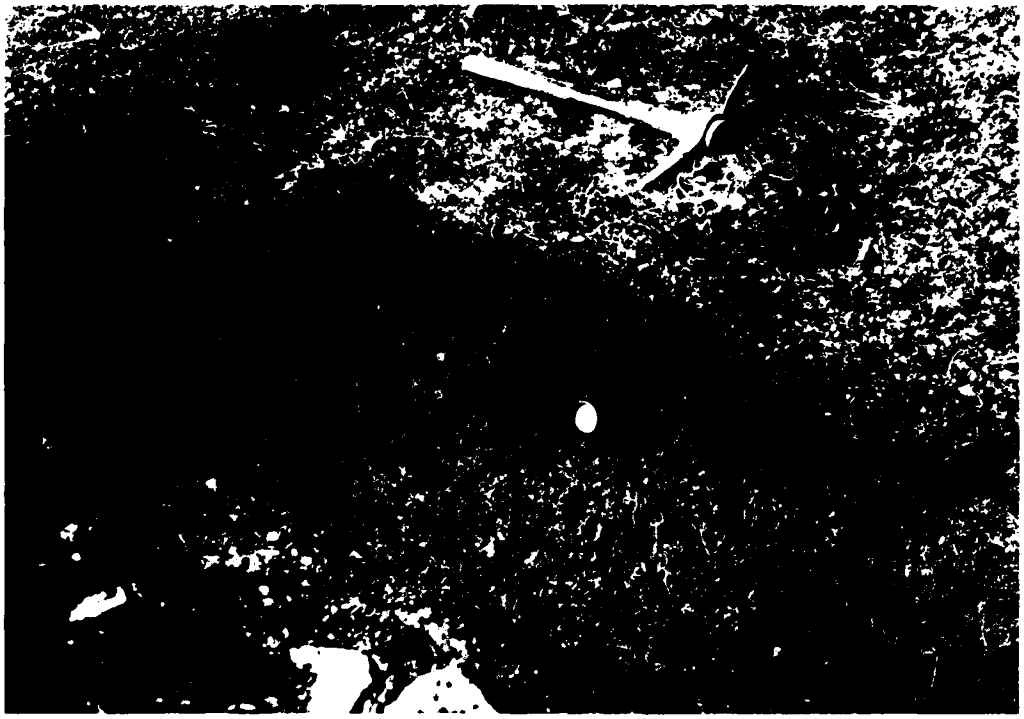


Figure 35. Excavation through a nonsorted polygon at site J (Fig. 4). The thickness of the organic zone is approximately 150 mm.

was underlain by inorganic olive-brown sediment composed of 85% gravel, 14% sand, and 1% silt. The contact between the two zones was marked in places by a concentration of large angular pebbles. Distorted layers of 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. In each excavation the deeper sediment was near saturation. At site F the local water table was encountered at a depth of only 920 mm.

Based on their size, the polygons may be either ice-wedge or desiccation polygons. Their diameter of about 1 m is quite large for desiccation features (Washburn 1973), but is very small for ice-wedge polygons (Péwé 1965). Washburn (1973) quotes Tricart (1967) as concluding that nonsorted polygons with diameters of 0.6 to 3 m are most likely desiccation features due to freeze drying. During laboratory analysis of desiccation cracking from air drying, Corte and Higashi (1964) observed that deeper and coarser soils tended to produce the largest forms. The largest polygons they produced in the

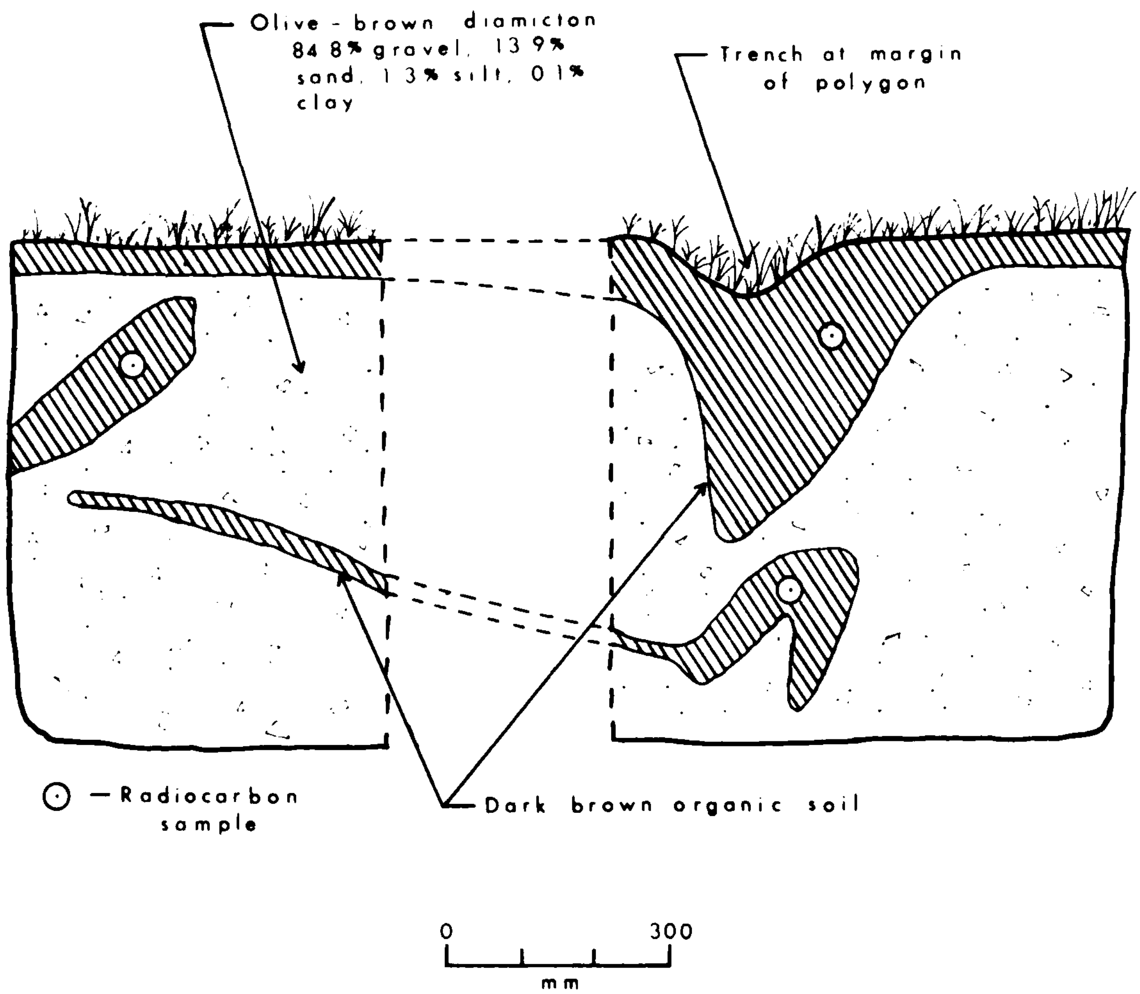
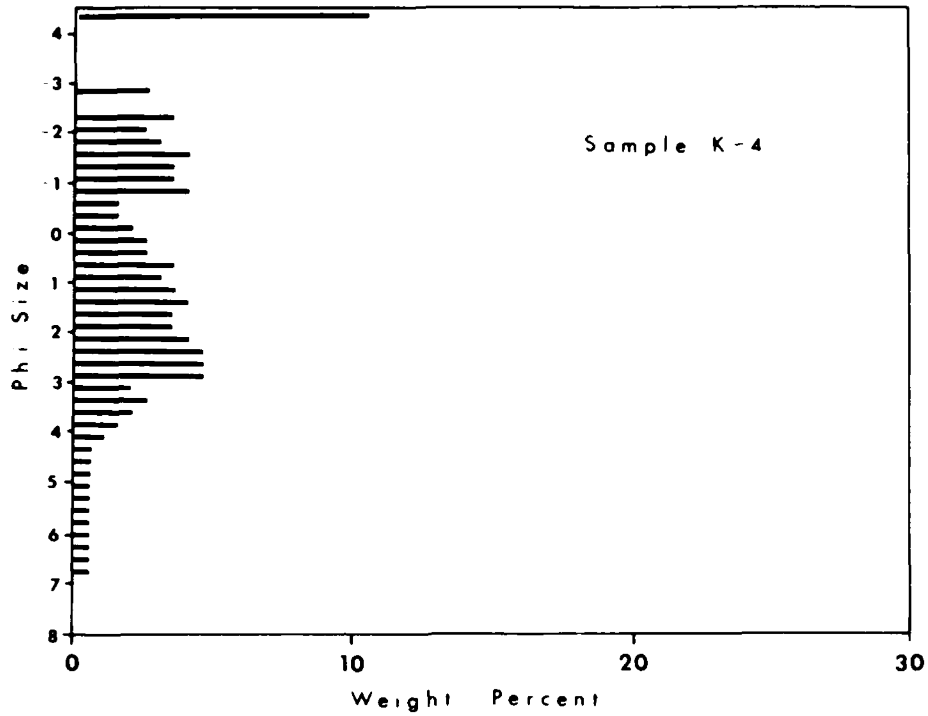


Figure 36. Nonsorted polygon at site L (Fig. 4). A composite view of the north walls of an L-shaped excavation is shown.

laboratory were about 0.3 m in diameter. Their coarsest sample, however, contained 30% silt and clay, compared to only 1.35% in the samples from Camp Valley. Although this may indicate that Camp Valley polygons are within the possible size limits for desiccation features, it is questionable that material with so few fine particles could develop distinct desiccation cracks. The width of the organic crack fillings and the presence of stones up to 100 mm in diameter along the sides and bottom of the fillings tend to indicate filling during the melting of ice-wedges rather than incremental filling of repeated desiccation cracks. These polygons are therefore interpreted to be relict ice-wedge polygons.



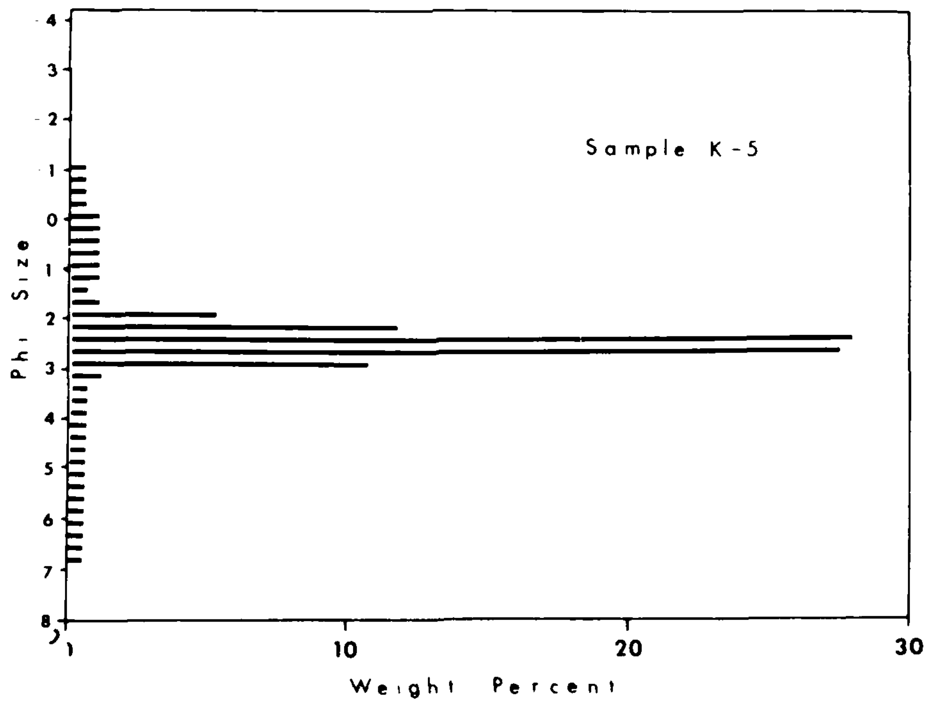


Figure 37. Particle size distribution of samples from site K (Fig. 4). Sample K-4 is geliflucticn debris. Sample K-5 is from this lenses of fine sand.

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 (Fig. 10). These sand lenses were from 4 to 12 mm thick and were about 50 mm below the original surface, now covered by the lobe. Grain size distribution of the sand is compared with typical gelifluction debris from Dakota Mountain in Figure 37. The thin deposits exhibited no cross-bedding or other structure that 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 surface morphology of grains of the sample was 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.

The original impression that the sand is tephra was easily discarded because of the lack of significant 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 and total lack of any other marine evidence. 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). Wind-transported sediment is often associated with dry periglacial environments (Embleton and King 1975).

Another reasonable hypothesis is that the sand was deposited along the shore of a small lake. Although the probability of encountering lacustrine beach 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

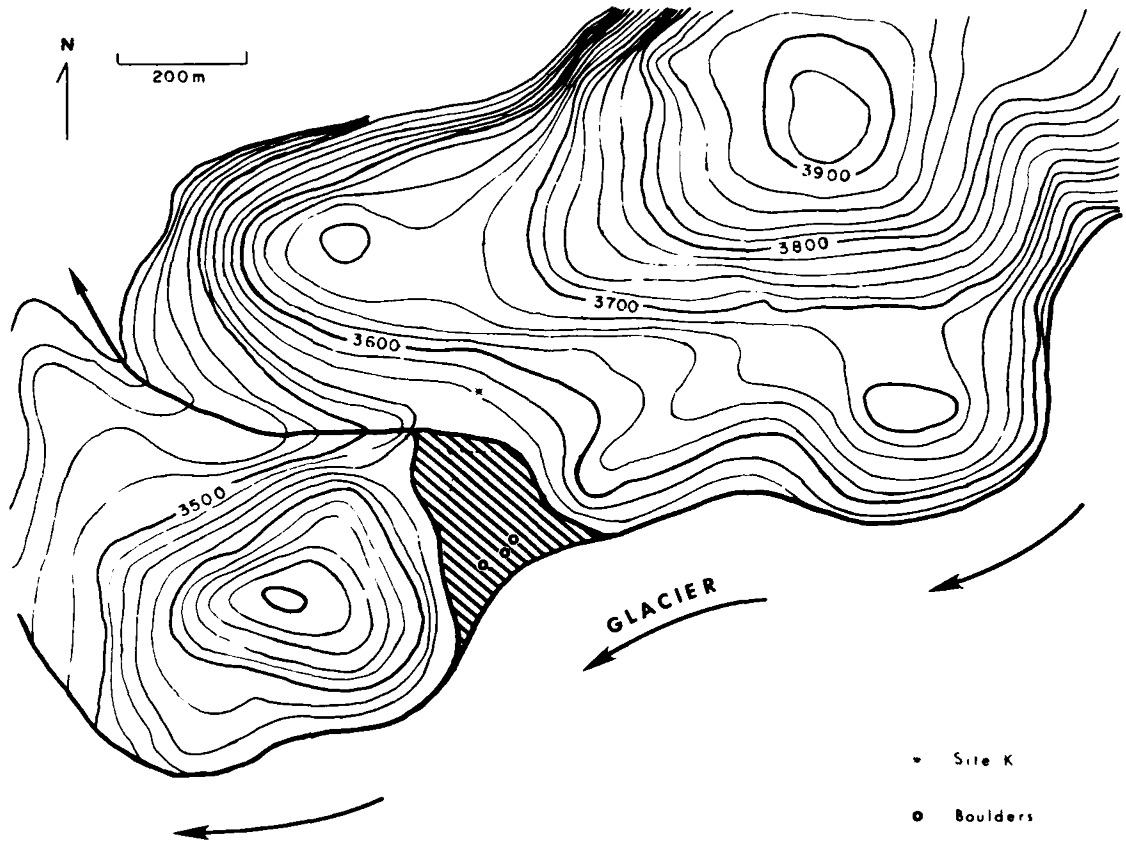


Figure 38. Map of Camp Valley area showing the relationship of the sand lenses at site K to a possible proglacial lake.

of the 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 the Bradley River to an elevation of about 1100 m, the drainage to the southeast would be blocked, forming a small proglacial lake against the side of the glacier and extending into a part of Camp Valley, as shown in Figure 38. The several large boulders near the southeast end of the valley appear to have been deposited there by the glacier, thus indicating that ice has at some time been sufficiently deep to block the southeast outlet. There is a distinct scarp about 2 m high at the logical site of the lake outlet that could mark the limit of headward erosion into the spillway. The sand unit is approximately 6 m above the level of the crest of the spillway. For the lake to have extended to the location of the sand, the drainage divide would have to have been relatively higher than at present. This difference in elevation may have existed during the past because of a topographically higher spillway that has since been eroded away.

Summary

On the basis of the above evidence, four events in the history of Camp Valley may be inferred. First, the valley floor was filled to an unknown depth by gelifluction deposits. Second, a large valley glacier blocked the southeast outlet of Camp Valley, producing a small proglacial lake. The sand lenses were perhaps deposited at the shore of that lake. The outlet stream eroded a spillway notch prior to recession of the glacier and draining of the lake. Third, small ice-wedge polygons developed on the former lake bottom. Finally, another climate change resulted in the thawing and subsequent filling of the ice-wedge casts.

Glacial History of Dakota Mountain

Dakota Mountain was selected as the study area because of its lack of glacial erosion features. Its smooth, rounded summits contrast distinctly 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 valleys 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). There is some evidence of previous glaciation of the mountain.

Two rocks were discovered on Dakota Mountain that appeared to be erratics. The first was collected 200 m south of site A at an elevation of about 1115 m. 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. The rock has a high content of microcrystalline quartz and is the result of low-grade metamorphism of a layered rock, probably of extrusive igneous origin. Its structure and composition are unlike any other samples observed on the mountain.

A second cobble 260 mm long was discovered on the side of Camp Valley at an elevation of 1065 m, 100 m northeast of the string bog (Fig. 4). The composition of the rock is a complex mixture of metamorphosed lithic fragments rich in quartz. One surface of the cobble forms a perfect plane that has been polished to an exceedingly smooth finish (Fig. 39). It is so well polished that no scratches or striations are visible, even through a hand lens. Upon examination using the scanning electron microscope, however, a number of subparallel striations and crescentic fractures were observed (Fig. 40).

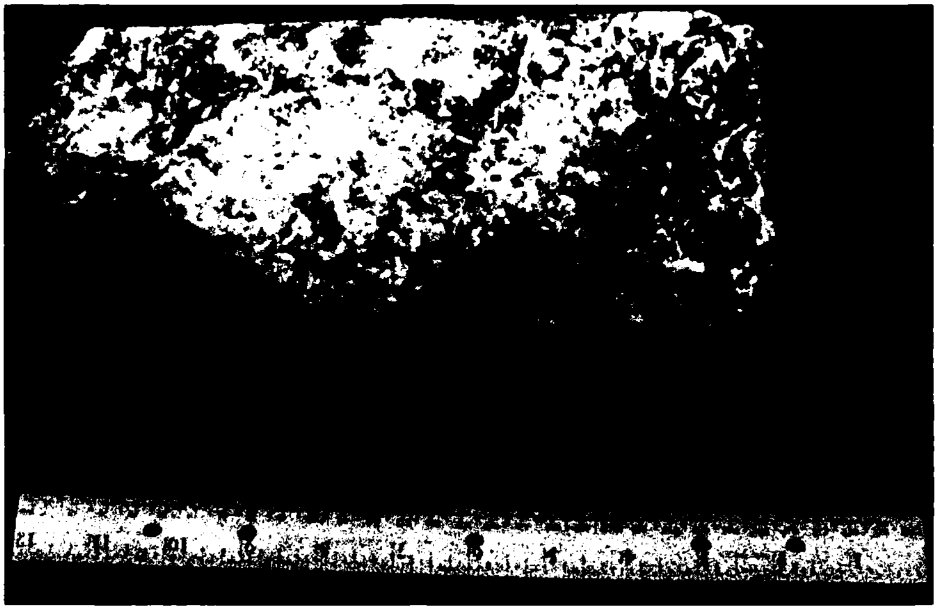


Figure 39. Polished faceted cobble from Camp Valley.

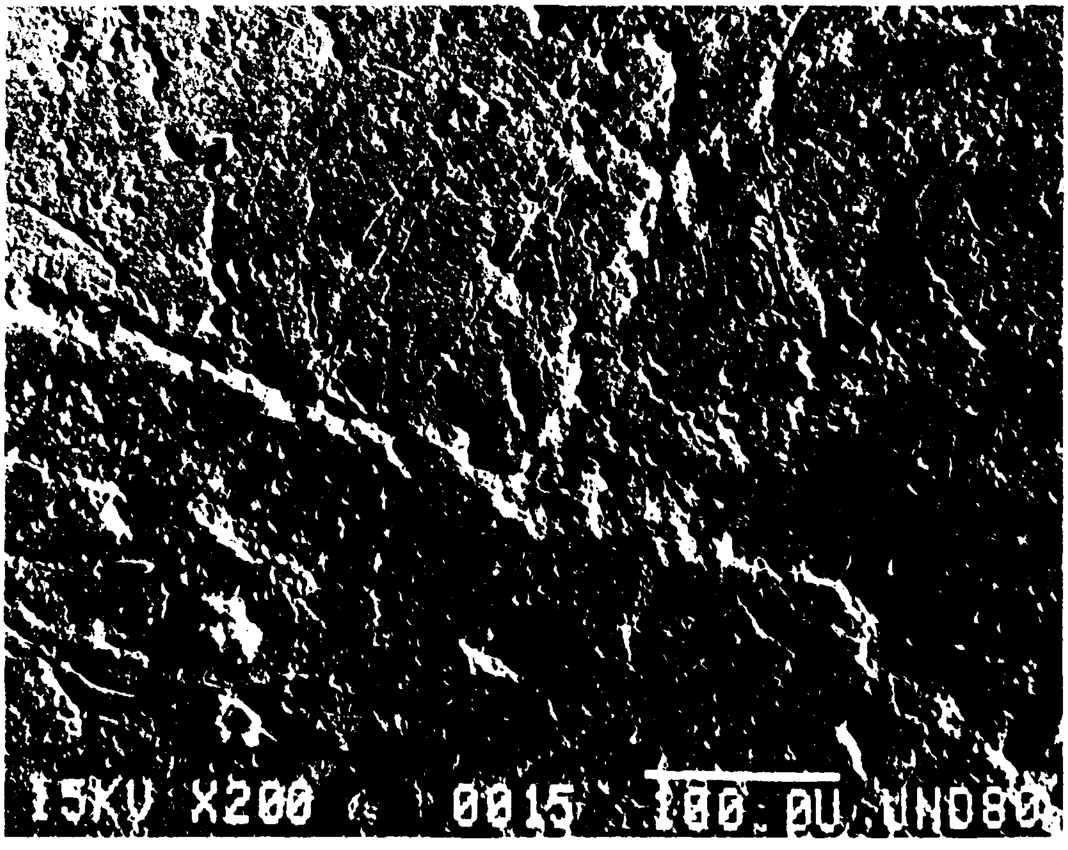


Figure 40. Scanning electron microscope photograph of the polished surface of the cobble in Figure 39. Note the striations and crescentic fractures. Magnification is 200x. The 100-micron bar indicates scale.

The composition of the two small erratics and especially the microscopic striations and crescentic gouges on the polished surface indicate that the mountain was at some time covered by glacial ice. It is possible for the larger erratic to have been transported into Camp Valley by ice rafting or fluvial action when meltwater drained across the mountain. The high elevation at which the smaller erratic was found essentially elimintes all processes other than glacial or human transport.

Karlstrom (1964) maps a small area, including Dakota Mountain, as last being covered by ice of Eklutna age, but shows that the surrounding lower region was buried beneath two later glaciations, the Knik and Naptowne. His chronology thus implies that Dakota Mountain has been free of glacial ice for about 90,000 years and that the adjacent area become ice-free between 14,000 and 9000 B.P. (Karlstrom 1964). 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) concluded that the cryoplanation terraces at their Mt. Hayes A-5 site formed during 50,000 to 70,000 years of periglacial attack. This duration was previously used (Bailey and Reid 1980) to conclude that it was probably impossible for the terraces on Dakota Mountain to have developed during only the 45,000 years since the end of the Knik glaciation (Karlstrom 1964). However, subsequent work by Reger (1975) revealed cryoplanation terraces in the Mint River area that are probably 10,000 to 25,000 years old. The possibility of glacial ice covering Dakota Mountain during the Knik glaciation therefore cannot be eliminated on this basis.

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 in Figure 41. The identification of these periglacial areas was based on their smooth rounded surface, a distinct contrast with 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 (Figure 41) such areas are distinct and generally easy to define. As far north as the Kenai River some areas could be iden-

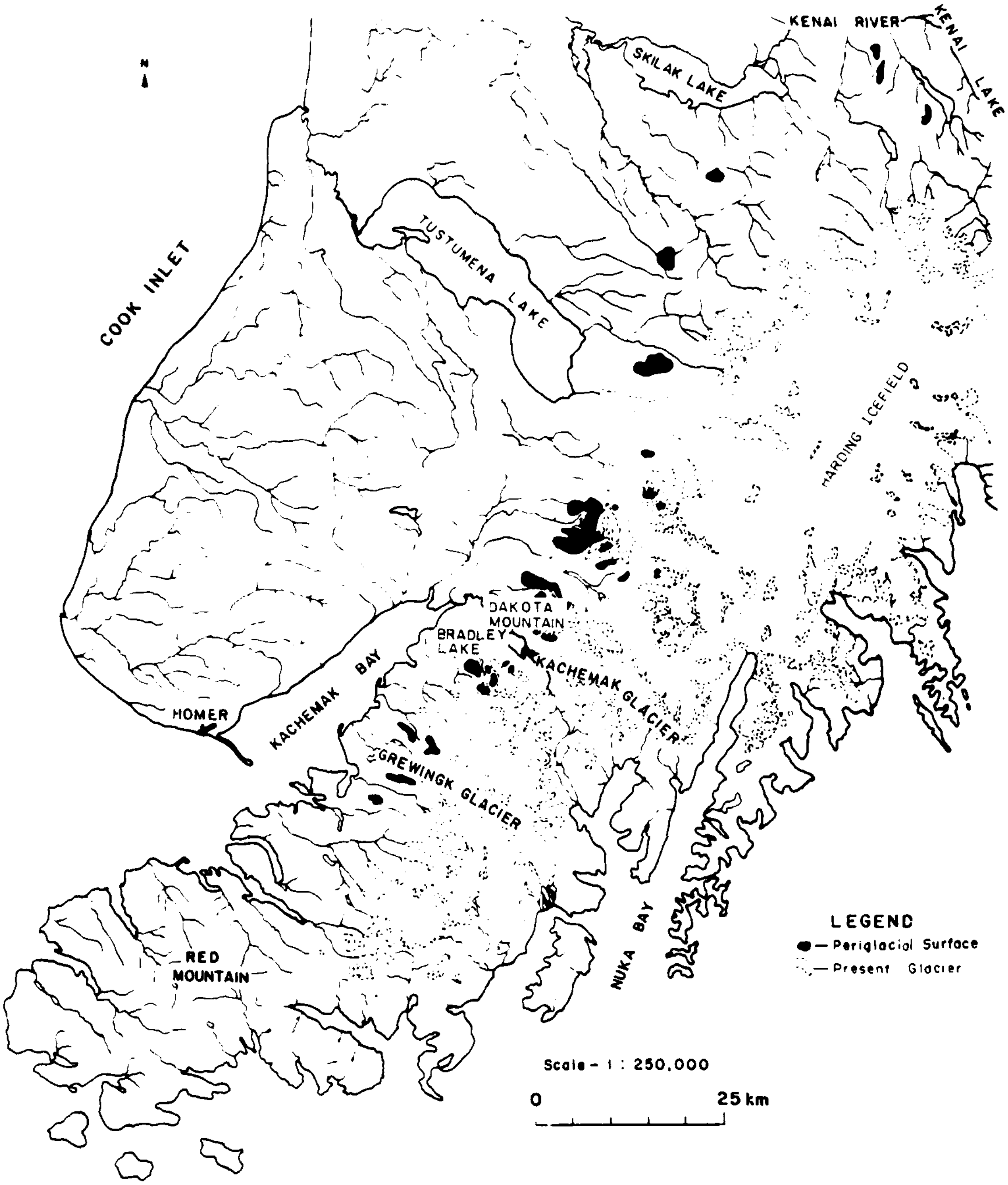


Figure 41. Periglacial surfaces in the southern Kenai Mountains, Alaska (Bailey, 1981).

tified; 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.

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 only scattered permafrost is present in the area. Extensive permafrost probably existed on Dakota Mountain in the recent past, but no permafrost presently exists that is shallow enough to affect surface processes. The conclusion that permafrost recently existed is 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 that are distinctly products of a previous colder environment. Included are the cryoplanation terraces, the nivation hollows, 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 relict forms that ceased developing at the time the near-surface permafrost thawed. The third group includes only those features that are now being formed or modified. 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 formed had a glacier blocked the southeast outlet of Camp Valley. The valley profile, transported boulders near the southeast outlet, and an eroded spillway notch all indicate that such a lake did exist.

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 was glaciated at some time in the past.

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.

LITERATURE CITED

Alexander, C.S., and L.W. Price (1980) Radiocarbon dating of the rate of movement of two solifluction lobes in the Ruby Range, Yukon Territory. Quaternary Research, 13: 365-379.

Anthony, L.M., and A.T. Tunley (1976) Geography and Geology of Alaska. Anchorage, Alaska: Polar Publishing, 273 pp.

Atwood, W.W. (1909) Mineral resources of southwest Alaska. U.S. Geological Survey Bulletin 379-C, p. 108-152.

Bailey, P.K. (1983) Periglacial geomorphology in the Kokrine-Hodzana Highlands of Alaska. In Permafrost: Fourth International Conference, Proceedings. Washington, D.C.: National Academy Press, p. 34-39.

Bailey, P.K., and J.R. Reid (1980) Periglacial geomorphology of Dakota Mountain, Alaska. In Proceedings of the North Dakota Academy of Science, vol. 34, p. 35.

Barnes, F.F. (1951) Preliminary report on coal deposits near Homer, Alaska. U.S. Geological Survey Bulletin 963-E, p. 203-208.

Barnes, F.F., and E.H. Cobb (1959) Geology and coal resources of the Homer District, Kenai coal field, Alaska. U.S. Geological Survey Bulletin 1085-F, p. 217-259.

Benedict, J.B. (1970) Downslope soil movement in a Colorado alpine region: Rates, processes, and climatic significance. Arctic and Alpine Research, 2: 165-226.

Beschel, R.L. (1965) Hummocks and their vegetation in the high arctic. In Permafrost: International Conference Proceedings. Washington, D.C.: National Academy of Sciences, p. 13-20.

Brooks, A.H. (1910) Mineral resources of Alaska. U.S. Geological Survey Bulletin 442, 432 pp.

Capps, S.R. (1924) Geology and mineral resources of the region traversed by the Alaska Railroad. U.S. Geological Survey Bulletin 755, p. 73-150.

Capps, S.R. (1931) Glaciation in Alaska. U.S. Geological Survey Professional Paper 170-A, p. 1-8.

Capps, S.R. (1940) Geology of the Alaska Railroad region. U.S. Geological Survey Bulletin 907, 201 pp.

Corte, A.E., and A. Higashi (1964) Experimental research on desiccation cracks in soils. U.S. Army Cold Regions Research and Engineering Laboratory, Research Report 66, 72 pp. AD615277.

Costin, A.B., J.N. Jennings, H.P. Black, and B.G. Thom (1964) Snow action on Mount Twynam, Snowy Mountains, Australia. Journal of Glaciology, 5(38): 219-228.

Cross, T.A. (1974) Computer program for grain-size analysis: Unpublished Fortran IV program on file in Geology Department of University of North Dakota.

Dall, W.H. (1896) Report on coal and lignite of Alaska. U.S. Geological Survey 17th Annual Report, pt. 1, p. 736-906.

Dall, W.H., and G.D. Harris (1892) Correlation papers - Neocene. U.S. Geological Survey Bulletin 84, 349 pp.

Eakin, H.M. (1916) The Yukon-Koyukuk region, Alaska. U.S. Geological Survey Bulletin 613, 88 pp.

Ekblaw, W.E. (1918) The importance of nivation as an erosive factor, and of soil flow as a transporting agency, in northern Greenland. In Proceedings of the National Academy of Science of the U.S.A., 4: 288-293.

Ellsworth, C.E., and R.W. Davenport (1915) A water power reconnaissance in south-central Alaska. U.S. Geological Survey Water-Supply Paper 372, 173 pp.

Embleton, C., and C.A.M. King (1975) Periglacial Geomorphology. New York: John Wiley and Sons, 203 pp.

Folk, R.L. (1974) Petrology of Sedimentary Rocks. Austin, Texas: Hemphill Publishing Company, 92 pp.

Galeshouse, J.S. (1971) Sedimentation analysis. In Proceedings in Sedimentary Petrology (R.E. Carver, Ed.). New York: John Wiley and Sons, p. 69-94.

Gardner, J. (1969) Snowpatches: Their influence on mountain wall temperatures and the geomorphic implications. Geografiska Annaler, 51(A): 114-120.

George, W. (1965) Water supply and drainage in Alaska. In Permafrost: International Conference Proceedings. Washington, D.C.: National Academy of Sciences, p. 420-425.

Grant, U.S., and D.F. Higgins (1909) Notes on the geology and mineral prospects in the vicinity of Seward, Kenai Peninsula. U.S. Geological Survey Bulletin 379-C, p. 98-107.

Grant, U.S., and D.F. Higgins (1910a) Reconnaissance of the geology and mineral resources of Prince William Sound, Alaska. U.S. Geological Survey Bulletin 443, 89 pp.

Grant, U.S., and D.F. Higgins (1910b) Preliminary report on the mineral resources of the southern part of the Kenai Peninsula. U.S. Geological Survey Bulletin 442, p. 166-178.

Grant, U.S., and D.F. Higgins (1913) Coastal glaciers of Prince William Sound and Kenai Peninsula, Alaska. U.S. Geological Survey Bulletin 526, 75 pp.

Henderson, E.P. (1956) Large nivation hollows near Knob Lake, Quebec. Journal of Geology, 64: 607-616.

Hollingworth, S.E. (1934) Some solifluction phenomena in the northern part of the Lake District. In Proceedings of the Geological Association, 45: 167-188.

Johnson, B.L. (1912) Gold deposits of the Seward-Sunrise region, Kenai Peninsula. U.S. Geological Survey Bulletin 520-E, p. 131-173.

Johnson, F.A. (1961) Waterpower resources of the Bradley River basin, Kenai Peninsula, Alaska. U.S. Geological Survey Water-Supply Paper 1610-A, p. A1-A25.

Karlstrom, T.N.V. (1952) Multiple glaciations in the upper Cook Inlet area, south-central Alaska (abstract). Geological Society of America Bulletin, 63: 1269.

Karlstrom, T.N.V. (1955a) Kenai lowland. In Permafrost and Groundwater in Alaska (D.M. Hopkins and T.N.V. Karlstrom, Ed.). U.S. Geological Survey Professional Paper 264-F, p. 133-134.

Karlstrom, T.N.V. (1955b) Late Pleistocene and recent glacial chronology of south-central Alaska (abstract). Geological Society of America Bulletin, 66: 1581-1582.

Karlstrom, T.N.V. (1957) Tentative correlation of Alaskan glacial sequences, 1956. Science, 125(3237): 73-74.

Karlstrom, T.N.V. (1958) Ground conditions and surficial geology of the Kenai-Kasilof area, Kenai Peninsula, south-central Alaska. U.S. Geological Survey Misc. Geologic Investigation Map I-269.

Karlstrom, T.N.V. (1964) Quaternary geology of the Kenai lowland and glacial history of the Cook Inlet region, Alaska. U.S. Geological Survey Professional Paper 443, 69 pp.

Krinsley, D.B. (1952) Multiple glaciation in the southwest Kenai Peninsula, Alaska (abstract). Geological Society of America Bulletin, 63: 1272.

Krinsley, D.B. (1953) Southwest Kenai Peninsula, Alaska. In Multiple Glaciation in Alaska (T.L. Péwé, et al., Ed.). U.S. Geological Survey Circular 289, p. 5-6.

Krinsley, D.H., and J.C. Doornkamp (1973) Atlas of Quartz Sand Surface Textures. Cambridge: Cambridge University Press, 91 pp.

Lewis, W.V. (1939) Snow-patch erosion in Iceland. Geographical Journal, 94(2): 153-161.

Linton, D.L. (1955) The problem of tors. Geographical Journal, 121: 470-487.

Marsh, W.M., and J. Dozier (1981) Landscape. Reading, Massachusetts: Addison-Wesley Publishing Company, 637 pp.

Martin, G.C. (1926) The Mesozoic stratigraphy of Alaska. U.S. Geological Survey Bulletin 776, 493 pp.

Martin, G.C., B.L. Johnson, and U.S. Grant (1915) Geology and mineral resources of Kenai Peninsula, Alaska. U.S. Geological Survey Bulletin 587, 243 pp.

Matthes, F.E. (1900) Glacial sculpture of the Bighorn Mountains, Wyoming. U.S. Geological Survey 21st Annual Report, p. 167-190.

McCabe, L.H. (1939) Nivation and corrie erosion in West Spitsbergen. Geographical Journal, 94(6): 447-465.

Mendenhall, W.C. (1900) A reconnaissance from Resurrection Bay to Tanana River, Alaska. U.S. Geological Survey 20th Annual Report, pt. 7, p. 271-340.

Moffit, F.H. (1906) Gold fields of the Turnagain Arm region. U.S. Geological Survey Bulletin 277, p. 7-52.

Nichols, R.L. (1963) Miniature nivation cirques near Marble Point, McMurdo Sound, Antarctica. Journal of Glaciology, 4(34): 477-479.

Péwé, T.L. (1965) Ice-wedges in Alaska - classification, distribution, and climatic significance. In Permafrost: International Conference Proceedings. Washington, D.C.: National Academy of Sciences, p. 76-81.

Péwé, T.L. (1970) Altiplanation terraces of early Quaternary age near Fairbanks, Alaska. Acta Geographica Lodziensia, 24: 357-363.

Péwé, T.L. et al. (not listed) (1953) Multiple glaciations in Alaska. U.S. Geological Survey Circular 289, 13 pp.

Péwé, T.L., and R.D. Reger (1968) Investigation of the origin, distribution and environmental significance of altiplanation terraces. U.S. Army Cold Regions Research and Engineering Laboratory, unpublished report, 186 pp.

Pilgrim, E.R. (1933) Nuka Bay district. In Mining Investigations and Mine Inspection in Alaska, Biennium Ending March 31, 1933 (B.D. Stewart, Ed.), Alaska Division of Mines and Minerals, p. 26-51.

Price, L.W. (1973) Rates of mass wasting in the Ruby Range, Yukon Territory. In Permafrost: The North American Contribution to the Second International Conference, Yakutsk. Washington, D.C.: National Academy of Sciences, p. 235-245.

Prindle, L.M. (1913) A geologic reconnaissance of the Fairbanks Quadrangle, Alaska. U.S. Geological Survey Bulletin 525, 220 pp.

Reger, R.D. (1975) Cryoplanation terraces of interior and western Alaska. Unpublished dissertation at Arizona State University, 326 pp.

Reger, R.D., and T.L. Péwé (1976) Cryoplanation terraces: Indicators of a permafrost environment. Quaternary Research, 6: 99-109.

Richter, D.H. (1970) Geology and lode-gold deposits of the Nuka Bay area, Kenai Peninsula, Alaska. U.S. Geological Survey Professional Paper 625-B, p. B1-B16.

Riehle, J.R. (1977) Airphoto interpretation and surficial geology of upper Kachemak Bay-English Bay area, Alaska. State of Alaska, Division of Geological and Geophysical Surveys Open File Report 110, 1 plate with explanation.

Russell, R.J. (1933) Alpine landforms of western United States. Geological Society of America Bulletin, 44(5): 927-950.

Schenk, E. (1965) Origin of string bogs. In Permafrost: International Conference Proceedings. Washington, D.C.: National Academy of Sciences, p. 155-159.

Schubert, C. (1973) Striated ground in the Venezuelan Andes. Journal of Glaciology, 12: 461-468.

Sharp, R.P. (1942) Soil structures in the St. Elias Range, Yukon Territory. Journal of Geomorphology, 5: 274-301.

Smith, P.S. (1939) Areal geology of Alaska. U.S. Geological Survey Professional Paper 192, 100 pp.

Soward, K.S. (1962) Geology of waterpower sites on the Bradley River, Kenai Peninsula, Alaska. U.S. Geological Survey Bulletin 1031-C, pp. 47-70.

Stanton, T.W., and G.C. Marin (1905) Mesozoic section on Cook Inlet and Alaska Peninsula. Geological Society of America Bulletin, 16: 391-410.

Stone, R.W. (1906) Coal fields of the Kachemak Bay region. U.S. Geological Survey Bulletin 277, pp. 53-73.

St.-Onge, D. (1965) La geomorphologie de l'Ile Ellef Ringnes, Territories du Nord-Ouest, Canada. Canada, Ministere des Mines et des Releves Techniques, Direction de la Geographie Etude, vol. 38, 46 pp.

St.-Onge, D. (1969) Nivation landforms. Geological Survey of Canada Paper 69-30, 12 pp.

Sugden, D.E., and B.S. John (1976) Glaciers and Landscape. New York: John Wiley and Sons, 376 pp.

Sugden, D.E. and B.S. John (1952) Geology, soil mechanics, and botany. Science, 115: 713-714.

Tarr, R.S., and L. Martin (1914) Alaskan Glacier Studies of the National Geographic Society in the Yakutat Bay, Prince William Sound, and Lower Copper River Regions. Washington, D.C.: National Geographic Society, 498 pp.

Thorn, C.E. (1976) Quantitative evaluation of nivation in the Colorado front range. Geological Society of America Bulletin, 87(8): 1169-1178.

Tricart, J. (1967) Le modele des regions periglaciaires. In Traite de Geomorphologie (J. Tricart and A. Cailleux, Ed.). Paris: SEDES, 512 pp.

Troll, C. (1944) Structurböden, Solifluktion, und Frostklimate der Erde. Geologische Rundschau, 34: 545-694. U.S. Army Snow, Ice and Permafrost Establishment Translation 43, October 1958, 121 pp.

Tuck, R. (1933) The Moose Pass-Hope District, Kenai Peninsula. U.S. Geological Survey Bulletin 849-I, p. 469-539.

U.S. Army Corps of Engineers (1955) Bradley Lake project - a reconnaissance report on potential power developments together with auxiliary possibilities. Office of the District Engineer, Alaska District.

U.S. Army Corps of Engineers (1978) Reanalysis of the Bradley Lake hydroelectric project. Office of the District Engineer, Alaska District.

Wahrhaftig, C. (1950) Physiographic history of southern Alaska, a hypothesis (abstract). Geological Society of America Bulletin, 61(12, pt. 2): 1532.

Wahrhaftig, C. (1965) Physiographic divisions of Alaska. U.S. Geological Survey Professional Paper 482, 52 pp.

Washburn, A.L. (1947) Reconnaissance geology of portions of Victoria Island and adjacent regions, Arctic Canada. Geological Society of America Memoir 22, 142 pp.

Washburn, A.L. (1956) Classification of patterned ground and review of suggested origins. Geological Society of America Bulletin, 67: 823-866.

Washburn, A.L. (1967) Instrumental observations of mass wasting in the Mesters Vig District, northeast Greenland. Meddelelser om Grønland, 166(4): 296 pp.

Washburn, A.L. (1970) Instrumental observation of mass wasting in an arctic climate. Zeitschrift für Geomorphologie, supplementband 9, p. 102-118.

Washburn, A.L. (1973) Periglacial Processes and Environments. London: Edward Arnold, 320 pp.

Williams, J.E. (1949) Chemical weathering at low temperatures. Geographical Review, 39: 129-135.

Williams, J.R., and R.M. Waller (1965) Groundwater occurrence in permafrost regions of Alaska. In Permafrost: International Conference Proceedings. Washington, D.C.: National Academy of Sciences, p. 159-164.

Williams, P.J. (1959) An investigation into processes occurring in solifluction. American Journal of Science, 257: 481-490.

END

FILMED

9-85

DTIC