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PATTERNED GROUND IN THE JUNEAU ICEFIELD REGION,
ALASKA - BRITISH COLUMBIA

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Major professor

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PATTERNED GROUND IN THE JUNEAU ICEFIELD REGION,

ALASKA - BRITISH COLUMBIA

By

Frederick Edward Nelson

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ABSTRACT

PATTERNED GROUND IN THE JUNEAU ICEFIELD REGION, ALASKA - BRITISH COLUMBIA

By

Frederick Edward Nelson

Patterned ground is found in abundance only in the more continental sectors of the Juneau Icefield region. Its concentration here is partially due to the sporadic winter snowcover, which allows the subsurface freezing required for effective frost sorting. In maritime sectors of the icefield, the concurrent onset of annual precipitation maximums and sustained subzero temperatures operate to produce a thick and relatively uniform snowcover, which prohibits pattern-generating processes. Although it was not possible to define a lower limit for patterned ground in the western reaches of the icefield, this limit was found to lie slightly below 1500 meters on the eastern margin. Owing to genetic differences, it is suggested that both small- and large-diameter patterned ground not be used in the definition of a singular lower limit.

Investigations of the internal structure of patterned-ground features reveal that the lateral margins of sorted stripes exhibit a distinctive fabric, characterized by a preferred azimuthal orientation parallel to the axis of the stripe, and steeply dipping b-axes. This fabric results from compression of the stone stripes as fine centers expand during the autumn freeze. Field evidence indicates that cobble geometry is an important factor influencing the efficacy with which frost-sorting operates.

ACKNOWLEDGMENTS

I have been assisted in this undertaking by so many people that it is impossible to mention them all here. Nonetheless, I extend my deepest appreciation to all those who helped in so many ways, both in the field and at Michigan State University. Thanks go to the many 1975 and 1976 Juneau Icefield Research Program participants who undertook tedious tasks in my behalf, often under adverse conditions. I am especially indebted to Dr. Robert Nichols, Professor Emeritus at Tufts University, for critical methodological comments and special insights into the study of geomorphology in the field.

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Dr. Dieter Brunnschweiler acted as supervisor of the research and served as chairman of my academic committee at Michigan State University. To Professor Brunnschweiler I owe my interest in periglacial and climatic geomorphology. His great enthusiasm and encyclopedic knowledge of geography have stimulated me in many ways. I especially wish to acknowledge Dr. Brunnschweiler's patient and generous aid in translation of foreign literature. This assistance, as well as his insightful criticisms and accessibility for discussion, have greatly enhanced this thesis.

Finally, I wish to acknowledge the labors of Mr. Chris Cialek of Michigan State, who executed almost all of the graphics for the thesis and served as a sounding board for many of the ideas contained in it. I also thank Mr. Cialek for permission to mutilate a copy of his fine map of the Cathedral Massif, which appears as Figure 4-3.

The thesis is dedicated to the memory of Stan Zieminin.

is this love...or is it just confusion?

- J. Hendrix

TABLE OF CONTENTS

Table of Contents (cont.)

LIST OF TABLES

LIST OF FIGURES

List of Figures (cont.)

CHAPTER I

INTRODUCTION

Over the past twenty years, a sizable North American contribution to the periglacial literature has accumulated, although little attention has been given to the traditional European theme of spatial variation in periglacial phenomena. The frequently-mentioned but inadequately documented relationship between continentality and alpine geomorphological features would appear to be particularly evident in the North American cordillera. By means of a transect in the Juneau Icefield region, an attempt is made in this thesis to clarify some of the questions regarding the origin and distribution of cryogenic landforms.

There has been considerable discussion, primarily in the German-language literature, regarding variations in the altitudinal threshold of sorted patterned ground in mountainous regions. While there is general agreement on a decrease in elevation of this limit poleward, Troll (1958, pp. 5-9, 60) and Hastenrath (1960) contend that the boundary follows tree-line and snowline, rising with increasing continentality. Hövermann (1960; 1962), among others, maintains an opposing viewpoint, arguing for a decrease in threshold elevations with progression from maritime to continental environments.

In a brief discussion of patterned-ground thresholds and related problems, Washburn (1973, p. 101) calls for detailed regional studies of periglacial features. A diverse regional base is required if the interrelationships and factors contributing to the occurrence of periglacial phenomena are to be better understood. Since there appear to be few regional periglacial studies from North America, such an undertaking appears appropriate.

At a more local scale, much remains to be learned regarding the internal structure of patterned ground. Conflicting reports, often based on casual observation, have been published on the nature and origin of cobble fabrics in the borders of patterned ground cells. Similarly, it has been suggested, without rigorous testing, that a given particle's geometry may influence its propensity for movement in a frost-affected soil matrix. The relationship between temporal and spatial aspects of snowcover and the occurrence of patterned ground is also inadequately documented. These problems are addressed in the present thesis.

1.1 Research Objectives

The primary goal of this study is determination and explanation of the distribution of patterned ground and permafrost in the Juneau Icefield region. Considerable selectivity is required, since such an objective is obviously too large a goal to be realized by a single worker in two field seasons. The study has therefore been limited by concentrating observations on a 200 km transect in the Northern Boundary Range between Juneau, Alaska (58° 22'N., 134° 35'W.), and Atlin, British Columbia (59° 35'N., 133° 38'W.). In this manner, the broad outline of the distribution and controls operative on the features in question can be constructed, to which subsequent observations may be added.

Because of its three-dimensional character, mountainous terrain demands that considerable attention be given to topographic and altitudinal factors influencing the distribution of small-scale landform elements.

An important problem which this thesis seeks to resolve is the direction assumed by the regional trend of the patterned ground and permafrost thresholds. An attempt is also made to combine observations of climatic, topographic, and edaphic factors controlling the distribution and threshold with a review of literature in order to account for the empirically-derived results. Explanation is offered in a largely deductive framework.

1.2 Research Hypotheses

It is hypothesized that the lower limit of large-diameter sorted patterned ground falls in response to conditions of increasing continentality. Furthermore, it is postulated that patterned ground is most likely to develop at sites with the following characteristics:

1) Parent material characterized by heterogeneously-sized components with high frost susceptibility. Such material is conducive to size-sorting because ice segregation is presumably required for effective frost sorting (Washburn, 1973, pp. 71-80). Many glacial tills have such characteristics.

2) Low-angle slopes with north to northeast exposures, where late-lying snowbanks provide sufficient moisture for ice segregation at the time of the autumn freeze. It is possible that these snowbanks have the effect of keeping the summer temperature centered about 0°C near their margins, thereby maximizing the number of potent freeze-thaw cycles at times when the ground is saturated. It is emphasized that the latter point is applicable only to small-diameter forms, in that it is only these that are affected by diurnal cycles.

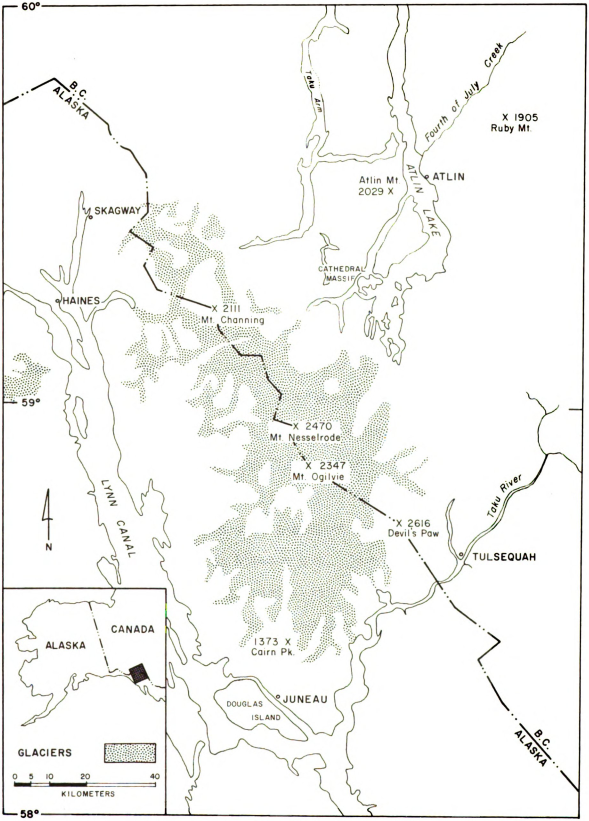
3) A mean annual temperature of 1°C or lower. This limit is suggested by Williams (1961, p. 344) as a crude limit for widespread patterned ground occurrence. Although it cannot be precisely determined

except by reliable microclimate observations, this boundary may be approximated by applying lapse rates. Bird (1967, p. 197) suggests that the southern limit of patterned ground in Arctic Canada may be identified with a mean annual air temperature of -4° C. However, French (1976, p. 195) maintains that the effective limit of miniature frost-related forms may be better approximated using William's limit. Since the elevation at which such a mean annual temperature occurs may be expected to decrease with increasing distance from oceanic influence, it should follow that the lower altitudinal limit of patterned ground in the Boundary Range is depressed inland. Another important factor in this regard is the effect of snow cover on soil temperatures. Mountainous areas characterized by a continental climate and sporadic snow cover are likely to experience a wider range of subsurface soil temperatures than oceanic areas with heavy snow accumulation, even though each locality may have identical mean annual air temperatures (Outcalt, 1967, p. 10). Assuming that sufficient moisture is available for frost sorting, as at the downslope edge of a perennial snowbank, continentality should play an important role in the development of widespread patterned ground.

1.3 The Study Area

The Juneau Icefield is the fifth largest area of continuous highland ice in North America. It covers an area of about 2700 km^2 northeast of the city of Juneau, in the northern Boundary Range on the Alaska - B.C. - Yukon border. This icefield extends from the Taku River Valley at its southern edge, to the vicinity of White Pass, northeast of Skagway, Alaska (Figure 1-1). The icefield is a system of interconnected glaciers and snowfields of variable elevation. Its main area may be regarded as a broad ice plateau cresting near the International Boundary at

Figure 1-1. The Northern Boundary Range.


60°
59°
58°
B.C.
ALASKA
Taku Arm
Fourth of July Creek
X 1905
Ruby Mt.
Atlin Mt.
2029 X
ATLIN LAKE
ATLIN
SKAGWAY
CATHEDRAL
MASSIF
HAINES
X 2111
Mt. Channing
X 2470
Mt. Nesselrode
X 2347
Mt. Ogilvie
X 2616
Devil's Paw
Taku River
TULSEQUAH
LYNN CANAL
N
ALASKA
CANADA
1373 X
Cairn Pk.
JUNEAU
DOUGLAS
ISLAND
GLACIERS
0 5 10 20 40
KILOMETERS
B.C.
ALASKA

approximately 1950 meters (Miller, 1964, p. 261). In the central icefield numerous nunataks protrude through the ice surface, some attaining heights of up to 1200 m above the surroundings. The form of many is that of the typical horn peak, although some having been overridden by ice, display rounded profiles. Many of the nunataks contain cirque-glaciers, whose ice flows out to merge with that of the plateau. The highest elevation in the area is attained by Devil's Paw (2616 m), on the southeastern flank of the Icefield.

In the southeastern sector of the icefield, the Taku-Llewellyn transection glacier system extends from tidewater at Taku Inlet nearly to the shores of Atlin Lake, some 100 km to the north (Figure 1-1). Although the regime of most outlet glaciers is negative or close to equilibrium, that of the largest, the Taku Glacier, is strongly positive. This glacier has advanced almost 12 km since the 1890's, while its east slope counterpart, the Llewellyn Glacier, has receded more than 3 km since 1920 (Miller, 1976, p. 275). This contrast has been explained with respect to the location of the zone of maximum accumulation on each. The Taku's maximum area lies between 900-1375 m on the maritime west slope, where conditions for accumulation of snow are optimal. However, Llewellyn's maximum area lies on the eastern slope between 900-1500 m, which is today well below the zone of maximum accumulation on this side of the range (_ibid_).

The Atlin area, where much of the research for this thesis was conducted, is northeast of the Juneau Icefield in the Cassiar District of northwestern British Columbia. The region has been repeatedly occupied by large north-flowing glaciers which have modified pre-existing structural and fluvially-cut depressions, resulting in precipitous valleys of the familiar U-shape. Many of these lineaments are now occupied by water bodies, the largest being Atlin Lake, which extends 105 km from the terminus of the Llewellyn Glacier to the north side of the Yukon - B.C. border. Based on palynological and stratigraphic evidences (Miller and Anderson, 1974; Tallman, 1975), the last deglaciation in the Atlin area is interpreted as having been well in progress by 10,000 years B.P. (Miller, 1976, p. 286). With the exception of Icefield outlet glaciers, glacierization is at present confined to small cirque glaciers in terrain above 1550 m west of Atlin Lake.

The Cathedral Massif is an isolated mountain block occupying an area of 8.25 km^2 near the southwest end of Atlin Lake (Figure 1-1). The highest point on the massif is Cathedral Peak (2118 m). The massif supports nine small cirque glaciers, which in recent decades have been downwasting and receding. A wealth of active and relict periglacial features is also found in this small area. These features are the subject of part of the research presented in later sections of this study. Jones (1975) has presented an interpretation of the geology and glaciology of the Cathedral Massif.

1.3.1 Bedrock Geology

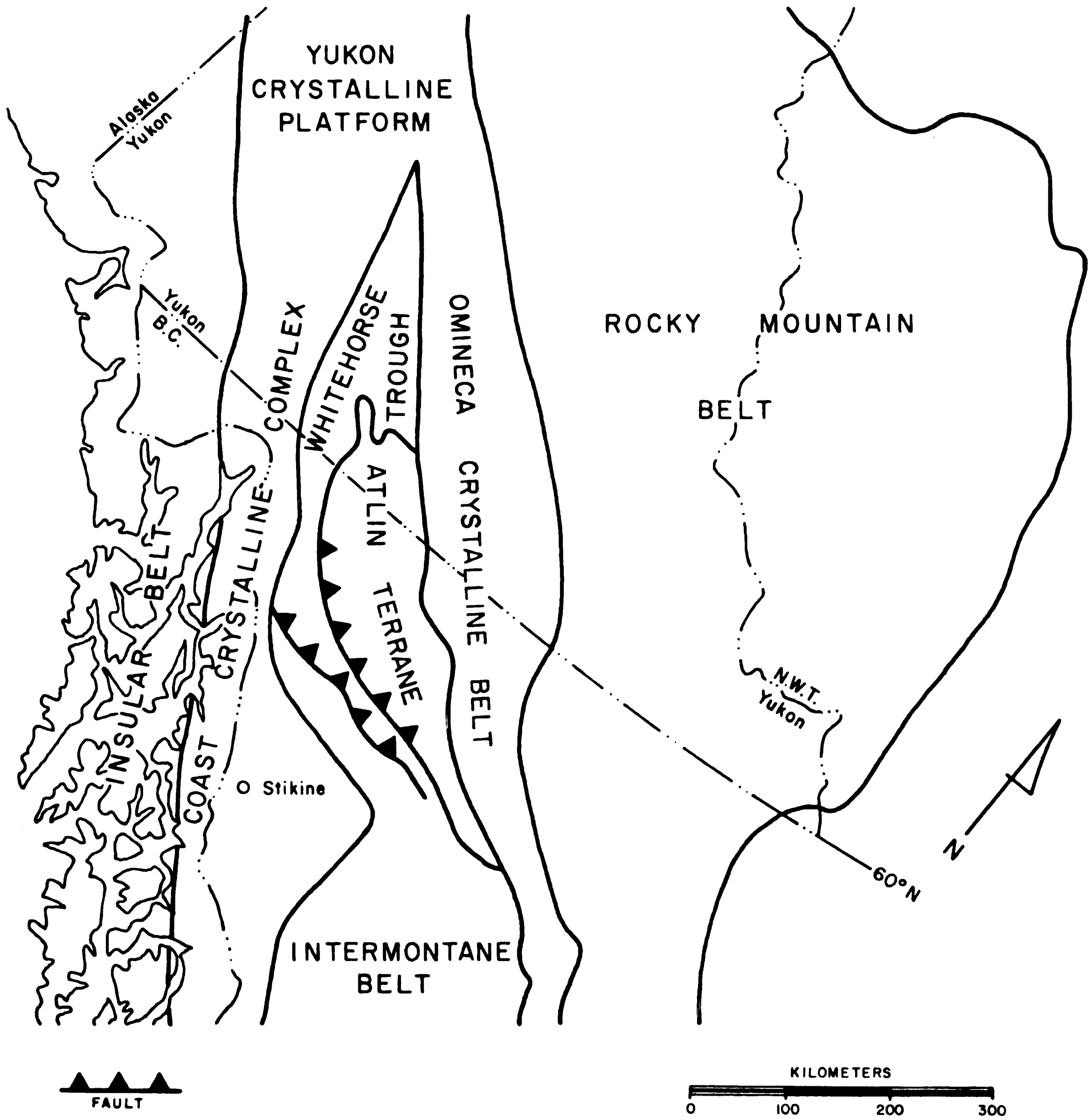
The Juneau Icefield is within the area of the Coast Range Batholith, a granitic emplacement of late Jurassic to Cretaceous age (Forbes, 1959; Miller, 1959; Naff, 1972). This batholith extends from northern Washington state to the vicinity of Skagway, Alaska, a distance of some 1760 kilometers. In the icefield area the batholith is composed of both plutonic and crystalline rocks of granodiorite petrology, known as the Coast Crystalline Complex. Less than one third of the exposed batholithic rocks are composed of plutons, large-scale occurrences of which are confined to the quartz monzonites and granites of the east marginal pluton (v. Forbes, 1959, p. 3). Near the International Boundary, an intrusive contact occurs between the plutonic rocks and the crystalline schists. On the west margin, the transition is of a more gradational nature (Forbes, 1959, p. 256).

Northwest of the icefield is a large fault-bounded area of primarily Upper Paleozoic rocks known as the Atlin Terrane. This area is the largest continuous occurrence of little metamorphosed rocks of this age in the western part of the North American Cordillera (Monger, 1975, p. 1). It has been suggested that the Atlin Terrane represents a large thrust sheet, displaced to the southwest over Lower Mesozoic rocks during late Jurassic time (ibid, p. 38). To the southwest, the Atlin Terrane is in contact with sedimentary rocks of the Intermontane Belt (Lower Jurassic), which overlie the Coast Crystalline Complex. Figure 1-2 depicts the general relationship between these areas. For detailed discussions of the geology of the area and adjacent districts, the reader is referred to the publications of Aitken (1955; 1959), Cairns, (1913), Forbes (1959), Gwillim (1901), Miller (1956; 1959) and Monger (1975).

1.3.2 Climate and Vegetation

The western slope of the Boundary Range experiences a relatively mild, marine cool summer climate (cfb in Köppen's classification). In winter the area is subjected to numerous cyclonic storms which originate in the Gulf of Alaska and the mid-Pacific. These moisture-laden depressions result in great accumulations of snow at higher elevations on the western slope of the Boundary Range. In summer, the Pacific high pressure cell is displaced northward and effectively blocks much cyclonic activity along the coast. The result is a precipitation maximum (55-60%)

Figure 1-2. Bedrock Configuration.


YUKON
CRYSTALLINE
PLATFORM
Alaska
Yukon
Yukon
B.C.
COMPLEX
WHITEHORSE
TROUGH
OMINECA
CRYSTALLINE
BELT
ROCKY MOUNTAIN
BELT
ATLIN
TERRANE
COAST
CRYSTALLINE
INSULAR
BELT
Stikine
N.W.T.
Yukon
N
60°N
INTERMONTANE
BELT
FAULT
KILOMETERS
0
100
200
300

occurring between October and April. It will be noted that this winter maximum is less pronounced than in coastal British Columbia or Washington, where the influence of the Pacific anticyclone in summer is stronger (Trewartha, 1961, pp. 267-273).

The presence of the cordillera exerts an important influence on the climate of the area to the east. Although the mountains do not completely block penetration of air from the Pacific, there is a distinct precipitation shadow effect. The Pacific air that does reach the interior subsides from high levels and is relatively dry (Bryson and Hare, 1974, p. 52). Thus, while Juneau has a mean annual precipitation of 1387 mm, Atlin, 200 km to the northeast, experiences only 285 mm/year, although a similar proportion of each falls during the October-April period.

The forest ecosystems of the respective areas reflect this climatic disparity. The abundant moisture at low elevations on the western flank of the mountains supports a lush growth of sitka spruce (Picea sitchensis) and its ecological successor, western hemlock (Tsuga heterophylla). Near timberline (600-700 m) mountain hemlock (Tsuga mertensiana) is common. The dense understory is compared of rusty menziesia (Menziesia ferrunginea), the aptly named devilsclub (Oplopanax horridus), bunchberry (Cornus canadensis), and five-leaf bramble (Rubus pedatus), among other species (Daubenmire, 1953; Viereck and Little, 1972).

The forest of the interior section near Atlin is basically unrelated ecologically to that of the coast (Daubenmire, 1953, p. 134). The dominant species are white spruce (Picea glauca), aspen (Populus tremuloides), birch (Betula papyrifera), and various species of pine. A comprehensive study of the vegetation of the Atlin region has been performed by Anderson (1970). The treeline (1300 m) is significantly higher than in the coastal area; this is attributable to a more sporadic snow cover and greater summer warmth in the interior at comparable altitudes (Wardle, 1971; 1974).

Since it may be of considerable interest as regards observations made later in this report, some attention is now focused on the problem of the continentality gradient between Juneau and Atlin. As noted by McBoyle and Steiner (1972), the notion of continentality and its antithesis, oceanicity, have long been the victims of a bipartition of thought:

> "on the one hand a concept derived from a hypothetical situation of a plane-surfaced land mass of regular shape where latitude has no relevance and where the geometrical center of the land mass would have the highest continentality; on the other a vision of continentality as the degree to which any part of that area exhibits a climate typical of being inland and away from the sea's influence" (ibid, p. 12)

It is in the latter sense that the continentality concept is applied here, i.e., the question is to what degree a station experiences large annual and diurnal temperature ranges. Succinctly, continentality is an inverse function of the influence on a station of the moderating effects of large water bodies, which is in turn a function of the difference in heat capacities of land and water, the atmospheric circulation, and of mountain barriers.

There have been numerous attempts at quantification of continentality through the use of indices (Zenker, 1888; Hann, 1903; Gorczynski, 1920; Johansson, 1931; Conrad, 1946; Ivanov, 1959). Most of these rely primarily upon the annual air temperature range. Since this range is to a large degree influenced by the latitudinal position of a station, compensation is made by dividing the annual temperature range by the sine of the station's latitude. Johansson's (1931) index of continentality has been used in the construction of a continentality map of Canada (MacKay and Cook, 1963) and in an interpretation of the glaciation level height in northern British Columbia and southeastern Alaska (Østrem, 1972). In the interest of comparability, computations using this index were made for Juneau and Atlin. It is recognized that this gives only a crude measure of continentality and does not deal with the attenuating effects introduced by elevational differences. The index does, however, give some indication of the magnitude of the continentality gradient existing between the two points. Johansson's index is given by

$$K = \frac{1.6A}{\sin\theta} - 14$$

where:

K = continentality coefficient (values range from 0 to 100)

A = mean annual temperature range (°C)

θ = latitude

Values obtained for Juneau and Atlin are, respectively, 17.7 and 38.6, confirming the existence of a pronounced continentality gradient between the coast and the interior. A. Thompson (1975, p. 8) suggests that this gradient attains its greatest steepness on the east slope of the Boundary Range, i.e., on the inland flank of the Juneau Icefield.

1.3.3 Previous Periglacial Research

Although prior investigations in the study area have centered for the most part on glaciological, botanical, and glacial geomorphological topics, some periglacial research has been conducted, most notably in the works of Hamelin (1964) and Tallman (1975).

Hamelin's investigations were of a reconnaissance nature, carried out in the summer of 1962 on the southern part of the icefield. His study emphasized lithological control, in that the homogeneous granular nature of many rocks in this region prevents the development of patterned ground. The predominance of steep slopes further limits the occurrence of many periglacial features. Where patterned ground was found, it was of the miniature type, imperfectly formed, and, as stressed by Hamelin, occurred on morainic material, not in areas of bedrock. The form of the nunataks is attributed in part to frost shattering, although it was noted that freeze-thaw cycles are minimal during summer. Frost-shattered debris is, however, a frequent occurrence on many nunataks.

Tallman's investigations were carried out in the Fourth of July Creek Valley northeast of Atlin during the period 1971-1974. Research centered around resistivity surveys of palsas and peat plateaus. In addition, C-14 dates were obtained from material in the basal layer of one peat plateau. Tallman also conducted reconnaissance-type research on sorted circles and "nivation hollows," discussion of which is deferred to a later section of this study.

Other periglacial-related studies include investigations on "tanks" and tors on Ptarmigan Ridge near Juneau by Fleisher (1972) and Zwick, *et*. *al*. (1974). The Atlin rock glacier has been the subject of recent lichenometric and movement surveys by Juneau Icefield Research Program personnel.

1.4 Terminology

a) Periglacial - Periglacial terminology has been described as "irrational, imprecise, incomplete, and non-systematic" (Hamelin and Cook, 1967, p. 11), a view to which this writer subscribes. The term periglacial itself has been used to convey a variety of meanings. The concept of a periglacial zone originated with Lozinski in 1909, who used it to refer to the frost-rubble areas peripheral to Pleistocene ice sheets (Jahn, 1954). The concept has now been extended so far that a recent text uses the term to refer to "cold-climate, primarily terrestrial, nonglacial processes and features regardless of data or proximity to glaciers" (Washburn, 1973, p. 2). On the other hand, Embleton and King (1975, p. 2) maintain that some semblance of the original meaning should be preserved in that periglacial should be used to refer to "a zone of indefinite width peripheral to the glacial ice of today or of any phases of the Pleistocene."

Despite disagreement regarding strict definition of the term, its imprecision seems appropriate when one views attempts to delineate the boundaries of the "periglacial environment." While most workers agree that those areas underlain by perennially frozen ground are in the periglacial realm, the problem of delineation becomes more difficult when attention is focused on transitional zones, such as those under the influence of subpolar oceanic climate or the northern parts of the boreal forests. These areas may lack perennially frozen ground, but the former experience frequent shallow frost cycles, while the latter are subjected to deep annual freezing and thawing of the ground. Although the paucity of data may render this criterion difficult to apply over broad areas, this writer considers the dominating effect of freezing and/or thawing to be an essential requirement for categorization of an area as "periglacial." In the absence of good microclimatic data to support this definition, we may use morphological phenomena which require freezing and thawing, usually in conjunction with water in the surficial material. Despite a call for abandonment of the term periglacial (Linton, 1969), its retention appears appropriate not only because its usage is so firmly established in the literature, but because the very vagueness so often criticized corresponds to the imprecision with which the boundaries of the periglacial realm are delineated. Following Brown and Kupsch (1974, p. 25) periglacial is broadly defined as:

1) The area, geomorphological processes, and deposits characteristic of the frost-affected immediate margins of existing and former glaciers and ice sheets.

2) the environment of (nonglacierized) cold regions in which frost action is (dominant); the features resulting from frost action.

It will be noted from the foregoing that no restrictive definition of the periglacial climate can be advanced. Indeed, the term periglacial denotes a variety of climatic types, ranging from the highly continental interior of Siberia to moist environments with small annual temperature range, typified by the subantarctic islands. Troll (1958) and Tricart (1969, pp. 19-27) provide useful discussions of the various periglacial climates.

Mountainous areas at all latitudes may fall within the periglacial realm if sufficient altitude exists. The threshold elevation of the alpine periglacial zone declines poleward, but its trend is less well known as one proceeds from oceanic to continental areas.

b) Permafrost - The merits of the term permafrost (Muller, 1947) have been widely discussed (Bryan, 1946a; 1946b; Brown, 1970). Although the expression has been severely criticized, its usage is so well entrenched that efforts to replace it have proven fruitless. An extended definition of the term has been presented by Stearns (1966, pp. 1-2), in which dry permafrost is defined solely on a temperature basis (0°C for two or more years), while ice-rich permafrost (wet frozen, in Stearns' terminology) occurs where enough of the existing pore water is frozen to cement the previously unconsolidated mineral and organic constituents. Thus, permafrost refers to a ground condition and is independent of the type of material involved.

c) Features of Mass Movement - As stressed by Benedict (1970, pp. 170-176), gelifluction and frost creep often operate in conjunction with one another, the effects of each being separable only through detailed instrumental observations. For this reason, descriptive terms such as stone-banked and turf-banked lobes are preferable to genetic terms, such as gelifluction lobes, since the latter may place undue emphasis on one process while neglecting another.

Turf-banked lobes and terraces are defined as "lobate or bench-like accumulations of slowly moving regolith with a continuous surficial mat of grasses and organic material." These terms correspond to the German "gebundene" (bound) gelifluction. Stone-banked lobes and terraces are described as "lobate or bench-like accumulations of slowing moving regolith overlain by or having crescentic banks of stony material." These features have their equivalent term in the German "ungebundene" (free) gelifluction.

Most of the remaining terminology used in this study is relatively straight-forward and requires little further clarification. Wherever possible, usage will conform to terminology in the glossary by Brown and Kupsch (1974).

CHAPTER II

INTENSIVE INVESTIGATIONS OF PATTERNED GROUND

Patterned ground is a phenomenon associated primarily with frost action in polar, subpolar, and alpine environments. A number of terminological and classificatory schemes concerning patterned ground have been developed in the last 65 years (v. J. Lundqvist, 1962, pp. 10-13). This paper will utilize the widely accepted Washburn system, in which the collective name patterned ground is used in reference to "the more or less symmetrical forms, such as circles, polygons, nets, steps, and stripes, that are characteristic of, but not necessarily confined to, mantle subject to intensive frost action" (Washburn, 1956, p. 824). Each of these forms may be either sorted (material within the feature is segregated by grain size) or unsorted. As this classification is purely descriptive, it sidesteps controversy while providing a basis for discussion among workers with conflicting views on the origin of patterned ground. More recently, Washburn (1970) has developed a genetic classification based on his previous terminology. The classification is presented in matrix form and is based on the premises:

1) patterned ground is polygenetic;
2) similar forms may have differing origins;
3) some processes may produce dissimilar forms;
4) more processes may be responsible for patterned ground than are presently recognized;
5) terminology should be kept as simple as possible.

Large-diameter patterned ground is arbitrarily defined here as those features whose unit cells average 0.50 meters or more in diameter or width; small-diameter patterned ground has a mesh size less than 0.50 meters.

2.1 Small-Diameter Patterned Ground

Small-diameter or "miniature" forms of patterned ground are those most frequently encountered in the study area; this was the only type found in the Alaskan sector. The features are found at a wide range of elevations and often occur in close proximity to, or within the cells of larger patterns. Small-diameter forms are characterized by shallow (<10 cm) depths of sorting, and the rock fragments comprising their coarse segments are proportional to the overall size of the features.

Several workers have regarded small-diameter patterned ground as the result of processes differing in degree or kind from those operative on larger patterns. Some (e.g. Troll, 1958, p. 63) consider the two types to be the products of different climatic regimes. The large and small patterns are, however, remarkably similar in appearance, scale expected, and the whole range of patterned ground forms is found in the small-diameter variety. Occasionally, occurrences are found where the transition from polygons to stripes can be clearly traced as declivity increases. Troll (1958, Fig. 29, p. 44) has published a striking photograph of this phenomenon.

Several investigators (e.g. R. Miller, et. al., 1954; Chambers, 1967) have remarked on the rapidity with which miniature forms can develop. After destruction, patterns may re-form in as little as two years.

It has been noted (Rapp and Rudberg, 1960, p. 149; J. Lundqvist, 1962, p. 76) that small-diameter forms are found only in areas devoid of vegetation, often on small patches where the plant cover has been removed by the actions of wind, frost, animals or man. This proved true at all sites investigated in the presently described field work.

2.1.1 Type I Forms

The first type of small-diameter patterned ground (hereafter referred to as "Type I") is associated with networks of cracks probably attributable to desiccation. Several occurrences of sorted polygons were noted on Cairn Peak, adjacent to the Lemon Creek Glacier on the west slope of the Boundary Ridge. These occur at 1340 m on a flat site with southeast exposure. Although imperfectly formed, the polygons are distinct, with a fresh and active appearance. The fine centers were found to be 12-25 cm in diameter, while the coarse borders varied between 2-6 cm in width. The stones comprising the borders occupied polygonal networks of cracks which extended several tens of cm below the surface, although rock fragments occupy only the uppermost 2-3 cm of these. The centers consisted of exclusively fine material in the surficial layer, but the soil was heterogeneous with respect to particle size at greater depth.

A variation of this type was found in abundance on the Cathedral Massif in the inland section of the Boundary Range. In some instances, the transition from polygons to stripes was seen over a very short distance (Figure 2-1). At 1620 m on the northeast slope of Frost Ridge, networks of nonorthogonal cracks were observed in clayey material on the treads of large stone-banked lobes. Where the microrelief on the lobes steepened, the cracks transverse to the slope were compressed, but those aligned parallel to the slope remained unaffected. Stones were found in many of the latter cracks, giving rise to a crudely sorted effect.

Figure 2-1. Type I small-diameter patterned ground, Cathedral Massif.

The first problem in the analysis of these patterns is the origin of the fissures which form the basis of the patterning. Thermal contraction is discounted as a cause, since cracks initiated in this manner reach their maximum width in midwinter and narrow as soil temperatures rise. The depth of snow cover in this locale also tends to rule out thermal contraction, by reason of the damping effect of snow cover on frost penetration. The patterns in question lie in an area which does not emerge from below the snow until at least late June. The small size of the patterns also militates against a thermal contraction origin.

Benedict (1966, p. 90) has drawn attention to the possibility that certain cracks may result from tensional forces in areas of extending flow in solifluction features. Such cracks would be oriented parallel to the contour and thus need not be considered further here, since the cracks in question form a regular polygonal pattern which is emphasized at right angles to the contour in steep areas. Likewise, cracks due to differential frost heave do not display regular polygonal patterning.

Desiccation appears to be the best explanation for these fissures. The features are similar in size and form to desiccation polygons studied in the field by Corte (1966b) and produced in laboratory studies (Corte and Higashi, 1960). The arrangement of cracks in these patterns is of the nonorthogonal type, indicating that all components of the systems developed simultaneously, rather than sequentially, as is the case in orthogonal systems. Most of the cells possess four or five sides, the optimum numbers reported for desiccation features by Corte and Higashi (1960, p. 21).

Corte (1966b, p. 131) notes that cracks are initiated at points where stones are situated in a drying soil. Therefore, desiccation cracking may of itself favor a sorted effect in a stone-rich soil. Stones are also moved into cracks by the actions of wind and rain (ibid., p. 131) and by frost creep. Once sorting has been initiated by these agents, subsequent cracking events are likely to occur in exactly the same locations. Chambers (1967, p. 12) has documented the re-formation of desiccation cracks in their initial positions even after destruction of the original networks.

The elongation of the polygonal micropatterns observed on Frost Ridge appears to be related to gravitative slope processes. Suppression of the transverse elements within the patterns may be indicative of microsolifluction (used here in Troll's sense, i.e., movement within the unit cell of each polygon). Such movement results in compression and eradication of transverse cracks, while the downslope-oriented cracks remain relatively unaffected. Such movement may occur during the thaw period when moisture from snowmelt is abundant, or it could result from concentration of moisture at the surface due to formation and ablation of needle ice. Frost creep may be expected to play a similar role. It is possible that rilling also accentuates the downslope-oriented cracks.

Frost sorting of stones is not necessarily inoperative in the above model, and indeed, probably takes place in limited fashion. This is indicated by the lack of stones in the shallow subsurface layers of some features. In Type I features, however, it is of secondary importance, since they are initiated by azonal or extrazonal processes, and can occur without the aid of primary frost sorting. It follows that Type I features are not necessarily indicative of a periglacial environment and should be excluded in attempts to establish frost-sorted patterned ground limits. This conclusion is supported by the existence of small-diameter sorted desiccation polygons in Illinois, documented by Corte (1966b, p. 131).

2.1.2 Type II Forms

A second type of small-diameter patterned ground (Type II) was found throughout the study area (Figure 2-2). This type appears similar to the larger forms discussed in the latter part of this chapter and may be fairly reliable indicator of periglacial conditions. Description from two sites should suffice, but it is noted that these features are also found on nunataks in the central icefield.

The first site is again on the southeast-facing slope of Cairn Peak near Juneau. Here, sorted stripes occur in small patches of bare earth devoid of the large schistose blocks found in the immediate surroundings. The vegetative cover has been disrupted by frost heaving assisted by wind; this slope is proximal with respect to prevailing wind direction and is probably snow-free in winter. The effect produced is that of the "turf exfoliation" described by Troll (1958, p. 34). When investigated in early July, these sites were already snow-free, although considerable depths of snow remained on adjacent slopes with orientations other than southeast.

The coarse stripes have a mean width of 13 cm and the fine stripes average 23 cm. Lengths are variable, but the stripes are strictly parallel and follow the fall line. The stone chips which compose the coarse stripes are of the same biotite schist as the surrounding debris and outcrops. Although some of the chips exceed 8 cm, most are smaller. Sorting is surficial, but the stone stripes occupy slight depressions. Subsurface material consists of rock fragments in a silty matrix, which

Figure 2-2. Type II small-diameter patterned ground, Cathedral Massif.

is apparently unaffected by sorting processes.

Type II features were frequently encountered in the Cathedral Massif. Noted occurrences were limited to stripes and were found at a wide range of elevations and exposures. One group of stripes, on a 17° slope at 1650 m was investigated in late August, 1975. The stony stripes averaged 2 m in length and 5-10 cm width, although larger stripes were also present. The stones of which these stripes were composed occupied slight linear (down-slope trending) depressions. The rock fragments in each were 0.5 to 5 cm diameter, but larger stones were scattered about the site. Intervening fine stripes were 4-8 cm wide. Upon excavation, sorting was evident to a depth of about 2.5 cm. At depths between 2.5 and 7.5 cm, the material consisted mainly of fines, indicating that the stones had been heaved to the surface from this layer. A heterogeneous mixture of fines and coarse material was found below 7.5 cm.

Needle ice may play an important role in producing the sorted effect in these stripes. Similar to phenomena observed in England by Hay (1936) and in New Zealand by Gradwell (1957), needle ice was formed during clear nights in which temperatures at the Camp 29 station (1615 m) were recorded below 0°C. In addition to fine soil, numerous small stones were lifted by the ice needles. During the following day, preferential ablation of the needles adjacent to the coarser stripes was observed. The direction of collapse was toward these stony fractions, resulting in movement of additional fragments into these stripes. R. B. King (1971, p. 381) has made a related observation of some interest to this discussion. Of 100 stones with an axial ratio of 2:1 or greater, 41 were upturned during a needle ice event, as opposed to 42 lifted entirely and 17 which were not affected. It is considered that such differential movements contribute to the formation and maintenance of small sorted stripes.

Since no cracks were found in association with these stripes, it is probable that they are the result of a different initiating mechanism than the Type I forms. Although somewhat smaller, the stripes bear strong similarity to those described from the English Lake District by Hay (1936; 1943) and Caine (1963). Hay (1943, p. 19) suggested that the frequent heaving associated with needle ice events would prevent formation of a network of anastomotic rills. Surface drainage would, therefore, be restricted to a straight-line course down the steepest slope. "Incipient hollows" thus formed would be natural sites for collection of coarser fragments heaved to the surface and overturned or uplifted by needle ice. Caine (1963, p. 176) cited differential heaving as being the initial patterning process but was unable to provide the precise mechanism. Washburn (1969, p. 178) favored rillwash with subsequent eluviation or washing in of stones as the initiator of some small stripes in northeast Greenland. This appears to be a special case, however, owing to the dendritic pattern displayed by the stripes. Troll (1958, p. 64) favored the role of frost creep deforming initially polygonal forms as a general explanation. Brockie (1968, pp. 197-198) was of the opinion that rill incision would result in stone accumulations, and thereafter differences in the thermal characteristics between these and the adjacent fines would promote inclined freezing fronts, which in turn would lead to lateral sorting of subsurface stones into the stripes of coarse fragments. J. Lundqvist (1962, p. 70) states that "there are probably no fundamental differences between the formation of miniature and large patterns," except their dependence on the diurnal rather than annual frost cycles.

Here the matter rests at present. Since no detailed investigations were attempted on the Type II patterned grounds, a specific genetic interpretation is not offered. Nicholson's (1976, p. 341) comment that "the initiation of patterns is more problematic than the mechanisms of development" holds for small-diameter patterns as well as for their larger counterparts, some aspects of which are discussed in the remainder of this chapter.

2.2 Large-Diameter Patterned Ground

Occurrences of active large-diameter patterned ground were not noted by this writer in the main icefield area, although some have been found at high elevation near the International border (Miller, 1977). As discussed in a subsequent section, conditions suitable for the widespread development of patterned ground are found primarily in the more continental parts of the Boundary Range. The observations comprising the remainder of this chapter were made at 1700 m on "Frost Ridge," situated in the Cathedral Massif, where presently active patterned ground is found in relative abundance. The intent of this section is not to provide a comprehensive genetic explanation for these features, as such as approach would require year-round instrumental observation. Interest is focused instead on some rather poorly known aspects of the internal structure of the patterned ground. These observations are presented separately in sections 2.2.1 through 2.2.4.

Site Description

The crest of Frost Ridge extends 1.5 km northeastward from its juncture at 1700 m with Splinter Peak, to an elevation of about 1200 m (Figure 4.3). Detrital cover conceals a transition from the igneous and metamorphic bedrock of the peak to thick layers of morainic material at the downslope extremity of the ridge. Jones (1975, p. 35) interprets this entire cover as a Wisconsin till, a view to which (with some reservation) this writer subscribes. The summit area of the ridge is gently convex, with 30°-35° slopes on the northwest and southeast flanks.

In the upper reaches of Frost Ridge, near its confluence with Splinter Peak, a field of well-developed sorted stripes occurs. The stripes are nearly continuous over a large part of the ridge summit and occupy primarily gentle (4°-10°) slopes with NE aspect. In places where the gradient is negligible, an occasional sorted circle is found. A view of the patterned area is presented in Figure 2-3. The general trend of stripe axes reflects their adjustment to the microrelief. Stone stripes are slightly sinuous and serve as channels for meltwater from perennial snowbanks upslope. They often meet one another at low angles, the intersections of which point downslope. The stripes are traceable as coherent entities over distances as great as 75 m. Interspersed are fine lobes composed primarily of silt.

Several stripe units were trenched normal to their long axes. Sorting extends to a depth of approximately 80 cm, but the separation of fines and stones is incomplete. The features correspond to Poser's (1932) "anchored" stone network. The largest particles were found near the surface in the stone stripes; stone size decreases with depth. Clasts of varying sizes are embedded within the fine stripes. Numerous stones protrude through these surfaces, some possessing a cap of fine soil. Details of these features are considered next.

2.2.1 Size and Spacing of Patterned Ground

Many workers (e.g. Goldthwait, 1976, p. 31; Nicholson, 1976, p. 339) have commented on what they perceived to be a great regularity in the

Figure 2-3. Overview of Frost Ridge patterned ground site.

spacing of patterned ground unit cells. On the other hand, J. Lundqvist (1962, p. 54) suggests that "the regularity seems to be somewhat overestimated in the literature." Statistical analyses of Frost Ridge patterned ground data indicate that the latter view is correct, even through casual observations had suggested otherwise.

Three parallel sampling traverses normal to stripe axes were carried out over the patterned area. Locations are shown in Figure 2-3. Data were collected concerning width and length of fine lobes and stone stripe width. Spearman rank-order correlation coefficients (Nie, et. al., 1975) were computed for all combinations of these variables in each transect, and for the entire set of 65 observations. Correlation coefficients are low, indicating that stripe spacing is essentially random. Large standard deviations for all variables tend to support this conclusion. The only correlation coefficient that is statistically significant at the 0.05 level, while maintaining even moderate strength is the plot between lobe width and length (.572) in Transect 3, where the features are thought to have formed relatively recently due to a decrease in mean snowbank size. This cannot, however, be construed as more than a low to moderate correlation, and the lack of significance in the other plots suggests that stripe spacing is indeed irregular.

The results of these analyses cast some doubt on Nicholson's (1976, p. 339) suggestion that the first cell to develop dictates the locations of subsequently formed patterns. Numerous other controls on pattern size and spacing have been proposed, including depths of frost penetration and soil sorting (Troll, 1958, pp. 57-58), clast size within the parent diamicton (Goldthwait, 1976, p. 33), and the spacing of blocks in the initial material (Corte, 1966a, pp. 230-231). It is possible that a

TABLE 2-1. DESCRIPTIVE STATISTICS AND RESULTS OF SPEARMAN RANK-ORDER CORRELATION FOR FROST RIDGE SORTED STRIPE DIMENSIONAL DATA.

	MEAN, LOBE LENGTH	STANDARD DEVIATION LOBE LENGTH	MEAN, LOBE WIDTH	STANDARD DEVIATION LOBE WIDTH	MEAN, STONE STRIPE WIDTH	STANDARD DEVIATION STONE STRIPE WIDTH
COMBINED SAMPLES	16.94	12.11	2.27	1.52	1.80	1.13
TRANSECT I	20.18	14.46	2.58	1.65	2.18	1.39
TRANSECT II	18.95	13.33	2.03	1.38	1.18	0.76
TRANSECT III	11.62	6.29	2.12	1.47	1.86	0.83

Combined samples (65 observations)

	Lobe Length	Lobe Width
Lobe Width	NS	
Stone Stripe Width	NS	NS

Transect I (25 observations)

	Lobe Length	Lobe Width
Lobe Width	NS	
Stone Stripe Width	NS	NS

Transect II (18 observations)

	Lobe Length	Lobe Width
Lobe Width	NS	
Stone Stripe Width	NS	NS

Transect III (22 observations)

	Lobe Length	Lobe Width
Lobe Width	S	
Stone Stripe Width	NS	NS

S indicates results are significant at .05 level.
NS indicates results are not significant at .05 level.

combination of these factors is responsible, and much work remains to be done on this problem before its solution. It is suggested that further research should be concentrated on circles, nets, or polygons, as the slope factor associated with stripes may complicate interpretive efforts.

2.2.2 Effects of Moisture

Fundamental differences in the form of patterned ground and its activity are related to temporal and spatial variations in moisture supply. Figures 2-4 and 2-5 illustrate this point with respect to sorted stripe morphology. The photos were taken at points within 75 m of one another on Frost Ridge. Figure 2-3 divides the patterned area into horizontal "zones" reflective of moisture supply. Each of these zones is discussed below.

Zone A

Zone A is at present the area of greatest apparent process intensity. Here stone stripes stand 10 cm or more above the level of the intervening fines, and carry minimal lichen cover. Vegetation, consisting primarily of *Carex* spp., *Potentilla*, and occasional *Cassiope tetragona*, is restricted to lobe margins and is in many places totally absent.[1] This lack of lichen and vegetation is partly attributable to late snow cover in this area. In 1975, Zone A did not experience complete meltout until mid-July. Probably more important in disruption of vegetation are cryogenic processes. The fine lobes are subject to significant accretions of segregation ice (observed by B. Otto, personal communication, August 1976). Heave is maximized at lobe centers (Jahn, 1970), so that vegetative colonization is inhibited, except at lobe margins.

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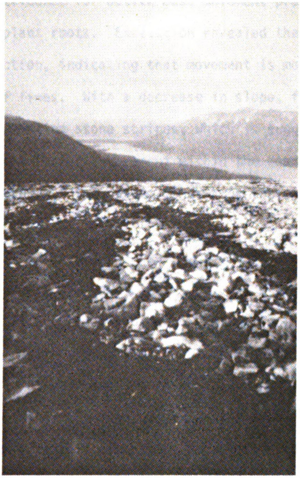
[1] I am indebted to Ruth Magnuson of Boulder, Colorado, for identifying vegetation samples.

Figure 2-4. Active "Zone A" sorted stripes.

Figure 2-5. Inactive "Zone C" sorted stripes.



Strong evidence for active mass movement processes in the lobes is provided by plant roots. Excavation revealed that these trail off in an upslope direction, indicating that movement is most rapid in the surficial layer of fines. With a decrease in slope, fines spread laterally and bury neighboring stone stripes, which is suggestive of more rapid movement in the former. Movement within the coarse stripes is not discounted, however, as the stones comprising these are very sparsely lichenized.

Apparently, the major factor responsible for the activity of stripes in Zone A is their abundant water supply. As can be seen in Figure 2-3, the trend of water-channeling stone stripes is such that Zone A is provided with a constant supply of moisture from snowbanks upslope. This condition was noted to persist throughout the summer, so that the features were still moist at the time of the autumn freeze. Heave and frost creep are maximized in such a situation. This relationship is a critical factor in the formation and maintenance of patterned ground.

Zone B

Zone B is characterized by rather heavily lichenized stone stripes and bulging turf-banked lobes. Here the lobes have a nearly continuous vegetative cover and occupy slopes of 6°-12°, steeper than those of the Zone A stripes. Some lobes spill over the sides of the ridge to continue as thin strips of fines for as much as 40 m downslope. In Zone B, solifluction probably exceeds frost creep, since fine lobes tend to override and bury stone stripes. In 1975, snow had largely disappeared here by 23 June, although the area still received an abundant supply of meltwater from upslope. This was attested by extreme saturation of the lobes, by their bulging profiles, and evidences of overridden vegetation at lobe fronts. Meltwater is channeled through stone stripes to points on the slope where the stones comprising them have been buried by solifIual debris. The high frost table in early summer prohibits percolation of water to depth, and promotes saturation of the upper layers. Water emerges at the base of each riser, flows overland short distances, and saturates the next lobe downslope. On some of the largest features, smaller lobes are superimposed, this probably being reflective of the area of maximum saturation.

Frost creep in the autumn is probably a less important process here than in Zone A, because this area is snow-free at a much earlier date, and because the snowbanks upslope have largely disappeared by the summer's end. Movement in the stone stripes themselves, therefore, is minimal, as indicated by their lichen cover. The net effect in this zone is eradication of preexisting patterns through burial by the active turf-banked lobes.

Zone C

This "zone" lies in the northwest part of the patterned area and is comprised of inactive sorted stripes. This conclusion is based upon several lines of evidence which presented themselves during the course of the investigation.

Stone stripes in this area are heavily lichenized and stand below the level of the intervening fine lobes. The latter have a subdued appearance and are covered with a nearly continuous mat of vegetation whose roots penetrate the soil vertically. This plant community is dominated by Salix, spp., Hierochloë alpina, and, particularly, Cassiope tetragona. Raup (1965, p. 27) indicates that Hierochloë alpina prefers dry sites, and that it is found only in stable soils. Kershaw (1976, p.

108) and Hulten (1968, p. 724) mention that Cassiope tetragona is also indicative of dry conditions, but Raup (1965, pp. 98-99) found it in a fairly wide range of moisture situations. This plant is not particularly tolerant of disturbance, however. Raup found that on stable heaths in Northeast Greenland, it had coverages of up to 90%, but on disturbed sites coverage fell to 1-6%. Since this plant is found in great abundance in Zone C, it is concluded that the site is indeed stable.

The factor responsible for this apparent lack of cryogenic activity is the paucity of moisture supply to this zone. Several spot checks in late August, 1976, revealed that fines in Zone A contained up to 55% greater water content (by weight) than did those of Zone C. Several small areas of bare soil on lobe treads display polygonal networks of desiccation cracks, also attesting to the relative summer dryness of this area. This dryness is partly due to lack of winter snow cover. At the time of the writer's first visit to the site in 1975, when the Camp 29 research facility was opened for the field season (23 June), this area was devoid of snow and already quite dry, while adjacent parts of Zone A had as much as 1 m of snow remaining. Winter winds probably keep the area snow-free. Possibly more important is the trend of meltwater-channeling stripes. The orientation of these is such that little moisture is delivered to Zone C from the perennial snowbanks upslope during the summer months, so that the entire area is desiccated by the time of the annual freeze. Even though winter frost penetration is probably greatest in Zone C, its effects are minimal in the absence of soil moisture.

Conclusions

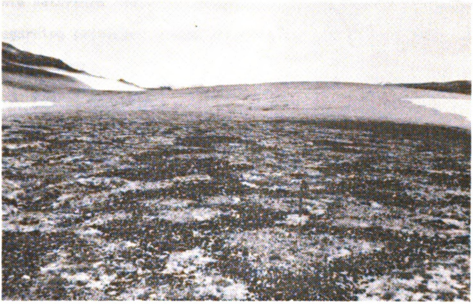
From these observations it appears that the Frost Ridge patterned ground developed during a period when annual snowfall was greater and/or summers were cooler than at present, allowing preservation of late snowbanks in strategic positions through the summer. Evidence that such a situation has existed on Frost Ridge is provided by the poorly developed "incipient" patterned ground emerging from beneath snowbanks during August at this and many other late snow sites in the Cathedral Massif. It is possible that these have formed since the 1750 advance (Jones, 1975) of cirque glaciers in this area. Since patterned ground could not be expected to develop beneath thick perennial snowbanks, it is likely that it has formed at the margin of retained snowpacks whose mean sizes diminish over the course of a long-term warming trend. As these new forms are developing, those farther from the moisture source become progressively less active.

Similar situations are found elsewhere in the Cathedral Massif. One striking example is illustrated in Figure 2-6. This site is adjacent to the Chapel Glacier, and overlooks Nelson Lake. Inactive, heavily lichenized polygons were found on a small knoll, the top of which becomes dry early in the summer. On the knoll's flanks, where late snowbanks persist, active patterned ground was found (Figure 2-7). The relationship is presumed to be identical to that described for the Frost Ridge site, indicating a past period of cooler temperatures and/or greater snowfall.

Every other active patterned ground site examined was provided with moisture originating in a lingering snowbank upslope, usually on north-facing slopes. These relationships suggest that patterned ground occurrence and activity are governed by a delicate balance between snowbank thickness and location, and the timing of moisture release. As noted by Benedict (1965, pp. 23-24), the optimal locations for patterned ground

Figure 2-6. Inactive patterned ground adjacent to Chapel Glacier. Note lichenized borders and vegetated centers.

Figure 2-7. Active patterned ground adjacent to Chapel Glacier. This site is the lighter colored area in background of Figure 2-6.



formation (and maintenance) are sites with thin or negligible winter snow-cover and which receive summer meltwater from late-lying snowbanks upslope. In such areas cryogenic activity is maximized by deep frost penetration into saturated regolith. This point is crucial to arguments made later regarding patterned ground distribution and will be taken up again in Chapter Four.

2.3 Fabric Analyses

Little research has been carried out on the arrangement of stones in sorted patterned ground features. There have been numerous and often conflicting casual observations, but very few precise surveys. In this section orientation data from a sorted stripe border are presented. It is hoped that statistical analysis of the data, combined with literature review, will help to relate observed fabrics to process in a meaningful way.

2.3.1 Previous Research

In order to appreciate such significance as exists in the fabrics of borders, some discussion must first be concentrated upon the orientation of blocks within the features' centers. Several studies (G. Lundqvist, 1949, pp. 345-346; Schmertmann and Taylor, 1965, pp. 23-24; Furrer and Bachmann, 1968, p. 9) have shown that there is usually a radial or centrifugal pattern of stone orientation in the centers of sorted circles and polygons. The long axes of the stones tend to be oriented at right angles to the nearest border and are often vertical (Corte, 1962, p. 16), or steeply dipping (Furrer and Bachmann, 1968, p. 9). The mechanism responsible for this orientation remains to be investigated, but it appears that the pattern may be due to one or both of two factors. The first may be a confirmation of the mass displacement hypothesis of patterned ground formation, which has been demonstrated experimentally by Dżułyński (1963) and Anketell, et. al. (1970). In this model, patterned ground results from an upwelling of fine particles into overlying coarser material due to "moisture controlled changes in density and intergranular pressure" (Washburn, 1973, p. 145). Such movement would probably result in stone orientations reflective of radial movement. A second process which could operate alone or in conjunction with mass displacement is reorientation of stones by repeated freezing and thawing. Such reorientation has been demonstrated (v. Washburn, 1973, pp. 76-79; French, 1976, pp. 32-33), and results from differential heave between the tops and bottoms of elongate stones during freezing. The inclined freezing fronts associated with sorted patterned ground (Schmertmann and Taylor, 1965, p. 62) may operate to promote rotation of stones into the radial pattern. The subject of stone reorientation will be taken up in more detail later in this chapter.

Sorted stripes are generally regarded as slope-induced variants of circular or polygonal forms. Initial sorting is thought to produce such concentrations of fines that the material becomes vulnerable to solifluction, with subsequent elongation of the patterns. This mechanism would operate in such a way as to destroy a radial fabric and replace it with one characteristic of solifluction deposits. Fabrics of the latter are well known (Benedict, 1966, pp. 26-27; 1970a, p. 205; 1976, pp. 63-64; Washburn, 1973, p. 189), and are characterized by upslope-dipping long axes aligned parallel to the direction of movement. Near lobe fronts, a transverse orientation becomes dominant. G. Lundqvist (1949, p. 342) presents a diagram suggesting a radial orientation pattern near the fronts of "stone banked flow earth cones." Furrer and Bachmann's (1968, p. 11) diagrams show that stones near the lateral margins of the fines possess long axis orientations oblique to lines of flow. This is suggestive of stone rotation during outfreezing as described above, or of lower rates of movement close to lobe margins. Stones undergoing ejection from the lateral margins of fine stripes were noted in the present study area. However, only further process-oriented study can pinpoint exactly the factors responsible for this oblique orientation.

The centrifugal pattern is not translated to the borders of patterned ground. These is some mechanism by which stones become rotated to positions paralleling the outlines of the features during or after ejection from the fine centers. This will be discussed more fully after literature review and presentation of field observations and data from the present study.

Many workers have made parenthetical reference to the orientation of blocks in patterned ground borders. Among these researchers there appear to be two contradictory lines of thought. The first regards long axes of stones as being predominantly vertical. Huxley and Odell (1924, p. 209) characterized the stones of polygon borders as "usually upended," as did Ahlmann (1963, p. 11), and Richmond (1949, p. 145), the latter commenting that stones are usually found "with their longer axis vertical." Bunting and Jackson (1970, p. 201) describe stones in the borders as "vertically oriented, but with no preferred directional orientation except in adjacent situations."

A second viewpoint is represented by Sharp (1942, p. 276), who found that "platy fragments lie flat in the central area and are set on edge in the borders" ("on edge" would indicate that intermediate or 'b' axes are vertical or near vertical). Sharp is corraborated in this by Benedict

(1965, p. 24) who states that "where tabular stones are present in the borders of polygons, they tend to stand on edge and to be oriented parallel to the sides of the polygons." Regarding sorted stripes, French (1976, p. 189) comments "the stones and boulders are commonly on edge with a long axis parallel to the line of movement of the stripe."

To the writer's knowledge, only a very few detailed investigations have been published which deal with the fabric of patterned ground peripheries. The first such study was made by G. Lundqvist (1949), whose diagrams suggest a near perfect agreement between the trend of the border and the blocky material within it, although he does mention that some of the fragments lie obliquely, or at right angles to the border.

Studies in the Alps and in Spitsbergen by Furrer (1968) and Furrer and Bachmann (1968) convinced them that the fabric of patterned ground is "form-specific," i.e., typical of the features. This conclusion has enabled them to identify fossil forms through fabric analysis. Their studies show a maximum (50%) number of stones parallel to the border, but a large minority (30%) transverse to it. Long-axis dips are much lower in the borders than in the central areas of fines.

G. Lundqvist (1962, p. 54) asserts that "the orientation of the boulders in the (coarse) stripes is directed strictly down the slopes, parallel to the stripes themselves," and presents diagrams to this effect. Brockie (1964, p. 98), commenting on "stone streams" in New Zealand remarks that "the orientation and dip of the major axis of individual rocks...reveals a markedly preferential orientation and dip in the direction of the stream...it is believed that the large surface rocks demonstrate a less perfect arrangement than the smaller material near the base." Brockie felt that the data were not amenable to statistical treatment due to close packing of the stones.

R. B. King (1972, p. 162) found that no preferential orientation existed in areas where rounded boulders formed "stone garlands," but where the garlands were comprised of platy phyllite blocks "circumferential orientation" did exist, apparently because of interaction between neighboring lobes.

2.3.2 Field Procedure and Data Analysis

On Frost Ridge, orientation data were obtained from a sorted stripe representative of Zone A stripes. This feature has an average slope of 3°-4°, a length of 13.7 m, and a mean width of 1.14 m (narrowing upslope, widening downslope). Three samples of 50 observations each were taken, one in each of the stone stripes bordering the fine lobe, and one from the "stone garland" at the feature's downslope margin. Measurements of a-axis azimuth, as well as a and b-axis dip were made with the Brunton compass. Only tabular blocks with axial ratios 2:1 were used for the analysis. Measurements were made in the smallest area possible, involving no more than 4 m of length in each stone stripe.

Orientation and a-axis dips were analyzed using a computer program developed by Mark (1971). Fabric diagrams are presented in Figure 2-8, and details of the analyses are summarized in Table 2-2. Diagrams were contoured by the Kalsbeek (1963) method. Although visual inspection in the field had suggested a random azimuthal orientation, vector analysis reveals that both stone stripe samples have preferred orientations significant at the .01 level.[2] The trend of the stripe was 55° while azimuths

[2]Since the analysis was completed, it has come to the writer's attention that there are problems inherent in the statistical test used in Mark's program. The correction term

Figure 2-8. Frost Ridge stone stripe fabrics. Ploted on Schmidt Net, Lower Hemisphere. Direction of local slope and intersection of plane of slope with hemisphere are indicated.

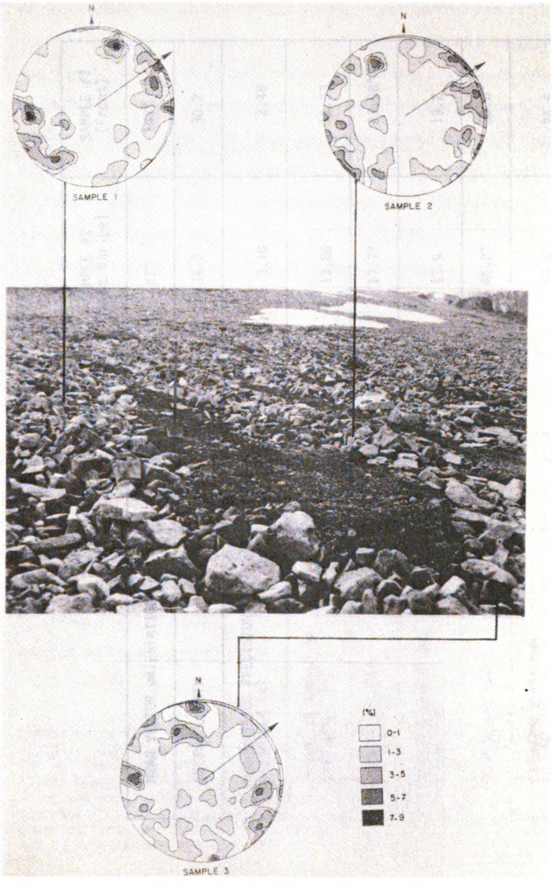

N
SAMPLE 1
N
SAMPLE 2
N
SAMPLE 3
(%)
0-1
1-3
3-5
5-7
7-9

TABLE 2-2. STONE STRIPE FABRIC DATA

	SAMPLE #1 (East Stripe)	SAMPLE #2 (West Stripe)	SAMPLE #3 (Front)
MEAN VECTOR ORIENTATION	62°	81°	148°
VECTOR LENGTH	37.4	34.2	30.2
ESTIMATE OF PRECISION PARAMETER (k)	3.88	3.10	2.48
SPHERICAL RADIUS OF CONFIDENCE (θ)	11.83	13.86	16.53
MEAN a-axis DIP	18.8°	17.7°	23.58°
STANDARD DEVIATION, a-axis DIP	13.2	13.9	19.2
MEAN b-axis DIP	51.6°	46.2°	36.8°
STANDARD DEVIATION b-axis DIP	26.5	27.6	26.5

of the maximum mean vector for the east and west stripes are 62° and 81° respectively, demonstrating a strong preferred orientation subparallel to the axis of the stripe. These samples approximate a spherical-normal distribution since "k" values exceed 3.0 in both cases (Andrews and Shmizu, 1966, p. 156). The spherical radius of confidence (θ) indicates a 5% probability that the true mean direction of all stones in the stripes is more than 11.8° from the calculated sample mean for the east stripe, and 13.9° in the west stripe (Mark, 1971, p. 2663).

The arrangement of blocks at the front of the fine lobe is fundamentally different from that in the lateral stripes. The orientation of the mean vector is 148°, normal to the trend of the feature itself, as was also reported by G. Lundqvist. However, corrected values in the vector analysis and the results of the Tukey X^2 test indicate that preferred orientation is weak or nonexistent, confirming what is suggested by visual inspection of the plotted values (Figure 2-8, Sample 3). The lack of fabric strength detected by these tests may be more the result of poor sampling than absence of preferred orientation, however. Acquisition of 50 observations necessitated taking some measurements from blocks close to or within the area in which the garland changes orientation as it grades into the lateral stripes. This probably introduced some distortion in the azimuth values.

$$S_1 = 1.24(R/N) - 0.302$$

suggested by Mark (1973, p. 1372) was used to enter a significance table (ibid.). The stone stripe samples were found to remain significant at the .01 level, but the garland was so only at the 0.1 level. As an additional check, a Tukey X^2 test (Harrison, 1957) was run using 20° class intervals and a 180° distribution. This test yielded results similar to the vector analysis (significant at the .05 level) in the cases of the stone stripes, but the null hypothesis of a uniform distribution could not be rejected for the garland.

2.3.3 Origin of Fabrics

It can be seen that the results of this analysis support the conclusions of the earlier workers cited above, who reported preferred orientations in the stones of patterned ground borders. The mechanisms responsible for this orientation are, however, still somewhat obscure. In this section the various hypotheses that have been suggested are reviewed, and data on a and b-axis inclination and orientation are used as a partial basis for deduction concerning processes responsible for observed fabrics.

Some investigators (e.g., R. B. King, 1971, pp. 383-384) explain the fabric of stone stripes as related to slope processes, usually solifluction, in the adjacent fine stripes. Although this explanation initially appears credible, several lines of evidence militate against it:

1) The blocks of sorted circles and polygons are also oriented in circumferential manner, parallel to the outline of the features. There must be a connective process operating to produce analogous fabrics in the various geometrical forms of patterned ground, as was recognized by G. Lundqvist (1949, p. 346).

2) If solifluction were the main control behind the orientation pattern, rates of movement would necessarily be greater in the fine lobes than in the stone stripes. Although movement surveys were not a part of the writer's present undertaking, various studies have established that movement may be greater in either the fine stripes (Chambers, 1966, pp. 29-30; 1970, p. 93; MacKay and Mathews, 1974) or the coarse stripes (Antevs, 1932, pp. 57-58; Washburn, 1947, pp. 87-88). Some investigators have found evidence for relative movement of both types within the same locality (Benedict, 1970a, pp. 203 & 207; Washburn, 1969, p. 187). This

apparent discrepancy can be explained by the predominance of solifluction in moist microenvironments, resulting in greater movement in the fine stripes. Where conditions are relatively dry, frost creep predominates and the stony stripes move more rapidly than the fines, owing to the latter's cohesion on resettling. In both cases, however, similar fabrics apparently exist (compare Benedict, 1970a, Figure 44, p. 204; with Benedict, 1966, Figure 3, p. 26). It therefore seems that creep is also a factor in producing downslope-oriented fabrics.

3) Forces exerted by differential downslope movement between coarse and fine stripes may not be sufficient to produce preferred downslope orientations in blocks near the centers of wide stone stripes. In King's discussion of stone orientation within stripes, he suggests that solifluction in "soil stripes" would operate in such a manner as to produce gentle inclinations in downslope-dipping stones projecting from adjacent stone stripes. Conversely, stones with upslope dips would tend to have their inclinations steepened by such movement. Unfortunately, the data presented by King in support of this hypothesis, which show maxima at both low and high dip angles, do not include the sense of the dips. This, in the writer's view, makes his supposition rather speculative.

King's assertion was tested using data available from the Frost Ridge stripes. Since the long-axis dips of stones with azimuthal orientations normal or subnormal to the stripe axis were of little use for this analysis, the dips of b-axes were substituted in these cases (the b-axis is perpendicular to the a-axis by definition). In this way, a sample of 100 stones was made available, 47 dipping between south and west (upslope), and 53 with dips between north and east. If the solifluction hypothesis were to be substantiated, we would expect the former group to display higher inclination angles, since the stripe trends N55°E. The two-sample Kolmogorov-Smirnov test was applied to the data. The cumulative frequency distributions are presented in Figure 2-9; a between-sample difference of 26.5% within any class interval is required to establish statistical significance at the 0.05 level. It can be seen that the null hypothesis of "no significant difference" between samples should be retained, making King's suggestions improbable, at least in the present study area.

It seems that the major clue to the origin of patterned ground border fabrics lies not so much in the azimuthal orientation (which could be produced by a variety of processes) as in the dips, particularly of the b-axes. Figures 2-10 and 2-11 show the frequencies of a and b-axis dips in 15° intervals. From these it can be seen that the blocks within stone stripes have more steeply inclined b than a-axes. This supports the observations of those workers cited above who remarked on the large number of stones lying "on edge." In both the east (Sample #1) and west (Sample #2) stripes, more than 50% of the stones are inclined $\geq$ 45°. By contrast, the great majority of a-axis inclinations are <30°. There is no apparent preference for either axis to dip predominantly up or down-slope.

This pattern of inclinations seems to suggest that the stone stripes are subjected to compressive forces. A mechanism which may account for both the preferred azimuthal orientation and the large proportion of edgewise blocks in all geometric forms of sorted patterned ground has been suggested by Goldthwait (1976, p. 31). "Squeezing" of the coarse borders by expansion of saturated fines during the fall freeze could be expected to set stones on edge, and may also account for aligned a-axes in situations where adjacent centers exert compressive forces. The

Figure 2-9. Cumulative frequency distributions, up- and downslope dips.

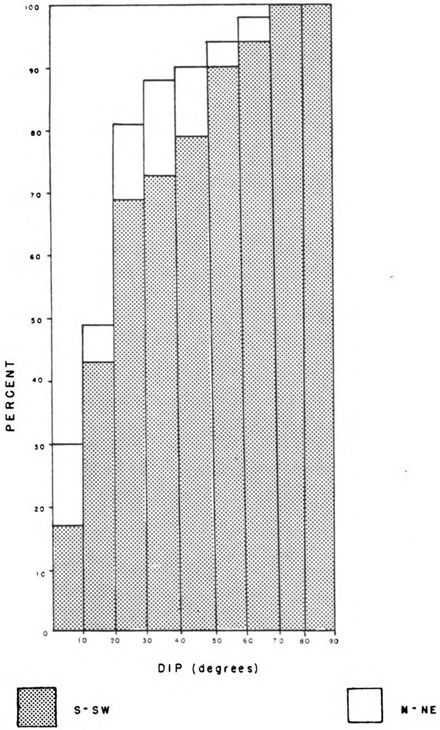
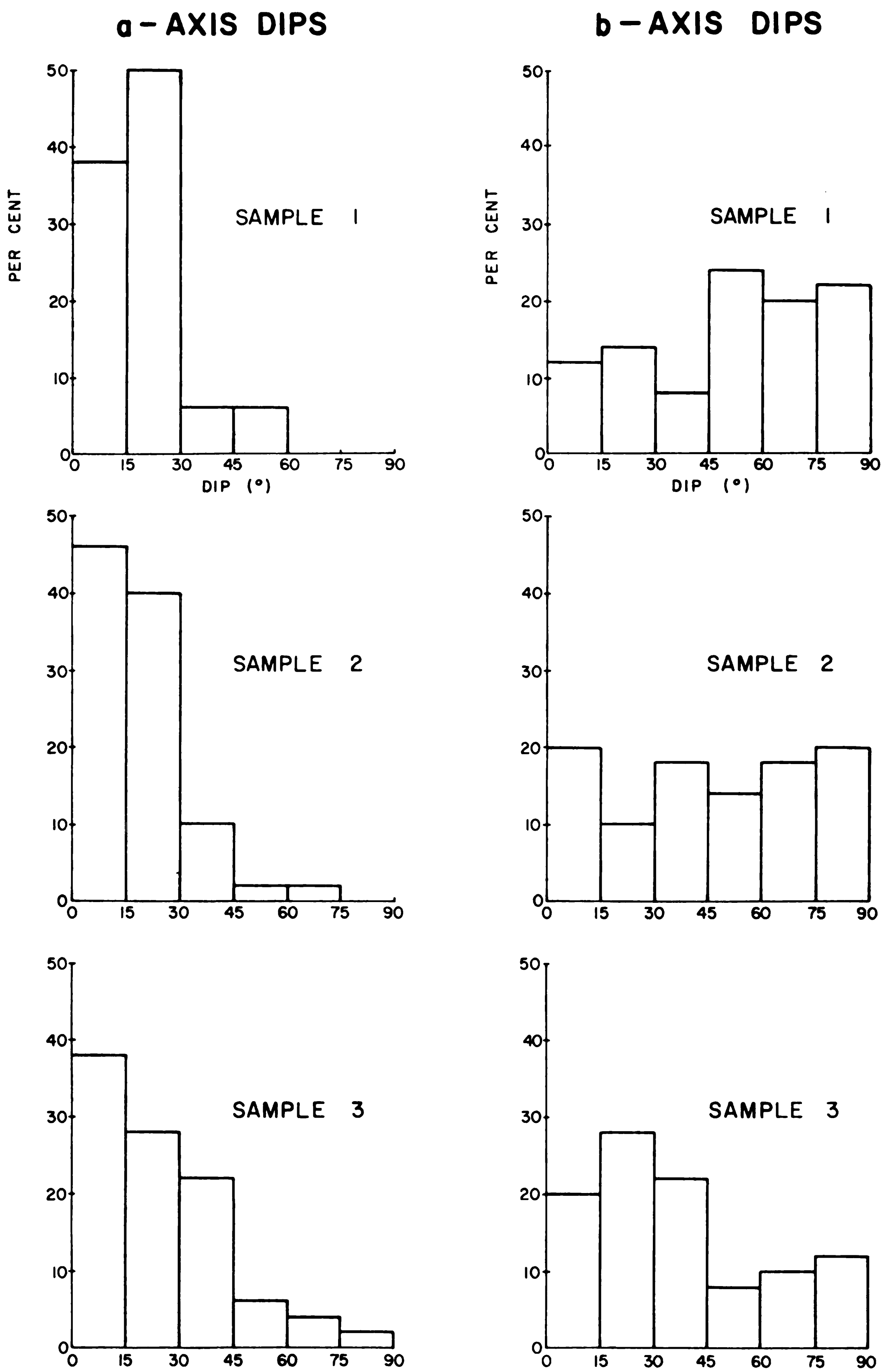

100
90
80
70
60
50
40
30
20
10
0
PERCENT
10
20
30
40
50
60
70
80
90
DIP (degrees)
S-SW
N-NE

Figure 2-10. Histograms of a-axis dips.

Figure 2-11. Histograms of b-axis dips.


a-AXIS DIPS
b-AXIS DIPS
PER CENT
PER CENT
SAMPLE 1
SAMPLE 1
SAMPLE 2
SAMPLE 2
SAMPLE 3
SAMPLE 3
DIP (°)
DIP (°)
0
10
20
30
40
50
0
15
30
45
60
75
90

rigidity of the frozen fines would effect reorientation of stones by pushing them into as compact an area as possible during expansion.

Lateral displacement within patterned ground features has been documented, and in some cases measured by other workers, although Goldthwait was apparently not aware of these works. Jahn (1966, p. 144; 1970, p. 120), working in Spitsbergern, measured heave amounting to about 5 cm in the lateral margin of a sorted circle's fine area, while in the center, he found heave as much as 15 cm. He remarks that "the movement of the central area pushes against the inside of the border causing the stones to slide down the steep slope " (Jahn, 1966, p. 144).

Taylor (Schemertmann and Taylor, 1965, p. 27), found horizontal heave of about 1.4 cm in a sorted circle near Thule, Greenland. He was not satisfied with the survey method used however, and strongly recommended that this problem be pursued in future work through the use of horizontal photography (ibid, p. 74).

Benedict (1970a, p. 201) used painted connecting lines to detect movement of adjacent stones in polygon borders. In one "frost-disturbed area," he found that 15 of 20 such marked stones had been displaced during one winter, apparently by "the influence of fine-textured centers."

It would seem, therefore, that expansion of fine centers is a plausible explanation for the fabrics that have been observed. A further indication lies in the b-axis inclination of blocks within the downslope margin of the fine lobe. Here, compression is minimized since forces are exerted from one direction only. Both the a and b-axis inclinations are relatively low, lending further support to the compression hypothesis.

It must be stressed that much more work is required to establish an adequate link between form and process. Recorded horizontal displacements are not of great magnitude, and careful study should be made of the effect of such movement on stone orientation and inclination. The influence of stone shape on orientation may also be of some significance, and should be considered in future studies, as indicated by King's (1972, p. 162) observation that rounded boulders show no preferred orientation. Finally, it should be emphasized that the suggestions presented here are based on a rather small number of samples. More observations are required before truly firm conclusions can be drawn. The writer hopes to extend these studies in the near future.

2.4 Particle Shape Analysis and Frost Sorting

It has long been suspected that "upfreezing" of stones from an initially heterogeneous mixture of fines and rock fragments may be at least partially responsible for the striking particle size segregation characteristic of sorted patterned ground. Detailed laboratory studies by Corte (1961; 1962; 1966) have shown this theory to be viable. That the shape of a stone may be an important factor influencing its propensity for migration and separation from a fine soil matrix has been touched upon by several workers (Price, 1970, p. 109; Taber, 1943, p. 1453; Washburn, 1973, p. 76), but to this writer's knowledge has not been rigorously tested, except by Corte (1966a, p. 200), whose work involving freezing of soil samples from the bottom up indicates that "particles of similar material...with less sphericity and greater contact area show a greater migration." It, therefore, seems reasonable to suspect that different shape characteristics predominate in the coarse and fine fractions of patterned ground, and that the shapes in these fractions may provide a partial basis for deduction of the particular processes involved.

2.4.1 Mechanisms of Stone Movement

There are two commonly-accepted mechanisms, dubbed the "frost-pull" and "frost-push" hypotheses (Washburn, 1973, pp. 71-80), by which differential movement between fines and stones may be explained, although there is a notable lack of field evidence to indicate the relative importance of each. In the frost-pull model, a stone within a freezing soil body is raised in association with expansion of the saturated fines surrounding it, leaving a void in its original position. The stone is not able to return to this position when thaw occurs because lateral thrusting during freezing narrows the void, and because thawing soil tends to slump into the cavity. Through repetition of this process a stone can gradually work its way to the surface.

According to the frost-push hypothesis, upward movement of stones occurs as ice lenses form around and at their bases. The fact that rock fragments are better heat conductors than fine soil results in the former acting as loci for development of segregation ice, which forces them upward. An important factor controlling the magnitude of movement by frost-push is the amount of unfrozen pore water in the fines overlying the migrating stone. High unfrozen water content results in relatively low soil strength, so that stone migration may not be significantly impeded.

In both models the magnitude of the movement increases with the effective vertical height of the stone. Washburn (1973, p. 71) cites empirical work by Kaplar (1969, p. 36) in which the maximum heave experienced by a stone due to frost-pull is a function of the stone's vertical height. A similar situation exists with the frost-push mechanism, where movement is proportional to the total thickness of segregated ice lenses at the base of, and surrounding the stone.

As noted in the section dealing with patterned ground fabrics, there is a process associated with upfreezing which operates to maximize the effective height of coarse particles and thereby to increase their capacity for movement. Stones are first gripped in their upper portions by a descending freezing front. Heave is directed upward, causing reorientation of elongate stones into positions of higher angle than the original postures. With repeated cycles, the long axis of a stone is rotated so that it becomes oriented normal to the frost line. Washburn (1973, p. 79) and French (1976, p. 32) provide diagramatic representation of this phenomenon. It appears that this process should not be restricted to horizontal freezing fronts, but may also be operative in conjunction with the inclined freezing fronts associated with lateral sorting. The end result in all cases would be rotation of the long axis to a position approximately parallel to the direction of heat flow, thereby maximizing the effectiveness of the sorting process, independent of the orientation assumed by the freezing plane.

2.4.2 Field Procedures and Assumptions

Four point samples of 50 stones each were obtained from a representative "Zone A" sorted stripe on Frost Ridge. The samples were taken from the uppermost 10-15 cm, and from near the depth of sorting (≈80 cm) in both the fine lobe and one adjoining stone stripe. Some effort was made visually to obtain stones of approximately the same size. Although there is a tendency for the largest rock fragments to be positioned near the surface in the stone stripes, many smaller stones were found throughout these rather tightly packed features so that sampling represented no apparent difficulties. All stones were of a relatively coarse-grained granodiorite type common in this area.

Stones were measured for computation of the Cailleux Roundness and Flatness Indices (Tricart and Schaeffer, 1950). The former is given by $(\frac{2R}{a})$ 1000, where R is the minimum radius of curvature in the principal plane, and a is the length of the long axis. This index calculates the degree to which the corners of a stone have been rounded, and is not an expression of geometrical shape. Values can range from near zero for very angular stones, to 1000 for extremely rounded particles.

Cailleux's flatness index is computed by $(\frac{a+b}{2c})$ 100, where a, b, and c are the long, intermediate, and short axes of the stone. Lithologies such as slate can produce values of 1000. King and Buckley (1968) have shown that this index is inversely related to the sphericity index, $(\frac{bc}{a^2})^{1/3}$, proposed by Krumbein (1941), and that it is therefore unnecessary to compute both. The Cailleux index was used in this study for its ease of computation.

These indices have the advantage of comparability, since they have been used by many investigators. The roundess index, in particular, has proven to be of value as an indicator of depositional mode and/or environmental conditions (King and Buckley, 1968), although the indices were used to somewhat different effect in this study.

As discussed in an earlier section, it is likely that the Frost Ridge patterned ground is developed in till, so that stones comprising the features were deposited under more or less uniform conditions. Differences between stones are, therefore, inherited and diffused throughout the till sheet due to glacial "mixing." Furthermore, the processes of mass movement associated with the features (frost creep and solifluction) are thought to be incapable of affecting the angularity of particles

(Benedict, 1976, p. 61), and analysis of weathering rind thicknesses showed no statistical difference between samples (see below). Thus, it would appear that such dissimilarities in shape and roundness as might be found in the stones of the various sorted stripe fractions would be attributable more to the propensity of the particles for movement under the influence of frost than modification by environmental parameters or depositional incongruity.

2.4.3 Data Analyses

Values for roundness and flatness were computed for each sample and comparison made by the Kolmorgorov-Smirnov test. Each sample was compared with all other samples. Results are presented in Tables 2-3 and 2-4.

An interesting spatial arrangement of shape characteristics is revealed by examination of the data. In the sample from depth in the fine stripe, the mean value for flatness is lower, but higher for roundness, than for any other sample. Comparison by the Kolmogorov-Smirnov statistic confirms this. There is a statistically significant difference (.05 level) in roundness for the plots of lobe depth against both lobe surface and stone stripe surface. Direction is such that higher roundness values occur at depth in the fines.

Even more interesting are the results of the flatness analyses. Although computed values are not particularly high in any sample (as might be expected with the rock type), there are statistical differences at the .05 level between lobe depth and both lobe surface and stone stripe surface. It will be noted that the plot between lobe depth and stone stripe depth is significant at a level somewhat above .10, but does not reach the critical limit at the .05 level, a situation which also

Figure 2-12. Cumulative frequency distributions, Cailleux flatness values (Kolmogorov-Smirnov test).

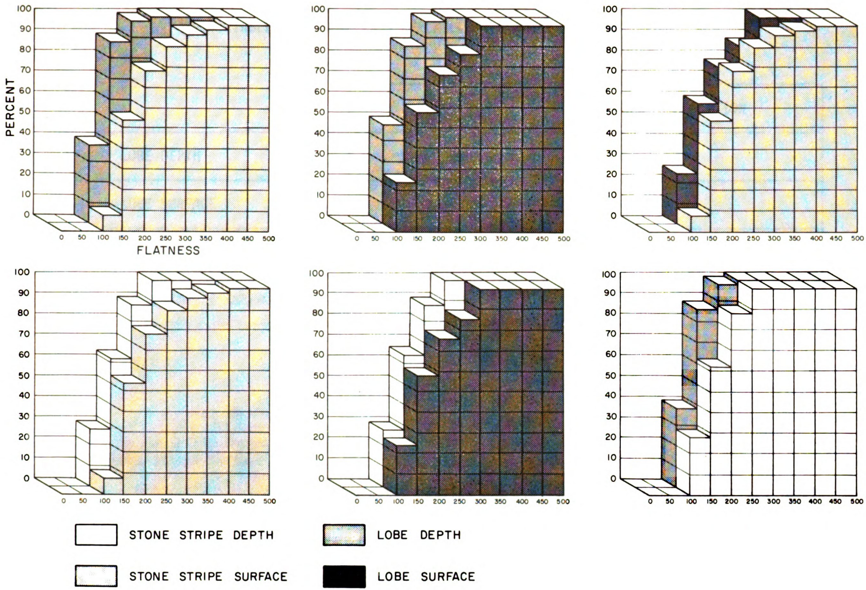

PERCENT
FLATNESS
0
50
100
150
200
250
300
350
400
450
500
STONE STRIPE DEPTH
STONE STRIPE SURFACE
LOBE DEPTH
LOBE SURFACE

TABLE 2-3. ANALYSIS OF CAILLEUX FLATNESS VALUES
by KOLMOGOROV-SMIRNOV TEST

	MEAN	STANDARD DEVIATION
LOBE DEPTH	164.94	33.19
LOBE SURFACE	202.82	63.28
STONE STRIPE DEPTH	182.68	47.42
STONE STRIPE SURFACE	210.10	60.70

	Lobe Depth	Lobe Surface	Stone Stripe Depth	Stone Stripe Surface
Lobe Depth				
Lobe Surface	S			
Stone Stripe Depth	S*	NS		
Stone Stripe Surface	S	NS	NS	

S - indicates results are statistically significant at .05 level
NS - indicates results are not statistically significant at .05 level
* - significant at level slightly below .05

Figure 2-13. Cumulative frequency distributions, Cailleux roundness values (Kolmogorov-Smirnov test).

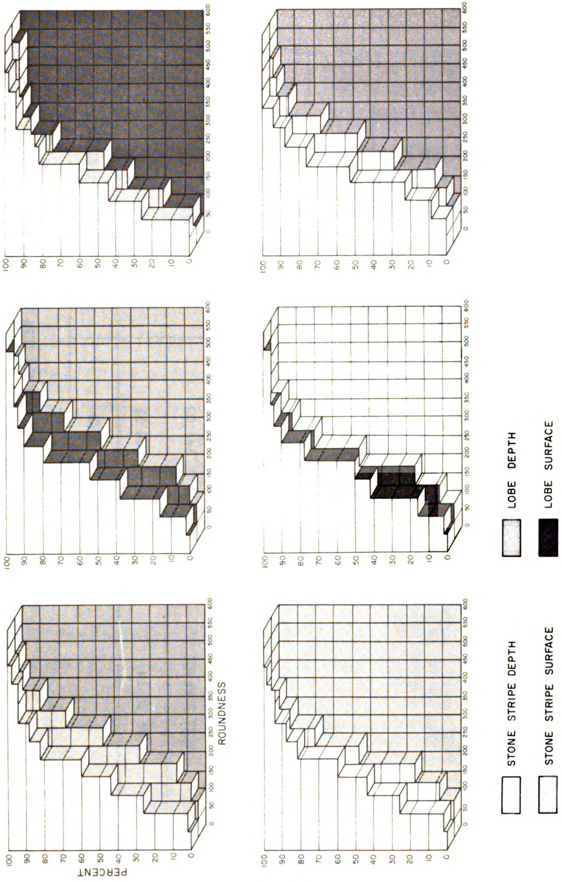

PERCENT
ROUNDNESS
0 10 20 30 40 50 60 70 80 90 100
0 50 100 150 200 250 300 350 400 450 500 550 600
STONE STRIPE DEPTH
STONE STRIPE SURFACE
LOBE DEPTH
LOBE SURFACE

TABLE 2-4. ANALYSIS OF CAILLEUX ROUNDNESS VALUES
by KOLMOGOROV-SMIRNOV TEST

	MEAN	STANDARD DEVIATION
LOBE DEPTH	296.22	82.92
LOBE SURFACE	241.08	97.33
STONE STRIPE DEPTH	246.22	80.73
STONE STRIPE SURFACE	227.50	96.46

	Lobe Depth	Lobe Surface	Stone Stripe Depth	Stone Stripe Surface
Lobe Depth				
Lobe Surface	S			
Stone Stripe Depth	S*	NS		
Stone Stripe Surface	S	NS	NS	

S - indicates results are statistically significant at .05 level
NS - indicates results are not statistically significant at .05 level
* - indicates significance at level slightly below .05

occurs in the same plot of the roundness analysis.

What emerges is a pattern of higher flatness and lower roundness values in stones situated where classic theories of patterned ground formation suggest that the stones should be segregated out of the fine center. As a check to insure that differential movement of stones is not attributable to discrepancy in stone size between samples, a-axis lengths for each sample were plotted against all other samples. These plots yield only one between-sample difference, that of lobe depth against stone stripe surface. Since different shape characteristics occur between several other combinations of samples, it appears that we can discount the possibility that stone size is the primary factor responsible for the observed differences between samples. The one difference that does occur indicates that more care should be taken to obtain stones within strictly defined size categories in future studies, since the dimensions of a stone are partially responsible for the magnitude of its movement.

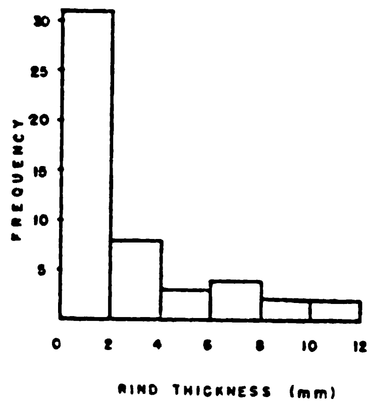
The possibility was also considered that the observed differences in stone shape are attributable to intensified chemical weathering within the relatively moist fine lobe. Thorn (1975), in a study of nivation processes, suggests that rock weathering rind thickness is a good indicator of the intensity of chemical weathering at a site. This assumption is also made here.

Micrometer calipers were used to measure weathering rind thickness to the nearest 0.5 mm on each of the particles for which Cailleux indices were calculated. Descriptive statistics and histograms of these data are presented as Table 2-5 and Figure 2-14, respectively. Although it would be desirable to examine the null hypothesis that the samples were

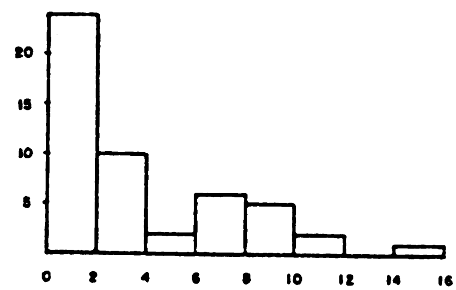
TABLE 2-5. DESCRIPTIVE STATISTICS FOR FROST RIDGE WEATHERING RIND DATA.

SAMPLE	MINIMUM	MAXIMUM	MEAN	STANDARD DEVIATION	SKEWNESS	KURTOSIS
LOBE SURFACE	0.0	11.0	2.42	2.89	1.56	1.52
LOBE DEPTH	0.0	16.0	3.40	3.68	1.34	1.31
STONE STRIPE DEPTH	0.0	19.0	3.71	4.84	1.77	2.44
STONE STRIPE SURFACE	0.0	13.0	3.33	3.71	1.22	0.21

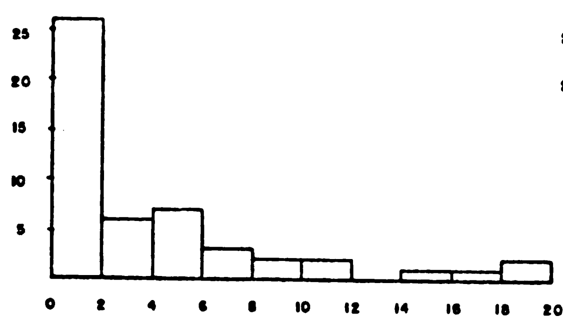
Figure 2-14. Histograms of weathering rind thicknesses.



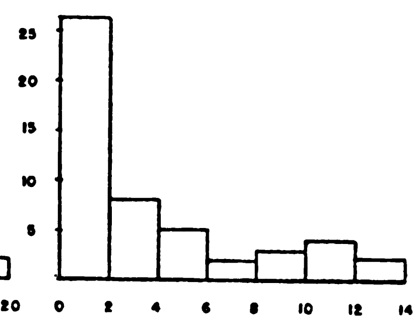
LOBE SURFACE



LOBE DEPTH



STONE STRIPE DEPTH



STONE STRIPE
SURFACE

drawn from the same population by the difference of means test or analysis of variance, the distinctly non-normal data distribution does not allow use of these techniques. Transformation is not possible, since many particles displayed no visible weathering rind. Unfortunately, neither of the nonparametric alternatives to the above tests (Mann-Whitney U and Kruskal-Wallis nonparametric analysis of variance) are appropriate, due to a large number of tied ranks. The observations were therefore treated as nominal-scale data by partitioning each sample into three arbitrary weathering rind classes, "thin," "medium," and "thick." Samples were then compared by means of the X^2 statistic. Although a considerable amount of information was undoubtedly lost by this procedure, X^2 appears to be one of the few tests whose use is valid in this situation. Comparison of each sample with every other failed to define a statistical difference between any pair at the 0.05 level of significance. Visual inspection of histogramed data tends to support this conclusion. The null hypothesis of no difference in chemical weathering intensity between samples is, therefore, retained. It should be noted, however, that coarse-grained rocks such as the granodiorite used here are not as desirable for this type of analysis as those of finer grain size. This is because chemical weathering tends to attack the bonds between coarse grains, which are removed with little retention of surficial discoloration on the rock (Birkeland, 1974, p. 75).

2.4.4 Interpretation of Shape Characteristics

The data presented seem to confirm that the arrangement of stone concentrations relative to the fine soil results from frost sorting. This conclusion is perhaps unspectacular in light of the widespread acceptance of this process as a factor in the formation of patterned ground, but it nonetheless provides additional support for the concept. The demonstrated coincidence of high flatness and low roundness values in the stone stripes, where stones are assumed to have been sorted out from the fines, indicates that shape plays an important role in governing a given stone's likelihood of being segregated. Since there appears to be no significant difference in chemical weathering in any fraction of the sorted stripe, it is difficult to explain the observed distribution of shapes in terms of any mechanism other than frost sorting.

A possibly more interesting conclusion is that the distribution of shape characteristics provides evidence for the importance of the frost-push mechanism. High flatness characteristics should be effectual in minimizing resistance offered by overlying frozen soil as a stone is forced upward by formation of segregation ice at its base. This would be particularly true if the stone has been subject to the rotational mechanism, so that its major axis becomes normal to the freezing plane, as discussed above. On the other hand, both sphericity and roundness would tend to prevent, or at least inhibit, movement by frost-push since the resistance offered would be greater with these traits. Theoretically, frost-pull should not discriminate between stones of different shapes (assuming equal sizes), so it appears that frost-push must play an important role in the sorting. Further evidence for the operation of this mechanism comes from the occasional "silt-capped" stones noted to be protruding from the fine lobes. As discussed by Washburn (1969, p. 56), these are indicative of rapid upfreezing caused by the formation of relatively thick ice lenses at the bases of stones.

Since it would be difficult to verify the above interpretations in the field, further study of the effect of stone shape on movement might be studied most profitably under controlled laboratory conditions. If the suggestions made here were shown by experimentation to be tenable, the analysis of shape characteristics may prove to be a valuable indicator of the relative efficacy of the frost-push mechanism under field conditions. That fragments of certain lithologies may be more susceptible to frost sorting is also suggested, since those with high flatness values may move more rapidly.

CHAPTER III

PERMAFROST DISTRIBUTION IN THE JUNEAU ICEFIELD REGION

Although the occurrence of patterned ground is not strictly dependent upon the presence of permafrost, large-diameter forms are characteristic of a permafrost environment (Jäckli, 1957, p. 21; Washburn, 1973, pp. 112, 123, 134, 241-242), and for this reason some attention will be focused on permafrost within the Juneau Icefield Region.

3.1 Literature Review

In the high mountains of most of the world, the extent of permafrost is very poorly known (Ives, 1974). There have been several attempts to portray the distribution of alpine permafrost through the use of theoretical calculations, but data derived from actual observations are few. The Boundary Range is no exception, although some investigations have been made on its eastern margin. The permafrost literature for the study area is reviewed below, and known occurrences are compared with calculated permafrost levels.

3.1.1 Southeast Alaska and Coastal British Columbia

Baranov (1964, pp. 10-13, 22-23) has discussed the distribution of permafrost in the high mountains of the world, basing his calculations on the mean January air temperature and the duration of subzero temperatures at various sites. Using these criteria, he speculates that the lower boundary of permafrost along the Pacific Coast of North America rises from 75 m in the vicinity of the Gulf of Alaska to 2500 m at 50°N.

He also suggests that this lower limit rises with increasing continentality.

Ferrien's (1965) map shows southeastern Alaska in its entirety as being "generally free of permafrost, but a few small isolated masses of permafrost (exist) at high altitudes." Further searching of the literature revealed no confirmed report of permafrost anywhere in southeast Alaska, although its existence in the high peaks of the Fairweather Range (Mt. Fairweather, 4663 m) can hardly be doubted. Ugolini (1966, p. 53) suggests that permafrost may exist above the 900 m level in the locality of Muir Inlet. This postulation is partially based upon the presence of turf-hummocks, a rather poor indicator of permafrost conditions (Washburn, 1973, p. 126).

Since observations of permafrost in mountainous areas under oceanic influence are extremely rare, Mathews' (1955) notes from the southern Coast Mountains of British Columbia assume a special significance. Several occurrences of frozen ground surviving throughout the summer were found at 1830 m on the Cinder Cone at Garibaldi Park (49°, 58'N, 123°, 00'W). One of the sites was within the walls of a natural tunnel in which no marked air circulation was observed; it is possible that this exposure is attributable to Balch ventilation. However, several occurrences more satisfactory for diagnostic purposes were found in the walls of channels being cut by meltwaters from a nearby glacier. Mathews emphasized that this permafrost had been very recently exposed by the glacier's retreat and that it was relict, and degrading under present climatic conditions. This conclusion is underscored by the more recent studies of MacKay and Mathews (1974, p. 354) in the same locality. Experiments using vials designed to burst upon freezing indicate that frost does not penetrate beyond 5 cm depth in winter, even at elevations above the level of an adjacent glacier. This situation is no doubt attributable to the damping effect of a heavy snow cover on the depth of winter freezing.

3.1.2 Interior British Columbia

Brown's (1967a) map of permafrost distribution in Canada portrays widespread alpine permafrost in northwestern British Columbia, but coverage does not extend into Alaska. Extensive permafrost in the southern Coast Ranges is shown, however, and a more limited distribution is indicated in the Kitimat and Pacific Ranges. The cordilleran section of this map was developed using lapse rates (1°C/164 m) to approximate the elevation of the 30°F (-1.11°C) mean annual air isotherm at 169 stations in the Canadian Cordillera; a least-squares regression line was then fitted to the data. By this method he estimates the lower limit of permafrost to be 1866-2139 m at 49°N., falling to 1159-1432 m (±135 m) at 54°N. Brown's (1976b, p. 20) field observations indicate that the lower limit of permafrost is "uniform" at about 1220 m throughout northern British Columbia. He estimates that the discontinuous zone lies between 1220 and 2440 m, and that above 2440 m permafrost is continuous.

Crampton (1977) has recently carried out investigations in northwestern British Columbia and found that permafrost thickness increases on a transect between Fort Nelson and the N.W.T. - Alberta - B.C. border. During August, scattered islands of ground ice were present at 425 m near Snake River, 55 km northeast of Fort Nelson. At a similar latitude, but 435 km to the west, Brown (1976b, p. 28) found no permafrost at the Cassiar townsite (1065 m). Just below 1370 m permafrost is sporadic; above this elevation it is widespread.

3.2 Permafrost Sites in the Juneau Icefield Region

There have been several permafrost sites noted in the Juneau Icefield Region, but their representativeness is not known, and no ground temperature data are available. Based upon these occurrences and glaciothermal investigations, Miller (1975, p. 119) has suggested that permafrost is widespread above 1675 m in the Atlin region, and above 1825 m in the central icefield. The known permafrost locations in this region are outlined below.

Fourth of July Creek Valley

At this location, palsas are found in a sphagnum bog at elevations down to 915 m (Miller, 1977, p. 475). It is well known that palsas may occur in the southernmost part of the discontinuous permafrost zone, since the thermal properties of the peat of which they are composed are particularly favorable for the development perennially frozen ground (v. Brown, 1966, p. 21). J. Lundqvist (1962, p. 93) suggests that the southern limit of palsa development coincides roughly with the -2° to -3°C mean annual air isotherm. Tallman (1975, pp. 111-132) has done extensive research on the Fourth of July Creek palsas and demonstrates that many are developing under present conditions. Applying a lapse rate of 1°C/164 m indicates a mean annual air temperature at 915 m of around -1.7°C in this vicinity. It therefore seems probable that this is the lowest level of aggrading permafrost; below about 900 m existing permafrost would appear to be relict.

Atlin Road

During construction of this highway an isolated occurrence of permafrost was discovered between Mileposts 5.5 and 6.5, on a slope below the road (Brown, 1976b, p. A-6). This permafrost is probably relict, since

Brown's investigations along the same road disclosed no other permafrost sites. According to the 1:250,000 Teslin map (Sheet 105c), elevations in this segment of the highway do not exceed 915 m.

Atlin Mountain

A rock glacier is situated on Atlin Mountain, immediately southwest of the Atlin townsite. It issues from an east-facing cirque at the 1500-1800 m level, and terminates well below 900 m. Movement in its lower part has been recently demonstrated by J.I.R.P. personnel (R. Flanders, personal communication, 1975), indicating retention of interstitial or relict glacier ice at low levels. However, since rock glaciers are mobile, ice within their lower portions cannot be taken as evidence of widespread *in situ* permafrost development at these levels.

Ruby Mountain

An excellent indication of extensive high level permafrost comes from this location 23 km northeast of the Atlin townsite. Here the adit of an abandoned tungsten mine at 1825 m contains large accretions of sublimation ice; a detailed description of the site is given by Tallman (1975, p. 107). It should be noted that this occurrence is not likely to have resulted from Balch ventilation, owing to the horizontal nature of the mine shaft. Furthermore, this site has a southwesterly aspect, which indicates that permafrost is widespread at similar elevations throughout this area.

Cathedral Massif

A number of direct and indirect evidences for permafrost existence are found here. These are outlined briefly below.

a) Ice-Cored Talus

On the shadowed, north-facing slope of "Mt. Edward Little," solid ice was observed at 1490 m, just below the surface of a scree mantle. A hummocky microtopography characterizes this site and is probably related to differential ablation of the ice core. Where the debris cover is thin, meltwater was abundant in late August, but where the cover exceeded 20 cm, the ice was apparently stable. It appears likely that this ice is relict from the last advance of the Cathedral Glacier, and was preserved by the insulating effect of scree accumulations derived from the steep slopes above, as suggested by Jones (1975, p. 128).

b) Torres Rock Glacier

This feature lies on the shaded side of the valley just southeast of the Cathedral Glacier. It is immediately below, and derived from, an unnamed cirque glacier terminating in an ice fall at 1660 m. The rock glacier itself extends from 1550 m to about 1225 m at its lowest point, and is separated from the clean ice by a steep bedrock wall. The rock glacier appears to have been derived through detachment of a segment of the true glacier above, with subsequent burial and preservation of the ice. This interpretation is based upon the discovery of a meltwater tunnel in the upper reaches of the rock glacier. Meltwater derived from the glacier ice upslope flows down the bedrock face and disappears below the upper surface of the rock glacier. Investigation of this tunnel revealed debris-entrained shear planes within solid ice, not far below the surface. Despite this discovery, it remains to be demonstrated whether this core of glacial ice persists in the lower reaches of the feature, or if these portions consist of interstitial ice of secondary origin. The insulating cover of rock debris appears to be derived from talus cones on flanking slopes, and may be partially due to debris entrainment to the surface along shear planes, in the manner suggested by Carrara (1973).

Jones (1975, pp. 124-128) has suggested, but not demonstrated, the existence of a similar ice core in a segment of the Cathedral terminal moraine. Excavation of this feature by this writer in late August revealed no ice, and positive temperatures were found at a depth slightly greater than one meter. While some of Jones' evidences do indeed suggest the existence of an ice core, its conclusive demonstration awaits further excavation or geophysical investigation.

c) Frost Ridge

Evidence for the existence of conditions favorable for the development or at least the persistence of permafrost, comes from the shaded north-facing slope of Frost Ridge. Here, perennial snowbanks remain at elevations down to 1550 m, and late-lying snowbanks and large-diameter patterned ground occur as low as 1490 m. Small ponds also persist on flatter sites.

A large perennial snowbank at 1585 m was investigated during the last week of August, 1975. Snow depth in its central part was 2.75 m, with numerous ice glands and lenticular inclusions. A sharp boundary was observed between this firn and infiltration ice (Shumskii, 1964, pp. 276-303) below. The latter's thickness was at least 3 m, but difficulty with the SIPRE drill bit prevented penetration to greater depth. The propensity displayed by the drill corer to freeze into the ice indicates that at depth the ice retains a reserve of cold, even at this late date. It is therefore possible that this site is within the "infiltration congelation zone" (Shumskii, 1964, pp. 427-431), where the cold reserve from winter freezing exceeds the heat expended on melting, and that derived from liquid precipitation. According to Shumskii, such conditions presume the presence of permafrost in adjacent terrain. This interpretation must be considered tentative for the study area, however, until more detailed thermal data are available. Miller (1975, p. 95) suggests that on the adjacent but more exposed Cathedral Glacier, the upper limit of temperate conditions (isothermal at 0°C) is approximately 1735 m. Above 1825 m, subpolar conditions exist. If subzero temperatures can be conclusively demonstrated at the snowpatch site described above, a good illustration of the influence of aspect will have been provided.

Central Icefield

Miller (personal communication, 1976) has noted the occurrence of springs on nunataks near Camp 8 (2195 m) in the upper reaches of the Juneau Icefield. He interprets this as evidence for meltout from ground ice, and puts the lower limit of permafrost at about 1825 m in the central icefield (Miller, 1975, p. 119). Andress (1963) and Freers (1966) have documented slightly negative temperatures 45 m below the surface of the upper Taku Glacier at the 1980 m level. On the same glacier at 2135 m, negative temperatures exist 150 m below the surface (M. M. Miller, written communication, 1977). In the highest reaches of the icefield (2164-2435 m) subpolar glacier conditions exist, and infiltration by meltwater hastens the densification process (Miller, 1975, p. 79). Although there appears to be a notable lack of literature connecting glaciothermal data with permafrost occurrence, it seems probable that the conditions described are indicative of widespread perennially frozen ground on the nunataks of the higher parts of the icefield. Study of the relationship between the thermal characteristics of glaciers and permafrost distribution in the surrounding terrain is a promising line of investigation, and could be of great use in the solution of the alpine permafrost problem, as indicated by the work of Haeberli (1975).

3.3 Calculated Permafrost Levels

Furrer and Fitze (1973), in an attempt to delimit permafrost distribution in the Swiss Alps, have applied three climatically defined approximations developed by investigators working in the Arctic. Two of the methods resulted in "nonsensical' values with respect to known occurrences of frozen ground. Although there are obvious problems involved in applying lowland arctic permafrost parameters in a highland situation, these workers found that Pihlainen's (1962) approximation yielded results consistent with known occurrences in the Alps. The present writer has made similar computations for the Juneau Icefield region, using the Pihlainen method. Temperature data are based on records from Juneau and Atlin (National Oceanic and Atmospheric Administration, 1976; Kerr and Kendrew, 1955, respectively), a decrease of 1°C/164 m is assumed. Because of the dangers involved in applying lapse rates to mountainous terrain (e.g., Brazel, 1974), and because variations in surface cover are not taken into consideration by this index, it is strongly emphasized that these computations are only a gross approximation of possible permafrost occurrence.

Pihlainen's approximation was derived by plotting mean annual air temperature on the y-axis against the thaw index (the sum of daily mean temperatures greater than 0°C on the x-axis). Values for stations in the Canadian Arctic and Subarctic with reliable climatic data were then plotted on this grid, and straight lines fitted to delineate the permafrost free, discontinuous, and continuous zones. The appropriate category for a location can be found by the equations:

$$MAAT + \frac{T}{780} = 0 \quad (1)$$

$$MAAT + \frac{T}{270} = 0 \quad (2)$$

where MAAT is the mean annual air temperature (°C), and T is the thaw index (Furrer and Fitze, 1973). If equation (1) yields a value less than zero, climatic parameters are suitable for permafrost. If equation (2) produces values below or equal to zero, continuous permafrost is possible. The effects of topography and local conditions are so great in the alpine case, however, that the resulting quiltwork of perennially frozen and permafrost-free sites requires replacing the term "continuous" with "widespread." Truly continuous permafrost probably exists only at very high elevations.

The computations yield the following boundaries:

TABLE 3-1. Computed Permafrost Levels

	West Slope	East Slope
Lower limit of permafrost (M.A.S.L.)	980	900
Permafrost widespread above (M.A.S.L.)	-	1220

It can be seen that there is a remarkable agreement between the lowermost occurrence of palsas in the Atlin locale and the calculated lower limit of permafrost. For the case of the "boundary" of widespread permafrost, the calculation yields a value that appears at least 250 m too low, if compared with available morphological evidences commonly associated with permafrost.

For coastal sector, we may infer that permafrost is climatically possible close to the 1000 m level. For reasons discussed below, a value for "widespread" permafrost in the coastal sector would be rather meaningless. The similarity in the calculated lower limits between the maritime and continental sectors is in fundamental agreement with the conclusions of Williams (1961, pp. 339-343), who shows that the depth of frost penetration and development of frozen ground phenomena is essentially independent of winter cold intensity. Williams indicates that the mean annual temperature is a far more important factor. Alternatively stated, in a comparison of two locations with similar mean annual air temperatures, one maritime, the other continental, nearly accordant depths of frost penetration can be expected. This is because the summer heat flux into the ground at the continental site offsets the correspondingly greater heat loss of winter.

3.4 Influence of Ground Cover

An important factor that has not been considered until this point is the effect of the ground cover on frost penetration. In particular, snow cover may cause drastic discrepancies in the thermal regimes of snow-covered and snow-free sites, even in immediately adjacent locations. Both the depth of frost penetration (Atkinson and Bay, 1940) and the magnitude of negative temperatures (Lachenbruch, 1959) may be damped. For these reasons, permafrost may not develop at sites which experience appreciable snow accumulations, even if other climatic parameters are favorable for its formation. Some aspects of the snow accumulation patterns are discussed below.

1) Snowfall Amounts and Ground Loads

As was noted previously, the mountains of the coastal sector are subject to substantial snow accumulation, while snowfall in the interior is far less. Schaerer (1970) has investigated the variation of ground snow loads in southern British Columbia. He shows that ground snow load increases exponentially with elevation in the west coast situation of Mt. Seymour, while the relationship is approximately linear farther inland. A similar situation may be expected across the northern Boundary Range, although the difference is probably not as great due to the smaller distances involved. It should also be noted that the interval between the elevation of the 0°C mean annual air isotherms and the zone of maximum precipitation is rather small in the coastal sector. Such patterns of ground cover are obviously more amenable to permafrost development in the interior than in coastal locations.

2) Timing of Snow Accumulation

Marcus (1964, pp. 61-65) has approximated the onset of accumulation conditions on the Lemon Creek Glacier for the years 1947-1957 through the use of radiosonde data. His computations show that accumulation usually begins in mid-to-late October at the 1000 m level, although it is occasionally delayed until early November. At 1400 m, accumulation conditions generally develop during early October. Therefore, at high levels, the onset of snow accumulation coincides with that period of the year during which precipitation is greatest. Heavy snow loads in the coastal sector during the autumn transition period effectively protect the ground from frost penetration. Although similar timing of accumulation onset and precipitation maximum may be expected farther inland (v. Chapter 1), absolute amounts of snowfall are far lower.

3) Density of the Snow Cover

As stressed by Kudryavtsev (1965, pp. 10-19), the effect of the snow cover can be correctly evaluated only if other climatic factors are taken into consideration. Given similar thicknesses of snow cover and identical mean annual air temperatures, the mean annual soil temperature will be higher in a continental than in a maritime climate. This is true not only because the density of snow under continental conditions is lower, but because removal of much of the summer heat stored in the soil will be prevented by the snow. Although the disparity in snow depths between the interior and coastal sectors is probably more than sufficient to offset the differences in density, the latter are not so great as would be the case if only snow thicknesses were considered.

On the other hand, the lower density of snow in the interior renders it vulnerable to drifting (Shumskii, 1964, pp. 230-239), so that many sites may have thin or negligible snow cover and are subject to deep frost penetration. Examination of air photos taken of the Cathedral Massif in December, 1948, confirms the existence of many snow-free sites, particularly on topographic highs such as ridge crests. Snow-free sites in winter are probably not as common under marine west coast conditions, by reason of the absolute amounts of snow involved, and because snow density is rather high. There are probably some winter snow-free sites in the coastal sector, especially where steep slopes predominate, but their frequency is undoubtedly more limited than in the interior.

3.5 Conclusions

1) Theoretically, if only air temperatures are taken into account, the lower limit of permafrost would appear to be at only slightly higher elevations on the western slope of the Boundary Range than in the interior. This remains to be demonstrated, however, since no reference to permafrost can be found in the literature and ground temperature data are not available in the study area.

2) The effects of the snow cover are probably so great in the

maritime sector that permafrost development is inhibited, and much less widespread than in the interior. Permafrost in the coastal sector, if it exists, is confined to wind-swept topographic highs where winter snow cover is minimal.

3) At lower elevations, under both maritime and continental conditions, permafrost occurrence is in large part controlled by aspect (restricted to ubac slopes), ground cover characteristics (snow and vegetation), and the thermal properties of the substratum.

4) The lower limit of permafrost is in equilibrium with present conditions in the Atlin area. We can, with some confidence, put the permafrost limit at about 915 m. This is under particularly favorable local conditions, however, and permafrost is widespread only at higher levels.

CHAPTER IV

DISTRIBUTION AND LIMITS OF PATTERNED GROUND

4.1 Literature Review

The question of the elevational threshold of patterned ground has been so widely addressed in the German-language literature (e.g., Troll, 1958; Hastenrath, 1959; Hövermann, 1962; Höllermann, 1967; 1972a; 1972c) that the latter investigator considers the problem "well worn" (Höllermann, 1972c). Most of these investigations were undertaken in Eurasia and North Africa, and it is in this region that the patterned ground limits are best known. Troll (1947) and Graf (1973) have synthesized most of this information in small-scale maps of patterned-ground occurrence for Eurasia.

As far as the situation in North America is concerned, Troll (1958, p. 8) remarked in his classic paper that the continent was so poorly studied that he could not attempt even a general descriptive account of the trend of patterned ground limits. In recent years there has been no shortage of patterned ground investigations on this continent, but few are concerned with delimitation of altitudinal zones of its occurrence. While many authors cite the elevation at which their studies were conducted, there is no assurance that these altitudes are the lowermost sites in any locality. The probability is strong that they often are not, since detailed site work is usually carried out on well-formed occurrences, and these are likely to be found well above the elevational threshold. To this writer's knowledge there has been only one detailed study published on the lower boundary of patterned ground in any area of North America. This investigation was performed by Höllermann (1972b) in the White Mountains of California/Nevada.

Studies of the patterned ground distribution were initiated in Europe by the 1930's (e.g., Poser, 1933). Troll's 1944 synthesis (Troll, 1958) went far toward making known the various types of patterned ground and their general world distribution. Troll (ibid, p. 7) believed that a climatic limit for patterned ground (Strukturbodengrenze) could be determined and that this limit "has a regular course which rises and falls with the forest boundary on the one hand and with the snow line on the other." Soon afterwards he published a map of Eurasia showing observed and theoretical patterned ground limits (Troll, 1947, Fig. 1, p. 164).

Hastenrath (1959; 1960) has examined regelation frequencies at various locations in the Alps and concluded that the number of freeze-thaw cycles is not the determining factor in patterned ground distribution. He considers vegetation as directly attributable to climate, and the crucial control over the lower limits. His conclusion is similar to Troll's in that he perceived this limit to follow the tree- and snowlines, increasing in elevation from the poles to the equator and from oceanic to continental regions.

A different viewpoint is maintained by Hövermann (1960; 1962), whose investigations convinced him that the lower limit of patterned ground descends with increased distance from oceanic influence therefore opposing the general trend of the tree and snowlines. He contends that on a continental scale, the amount of precipitation is not a primary control over patterned ground distribution. Instead, he considers thermal considerations more important, especially the number of freeze-thaw cycles. Hövermann believes that the magnitude of frost events also controls their morphologic effectiveness, and states that temperatures -4° to -5°C are needed for effective sorting to occur.

More recent investigations support the views of Troll and Hastenrath. Höllermann (1972a) studied patterned ground in the Pyrenees and found that its lower limit rises from west to east in response to decreasing oceanic influence. Graf (1973, p. 145) has published an isopleth map of thresholds of patterned ground for Eurasia whose trends are in agreement with Troll's (1947), although numerical values differ somewhat. Graf (ibid, pp. 149-150) also presents profiles along the 65th and 38th parallels, which show a general west-east increase in patterned ground and solifluction limits. Höllermann (1972b) makes the significant observation that patterned ground limits are not determined by thermal conditions so much as by vegetation cover in humid regions. Under arid conditions the relationship between soil moisture and the temporal occurrence of frost action is the critical factor. In most areas the solifluction limit is well below the patterned ground boundary, but in dry regions these limits coincide.

J. Lundqvist (1962, pp. 95-96; 1966, p. 148) concluded that edaphic and vegetative factors determine, respectively, the upper and lower limits of patterned ground in the Swedish Caledonides. These controls operate within a broad climatic framework in which local conditions are most important. The upper limit coincides with a lack of soil at high levels, while occurrences are prohibited at lower levels by "thick vegetation." Lundqvist also found that sorted features are most common in the southern Caledonides, where the climate is most continental.

It should be noted that these authors all have taken the occurrence of small-diameter patterned ground as their lower limit. Troll (op. cit., p. 83) believed that large-diameter forms generally occur below the level of the miniature features in the Alps. However, the more detailed subsequent observations of Kelletat (1969) in Italy, Höllermann (1967), Furrer (1965), and Furrer and Dorigo (1972) in the Alps and Preusser (1973) in Iceland show that not only is the threshold for the miniature forms lower, they may also occur over a wider range of elevations. According to Furrer and Dorigo (1972, p. 104), large-diameter patterned ground is found above the "permafrost boundary," while small-diameter forms lie closer to or may straddle it.

Furrer (1965) is cited by Washburn (1973, p. 101) as having outlined a characteristic altitudinal sequence of patterned ground forms in the Alps. This sequence is, in ascending order:

1) zone of plowing blocks;
2) zone of garlands;
3) zone of earthflows;
4) zone of miniature patterned ground;
5) zone of sorted or stony lobate forms;
6) zone of large sorted patterned ground.

An interesting approach to the study of patterned ground distribution was taken by Caine (1972), who statistically analyzed 79 small-diameter occurrences in the English Lake District to determine the relative importances of lithology, elevation, and orientation. The lower limit was taken to be ≈600 m, while modes occurring at the 700 and 820 m levels are related to low-angle slopes. Aspect appears not to be an important factor here, since application of Rayleigh and X^2 tests to orientation data failed to define a preferred azimuthal class. The climatic control was, therefore, interpreted to be that of temperature effects induced by elevation, rather than radiation or wind effect. Nearest neighbor analysis and examination of reflexive links show that occurrences are more tightly clustered on slates than on volcanic rocks. This association was thought to be more a function of the frost susceptibility of weathering products than of the rock itself. Caine concludes the study by emphasizing the need for multivariate analysis of the problem, particularly when large geographic areas are investigated.

The classic view that patterned ground limits are determined by the macroclimate is not sufficient; in recent years the importance of meso- and microenvironmental parameters have become increasingly appreciated. Exemplary in this regard are the works of Höllermann (1972b) and Furrer (1965b), who show that the lower boundary of the "subnival" zones ascends 400 m in the 85 km between Lake of Thun and the Matterhorn. It is also clear that patterned ground may be found over a wide range of climatic situations. Unfortunately, the polygenetic nature of patterned ground, and the fact that forms occurring under different climatic regimes may be so dissimilar in size, appearance, and/or genesis, indicate that synthesis on a global or continental scale can be quite misleading. This problem may be at the root of disagreements over the trend of patterned ground elevational thresholds in mountainous regions. It is this writer's opinion that study of the effects of latitude or continentality of patterned ground distribution should be pursued with only comparable forms considered in a given study area. As was shown above, some forms of small and large-diameter patterned ground, although similar in appearance, may not be merely reflections of the opposing ends in a continuum of process intensity or frost cycle duration. Rather, they may be unrelated genetically and both should not be used indiscriminately for defining a singular lower limit of patterned ground occurrence.

4.2 Distribution of Patterned Ground in the Juneau Icefield Region

Since no large-diameter patterned ground was discovered on the west slope of the Boundary Range, the prerequisite for homogeneous forms to be used in defining regional trends of the Strukturbodengrenze is not fulfilled. If only small-diameter patterned ground is considered, the lower limit rises inland, as discussed below. The distribution of large-diameter patterned ground in the Juneau Icefield region may be similar to that of permafrost, but is subject to the same uncertainties.

4.2.1 West Slope

No occurrences of large-diameter forms were noted on the west slope, but it was not possible to investigate terrain above 1375 m in this area. The assemblage of small-scale cryogenic forms (plowing blocks, small turf-banked lobes, miniature patterned ground) here indicates that between 1200-1375 m the lowermost periglacial étage (v. Rundberg, 1972) is reached. It is therefore possible that large-diameter patterned ground may indeed exist at higher levels, for example in the Fairweather Range. However, this writer found no references to such sites in the geomorphological literature dealing with southeast Alaska. It appears certain, however, that far fewer occurrences are likely under maritime conditions than continental, owing to the depth of the winter snow cover and timing of the onset of the accumulation season (v. section 3.4), and their attendant influence on soil freezing and the depths of frost penetration. A similar relationship has been suggested by W. Thompson (1962) for rock glaciers in the Olympic and Cascade Ranges of Washington. These features are absent throughout the area of oceanic conditions, but rock glaciers were discovered where the climate is of a more continental nature, as on the eastern slope of the Cascades adjacent to the Okanogon region. Thompson attributes this distribution to the effects of heavy ground snow loads on the Balch ventilation process. Where show cover is thin, Balch ventilation is unimpaired, and rock glaciers may form. A similar distribution of rock glaciers was observed in the Juneau Icefield Region. None are found in the coastal sector, but they become increasingly frequent in the Atlin region, as well as in the area of the Haines Cutoff, both of which are orographically sheltered. Hansen (1976) has also noted a greater frequency of turf-banked terraces in the continental parts of the Olympic Mountains than on the seaward side. It seems likely that the distribution of all these features is controlled by the depth and timing of the snow cover.

4.2.2 Interior of Icefield

In the central icefield area, widespread occurrence of large-diameter patterned ground is prevented by edaphic, lithological, and gradient factors, as well as by a heavy snow cover.

Lietzke and Whiteside (1972) estimate that on the nunataks of the cnetral icefield, only 2% of the surfaces snow-free in summer possess a soil mantle, while the rest are composed of bedrock or rubble. Since effective frost sorting requires an appreciable percentage of fines and a wide range of grain sizes, little patterned ground development can be expected, on this basis alone.

The predominantly granitic character of the nunataks in this area is also a factor preventing formation of sorted patterned ground. The homogeneous gravelly nature of the weathering products of these granular lithologies effectively prohibits both frost sorting and solifluction processes. Furthermore, the predominance of steep slopes dictates that most have a positive denudation balance (Jahn, 1968), so that topographic sites suitable for patterning are both rare and limited in extent (Figure 4-1). Also pertinent in this regard is the general observation that on the occasional flat sites, covers of perennial snow and ice persist, especially in the more maritime sectors of the icefield and at shadowed sites. With increasing elevation and continentality, and decreasing snow cover, conditions for patterning become more favorable, and some occurrences of large-diameter patterned ground have been noted on relatively level topographic sites above 2135 m in the vicinity of Mt. Nesslerode near the international border (Hamelin, 1964; Miller, 1977). At these elevations, we are well into the "frost-shatter zone" of Rudberg (1972), where blockslopes and blockfields occupy large areas, a situation much less pronounced on nunataks in the vicinity of Camp 10.

4.2.3 Atlin Region (East Slope)

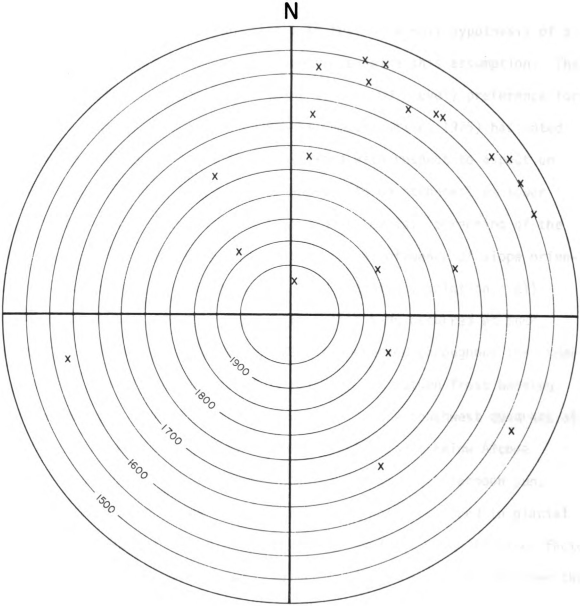
Patterned ground in the interior has a much wider distribution than in any other area investigated. In addition to sites in the Cathedral Massif described above, patterned ground has been found on Teresa Island, in relative abundance above 1925 m adjacent to the Fourth of July Creek Valley (Tallman, 1975, pp. 110-111), and elsewhere (Miller, 1977).

The writer's investigations were concentrated in the Cathedral Massif, where 22 separate patterned ground sites were mapped. The mapping procedure was to follow contours in the study area at 50 m intervals. Occurrences were plotted on a preliminary edition of the present base map by compass and map triangulation, with the assistance of a pocket altimeter.

Figure 4-2 illustrates the elevation and aspect of the 22

Figure 4-1. View to west from Camp 10 in interior of Juneau Icefield, showing predominance of steep slopes typical of the area.

Figure 4-2. Polar diagram showing aspect and elevation of patterned ground sites, Cathedral Massif.


N
1900
1800
1700
1600
1500

sites.[1] The diagram suggests that patterned ground is most likely to occur on slopes in the NE guadrant; a X^2 test on a null hypothesis of a uniform azimuthal distribution was used to examine this assumption. The results indicate a strong (significant at the .001 level) preference for the NE quadrant. S. Buttrick (personal communication, 1975) has noted that patterned ground is similarly situated with respect to aspect on nearby Teresa Island. This control appears to be strongest at lower elevations, and decreases somewhat at higher levels. Screening of the horizon by local topography may counteract the influence of slope orientation, however, by shielding a site from incoming insolation. All patterned ground sites with aspect other than N-NE occurred at such locations. At these sites, snowbanks are preserved throughout the summer, inhibiting vegetation and providing moisture for autumn frost heaving. A prime example is the anomolous occurrence in the southwest quadrant at 1575 m. This site is situated in Chapel Valley, just below Alcove Glacier's cirque; it is effectively shielded from the afternoon sun.

Most patterned ground sites investigated were developed in glacial till. This material is not a prerequisite, however, since if other factors are conducive to its development, patterned ground may occur wherever the local bedrock has been converted by weathering processes into a fairly wide range of grain sizes.

Another factor contributing to the relative abundance of patterned ground in the Atlin area is the high frequency of low-angle slopes at relatively high elevations (i.e., above 1500 m), where other conditions

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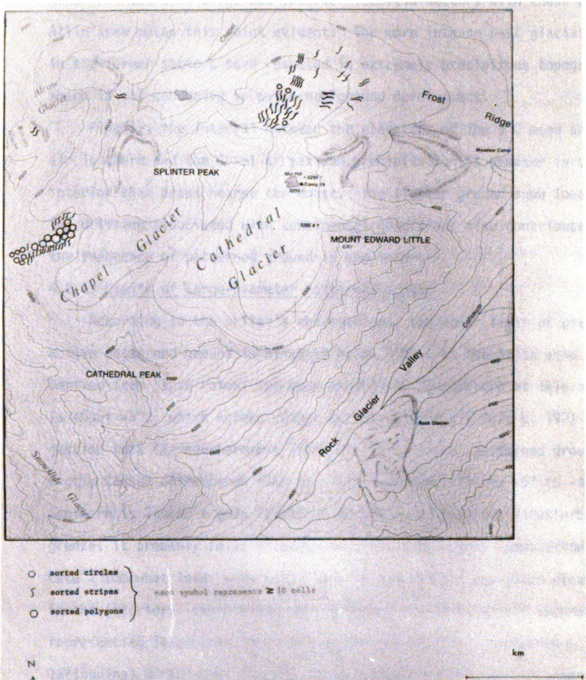
[1]It is emphasized that a greater number of cells was found in terrain above 1600 m, but that many of these were large systems of individual cells, and were therefore tallied as single occurrences. Inspection of Figure 4-3 will clarify the distribution of cells in absolute numbers.

Figure 4-3. Map of patterned ground sites in the Cathedral Massif.



PATTERNED GROUND IN THE CATHEDRAL MASSIF are optimal for patterned ground development. Comparison of topographic maps from the west slope and interior icefield sectors with those of the Atlin area makes this point evident. The more intense past glaciations in the former sectors have resulted in extremely precipitous topography, which is not conducive to patterned ground development.

Finally, the interval between the elevation of the 0°C mean annual air isotherm and the level of maximum precipitation is greater in the interior than areas nearer the coast. The lighter ground snow loads and the drifting associated with continental conditions also contribute to the frequency of patterned ground in the interior.

4.2.4 Limits of Large-Diameter Patterned Ground

According to the writer's observations, the lower limit of presently active patterned ground is slightly below 1500 m in the Atlin area. Derived from lapse rates, the mean annual air temperature at this altitude is about -5°C, which agrees rather well with Bird's (1967, p. 197) suggestion that the southernmost limit of "conspicuous" patterned ground in arctic Canada corresponds with the -4°C isotherm. If the -5° to -4°C isotherm is indeed a good indicator of the large-diameter Strukturbodengrenze, it probably falls slightly from SW to NE, since computations indicate a somewhat lower mean annual air temperature at any given elevation in the interior. Lapse rates are, however, not particularly accurate for representing local conditions in mountainous terrain. Furthermore, the latitudinal difference of about 135 km between Juneau and Atlin has not been taken into consideration and is probably of some importance. There are at present too many unknowns for a definitive statement on the trend of large-diameter patterned ground thresholds in this area.

4.2.5 Local Variations

While in a very broad sense, the regional climate may be viewed as the primary control over patterned ground occurrence, microenvironmental parameters are of great importance at the local level. This is well illustrated by the presence of active and inactive features in immediately adjacent situations, as discussed in Chapter II. Furthermore, once the critical elevational threshold has been reached (determined over a broad area by the mean annual air temperature and hence the macroclimate) patterned ground occurs over a wide range of elevations.

Benedict (1976) has made a strong case for distinguishing between environments conducive to the present development of solifluction features and those environments that serve only to maintain forms developed previously during a more rigorous climatic interval. This also appears true for patterned ground, and the relationship is not restricted to large-scale climatic change and accompanying vertical adjustments of the altitudinal zones. Also important are subtle changes in local conditions, such as snowmelt patterns.

Above the 1600 m level in the Cathedral Massif, the patterns appear to be still in developmental stages, as evidenced by silt-capped stones and minimal lichenization at the more suitable sites. It also seems likely that patterned ground has developed rather recently near the Balcony Glacier (Figure 4-4) at 1950 m. Moderately well-developed sorted stripes are found near the lower margin of this small glacier. The stripes have probably formed since the waning of the 18th century neoglacial maximum, when the Balcony's ice covered a much larger area than at present.

On the other hand, below 1600 m and descending to what appears to be the lower limit of presently active patterned ground at about 1490 m, the features have a more subdued appearance, although they are not necessarily heavily vegetated or lichenized. It would be most instructive to obtain comparative movement data from sorted stripes at various elevations, in order to determine differences in process intensity and to ascertain the lower boundary of activity within patterned ground. On the basis of morphological evidences, observed during the 1976 field season (in which summer ablation on nearby glaciers exceeded the average of most years), the latter "boundary" lies approximately 100 m below the lower level at which perennial snowbanks survive.

Of considerable interest to the delineation of altitudinal sequences of patterned ground are the large sorted circles found on the shore of a small unnamed lake at 975 m in the Fourth of July Creek Valley (Figure 4-5). Since large-diameter patterned ground is usually found only at considerably higher levels in this area, Tallman (1975, p. 110) and Miller (1976, p. 267) have interpreted these features as relicts from the early Holocene (7000-9000 years B.P.). This assumption is based on C-14 dates obtained from organic material within the basal layers of adjacent bogs, and by the discovery of similar features at low elevation on the west slope of the Boundary Range.

In the writer's opinion, these features are to be considered extrazonal and recently active, although their present inactivity is not disputed. The difference of opinion in this matter thus involves the length of time involved since cessation of activity in the patterned ground. The present interpretation is based on the following points:

1) It is unlikely that these features have remained inactive since the early Holocene (as was recognized by Tallman) since such a situation would almost certainly result in their eradication by sedimentation in

Figure 4-4. Sorted stripes at margin of Balcony Glacier, 1950 m, Cathedral Massif. Note trim line on facing wall.

Figure 4-5. Extrazonal patterned ground at 975 m, Fourth of July Creek Valley.

Creek

this topographically depressed site.

2) The patterned ground is in close proximity to the palsa bogs discussed in Chapter III, and are, therefore, at present in the lower part of the discontinuous permafrost zone. It is possible that only a slight depression of the mean annual air temperature would be sufficient to reactivate them.

Troll (1958, p. 41) has discussed "azonal" patterned ground attributable to "nonclimatic intensification" of frost processes. One such group is patterned ground on lakeshores, often found far below the "climatic limit" for a particular locale. Conditions especially conducive for the development of patterned ground are induced by seasonal (summer) soaking of the soil. By autumn, when lake levels have fallen, the saturated sediments are subjected to deep freezing, a condition favorable to the development of patterned ground. This summer saturation provides a high effective "precipitation," so that large accretions of segretation ice and associated sorting processes are possible. Tallman (1975, p. 110) has noted that these circles are frequently under water in summer, and concluded that this condition has resulted in termination of their growth, a view with which this writer does not concur. Troll (op. cit., p. 41) has cited a large number of localities where pattern formation was enhanced at lakeshore sites, and J. Lundqvist (1962, pp. 78-82) reports a number of similar situations in Sweden. The Fourth of July circles bear striking similarity to those in photographs presented by Lundqvist, and it seems reasonable to conclude that their development is the result of nonclimatic intensification of pattern-generating processes. It may be that cessation of their activity is due not only to a recent warming trend, but to lower mean summer lake levels. When viewed by this writer in early July, 1975, the Fourth of July patterned ground already lay above lake level. Tallman (1975, pp. 107-110) documents the existence of a number of "nivation hollows" nearby, which in recent years have experienced complete meltout during summer. The dearth of lichen within these hollows testifies to their occupation by late lying snow and ice within very recent times. An increased snowpack, and the presence of snow at lower levels than at present would undoubtedly result in the lake maintaining high levels until later in the summer. Under such conditions we may expect a higher moisture content at the onset of the autumn freeze, with a corresponding increase in susceptibility to cryogenic processes. Since the features have not been buried by sedimentation, it appears likely that the patterned ground at this location suffered termination of its activity with the climatic warming and rise in the regional snow line following the demise of the 18th century neoglacial maximum.

These observations show that even though patterned ground may in the future be a useful tool in environmental reconstruction, its sensitivity to changes in local conditions warrants extreme caution in interpretation. Much remains to be learned about the many factors affecting its behavior under changing climatic regimes.

4.2.6 Limits of Small-Diameter Patterned Ground

It has been previously shown that small-diameter forms of sorted patterned ground are to be regarded as extrazonal or even as azonal phenomena, owing to their distribution over a wide range of latitudes and altitudes. However, conditions for their development are probably optimal at sites marked by frequent small-magnitude frost heave cycles and lacking a restrictive vegetation cover. Even though the delimitation of the range of small-diameter patterns was not a primary objective of this study, it may be concluded that these features can form under less severe conditions than the large-diameter variety, although the two types may coexist at a given site.

It is certain that small-diameter forms exist at lower elevations in the martitime sector than in the interior. Their development appears to be dependent upon, or coincident with, the presence of bare patches of soil. While the lowermost site investigated by this writer was at 1325 m on Cairn Ridge near Juneau, Ugolini (1966, pp. 34-35) found similar features at 800 m near Muir Inlet. In the same locality, Goldthwait (written communication, 1977) discovered active miniature polygons at 760 m. By contrast, the lowest site noted in the Cathedral area was about 1490 m, although they are widespread at this level, and may exist below. It appears likely that the situation is similar to that observed in Europe, where miniature, but not large-diameter forms are found at anomolously low elevations in oceanic situations. For this reason - and other stated in Chapter II - it seems wise to separate small and large-diameter forms when attempting to trace the regional threshold of patterned ground. Even though the Strukturbodengrenze of the small-diameter forms rises in response to increasing continentality, it is possible that the threshold of the large-diameter variety has an opposite trend. This is particularly likely to be true if the "lower limit" of the patterned ground is taken not as the lowest of isolated occurrences, but as the arithmetic average of the lowest sites in an area, as suggested by Furrer and Dorigo (1972).

4.3 Conclusions and Recommendations

Data on the lower limits of large-diameter patterned ground are too few at present to delimit a regional trend in its elevational threshold across the northern Boundary Range. Other aspects of the research hypothesis do appear to be substantiated, however. It is apparent that occurrences are more widespread in the interior, primarily due to continental conditions of solid precipitation and ground cover, as well as a high frequency of flat sites at high elevation. The trend of the small-diameter variety may be traced from relatively low levels under maritime conditions near Juneau to higher elevations in the interior. The genetic differences between these two varieties is stressed, however, and it is possible that their lower boundaries have opposite trends.

At a particular site, patterned ground develops only where conditions allow for saturation of the regolith at the time of the autumn freeze. Such conditions are optimal at the downslope edge of late-lying or perennial snowbanks. Aspect is a very important control because snowbanks are most likely to persist on slope facing north to northeast. Relatively low-angle (<15°) slopes and heterogeneously-sized parent material are also prerequisites to the development of large-diameter patterned ground.

It is recommended that the problem of the trend of elevational thresholds of patterned ground be pursued further in the Alaska-Yukon-British Columbia area, since the north-south trending coastal ranges provide an exceptionally steep continentality gradient not often found on other continents. If windswept topographic highs remain snow-free in winter, the high peaks of the Fairweather Range must provide sufficient elevations for the development of both permafrost and patterned ground. It is suggested that this area be investigated for the occurrence of both phenomena, discovery of which would greatly enhance our knowledge of maritime and alpine periglacial conditions.

BIBLIOGRAPHY

BIBLIOGRAPHY

Ahlmann, H. W. (1936)
Polygonal Markings
Geografiska Annaler, Bd. 18, pp. 7-19

Aitken, J. D. (1955)
Atlin, British Columbia (preliminary map),
Paper 54-9, Canada Department of Mines and Technical Surveys,
Geological Survey of Canada.

--------, (1959)
Atlin Map-Area, British Columbia
Memoir 307, Geological Survey of Canada, 89 pp.

Anderson, J. H. (1970)
A Geobotanical Study in the Atlin Region in Northwestern British Columbia and South-Central Yukon Territory
Ph.D. Thesis, Department of Botany and Plant Pathology,
Michigan State University, 380 pp.

Andress, E. C. (1962)
Névé Studies on the Juneau Icefield, Alaska, 1961 With Special Reference to Glacio-Hydrology on the Lemon Glacier
M. Sc. Thesis, Department of Geology, Michigan
State University, 174 pp.

Andrews, J. T. and Shimizu, K. (1966)
Three-Dimensional Vector Technique for Analyzing Till
Fabrics: Discussion and Fortran Program
Geographical Bulletin, vol. 8, pp. 151-165.

Anketell, J., Cegła, J., and Dżułyński, S. (1970)
On the Deformational Structures in Systems with Reversed
Density Gradients
Rocznik Polskiego Towarzystwa Geologicznego, vol. 40,
pp. 1-30.

Antevs, E. (1932)
Alpine Zone of Mt. Washington Range
Auburn, Maine: Merrill & Webber, 118 pp.

Atkinson, H. B. and Bay, C. E. (1940)
Some Factors Affecting Frost Penetration
Transactions of the American Geophysical Union, pt.3, pp. 935-947.

Baranov, I. Ya. (1964)
Geographical Distribution of Seasonally Frozen Ground and Permafrost
In: Principles of Geocryology, part I, Chapter VII, (1959), Academy of Sciences of the U.S.S.R., Moscow.
Ottawa: National Research Council of Canada, Division of Building Research, Technical Translation 1121, 85 pp.

Benedict, J. B. (1965)
Patterned Ground on Niwot Ridge, Boulder County, Colorado
pp. 23-26 in: Schultz, C. B., and Smith, H. T. U., (eds.), Guidebook for One-Day Field Conferences, Boulder, Colorado, INQUA, 7th Congress, Boulder.
Lincoln: Nebraska Academy of Sciences.

--------, (1966)
Radiocarbon Dates From a Stone-Banked Terrace in the Colorado Rocky Mountains, U.S.A.
Geografiska Annaler, vol. 48A, pp. 24-31.

--------, (1970a)
Downslope Soil Movement in a Colorado Alpine Region: Rates, Processes, and Climatic Significance
Arctic and Alpine Research, vol. 2, pp. 165-226.

--------, (1970b)
Frost Cracking in the Colorado Front Range
Geografiska Annaler, vol. 52A, pp. 87-93

--------, (1976)
Frost Creep and Gelifluction Features: A Review
Quaternary Research, vol. 6, pp. 55-76.

Bird, J. B. (1967)
The Physiography of Arctic Canada with Special Reference to the Area South of Parry Channel, Baltimore: The John Hopkins Press, 336 pp.

Birkeland, P. W. (1974)
Pedology, Weathering, and Geomorphological Research
New York: Oxford Press, 285 pp.

Brazel, A. J. (1974)
A Note on Topoclimatic Variation of Air Temperature, Chitistone Pass Region, Alaska
Icefield Ranges Research Project, Scientific Results, vol. 4, pp. 81-86.

Brockie, W. J. (1964)
Patterned Ground - Some Problems of Stone Stripe Development in Otago
Fourth New Zealand Geography Conference, Proceedings, pp. 91-104.

--------, (1968)
A Contribution to the Study of Frozen Ground Phenomena-Preliminary Investigations into a Form of Miniature Stone Stripes in East Otago
Fifth New Zeland Geography Conference, Proceedings, pp. 191-201.

Brown, R. J. E. (1966)
Influence of Vegetation on Permafrost
pp. 20-25 in: Permafrost International Conference, 11-15 November, 1963, Lafayette, Indiana, National Academy of Sciences - National Research Council Publication 1287, 563 pp.

--------, (1967a)
Permafrost in Canada
Geological Survey of Canada, Map 1246A.

--------, (1976b)
Permafrost Investigations in British Columbia and Yukon Territory
Ottawa: National Research Council of Canada, Division of Building Research, Technical Paper no. 253, 55 pp. + appendices.

--------, (1970)
Permafrost in Canada
Toronto: University of Toronto Press, 234 pp.

--------, and Kupsch, W. O. (1974)
Permafrost Terminology
Ottawa: National Research Council of Canada, Associate Committee on Geotechnical Research, Technical Memorandum no. 111, NRCC 14274, 62 pp.

Bryan, K. (1945a)
Cryopedology - the Study of Frozen Ground and Intensive Frost Action with Suggestions on Nomenclature
American Journal of Science, vol. 244, pp. 622-642.

--------, (1946b)
Permanently Frozen Ground
Military Engineer, vol. 38, p. 168.

Bryson, R. and Hare, F. K. (1974)
Climates of North America, World Survey of Climatology, vol. 11, New York: Elsevier Scientific Publishing Company, 404 pp.

Bunting, B. T. and Jackson, R. H. (1970)
Studies on Patterned Ground on SW Devon Island, N.W.T.
Geografiska Annaler, vol. 52A, pp. 194-208.

Cairnes, D. D. (1913)
Portions of Atlin District, British Columbia: With Special Reference to Lode Mining
Memoir 37, Canada Department of Mines, Geological Survey Branch, 129 pp.

Caine, N. (1963)
The Origin of Sorted Stripes in the Lake District, Northern England
Geografiska Annaler, vol. 45, pp. 172-179.

--------, (1972)
The Distribution of Sorted Patterned Ground in the English Lake District
Revue de Géomorphologie Dynamique, vol. 21, pp. 49-56.

Carrara, P. E. (1973)
Transition From Shear Moraines to Rock Glaciers (letter)
Journal of Glaciology, vol. 12, p. 149

Chambers, M. J. G. (1966a)
Investigations of Patterned Ground at Signy Island, South Orkney Islands, I: Interpretation of Mechanical Analyses
British Antarctic Survey Bulletin, no. 9, pp. 21-40.

--------, (1966b)
Investigations of Patterned Ground at Signy Island, South Orkney Islands, II: Temperature Regimes in the Active Layer
British Antarctic Survey Bulletin, no. 10, pp. 71-83

--------, (1967)
Investigations of Patterned Ground at Signy Island, South Orkney Islands, III: Miniature Patterns, Frost Heaving and General Conclusions
British Antarctic Survey Bulletin, no. 12, pp. 1-22

Conrad, V. (1946)
Polygon Nets and Their Physical Development
American Journal of Science, vol. 244, pp. 277-296.

Corte, A. E. (1961a)
The Frost Behavior of Soils. I. Vertical Sorting
Highway Research Board Bulletin, 317, National Academy of Sciences - National Research Council publication 963, pp. 9-34.

--------, (1961b)
The Frost Behavior of Soils. II. Horizontal Sorting
Highway Research Board Bulletin, 331, National Academy of Sciences - National Research Council Publication 1013, pp. 46-66.

Corte, A. E. (1962)
Relationship Between Four Ground Patterns, Structure of the Active Layer, and Type and Distribution of Ice in the Permafrost
U.S. Army, Corps of Engineers, Cold Regions Research and Engineering Laboratory Research Report 88, 79 pp. + appendices, figures.

--------, (1966a)
Particle Sorting by Repeated Freezing and Thawing
Biuletyn Peryglacjalny, no. 15, pp. 175-240.

--------, (1966b)
Experiments on Sorting Processes and the Origin of Patterned Ground, pp. 130-135 in:
Permafrost International Conference,
11-15 November, 1963, Lafayette, Indiana, National Academy of Sciences - National Research Council Publication no. 1287, 563 pp.

--------, and Higashi, A. (1960)
Experimental Research on Desiccation Cracks in Soil
U.S. Army, Corps of Engineers, Snow Ice and Permafrost Research Establishment Research Report 66, 48 pp.

Crampton, C. B. (1977)
Changes in Permafrost Distribution in Northeastern British Columbia
Arctic, vol. 30, pp. 61-62.

Daubenmire, R. (1953)
Notes on the Vegetation of Forested Regions of the Far Northern Rockies and Alaska
Northwest Science, vol. 27, pp. 125-138.

Dżułyński, S. (1963)
Polygonal Structures in Experiments and Their Bearing on Some Periglacial Phenomena
Bulletin de L'Académie Polonaise des Sciences série des Sciences Géologiques at Géographiques, vol. 11, pp. 145-150.

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

Ferriens, O. L. (1965)
Permafrost Map of Alaska,
U.S. Geological Survey, Miscellaneous Geological Investigations, Map I-445.

Fleisher, J. (1972)
Periglacial Features Above the Névé-Line pp. 78-81 in:
Miller, M. M. (ed.)
A Principles Study of Factors Affecting the Hydrological Balance of the Lemon Glacier System and Adjacent Sectors of the Juneau Icefield, Southeastern Alaska, 1965-69,
East Lansing: Institute of Water Research, Michigan State University, 92 pp. + maps, diagrams

Forbes, Robert B. (1959)
The Bedrock Geology and Petrology of the Juneau Ice Field Area, Southeastern Alaska
Ph.D. Thesis, Department of Geology, University of Washington.

Freers, T. R. (1966)
A Structural and Morphogenetic Investigation of the Vaughan Lewis Glacier and Adjacent Sectors of the Juneau Icefield, Alaska
M. Sc. Thesis, Department of Geology, Michigan State University, 132 pp.

French, H. M. (1976)
The Periglacial Environment
New York: Longman Group, 309 pp.

Furrer, G. (1965a)
Die Höhenlage von Subnivalen Bodenformen
Univ. Zürich, Habilitationsschrift Philosophischen Fakultät-II, 89 pp.

--------, (1965b)
Die Subnivale Höhenstufe und ihre Untergrenze in den Bündner and Walliser Alpen
Geographica Helvetica, Bd. 20, pp. 185-192.

--------, (1968)
Untersuchungen au Strukturböden in Ostspitzbergen, ihre Bedeutung für die Erforschung Rezenter und Fossiler Frostmusterformen in den Alpen bzw. im Alpenvorland
Polarforschung, Bd. 6, pp. 202-206.

--------, and Bachmann, F. (1968)
Die Situmetrie (Einregelungsmessung) als Morphologische Untersuchungsmethode
Geographica Helvetica, Bd. 23, pp. 1-14.

--------, and Dorigo, G. (1972)
Abgrenzung and Gliederung der Hochgebirgsstufe der Alpen mit Hilfe von Solifluktionsformen
Erdkunde, Bd. 26, pp. 98-107.

Furrer, G. and Fitze, P. (1973)
Treatise on the Permafrost Problem in the Alps, pp. 10-29 in: Translation of Two Swiss Articles on Permafrost in the Alps
Ottawa: National Research Council of Canada, Division of Building Research, Technical Translation 1657, 29 pp.
Originally published in: Vierteljahrsschrift der Naturforschenden Gessellschaft in Zürich, 115, (1970), pp. 353-368.

Gradwell, M. W. (1957)
Patterned Ground at a High Country Station
New Zealand Journal of Science and Technology, vol. 38, pp. 793-806.

Goldthwait, R. P. (1976)
Frost Sorted Patterned Ground: A Review
Quaternary Research, vol. 6, pp. 27-35.

Gorcynski, W. (1920)
Sur le Calcu du Degré du Continentalisme et son Application dans la Climatologie
Geografiska Annaler, Bd. 2, pp. 324-331.

Graf, K. (1973)
Vergleichende Betrachtungen zur Solifluktion in Verschiedenen Breitenlagen
Zeitschrift für Geomorphologie, Supplementband 16, pp. 104-154.

Gwillim, J. C. (1901)
Report on the Atlin Mining District, British Columbia
Geological Survey of Canada, Annual Report, vol. 12, 1899, pp. 1B-48B.

Haeberli, W. (1975)
Eistemperaturen in den Alpen
Zeitschrift für Gletscherkunde and Glazialgeologie, Bd. 11, pp. 203-220.

Hamelin, L.-E. (1964)
Périglaciare du Massif Juneau en Alaska
Biuletyn Peryglacjalny, nr. 13, pp. 5-14.

--------, and Cook, F. A. (1967)
Le Périglaciaire Par Image - Illustrated Glossary of Periglacial Phenomena
Quebec: Les Presses de l'Université Laval, 237 pp.

Hann, J. (1903)
Handbook of Climatology
London: MacMillan & Co., 437 pp.
Translation by R. De Courcy Ward.

Hansen, K. (1976)
The Nature and Distribution of Turf-Banked Terraces in the Olympic Mountains, Washington
M.A. Thesis, Department of Geography, Portland State University, 81 pp.

Harrison, P. W. (1957)
New Technique for Three-Dimensional Fabric Analysis of Till and Englacial Debris
Journal of Geology, vol. 65, pp. 98-105.

Hastenrath, S. (1959)
Zur Vertikalen Verteilung von Frostwechseln and Froststrukturböden in den Alpen
Berichte des Deutschen Wetterdienstes, Bd. 8, pp. 288-292.

--------, (1960)
Klimatische Voraussetzungen and Grossäumige Verteilung der Froststrukturböden
Zeitschrift für Geomorphologie, Bd. 4, pp. 69-73.

Hay, T. (1936)
Stone Stripes
Geographical Journal, vol. 87, pp. 47-50.

--------, (1943)
Notes on Glacial Erosion and Stone Stripes
Geographical Journal, vol. 102, pp. 13-20.

Höllermann, P. W. (1967)
Zur Verbreitung Rezenter Periglazialer Kleinformen in den Pyrenaen and Ostalpen (mit Ergänzungen aus dem Apennin und dem Französischen Zentralplateau)
Göttinger Geographische Abhandlungen, Heft 40, pp. 1-198.

--------, (1972a)
Zur Naturräumlichen Höhenstufung der Pyrenäen pp. 36-60 in: Troll, C. (ed.)
Geoecology of the High Mountain Regions of Eurasia, Wiesbaden: F. Steiner, 299 pp.

--------, (1972b)
Beiträge zur Problematik der Rezenten Strukturbodengrenze
Göttinger Geographische Abhandlungen, Heft 60, pp. 235-260.

--------, (1972c)
Zur Frage der Unteren Strukturbodengrenze in Gebirgen der Trockengebiete
Zeitschrift für Geomorphologie, Supplementband 15, pp. 156-166.

Hövermann, J. (1960)
Uber Strukturboden in Elburs (Iran) and zur Frage des Verlauis der Strukturbodengrenze
Zeitschrift für Geomorphologie, Bd. 4, pp. 173-174.

--------, (1962)
Uber Verlauf and Gesetzmässigkeit der Strukturbodengrenze
Biuletyn Peryglacjalny, nr. 11, pp. 201-207.

Hulten, E. (1968)
Flora of Alaska and Neighboring Territories
Stanford: Stanford University Press, 1008 pp.

Huxley, J. S. and Odell, N. E. (1924)
Notes on Surface Markings in Spitsbergen
Geographical Journal, vol. 63, pp. 207-229.

Ivanov, N. N. (1959)
Belts of Continentality on the Globe
Izvestiia Vsesoivznoe Geografiia Obshchestovo, 91, pp. 410-423.

Ives, J. D. (1974)
Permafrost pp. 159-194 in:
Ives, J. D., and Barry, R. G., (eds.),
Arctic and Alpine Environments,
London: Metheun & Co., 999 pp.

Jäckli, H. (1957)
Gegenwartsgeologie des Bündnerischen Rheingebietes
Beiträge zur Geologie der Schweiz, Geotechnische Serie 36, 136 pp.

Jahn, A. (1954)
Walery Lozinski's Merits for the Advancement of Periglacial Studies
Biuletyn Peryglacjalny, nr. 1, pp. 117-124.

--------, (1966)
Origin and Development of Patterned Ground in Spitsbergen
pp. 140-145 in:
Permafrost International Conference,
11-15 November, 1963, Lafayette, Indiana, National Academy of Sciences - National Research Council Publication 1287, 563 pp.

--------, (1968)
Denudational Balance of Slopes
Geographia Polonica, 13, pp. 9-29.

--------, (1970)
Soil Movements Under the Influence of Freezing
pp. 119-123 in:
Ecology of the Subarctic Regions,
Paris: UNESCO, 364 pp.

Johansson, O. V. (1931)
Die Hauptcharakteristika des Jährlichen Temperaturganges
Gerlands Beitrage zur Geophysik, Bd. 33, pp. 406-428.

Jones, V. K. (1975)
Contributions to the Geomorphology and Neoglacial Chronology of the Cathedral Glacier System, Atlin Wilderness Park, British Columbia
M. Sc. Thesis, Department of Geology, Michigan State University, 183 pp.

Kalsbeek, F. (1963)
A Hexagonal Net for the Counting Out and Testing of Fabric Diagrams,
Neues Jahrbuch für Mineralogie, Monatshefte, vol. 7, pp. 173-176.

Kaplar, C. W. (1969)
Phenomena and Mechanism of Frost Heaving (preprint)
49th Highway Research Board Annual Meeting, Washington, D.C. 1970, 44 pp.

Kelletat, D. (1969)
Verbreitung and Vergesellschaftung Rezenter Periglazialerscheinungen im Appenin
Göttinger Geographische Abhandlungen, Heft 48, 114 pp.

Kendrew, W. G. and Kerr, D. (1955)
The Climate of British Columbia and the Yukon Territory
Ottawa: Edmond Cloutier, 222 pp.

Kershaw, G. P. (1976)
The Periglacial Environment and its Limitations to Development. The Mactung Case Study, Northwest Territories - Yukon Territory
M. A. Thesis, Department of Geography, University of Waterloo, 298 pp. + maps.

King, C. A. M. and Buckley, J. T. (1968)
The Analysis of Stone Size and Shape in Arctic Environments
Journal of Sedimentary Petrology, vol. 38, pp. 200-214.

King, R. B. (1971)
Boulder Polygons and Stripes in the Cairngorm Mountains, Scotland
Journal of Glaciology, vol. 10, pp. 375-386.

--------, (1972)
Lobes in the Cairngorm Mountains Scotland
Biuletyn Peryglacjalny, no. 21, pp. 153-167.

Krumbein, W. C. (1941)
Measurement and Geological Significance of Shape and Roundness of Sedimentary Particles
Journal of Sedimentary Petrology, vol. 11, pp. 64-72.

Kudryavtsev, V. A. (1975)
Temperature, Thickness, and Discontinuity of Permafrost
In: Principles of Geocryology, part I, Chapter VIII, (1959), Academy of Sciences of the U.S.S.R., Moscow.
Ottawa: National Research Council, Division of Building Research, Technical Translation 1187, 75 pp.

Lachenbruch, A. H. (1959)
Periodic Heat Flow in a Stratified Medium with Application to Permafrost Problems
United States Geological Survey Bulletin 1083-A, pp. 1-36.

Lietzke, D. A. and Whiteside, E. P. (1972)
Comparison of Spodosols in Nunatak Soils of the Juneau Icefield and the Glacial Soils of Michigan
in: Miller, M. M. (ed.)
Arctic and Mountain Environments Symposium, Program with Abstracts, April 22-23, 1972, Michigan State University. (unpaged)

Linton, D. L. (1969)
The Abandonment of the Term Periglacial pp. 65-70 in:
E. M. Van Zinderen Bakker, (ed.)
Paleo-Ecology of Africa and of the Surrounding Islands and Antarctica, Cape Town: Balkema, vol. 5.

Lundqvist, G. (1949)
The Orientation of the Block Material in Certain Species of Flow Earth
Geografiska Annaler, Bd. 31, pp. 335-347.

Lundqvist, J. (1962)
Patterned Ground and Related Frost Phenomena in Sweden,
Sveriges Geologiska Undersökning, ser. C, no. 583, 101 pp.

--------, (1966)
Patterned Ground in Sweden pp. 146-149 in:
Permafrost International Conference
11-15 November, 1963, Lafayette, Indiana, National Academy of Sciences - National Research Council Publication 1287, 563 pp.

MacKay, D. K. and Cook, F. A. (1963)
A Preliminary Map of Continentality for Canada
Geographical Bulletin, no. 20, pp. 76-81.

Mackay, J. R. and Mathews, W. H. (1974)
Movement of Sorted Stripes, the Cinder Cone, Garibaldi Park, B.C., Canada
Arctic and Alpine Research, vol. 6, pp. 347-359.

Marcus, M. G. (1964)
Climate - Glacier Studies in the Juneau Ice Field Region, Alaska
Chicago: Department of Geography Research Paper No. 88, The University of Chicago, 128 pp.

Mark, D. M. (1971)
Rotational Vector Procedure for the Analysis of Till Fabrics
Bulletin of the Geological Society of America, vol. 82, pp. 2661-2666.

--------, (1973)
Analysis of Axial Orientation Data, Including Till Fabrics
Bulletin of the Geological Society of America, vol. 84, pp. 1369-1374.

Mathews, W. H. (1955)
Permafrost and its Occurrence in the Southern Coast Mountains of British Columbia
Canadian Alpine Journal, vol. 38, pp. 94-98.

McBoyle, G. R. and Steiner, D. (1972)
A Factor-Analytic Approach to the Problem of Continentality
Geografiska Annaler, vol. 54A, pp. 12-27.

Miller, M. M. (1956)
Contributions to the Glacial Geology and Glaciology of the Juneau Icefield, S. E. Alaska
Ph.D. Thesis, University of Cambridge, 2 vol., 800 pp.

--------, (1959)
Bedrock Elements in the Morphology of the Juneau Icefield, Northern Boundary Range, Alaska-Canada 11 pp. paper in:
Miller, M. M., (ed.),
Manual of Glaciology, unpaged mimeo, 3 volumes, updated annually.

--------, (1964)
Inventory of Terminal Position Changes in Alaskan Coastal Glaciers Since the 1970's
Proceedings of the American Philosophical Society, vol. 108, pp. 257-273.

--------, (1975)
Mountain and Glacier Terrain Study and Related Investigations in The Juneau Icefield Region, Alaska - Canada
Durham, N.C.: U.S. Army Research Office, 136 pp. + appendices.

--------, (1976)
Alaskan Glacier Commemorative Project, Phase V: Studies in Quaternary Chronology and Glaciology of the Alaska - Canada Boundary Range
National Geographic Society Research Reports, 1968 Projects, pp. 255-304.

--------, (1977)
Quaternary Erosional and Stratigraphic Sequences in the Alaska - Canada Boundary Range pp. 463-492 in:
Mahaney, W. C. (ed.)
Quaternary Stragigraphy of North America,
Stroudsburg, Pa.: Dowden, Hutchinson & Ross.

Miller, M. M. and Anderson, J. H. (1974)
Out-of-Phase Holocene Climatic Trends in the Maritime and Contenental Sectors of the Alaska - Canada Boundary Range
pp. 33-58 in: Quaternary Environments Proceedings, York University Symposium, Geographical Monograph no. 5.

Miller, R. Common, R. and Galloway, R. (1954)
Stone Stripes and Other Surface Features of Tinto Hill
Geographical Journal, vol. 120, pp. 216-219.

Monger, J. W. H. (1975)
Upper Paleozoic Rocks of the Atlin Terrane, Northwestern British Columbia and South-Central Yukon
Geological Survey of Canada Paper 74-47, 63 pp.

Muller, S. W. (1947)
Permafrost or Permanently Frozen Ground and Related Engineering Problems
Ann Arbor: Edwards Brothers, 231 pp.

Naff, J. D. (1972)
Bedrock Lithologies of the Coast Range U.S. - Canada in:
Miller, M. M. (ed.)
Arctic and Mountain Environments Symposium, Program with Abstracts, April 22-23, 1972, Michigan State University.

Nicholson, F. H. (1976)
Patterned Ground Formation and Description as Suggested by Low Arctic and Subarctic Examples
Arctic and Alpine Research, vol. 8, pp. 329-342.

Nie, N., Hull, C., Jenkins, J., Steinbrenner, K., and Bent, D. (1975)
Statistical Package for the Social Sciences
New York: McGraw-Hill, 675 pp.

Østrem, G. (1972)
Height of the Glaciation Level in Northern British Columbia and Southeastern Alaska
Geografiska Annaler, vol. 54A, pp. 76-84.

Outcalt, S. I. (1967)
Stone Banked Terraces
Unpublished manuscript, Department of Geography, University of British Columbia, 20 pp.

Pihlainen, J. A. (1962)
An Approximation of Probable Permafrost Occurrence
Arctic, vol. 15, pp. 151-154.

Poser, H. (1932)
Einige Untersuchungen zur Morphologie Ostgrönlands
Meddelelser om Grønland, Bd. 94, pp. 1-55.

Poser, H. (1933)
Das Problem des Strukturbodens
Geologische Rundschau, vol. 24, pp. 105-121.

Preusser, H. (1973)
Hypsometrischer Formenwandel der Polygone in Island
Zeitschrift für Geomorphologie, Supplementband 16, pp. 155-160.

Price, L. W. (1970)
Up-Heaved Blocks: A Curious Feature of Instability in the Tundra
Proceedings of the Association of American Geographers, vol. 2, pp. 106-110.

Rapp, A., and Rudberg, S. (1960)
Recent Periglacial Phenomena in Sweden
Biuletyn Peryglacjalny, nr. 8, pp. 143-154.

Raup, H. (1965)
The Structure and Development of Turf Hummocks in the Mesters Vig District, Northeast Greenland
Meddelelser om Grønland, Bd. 166, 113 pp.

Richmond, G. M. (1949)
Stone Nets, Stone Stripes, and Soil Stripes in the Wind River Mountains, Wyoming
Journal of Geology, vol. 57, pp. 154-174.

Rudberg, S. (1972)
Periglacial Zonation - A Discussion
Göttinger Geographische Abhandlungen, Heft 60, pp. 221-233.

Schaerer, P. A. (1970)
Variation of Ground Snow Loads in British Columbia
Proceedings, Western Snow Conference, vol. 38, pp. 44-48.

Schmertmann, J. H. and Taylor, R. S. (1965)
Quantitative Data from a Patterned Ground Site Over Permafrost
U.S. Army, Corps of Engineers, Cold Regions Research and Engineering Laboratory Research Report 96, 76 pp.

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

Shumskii, P. A. (1964)
Principles of Structural Glaciology
New York: Dover Publications, 497 pp.
Translation by D. Kraus.

Stearns, S. R. (1966)
Permafrost (Perennially Frozen Ground)
Cold Regions Science and Engineering, Part I, Section A2, U.S. Army, Corps of Engineers, Cold Regions Research and Engineering Laboratory, 77 pp.

Taber, S. (1943)
Perennially Frozen Ground in Alaska: Its Origin and History
Bulletin of the Geological Society of America, vol. 54, pp. 1433-1548.

Tallman, A. M. (1975)
The Glacial and Periglacial Geomorphology of the Fourth of July Creek Valley, Atlin Region, Cassiar District, Northwestern British Columbia
Ph.D. Thesis, Department of Geology, Michigan State University, 178 pp.

Thompson, A. H. (1975)
Continentality Across the Juneau Icefield in Stormy and Fair Weather pp. 8-16 in:
Miller, M. M., (ed.),
Mountain and Glacier Terrain Study and Related Investigations in the Juneau Icefield Region, Alaska - Canada,
Durham, N.C.: U.S. Army Research Office, 136 pp. + appendices.

Thompson, W. F. (1962)
Preliminary Notes on the Nature and Distribution of Rock Glaciers Relative to True Glaciers and Other Effects on the Climate on the Ground in North America
International Association for Scientific Hydrology, Colloque d'Obergurgl. Commission of Snow and Ice, Publication no. 58, pp. 212-219.

Trewartha, G. T. (1961)
The Earth's Problem Climates
Madison: University of Wisconsin Press, 334 pp.

Tricart, J. (1969)
Geomorphology of Cold Environments
London: MacMillian, 320 pp.
Translation by E. Watson.

--------, and Cailleux, A. (1972)
Introduction to Climatic Geomorphology
New York: St. Martin's Press, 295 pp.
Translation by C. J. Kiewiet de Jonge.

--------, and Schaeffer, R. (1950)
The Study of Erosion Systems Through a Consideration of the "Roundness of Index" of Pebbles
Revue de Géomorphologie Dynamique, vol. 1, pp. 151-152.

Troll, C. (1947)
Die Formen der Solifluktion und die Periglaziale Bodenabtragung
Erdkunde, Bd. 1, pp. 162-175.

Troll, C. (1958)
Structure Soils, Solifluction, and Frost Climates of the Earth
U.S. Army, Corps of Engineers, Snow Ice and Permafrost Research Establishment Translation 43, 121 pp.
Translation from Geologische Rundschau, Bd. 34, (1944), pp. 545-694, by H. E. Wright, Jr.

Ugolini, F. C. (1966)
Soils pp. 29-72 in:
Soil Development and Ecological Succession in a Deglaciated Area of Muir Inlet, Southeast Alaska
Ohio State University, Institute of Polar Studies, Report no. 20, 167 pp.

Wallis, A. L., Jr. (1977)
Comparative Climatic Data Through 1976
Asheville, N.C.: National Oceanic and Atmospheric Administration, Environmental Data Service, (unpaged)

Wardle, P. (1971)
An Explanation for Alpine Timerline
New Zealand Journal of Botany, vol. 9, pp. 371-402.

--------, (1974)
Alpine Timberlines pp. 371-402 in:
Ives, J. D., and Barry, R. G., (eds.),
Arctic and Alpine Environments,
London: Methuen & Col., 999 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.

--------, (1956)
Classification of Patterned Ground and Review of Suggested Origins
Bulletin of the Geological Society of America, vol. 67, pp. 823-865.

--------, (1969)
Weathering, Frost Action, and Patterned Ground in the Mesters Vig District, Northeast Greenland
Meddelelser om Grønland, Bd. 176, 303 pp.

--------, (1970)
An Approach to a Genetic Classification of Patterned Ground
Acta Geographica Lodziensia, no. 24, pp. 437-446.

--------, (1973)
Periglacial Processes and Environments
New York: St. Martin's Press, 320 pp.

Watson, E. and Watson, S. (1971)
Vertical Stones and Analogous Structures
Geografiska Annaler, vol. 53A, pp. 107-114.

Williams, P. J. (1961)
Climatic Factors Controlling the Distribution of Certain Frozen Ground Phenomena
Geografiska Annaler, vol. 43, pp. 339-347.

Zenker, W. (1888)
Die Verteilung der Wärme auf der Erdoberfläche
Berlin.

Zwick, T., Cadwell, D., Miller, M., and Fleisher, J. (1974)
Tank and Tor Topography on Peripheral Aretes of the Juneau Ice-field, Alaska Unpublished Paper Given at:
Quaternary Environments Symposium, York University.