Frost Action and Vegetation Patterns on Seward Peninsula Alaska

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By D. M. HOPKINS *and* R. S. SIGAFOOS

CONTRIBUTIONS TO GENERAL GEOLOGY, 1950

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A Study of the Geomorphic Significance of Vegetation Patterns as Related to Frost Action at High Latitudes and in Areas of Perennially Frozen Ground

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FROST ACTION AND VEGETATION PATTERNS ON SEWARD PENINSULA, ALASKA

By D. M. Hopkins and R. S. Sigafoos

ABSTRACT

Cottongrass tussocks, frost scars, peat rings, tussock rings and groups, and tussock-birch-heath polygons in the Imuruk Lake area, Seward Peninsula, Alaska, are products of the interaction of congeliturbation (frost churning) and vegetation development. These cryopedologic features are found on poorly drained areas on summits, slopes of less than 10°, and lowlands where silty mineral soil is present beneath a cover of peat or turf less than 3 feet thick. Perennially frozen ground is present at depths of 3 feet or less.

The tussock is a ball-like tufted plant form characteristic of certain grasses and sedges found in swampy areas. Differential frost heaving increases the height of tussocks of cottongrass (*Eriophorum vaginatum* subsp. *spissum*) by lifting the plant above the soil surface during the autumn freezing cycle. Frost scars are areas of bare soil resulting from disruption of the vegetative cover by local intense frost heaving.

Peat rings, tussock rings, and tussock groups consist of vegetation patterns associated with widely spaced mounds of mineral soil projecting through otherwise continuous layers of peat or turf. Tussock-birch-heath polygons consist of closely spaced mounds of mineral soil separated by channels filled with peat. The peat rings, tussock rings, tussock groups, and vegetation polygons represent stages in several developmental series, all of which start with frost scars as the initial form. The final features of these developmental series are the result of congeliturbation, a process which is effective chiefly during the fall freezing cycle and which is modified by the development of vegetation.

All of the cryopedologic features probably have been present in the area during and since the last glaciation on Seward Peninsula. Changes in climate probably have been reflected by changes in the local distribution of the features.

The concept of a "climax" vegetation must be modified when applied to tundra vegetation. Disturbance of the substratum recurs repeatedly, and all stages in the plant succession exist on unstable surfaces. The vegetation in areas of frost scars, peat rings, tussock rings and groups, and vegetation polygons represents an equilibrium assemblage adjusted to the climate in which it exists, but differs from a "climax" assemblage in that bare areas and areas covered by pioneer plants are intimately mixed among areas covered by assemblages representing the highest stage in the succession.

Fossil tussock-birch-heath polygons may eventually be recognized in northern United States and Europe. Their presence would indicate the probable former presence of perennially frozen ground, and the former depth of summer thaw could be inferred from the vertical dimensions of the polygons.

Recognition on aerial photographs of the cryopedologic features described above will assist in the interpretation of terrain conditions.

INTRODUCTION

Intensive frost action in areas of perennially frozen ground produces microrelief features in soil, some of which have been grouped under the term "structure soil." The interrelationship between developing vegetation and intensive frost action produces patterns in the distribution of plants comparable to some of those formed in soil. Detailed studies of these features and patterns are essential to an understanding of the nature and intensity of geomorphic and biological processes that shape the landscape of tundra regions. Many of the small-scale features are described and illustrated by Griggs (1934), Polunin (1934, 1935), Porsild (1938), Raup (1941, 1947), and Sharp (1942). Troll (1944) summarizes most of the previous literature.

During the summers of 1947, 1948, and 1949 the writers conducted areal geomorphic and botanical studies on Seward Peninsula, Alaska. The studies were part of the permafrost program of the United States Geological Survey and were intended to lead to a better understanding of perennially frozen ground and of the geomorphic processes characteristic of high latitudes. The features described in this paper were studied in detail in the Imuruk Lake area (fig. 18) but were observed in many other places on Seward Peninsula.

Seward Peninsula is subject to a rigorous, subarctic climate, in which geomorphic processes associated with frost action and perennially frozen ground are dominant and geomorphic processes characteristic of more temperate regions are inconspicuous and of minor importance. Congelifraction and congeliturbation (Bryan, 1946, pp. 626, 633) are by far the dominant processes in the shaping and reduction of slopes in the Imuruk Lake area. Frost churning prevents the development of a "normal" soil profile. The instability of the soil and the presence of frozen ground throughout the summer exclude many plant species from the region, affect the form of those that are present, and have far-reaching effects upon the development of plant communities (Griggs, 1934; Polunin, 1934, 1935; Porsild, 1938; Raup, 1941, 1947; Sigafoos, 1949).

The present paper discusses cottongrass tussocks, frost scars, peat rings, tussock rings, and tussock-birch-heath polygons. All of these features result from the interaction of congeliturbation and the growth and development of vegetation. Frost scars ("spot medallions" of Sochava, 1944; "mud circles" of Washburn, 1947, p. 99) and tussocks ("niggerheads" of Alaskan parlance) are well known to travelers on the tundra and are not limited to arctic and subarctic regions. Frost scars and tussocks have been observed by the writers at low altitudes in northern New England. Previous descriptions of peat rings, tussock rings, and tussock-birch-heath polygons have not come to the attention of the writers. It is believed, however, that variations of these features are widespread in tundra regions, and it is suggested that "fossil" examples eventually may be recognized in temperate regions adjacent to the southern margins of the ice sheets of Pleistocene age.

DEFINITIONS

Several of the botanical terms used in this paper may be unfamiliar to some of our readers, and others have not been clearly defined in previous papers. The writers' usage of these terms is given below.

"Heath," in the strict sense, refers to members of the family Ericaceae, but the writers use the term to mean an assemblage of plants that includes *Ledum palustre* subsp. *decumbens*, *Vaccinium uliginosum*, *V. vitis-idaea* subsp. *minus*, and *Empetrum nigrum*.

"Peat" is a deposit of partly decomposed plant parts.

"Sod" is a tight, interwoven mat of rhizomes (horizontal underground stems) or stolons (horizontal above-ground stems) from which jointed aerial stems (culms) of grasses or grasslike plants arise. The mat forms a nearly uniform vegetation blanket.

"Turf" includes low vegetation other than sod of both open and closed stands of plants.

Processes grouped under the general term "frost action" are dominant factors in the development of soil and vegetation and in the shaping of the landscape in the rigorous climate that prevails on Seward Peninsula. Bryan (1946) attempted to clarify the terminology of processes associated with intensive frost action. Because the processes are discussed at length in this paper, it seems desirable to define more clearly their scope and interrelationships according to the usage of the writers (fig. 17).

"Cryopedologic processes" include all processes involving intensive frost action or perennially frozen ground. "Pergelation" and "depergelation" (the formation and decay of perennially frozen ground, Bryan, 1949, p. 101) and the cracking of the surface of the frozen ground owing to sudden large temperature fluctuations below freezing are examples of cryopedologic processes. Microrelief features that result from cryopedologic processes, including "structure soils," can be termed "cryopedologic surface features."

"Intensive frost action" is a general term designating all geomorphic processes dependent upon repeated cycles of freezing and thawing. Two broad categories of processes, "congelifraction" and "congeliturbation," are recognized under intensive frost action. Congelifraction can be defined as frost splitting (Bryan, 1946, pp. 626–627). Congeliturbation, as used by the writers, includes all processes by which repeated cycles of freezing and thawing result in churning or stirring

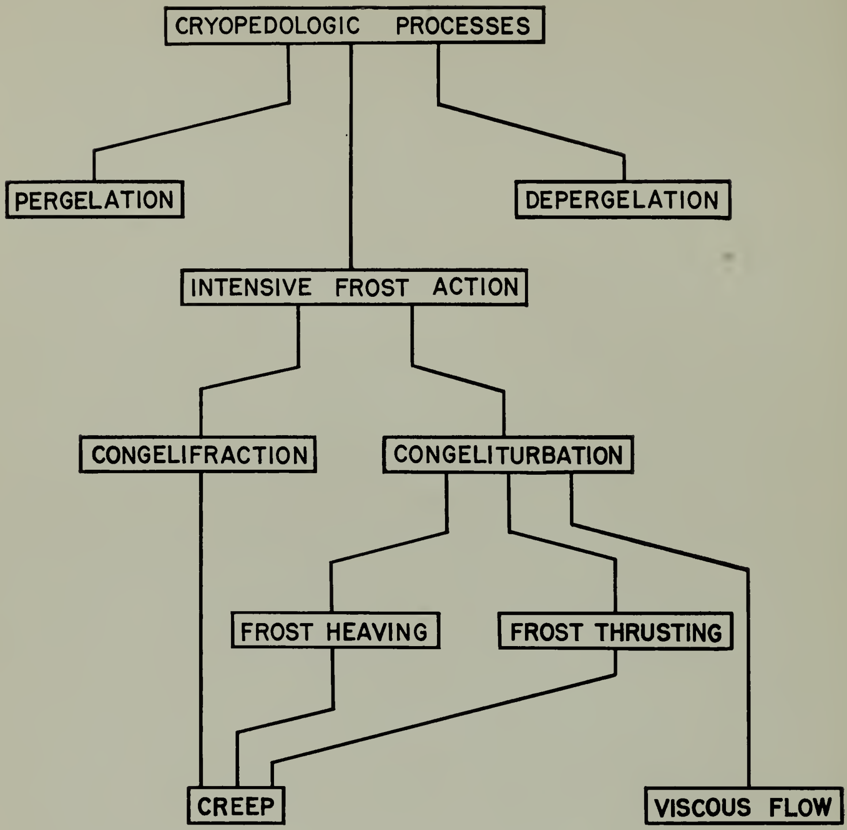

FIGURE 17.—Scope and interrelationships of certain cryopedologic processes.

of the soil, with or without net down-slope movement. The soil is churned in place on horizontal surfaces by small differential movements resulting from frost heaving (vertical expansion), frost thrusting (horizontal expansion) (Eakin, 1916, p. 76), and subsidence during thawing. The soil is moved down slope by creep resulting from these processes and by viscous flow if the moisture content is sufficiently high. Additional categories of "intensive frost action" could be suggested, but they lie beyond the scope of this discussion.

ACKNOWLEDGMENTS

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GEOLOGIC AND GEOGRAPHIC ENVIRONMENT

LOCATION

Seward Peninsula is in northwestern Alaska between the Bering Sea and the Arctic Ocean (fig. 18). The features discussed in this paper were studied along a transect extending across the peninsula from Nome on the southwest to Deering and Candle on the northeast. Most of the work was concentrated near the center of the peninsula in the Imuruk Lake area. Imuruk Lake lies at latitude 65°35′ N. and longitude 163°10′ W., 100 miles northeast of Nome and 60 miles south of the Arctic Circle.

CLIMATE

Year-round weather observations are lacking in the Imuruk Lake area. A weather station was maintained by the 11th Weather Squadron at Lava Lake, near the western margin of the area, from April through November 1945, and fragmentary weather records were collected by the Geological Survey during the summers of 1947 and 1948. The following remarks are based upon these records and upon Weather Bureau data for Candle, Shishmaref, and Council, Alaska (U. S. Weather Bureau, 1943).

The climate is rigorous and continental, characterized by cool summers and very cold winters (fig. 19). The mean annual temperature is probably about 20° F. The absolute maximum temperature recorded at Candle prior to 1943 is 85°; the absolute minimum is −60°. Subfreezing temperatures predominate from early October to mid-May, although occasional thaws probably can be expected during most of the winter months. Nocturnal frosts are common during all of the summer months. Mean diurnal temperature fluctuations range in amplitude from 13° during October to 23° during June. The mean annual precipitation is probably between 7 and 8 inches, of which about 25 percent falls as snow. More than 50 percent of the annual precipitation occurs during a well-defined rainy season extending from July through September.

Winters are cold and rather dry. Clear weather predominates, but intense storms, accompanied by high winds and precipitation, are frequent. The sun rises above the horizon only a short distance and

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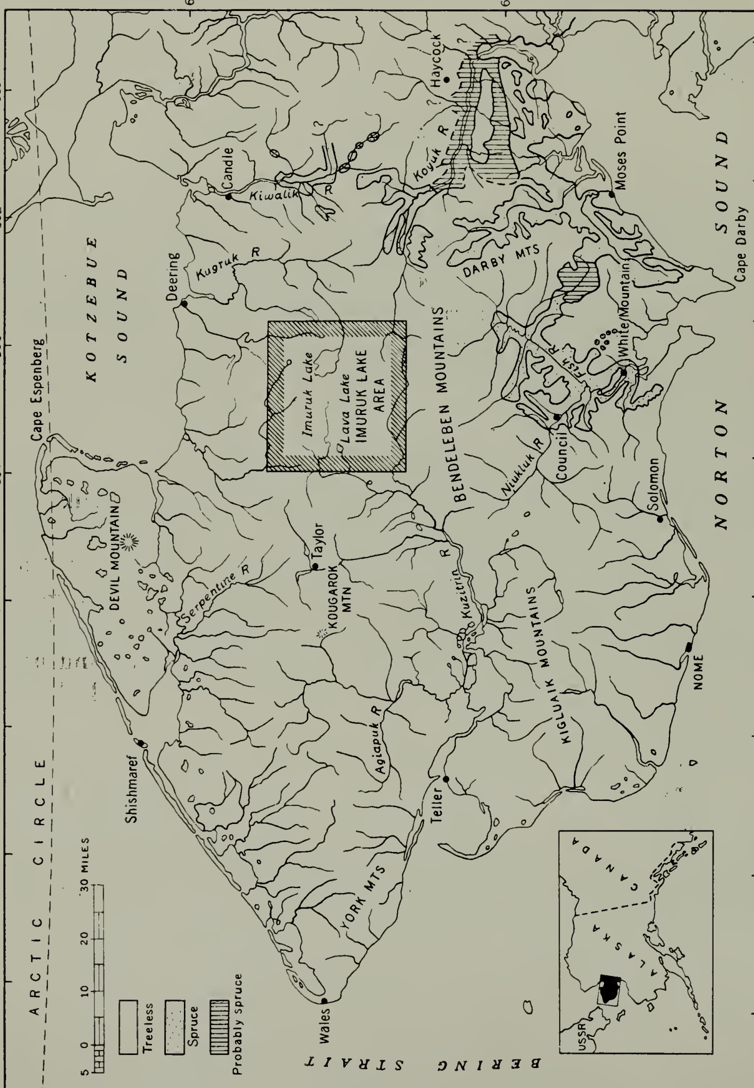

FIGURE 18.—Index map of Seward Peninsula, Alaska, showing location of Imuruk Lake area and distribution of forested areas.

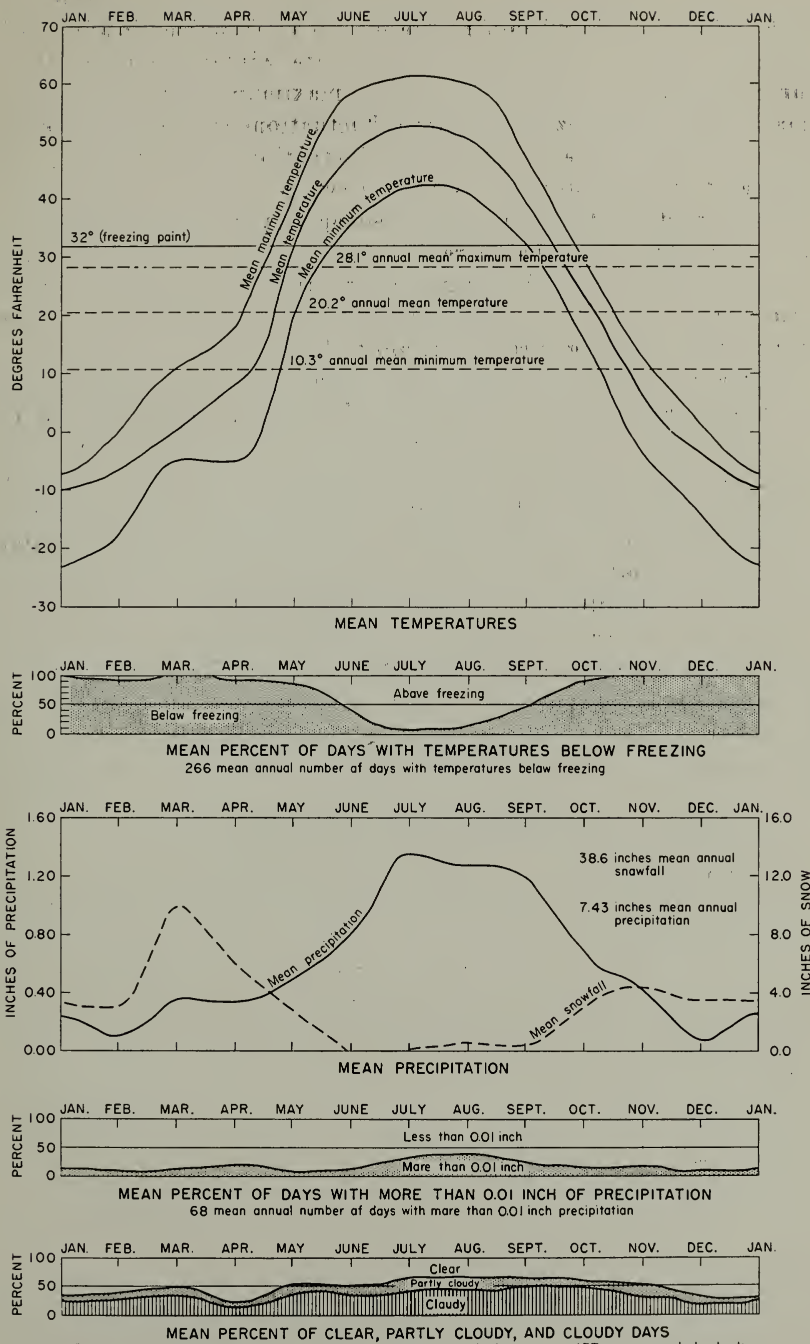

FIGURE 19.—Climatic data for Candle, Alaska.

for only a few hours each day during early winter; consequently, diurnal fluctuations in temperature due to solar warming are small. Longer days and a higher sun during late winter are reflected by diurnal fluctuations of 15° to 30°, but the maximum daily temperatures remain well below freezing. Diurnal fluctuations are marked throughout the winter, however, by sharp fluctuations accompanying the passage of cyclonic storms. Winter thaws generally are confined to stormy periods. Storms are less frequent during April, May, and June, and diurnal temperature fluctuations due to solar warming become conspicuous. Thawing temperatures are common at noon during late April and early May, and by late May temperatures remain above freezing throughout most of the day.

Summers are cool and moist. Low ceilings and short nights reduce the amplitude of diurnal temperature fluctuations, especially during July and August. Seventy percent of the annual precipitation is concentrated in the period from May through September, and much of it falls as drizzle or as light showers. Few days pass without at least a trace of precipitation. Moderate temperatures and prevailing high humidities inhibit surface evaporation; consequently, the summer climate is wet despite the low total rainfall.

Killing frosts occur in middle or late August, and by early September frosts occur nearly every night. After early October freezing temperatures predominate. Even during September and October the duration and intensity of subfreezing temperatures is related more closely to cyclonic conditions than to diurnal-nocturnal fluctuations.

TOPOGRAPHY AND DRAINAGE

The Imuruk Lake area is a broadly rolling upland ranging from 500 to 1,000 feet in altitude. The most conspicuous relief features are isolated hills, 300 to 800 feet high, characterized by broad, dome-shaped summits and smooth, gentle slopes rarely exceeding 10°. The hills are separated by undulating lowlands with a relief of 100 to 300 feet; distances from divides to the axes of adjacent stream valleys commonly are 1 to 3 miles.

Drainage is poor throughout most of the region. An integrated drainage pattern is lacking over large areas, and lakes, ponds, and swamps are abundant. Luxuriant vegetation, low evaporation, and the presence of perennially frozen ground at shallow depths inhibit surface runoff and subsurface drainage and maintain moist conditions in silty soils on even relatively steep slopes.

Most of the lowland areas are drained by small, sluggish, widely spaced watercourses. Drainage lines are completely lacking on some slopes, and extremely wet conditions prevail over the entire surface.

More commonly, however, the slopes are drained by sets of long, shallow, subparallel swales separated by broadly convex interfluves on which swampy ground is lacking. Commonly, 3 to 20 swales join abruptly near the foot of the slope in a ragged candelabralike pattern. Some swales head in swampy oval indentations on the upper slopes; others merge with the swampy ground at the hill summits. Definite channels containing running water generally are lacking in the swales; instead, the floors are swampy and choked with vegetation.

GEOLOGY

Most of the Imuruk Lake area is underlain by basalt and andesite lava flows of Quaternary age. Pre-Quaternary bedrock consists of granite, marble, and schist (Moffit, 1905). Terraces composed of unconsolidated sediments are present along the shores of Imuruk Lake and in the valleys of some of the larger streams.

No part of the Imuruk Lake area has been glaciated, but small glaciers were present to the south in the Bendeleben Mountains. At least two distinct glacial advances are recorded.

SOILS AND SOIL-MAKING PROCESSES

The existing soils of the Imuruk Lake area originated in a climate similar to or more rigorous than the present one. Congelifraction (frost riving, Bryan, 1946, pp. 626–627) is the dominant process of rock weathering in such a climate and ultimately produces, under ideal conditions, a well-sorted silty soil containing few large rocks and very few particles in the clay-size range (Taber, 1943, pp. 1449–1450; Troll, 1944, pp. 573–575; Hopkins, 1949, p. 121). The degree to which this end is approached depends upon the age of the soil, the topography and drainage of the site, and the texture and mineral composition of the parent rock.

Bare bedrock or coarse rubble of pre-Quaternary age is exposed throughout the area of the lava flows of Quaternary age and on the upper slopes of hills underlain by marble or granite. The lower slopes of granite hills consist generally of sandy soil with abundant rocks. Areas underlain by schist or by older Quaternary flows and the lower slopes of hills underlain by marble generally bear a mantle of uniform silty soil 5 to 20 feet thick. Particles between 0.01 and 0.1 millimeter in size make up 70 to 95 percent of these soils.

A mantle of peat of variable thickness is present on almost all surfaces where bedrock is covered by silty soil. Luxuriant vegetation, poor drainage, and low evaporation favor the accumulation of peat, not only on lowlands but also on hilltops and on slopes of less than 10°. The peat mantle is 5 to 20 feet thick in swampy lowlands and swales and 1.5 to 3.0 feet thick on wet summits and wet slopes. Even in the "drier" sites a discontinuous layer of peat or turf as much as 1.5 feet thick mantles the silty mineral soil.

Peat in the Imuruk Lake area is coarsely fibrous and little decomposed. It consists of recognizable fragments of willows, sedges, and mosses in a sooty matrix of black finely comminuted organic matter. Living roots and stems are an important constituent of the peat within 6 inches of the surface. In some of the wetter sites the black peat is overlain by a reddish peatlike mat of living mosses 0.5 to 1.5 feet thick.

Rock and sandy soils generally are dry and well-drained on horizontal surfaces as well as on slopes. Subsurface drainage is good, because perennially frozen ground lies at depths exceeding 3 feet in these materials.

The moisture content of silty soils varies, but even the "driest" soils are extremely wet compared with soils having a similar texture in temperate regions. Surface runoff is impeded by the vegetation; surface drainage is retarded by the impermeability of the soils and by the presence of perennially frozen ground at shallow depths. Low evaporation and the melting of frozen ground helps to maintain the high moisture content. The wettest soils will not stand in the walls of excavations, and artificial holes quickly fill by flowage from the walls. Drier soils will stand in the walls of excavations; but, when samples of these "dry" soils are sacked and hung to dry, water drains from them.

Areal variations in soil moisture in silty soils depend upon the depth of thaw, the degree of slope at the site, the position of the site in relation to drainage lines, and the character of the parent material. In general, the moisture content varies inversely with the depth of thaw and the degree of slope. Soils on slopes where definite drainage lines are lacking are much wetter than the interfluvial soils on slopes with well-defined swales. Soils derived from marble are generally wetter than soils derived from other rock.

Peat is completely saturated with moisture in almost all areas, The peat is coarse, open-textured, and more permeable than silty mineral soil, and in some of the features described below ground-water circulation above the frost table is concentrated in the peat.

PERENNIALLY FROZEN GROUND AND FROST ACTION

Perennially frozen ground is present throughout northern Seward Peninsula, except near lakes, large streams, and warm springs. Drill-hole data and comparisons with other areas indicate that frozen ground extends to depths ranging from 50 to at least 300 feet. The character of the perennially frozen zone is described by Hopkins (1949, pp.

121–122). The surface layers thaw during the summer to depths ranging from 1 to 10 feet, depending upon the character of the soil, the vegetative cover, topography, exposure, and drainage conditions. The relationships between these factors and depth of thaw are described in greater detail in the discussion of the individual cryopedologic features.

Frost scars, peat rings, tussock rings and groups, and tussock-birch-heath polygons in the Imuruk Lake area are underlain by perennially frozen ground and are formed by frost heaving, frost thrusting, and creep in the upper layers of the soil which are subject to annual cycles of freezing and thawing.

Frost heaving and frost thrusting result from volume increase in masses of soil due to the segregation of masses of clear ice during freezing. Taber (1930) has shown that when silty soils are subjected to subfreezing temperatures in the presence of abundant moisture they absorb a quantity of water greatly in excess of the natural porosity of the unfrozen material. The excess water is present as segregations of clear ice, which commonly comprise 50 to 80 percent of the volume of the frozen material (Taber, 1943, pp. 1517–1518). The water forming these clear ice segregations can be derived from any nearby source and is drawn upward or laterally to the growing ice crystals through capillary interspaces in the soil.

If clear ice lenses formed in equal abundance in all of the materials at the surface, frost heaving would consist of a uniform dilation of the entire surface. The surface of the tundra is characterized, however, by a multitude of small-scale inhomogeneities, which result in large local differences in the intensity of frost heaving. Among the principal causes of differential frost heaving are variations in the thicknesses of peat and mineral soil, in the character of the vegetation cover, in the amount of moisture present, and in the amount of snow cover during the critical autumn freezing period.

The intensity of frost heaving varies inversely with the thickness of peat or turf covering the mineral soil. Two factors are involved in this relationship: (1) Ice lenses form more abundantly in silty mineral soil than in peat, probably because water is drawn less readily through the large openings that predominate in the peat and because the tough, fibrous structure of the peat resists disruption by growing ice crystals and (2) silt is a much better heat conductor than peat or turf. Summer thaw penetrates much deeper into bare mineral soil than into peat, and severe autumn frosts produce several inches of frozen ground in bare areas, whereas only the subaerial portions of vascular plants are frozen in dry turf a few inches away. Thick wet mats of living sphagnum are poorer insulators than dead peat, and frost penetrates into them almost as rapidly as into mineral soil. At Nome, following several days with minimum temperatures of 10° to 27.5° F., ice an inch thick formed on open puddles. At the same time the ground froze to a depth of more than 6 inches in bare soil, 3 to 5 inches in living sphagnum, 1 to 4 inches in wet peat, and 0 to 2 inches in dry peat and turf.

If the entire soil surface freezes at a uniform rate, then, according to Taber (1943, p. 1523), the segregation of ice lenses is favored by slow freezing. When the rate of freezing varies widely within a radius of a few feet, however, ice lenses are formed most abundantly in the material that freezes first, because water is drawn laterally to growing ice lenses in the freezing soil from adjoining unfrozen areas. Thus, areas of bare soil or areas covered by only a thin mantle of peat will freeze rapidly and will expand at the expense of areas nearby that freeze more slowly because they are mantled by a thick layer of peat (fig. 28, *A*, *B*).

Frost heaving in bare areas or areas covered with isolated plants is more intense than in areas covered with dense vegetation. The tightly interlocked roots and stems form a dense mat of vegetation that resists expansion at the surface and an insulating blanket that retards freezing of the underlying soil.

Differences in snow cover during early fall play an important role in differential frost heaving. Intense winds are effective close to the ground surface in exposed places; an early snowfall followed by high winds results in a pattern of drifts and bare patches. Distribution of drifts is determined in part by the vegetation; drifts accumulate in willow thickets and in local areas of tall plants in the cottongrass tussock-birch-heath community. Snow-covered areas are insulated from the cold air, while freezing temperatures penetrate rapidly into nearby snow-free spots. Intense dilation of the snow-free areas and relative stability in the snow-covered areas can be expected.

If other conditions are uniform, the surface layer of the wettest spots can be expected to distend more than dryer spots nearby, because a large supply of water is available for the formation of clear ice lenses. Frost heaving and other cryopedologic processes proceed with maximum intensity in areas adjacent to persistent snow banks, because abundant meltwater is present during the fall freezing cycle.

Repeated freeze-thaw cycles in soils on slopes result in net down-slope movement. Two components, creep and viscous flow, contribute to this movement. Creep results from the expansion of the soil normal to the slope during freezing followed by vertical subsidence during thawing. Viscous flow occurs in thawed soils that contain excessive water owing to the thawing of ice lenses. In many localities additional water is provided by seepages or by melting snow banks. It is commonly impossible to distinguish between down-slope movements due to creep and those due to flow.

CONGELITURBATION AND INSTABILITY OF THE SOIL SURFACE

Cryopedologic processes affect to some degree all parts of the soil surface layers. Each winter the surface is subject to general upward expansion throughout moist areas underlain by peat or silty mineral soil. The dilation is not uniform, however, and differential frost heaving is a general phenomenon, not an exceptional one. Small mounds and hummocks are raised where differential heaving is slight, and the turf is broken where it is intense. Slight differential heaving is favored by thick turf, intense heaving by thin turf.

The character of the soil is determined and modified by cryopedologic processes. The parent rock is reduced to small-grade sizes by congelifraction operating over a long period of time. That part of the resulting silty soil that lies above the frost table is churned by congeliturbation. In the course of long-continued cycles of freezing and thawing, soil particles at the surface are moved to a considerable depth within the zone of annual thaw, and new particles that lie within this zone are brought to the surface and exposed to subaerial weathering processes. Peat and dead plants are churned beneath the surface and increase the amount of organic matter in the soil. In cut banks of streams the zone subject to annual thawing can readily be distinguished from the underlying perennially frozen soil by color and structure.

On horizontal surfaces perennially frozen soil is light blue-gray and more or less structureless in the Imuruk Lake area. The annually thawed zone is yellow-gray when dried and characterized by contorted streaks of reddish limonite-stained silts and dark grayish-brown amorphous organic material. Where the parent material consists of water-laid silt, stratification is completely destroyed in the zone subject to annual thawing.

Intensive congeliturbation limits the vegetation to species adapted to existence upon an unstable substratum. The pioneer plants are those able to survive intense disturbance. Concepts of "pioneer" and "climax" communities lose much of their significance, however, in wet tundra, because even the late stages in the succession must be regarded as existing in unstable equilibrium with an environment subject to sudden, severe change. Bare areas are colonized by pioneers, followed by species later in the succession; however, these later species eventually are destroyed when local intense congeliturbation creates a new bare area and the cycle is repeated.

VEGETATION

The Imuruk Lake area lies beyond the arctic timber line within the tundra region (Griggs, 1934; Raup, 1941; Palmer and Rouse, 1945). Spruce occurs 30 to 50 miles south and east of Imuruk Lake, and isolated stands of small cottonwood (*Populus tacamahacca*) trees occur in the dissected upland at the north and southwest margins of the area. The vegetation of the Imuruk Lake area consists of dwarf shrubs, sedges, grasses, other herbaceous plants, and mosses on the uplands with large, shrubby willows confined, for the most part, to watercourses. Alder thickets are scattered on steeper better-drained slopes.

The large number of vegetation types in the tundra makes their classification difficult, but the broad categories suggested by Middendorf in 1864 stand as the most useful distinctions yet proposed. In the Siberian arctic, he recognized dry or high tundra and wet or low tundra. On the Seward Peninsula, dry tundra is characterized by the predominance of low matted woody plants and grasses, which are the tallest plants, reaching 6 to 10 inches in height. It is confined to areas in which the soil is relatively dry and well-drained and of sandy or rocky texture. Wet tundra is characterized by the predominance of species of the Cyperaceae family, mostly species of the genera *Eriophorum* and *Carex*, and is confined to areas in which the soil is wet, poorly drained, and composed largely of silt and peat. It is in this wet tundra that an organization and pattern of the vegetation can be distinguished. The patterns observed in the two following vegetation types are discussed in later sections.

Tussock-birch-heath vegetation is dominant on fairly well drained slopes and uplands away from the drainage lines. The following species are found in this community. The nomenclature used follows that of Húlten (1941–1948).

Primary species: *Eriophorum vaginatum* subsp. *spissum*, *Betula nana* subsp. *exilis*, *Empetrum nigrum*, *Ledum palustre* subsp. *decumbens*, *Vaccinium uliginosum*, and *V. vitis-idaea* subsp. *minus*.

Secondary species: *Arctagrostis latifolia*, *Poa arctica*, *Carex bigelowii*, *Carex lugens*, and *Rubus chamaemorus*.

The *Eriophorum* [1] grows only as tussocks, 6 to 15 inches in diameter and 2 to 12 inches high. The tussocks are more or less evenly spaced at intervals of a few inches to 2 feet and are rooted in the mineral soil. Woody shrubs grow in the moss peat and *Sphagnum* mosses in the spaces surrounding the tussocks. The soil is silty and moist, and depths to the perennially frozen ground range from 15 to 36 inches.

[1] *Eriophorum vaginatum* subsp. *spissum* is one of several species of this genus that forms tussocks but is the only one identified by the writers in the Imuruk Lake area. In later sections it is referred to as cottongrass and tussocks unless otherwise noted. To avoid confusion, *Eriophorum angustifolium*, also commonly known as cottongrass, is referred to by its Latin name.

The form and distribution of the plants in this community, as affected by congeliturbation, is discussed later. The birch and heath shrubs tend to grow with the accumulation of *Sphagnum* moss peat; the apexes continue to elongate while the lower portions of the plants become buried and subsequently die. The birch and heath shrubs are not rooted in the mineral soil, but adventitious roots extend into the moss peat from the dense tangle of branches and stems, forming a tight mat. The stems also grow around the tussocks that are adjacent to the birch-heath community, so that the tight mat is firmly anchored to the mineral soil. A mat of this type cannot be removed without tearing it unless the stems are cut around a small section.

A sedge sod occurs in poorly drained sites where water occurs at the surface and its lateral movement is slow. Such places are found on broad hill summits and gentle slopes, in drainage lines, and around the margins of many ponds. The following list of species has been compiled from these habitats.

Primary species: *Eriophorum angustifolium* and *Carex aquatilis.*

Secondary species: *Eriophorum scheuchzeri*, *Scirpus cespitosus*, *Carex rotundata*, *C. membranacea*, and *Salix* cf. *flagellaris*.

The sod is an interwoven mass, 6 to 10 inches thick, of rhizomes (underground horizontal stems) of *Carex aquatilis* firmly rooted in a thick layer of fibrous peat. The peat consists of an accumulation of dead parts of *Carex*, *Eriophorum*, and mosses. This type of sod is extremely tenacious, and only with difficulty can it be cut with a shovel. Because of its tough structure, the sod reacts to pressure as a tight-layered mass rather than as an inert blanket or as discrete plants. It modifies and restrains the forces of congeliturbation. The peat mantle ranges in thickness from 1 to 10 feet but is interrupted locally by areas of bare soil. Depths to perennially frozen ground range from 15 to 40 inches, depending upon the thickness of the peat, drainage conditions, and texture of the underlying soil.

Willow and birch thickets also are prominent in the Imuruk Lake area. Willow (*Salix pulchra*) thickets 4 to 10 feet high occur in the lower reaches of the swales draining higher slopes, on steep lake banks, and on flood plains of the larger streams. Depth to perennially frozen ground is more than 6 feet, and frozen ground may be absent locally under flood plains. Definite channels of running water are present under the willows in the swales; these channels are among the few sites where erosion by running water is occurring in the Imuruk Lake area. Thickets of birch (*Betula nana* subsp. *exilis*) occur on the better-drained, higher parts of steep banks and well-drained slopes. Depth to perennially frozen ground in these thickets is not known to the writers but it is probably more than 6 feet, or comparable to that under the willow thickets.

These plant communities are clear-cut and can be defined in space and correlated with factors in the environment. The three factors most closely correlated with the distribution of the communities are drainage conditions, depth to perennially frozen ground, and the intensity and character of congeliturbation. These in turn are determined, in part, by topography, type of soil, and the character of the vegetation. Each type of vegetation, however, is found locally within the area dominated by another type.

CRYOPEDOLOGIC FEATURES

Frost scars, peat rings, tussock rings, tussock groups, and tussock-birch-heath polygons are characteristic features of certain widespread environments in northern Seward Peninsula and elsewhere in tundra regions in Alaska. These features represent stages in several developmental series, in each of which the frost scar is the initial form. The interrelationships between different features are discussed under the heading "Conclusions."

Peat rings, tussock rings and groups, and tussock-birch-heath polygons are best developed in areas underlain by silty mineral soil mantled with peat less than 3 feet thick. Frost scars are found on all types of soil, but the description presented here applies chiefly to frost scars in silty mineral soil.

The descriptions of individual features are based upon the writers' observations in northern Seward Peninsula. Similar features in other parts of Alaska differ considerably in certain details. Discussion of some of these variations, however, lie beyond the scope of this paper.

FROST SCARS

Tundra vegetation is rarely complete and unbroken. Small patches of bare soil are characteristic and conspicuous features scattered through the vegetation. As frost action is a major factor in the formation of these bare patches, the name "frost scar" is proposed. The "spot medallions" of Sochava (1944) and the "mud spots" of Washburn (1947, p. 99) are types of frost scars.

Frost scars in various environments range from a few inches to several tens of feet in maximum diameter. In areas of sedge sod or cottongrass tussock-birch-heath vegetation the frost scars are larger than intertussock areas and range from 1.5 to 10 feet in diameter. Some of the scars are irregular, and others are circular or oval. They are conspicuously convex from late autumn through spring and are flat during middle and late summer. A network of small cracks (miniature zellenboden, Troll, 1944, p. 619) resembling drying cracks generally is present on the surface of the larger scars. Moisture conditions vary widely, but the soil of the frost scars generally appears drier during the summer months than the surrounding turf or peat. The bare soil thaws more rapidly and to greater depth during summer than the adjoining turf and peat, so that the larger frost scars are underlain by depressions in the frost table (fig. 28, *C*). Conversely, during at least the early part of the autumn freezing cycle the bare soil freezes more rapidly than soil having a partial or complete cover of turf or peat.

Bare areas in the tundra originate in a variety of ways. Burrowing mammals can destroy the stems and roots of plants and probably are effective in initiating a break in the turf, which can be enlarged by congeliturbation. Close grazing by reindeer is an important factor in breaking turf in some localities (Palmer and Rouse, 1945, p. 26). From the air, reindeer corrals near Teller, Alaska, can be distinguished from the surrounding tundra by the presence of closely spaced frost scars in the corrals as contrasted with their absence or relative scarcity in adjoining ungrazed tundra. Cottongrass tussocks overturned by frost heaving are found locally; the area can become the nucleus of a growing frost scar. In areas mantled with a continuous layer of peat or turf, the surface cover can be broken during the autumn freezing cycle by intense dilation of the underlying mineral soil in spots where the peat is relatively thin (fig. 28, *A*, *B*), in exceptionally wet spots, or in spots swept bare of snow by the wind following an early snowfall. Elton (1927, p. 171) observed small patches of fresh soil where "the plant-covered surface layer had been rent, giving the appearance of three slits meeting in a central point."

Once formed, frost scars tend to be self-perpetuating. Because bare soil thaws to a greater depth than soil covered with peat or plants, a thicker zone is available in which clear ice can form during the autumn freezing cycle. This condition is augmented by the tendency for bare soil to freeze much more rapidly than turf- or peat-covered soil. The supply of moisture available at depth for the formation of ice lenses is limited by the frost table, which lies 18 to 40 inches below the surface. During rapid freezing of the soil in the frost scar, water is drawn laterally to the growing ice crystals from the unfrozen soil and peat under adjoining turf-covered areas. Thus, some of the water which might otherwise have contributed to the formation of clear ice lenses beneath the vegetated areas augment, instead, the dilation of the bare areas.

During the first stages of freezing, expansion of the soil is relieved by uparching of the surface. The drying cracklike miniature zellenboden probably are dilation cracks, which result from continued arching and expansion after freezing has progressed deep enough to create a rigid cover over the scar (fig. 28, *C*). Upward dilation is greatly hindered, however, after a hard crust of frozen soil several inches thick has formed at the surface of the bare patch, and most of the later expansion is relieved by lateral thrusting into the adjacent unfrozen layer of peat.

Despite continuing frost heaving, many frost scars eventually become partly or completely colonized by vegetation. The interaction of vegetative growth with continuing congeliturbation results in the evolution of new forms. In wet areas mantled with a considerable thickness of peat, the frost scars evolve into peat rings, tussock rings, or tussock groups. In drier areas dominated by cottongrass-birch-heath vegetation, they develop into tussock-birch-heath polygons. In sandy or rocky soils frost scars evolve into still other forms, the discussion of which is outside the scope of this paper. In certain environments the scars are colonized by structureless tundra indistinguishable from the surrounding vegetation.

Colonization of the scars is accomplished by the seeding of new plants within the bare patches and by encroachment of runners of old plants from the margins. These two methods of colonization proceed at different rates in various environments. Species that migrate into a bare area are limited to those in the surrounding plant population (Gleason, 1917), so that the rate of stabilization is, in turn, dependent upon the adjacent species. Some of these, however, may not be able to survive in the new habitat until a "seed bed" has been prepared for their migration. In a sedge marsh, for example, dispersal by seed seemingly is most effective in plant migration, and observations indicate that the soil must be somewhat stabilized by *Eriophorum angustifolium* before *Carices* become established. *E. angustifolium* invariably is the first plant found on otherwise bare soil in this environment. In areas dominated by cottongrass-birch-heath vegetation, migration of plants occurs by seed dispersal and germination, and by vegetative growth of stems and rhizomes. Cottongrass tussocks become established on new sites only by germination of seed and only on soils where the intensity of congeliturbation has been reduced by the growth of other species or by the presence of small, thin fragments of peat. Birch and heath, in this habitat, grow only in moss or moss peat; it is necessary, therefore, that species of *Sphagnum*, *Calliergon*, and *Hypnum* become established prior to invasion by birch and heath. These mosses grow only in moist areas, such as the spaces between cottongrass tussocks. Considerable development of the tussocks, therefore, is necessary before migration of the mosses can begin. Birch and heath, which migrate mostly by growth of stems, follow when peat has accumulated beneath the mosses. It can be seen that the rate of stabilization of a frost scar will be faster if the vegetation development from bare soil to the "mature" stage is accomplished in a few steps, as in the sequence *Eriophorum angustifolium* through *Carex* spp. In some environments new frost scars are formed before sufficient time has elapsed to permit the maturation of vegetation that requires many steps.

In other types of environments frost scars occur in areas dominated by *Dryas*. Here, encroachment by runners at the margin of the scar becomes an important factor in stabilization.

Growth of new plants at the center of a frost scar is inhibited by renewed dilation of the scar during the autumn freezing cycle and by the formation of miniature zellenboden, which are capable of breaking the roots of young plants. Needle ice ("kammeis" or "pipkrake" of various authors) is the chief agent hindering encroachment of vegetation at the margins of the scar. Ice needles form beneath the thin marginal turf during sharp nocturnal frosts and uproot and overturn the advancing vegetation. The frost scar can be enlarged under favorable conditions by this process.

It can be seen from the foregoing statements that colonization of the scars is a slow process, which is hindered by continued congeliturbation within the scars. Shifts in the balance of plant growth versus congeliturbation result in net advances or net losses in the progress of colonization. Predominance of one process over the other appears to be a cyclic "good year-bad year" phenomenon in some localities. On the Arctic coastal plain of Alaska observations over a period of several years indicate that during some years many frost-formed and wind-formed scars are in the process of stabilization by vegetation, but during other years most of the scars appear active and many new scars are formed (Black, R. F., personal communication). In many areas on the Seward Peninsula, however, newly formed frost scars, older well-developed frost scars, and old, nearly stabilized frost scars can be found within a few hundred feet of one another.

Variations from year to year in the number and sharpness of diurnal freeze-thaw cycles probably are reflected by general regional growth or decay of frost scars. During years when short-period freezing cycles are numerous and sharp, repeated cycles of needle-ice growth should result in general disruption of marginal vegetation, with a net growth of many scars. In years of few nocturnal frosts and mild temperatures, the marginal vegetation probably makes a net gain on most bare-soil areas. The favorability of the growing season is another important factor governing encroachment of vegetation upon the scars. Drying winds are important in inhibiting colonization of frost scars in northern Alaska (Black, R. F., personal communication).

The distribution of snow cover in time and space also is important. The flat surfaces of the frost scars lie somewhat below the level of the surrounding vegetation during early autumn. If an early snowfall precedes the freezing of the soil, snow is likely to accumulate to greater depths on the surfaces of the frost scars than on the surrounding vegetation. Such an occurrence retards the freezing of the soil in the scar and should reduce the amount of dilation of the center. Later short-period cycles of freezing and thawing in the air would be less effective beneath the snow cover, and thus disruption of marginal vegetation by needle ice would be at a minimum. If the first snowfall is delayed until freezing temperatures have lasted long enough for dilation of the scars to take place, the snow will collect in the vegetated areas, and disruption of marginal and surface vegetation on the scars will be increased.

In summary, colonization of frost scars by vegetation appears favored by an early sudden freeze-up with few previous nocturnal frosts and by an early snowfall, especially if it occurs before final freeze-up.

TUSSOCKS

The tussock is a tufted plant form characteristic of certain grasses and sedges growing in areas in which congeliturbation is active. It consists of a ball-like mass of living and dead plant parts that stands as a small mound or hummock above the ground surface in areas where the water table and silty mineral soil are close to the surface. Tussocks are a characteristic plant form in tundra regions, but they also are common in swamps at least as far south as Baltimore, Md. (Black, R. F., personal communication). The important role of congeliturbation in the origin of tussocks near Boston, Mass., will be discussed in a future publication.

Many tussocks are formed by the interaction of plant growth and differential frost heaving in wet mineral soil. Although several species occur in tussock form, the developmental processes described below pertain to *Eriophorum vaginatum* subsp. *spissum*, the cottongrass tussock or "niggerhead" of the Alaskan layman. Cottongrass tussocks and "earth hummocks" ("palsen" or "torfhügeln" of German writers) described by Sharp (1942, pp. 297–299) are formed in a similar manner, but the tussocks are quite different.

The tussock is a single plant; its leaves, culms (jointed stems), and roots give it characteristic form. Small year-old tussocks consist of small tufts without winterkilled leaves (fig. 20). Culm bases rest directly on mineral soil. The older, well-developed tussocks are mounds nearly spherical to vertically elongate in shape and are 2 to 12 inches high (fig. 21). Dead and living culms and leaves cover the surface and give the tussock its ball-like form. The culm bases form a tight mat in the upper 1 to 2 inches of the tussocks. A zone of tightly packed roots lies immediately below the culms and accounts for most of the height of the tussock. The distal ends of the roots grow in a low mound of mineral soil, which projects 1 to 6 inches above the level of the soil in inter-tussock areas.

FIGURE 20.—Vertical section through seedling tussock of cottongrass. Note rhizomes resting directly in mineral soil and lack of winterkilled leaves.

The thickened culm bases form a tight mat, because new upright culm branches form from buds beneath the leaf sheaths surrounding older culm bases. The upright culms die each year, leaving only the thickened culm base, which elongates but 1 to 2 millimeters each year. Leaves form as the upright culm is elongating, and when the leaves are mature new buds form on the thickened culm bases (fig. 22, *A*, *C*).[2]

[2] Some species of *Eriophorum*, *Carex*, and grass reproduce vegetatively by runners or stolons (fig. 22, *B*). Stolons arise from buds on the culm bases, but annual growth varies from 1 to 2 inches or more. From scattered nodes grow aerial stems and new leaves. This type of growth produces a loose mat or sod.

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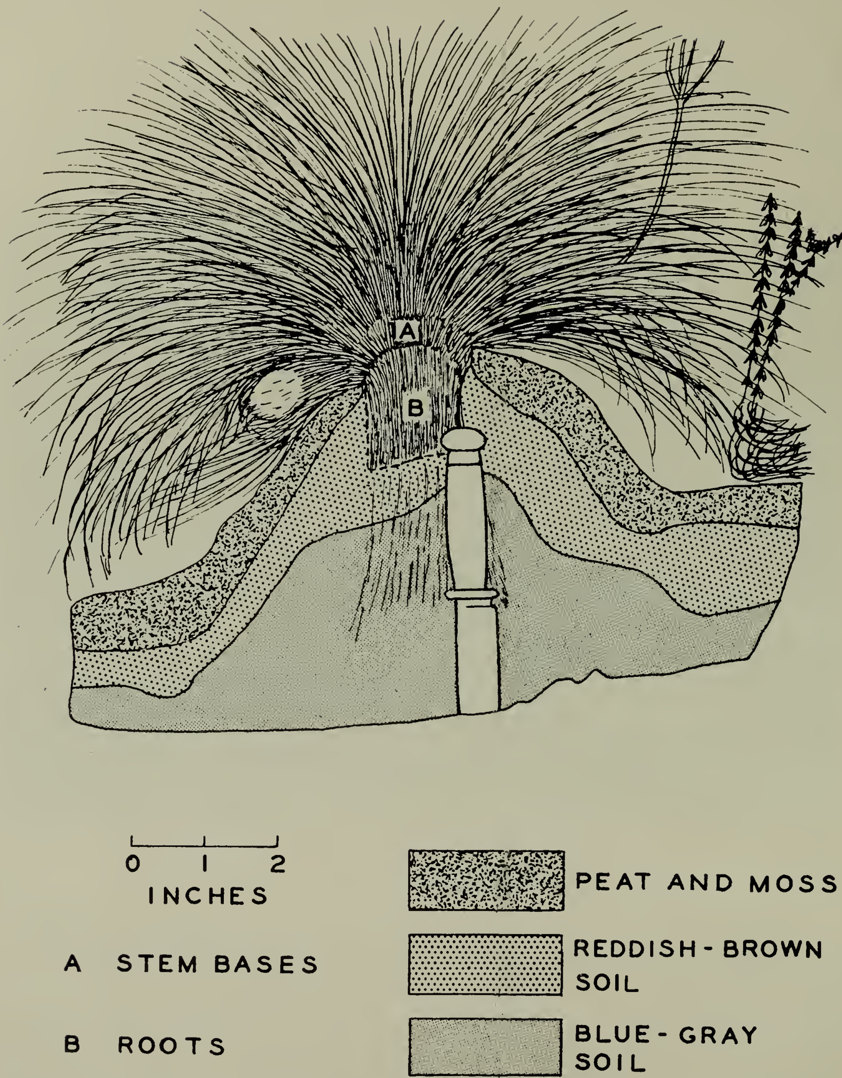


FIGURE 21.—Vertical section through young cottongrass tussock. Most of height of tussock consists of roots in mound of mineral soil.

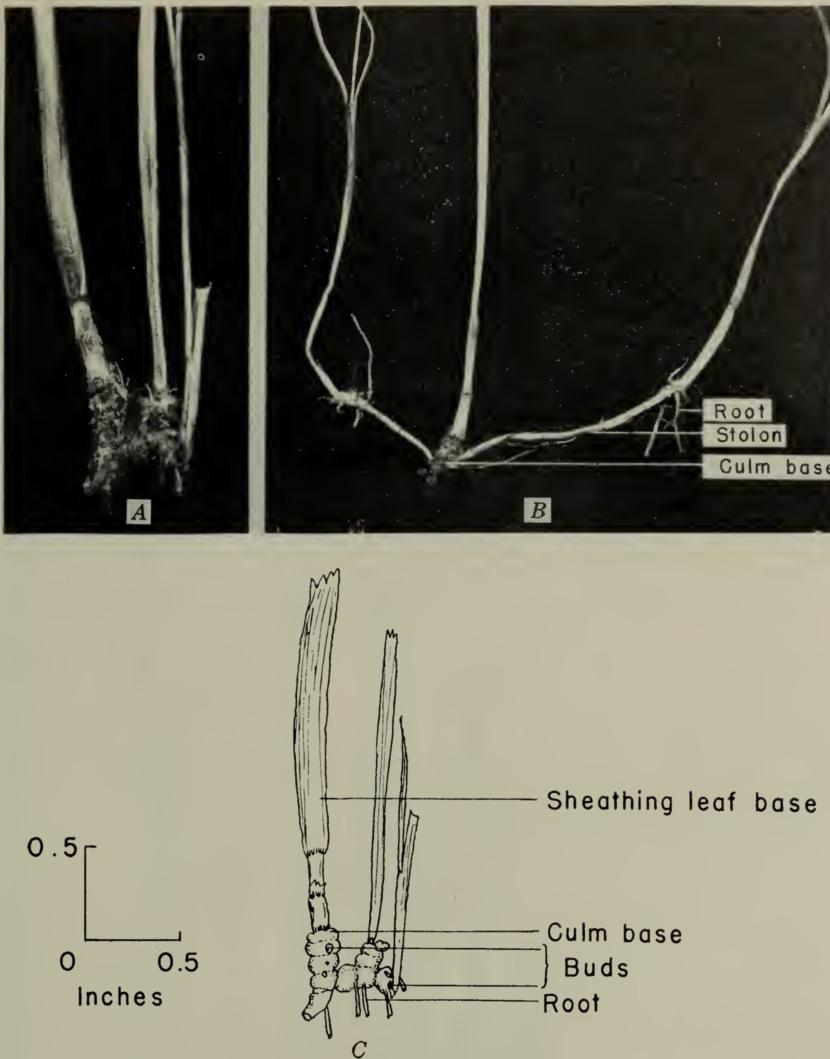


FIGURE 22.—Culm bases of *Eriophorum vaginatum* subsp. *spissum* and stolons of *E. russeolum* var. *leucothrix*. *A*. Thickened culm base and upright culms of *E. vaginatum* subsp. *spissum*. Narrow part of culm is the annual growth that dies each year. The thickened part below represents growth that is perennial, and from it grow roots and upright culms. *B*, Stolons and upright culms of *E. russeolum* var. *leucothrix*. Horizontal branch is stolon that grew in one year; upright culms grow from distal ends of stolons. *C*, Drawing of thickened culm base and upright culms of *A*.

As the number of new stems increases at the center of the tussock, old stems are crowded aside and die, leaving a mass of dead rhizomes and leaf bases fringing the sides. The root zone consists of a tightly packed mass of contorted living and dead annual roots. Individual roots, which are long and slender, can be traced to their point of attachment on the rhizome.

The height of the mound of mineral soil at the base of the tussocks appears to vary directly with the height of the tussock (fig. 23). Mineral soil probably occurs higher within the zone of roots than could be detected by field observation.

The larger tussocks are spaced at intervals of a few inches to 2 feet

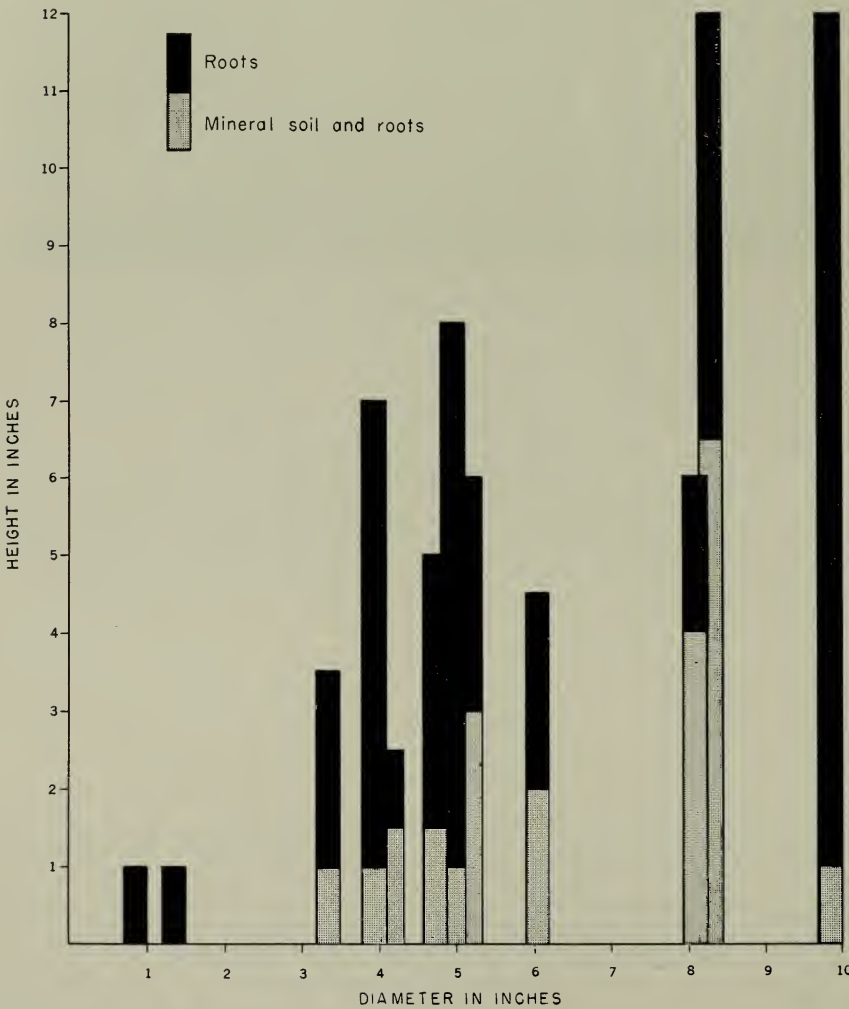


FIGURE 23.—Relationship shown in 12 cottongrass tussocks between height and diameter of tussock and height of mineral soil mound at base. Total length of each bar represents height of single tussock; diameter of tussock is shown by position of bar on horizontal line. Stippled portion of bar represents height of mineral soil mound at base of tussock; black portion represents height of roots extending above soil mound.

FIGURE 24.—Group of cottongrass tussocks.

and are surrounded by a thick mat of mosses (species of *Sphagnum*, *Calliergon*, and *Hypnum*) or by low areas in which vegetation of equivalent size is lacking (fig. 24). If thick mats of moss are lacking, the soil surrounding the tussocks is bare or is covered with humus and low mosses forming a layer less than an inch thick.

The culms, which are the only parts that can increase the height of the plant by growth, form only a small fraction of the height of the tussock. The height, therefore, is due to some cause other than the growth of the culms. Two hypotheses might explain this height: The culms started at the level at which they are found and the surrounding soil was removed by erosion or the culms started at a lower level and were pushed upward to their present position by frost action.

In a few exceptional localities the relief of the tussocks has been increased by rill erosion in the intertussock areas. These tussocks are exceptionally high and stand 30 to 36 inches above the surrounding soil. Rill markings between the tussocks and small silt fans farther down the slope testify to soil removal by running water. Most tussocks, however, do not owe their height to soil erosion, for rill markings and stratified sediments are lacking. The possibility of soil removal by creep or viscous flow of the soil also can be disregarded, because the tussocks commonly occur in soil areas completely enclosed by peat. No outlet exists through which the soil could have been removed. Most tussocks appear to have been pushed to their present height by vertical heaving beneath the plants.

During the autumn freezing cycle, the sides of the tussocks and the *Sphagnum* mosses and mineral soil surrounding the tussocks freeze more rapidly than the matted culm bases. The writers have observed that the culm bases were still unfrozen after the mosses had frozen to a depth of 4 inches and the mineral soil and sides of the tussocks had frozen 1 to 2 inches. Lower moisture content and better insulation due to the presence of dead air spaces account for the slow rate of freezing of the culms and roots. The freezing mineral soil between the tussocks expands and moves laterally into the thawed zone beneath the tussock, forcing it upward (fig. 28, *G*). Repeated cycles of frost thrusting from the intertussock areas raise a mound of mineral soil beneath the tussock and force the proximal portions of the roots vertically out of the soil.

Tussocks involving species other than *Eriophorum vaginatum* subsp. *spissum* are formed by other processes in addition to congeliturbation. Tussocks of the sedge, *Carex aquatalis*, are present but uncommon in the Imuruk Lake area. Much of the height of these tussocks is due to the growth of culms, but frost heaving is a contributing factor. Tussocks of *Calamagrostis* spp., occurring in Massachusetts and on the Seward Peninsula are due largely to the growth of culms but can start on tussocks of other species formed and enlarged by congeliturbation in the manner previously described. Frost heaving is responsible for much of the height of tussocks of *Carex* spp. found in marshes near Concord, Mass.

PEAT RINGS

Peat rings are low ridges of peat surrounding circular or oval patches of mineral soil (figs. 25 and 26). The rings are found on poorly drained uplands and on long smooth wet slopes of 10° or less. They are most common on southwestward-, southward-, or southeastward-facing slopes. Areas where peat rings occur are mantled by 1 to 3 feet of peat overlying mineral soil, on which is growing a tight sedge sod. Water stands about the lower parts of the plants and in all minor depressions.

On nearly horizontal surfaces the rings are more or less circular and are 4 to 12 feet in diameter. The centers of some rings in the Imuruk Lake area are bare but more commonly support a sparse and broken cover of vegetation. Isolated fragments of peat and torn sedge sod (*Carex aquatilis*) are scattered over the surface. Seedlings of *Eriophorum angustifolium*, *E. vaginatum* subsp. *spissum*, and *Scirpus cespitosus* grow in the wetter areas. On the slightly drier

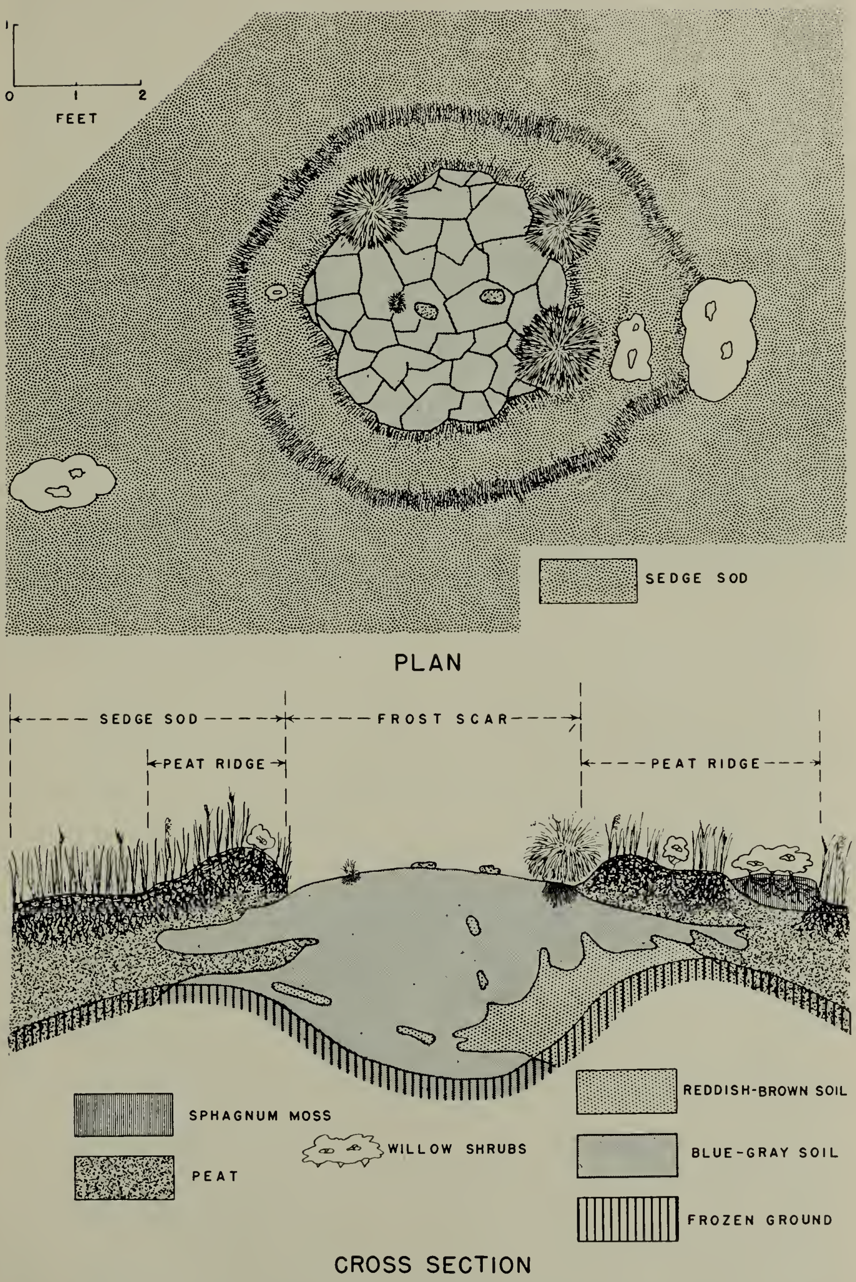


FIGURE 25.—Plan and cross section of peat ring.

FIGURE 26.—Large and small peat rings. In right foreground small, young peat ring consists of bare soil partly covered with standing water and surrounded by low ridge of peat. In background 10-inch white square rests against peat ridge of large, old peat ring the center of which is overgrown by *Eriophorum angustifolium*.

spots small tussocks of *Eriophorum vaginatum* subsp. *spissum*, as well as plants of *Empetrum nigrum* and *Vaccinium uliginosum*, cover small areas. Most of the surface of the soil, however, is bare. In most rings the soil area is slightly convex, with the center standing a few inches higher than the margins. Miniature zellenboden generally are present.

The marginal peat ridges range from 8 to 36 inches in height and 2 to 4 feet in width. For the most part, the vegetation on the ridge is similar to that in the surrounding marsh and consists of a dense, tight mat of sedge sod composed of a tangle of stolons, rhizomes, and roots of *Carex aquatilis* in which the following secondary species grow: *Eriophorum angustifolium*, *Salix reticulata*, *S. pulchra*, *Betula nana* subsp. *exilis*, *Rubus chamaemorus*, *Empetrum nigrum*, *Ledum palustre* subsp. *decumbens*, and *Vaccinium uliginosum*. In limestone areas *Silene acaulis*, *Saxifraga hirculus*, *Dryas integrifolia*, and *Cassiope tetragona* also are present. Nearly all of the secondary species occur on the top and inner face of the ridge. The vegetation has retained the form it had before the formation of the ridge, but additional species have become established both on the ridge and around it. In some rings a few well-formed tussocks of *Eriophorum*

PEAT RINGS ON VALLEY SLOPES.

Oblique aerial photograph showing distribution of peat rings on slopes of a shallow valley. Total relief is about 100 feet. Light comes from the west (left).

vaginatum subsp. *spissum* are rooted in the mineral soil at the inner margin of the ridge.

In cross section the rings consist of local mounds of mineral soil projecting through an otherwise continuous layer of peat a foot or more thick (fig. 25). On Seward Peninsula the marginal ridge generally consists of peat, but some rings examined by the writers consisted of a ridge of mineral soil about a foot high, capped on the outer slope by a layer of peat a foot thick. The peat of the ridges is intruded by involutions of mineral soil from the centers. Roots of sedge and stems and roots of the other species present are interwoven with the peat in the ridges. The roots of cottongrass tussocks extend through the thin marginal peat into the mineral soil. During middle and late summer the frost table under the soil mound is a basinlike depression 1 to 2 feet deep, whereas under the peat ridge there is a ridge in the frost table a few inches high.

Moisture conditions in the soil centers of peat rings vary widely from time to time and from place to place during the summer. During the spring thaw and the late summer rainy season the centers consist of fluid, saturated silt. During summer dry periods the centers remain saturated in some areas; in others the centers are moist, but not saturated, and will stand in vertical walls for several days in artificial excavations. The peat surrounding the rings, however, is saturated, and water draining from it quickly fills an excavation.

On gentle slopes the peat ridges are slightly elongate (fig. 27), the down-slope axis reaching 20 to 100 feet on slopes of 7° to 10°. Closely spaced rings on these slopes commonly are arranged in trains extending down slope (pl. 2). The soil centers of elongate rings are less conspicuously convex than those of circular rings. The soil center lies 6 to 12 inches below the general level of the slope at the up-slope end of the ring and a few inches above the general level at the lower end. The marginal peat ridge is highest at the down-slope end of the ring, where it acts as a dam, holding in the mineral soil. At the up-slope end, the ridge generally is missing, and in some localities narrow gullies 6 to 18 inches deep extend 5 to 20 feet up slope from the heads of rings.

Elongate peat rings differ from "solifluction lobes" (Washburn, 1947, pp. 90–92) in several respects. The lobes lack a marginal peat ridge, and typical lobes are larger in all dimensions than peat rings. Solifluction lobes generally consist of unsorted silt, sand, and gravel with many rocks more than 6 inches in diameter; the soil in peat rings examined by the writers consisted of silt with a little sand and a few pebbles but contained no rock fragments more than 3 inches in longest dimension. Forms transitional between solifluction lobes and elongate peat rings probably exist.

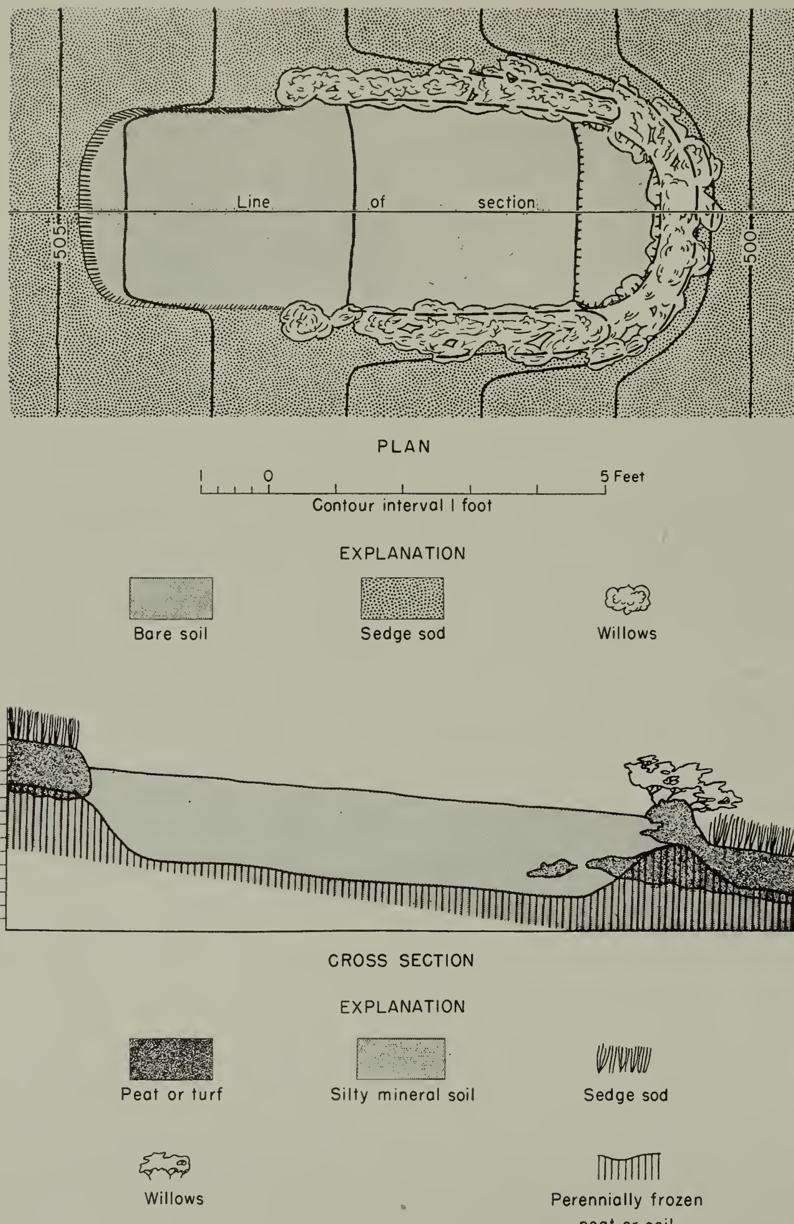


FIGURE 27.—Plan and cross section of elongate peat ring.

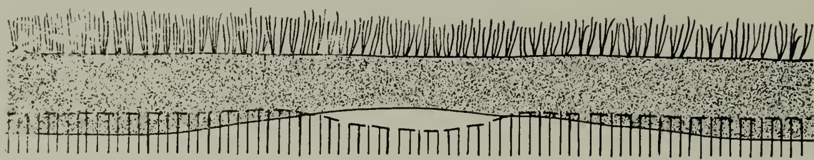
Elongate rings with completely bare soil centers were observed in only one locality. More commonly, the elongate rings bear a nearly complete cover of sedge (*Carex aquatilis*) and cottongrass (*Eriophorum angustifolium*) and a few herbaceous flowering plants.

Peat rings originate as frost scars in swampy areas covered by a layer of peat and a tight, nearly homogeneous sod, the combined thickness of which is approximately equal to the depth of annual thaw. Intense frost heaving disrupts the sod cover and forces mineral soil to the surface in scattered areas where summer thaw extends below the peat into the mineral soil (fig. 28, *A*). The scars are few in number and widely spaced in the marsh because of the relatively great thickness of the peat cover and because of the great strength of the fibrous sod when frozen. Once the surface cover is breached and the mineral soil is heaved to the surface, differential frost heaving reaches maximum intensity in the bare-soil areas. Extreme dilation of the scars upon freezing is favored by the presence of abundant moisture in the adjoining swamp, while dilation in the inter-ring areas is at a minimum because summer thaw does not extend through the peat into the mineral soil.

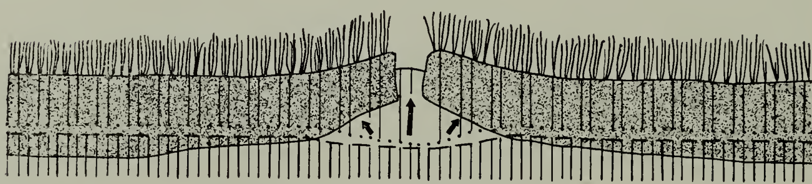
Frost thrusting from the soil centers during later freezing cycles pushes aside the surrounding peat and sod and warps it into a circular ridge surrounding the scar (fig. 28, *D*). As the frozen layer thickens beneath the bare area, involutions of mineral soil are thrust into the lower parts of the marginal peat (fig. 28, *E*). Outward displacement of the peat at depth is prevented by the presence of an incompressible ridge of frozen ground; part of the displaced peat must be moved, therefore, toward the center of the scar at depth through still unfrozen soil. The increment of movement during each freezing cycle is very small, and a great many cycles must be required to produce a ring as well-developed as the one shown in figure 25.

Part of the relief of the marginal ridges results from the accumulation of peat after the ridge is formed. The dense tangle of living roots enmeshed in the peat protects the ridge from later destruction by congeliturbation.

Elongate peat rings originate as frost scars on swampy slopes where the combined thickness of peat and sod is approximately equal to the depth of thaw. During the early stages of development viscous flow in the saturated soil centers and creep due to dilation and subsidence of the centers are effective in elongating the frost scars. During the raising of the marginal peat ridges differential frost thrusting also elongates the soil centers. Frost thrusting is most effective down slope and relatively ineffective upslope. As a result, the peat ridges are raised highest at the down-slope ends of the rings and commonly are missing at the up-slope ends. After a well-developed peat ridge has been formed, down-slope movement in the soil centers is retarded by the peat itself and by the presence of shallow frozen ground within the ridge. Creep and viscous flow reduce the slope of the soil area within the peat ridge to a lower angle than that of the inter-ring



STAGE A



STAGE B

STAGE C

STAGE D

STAGE E

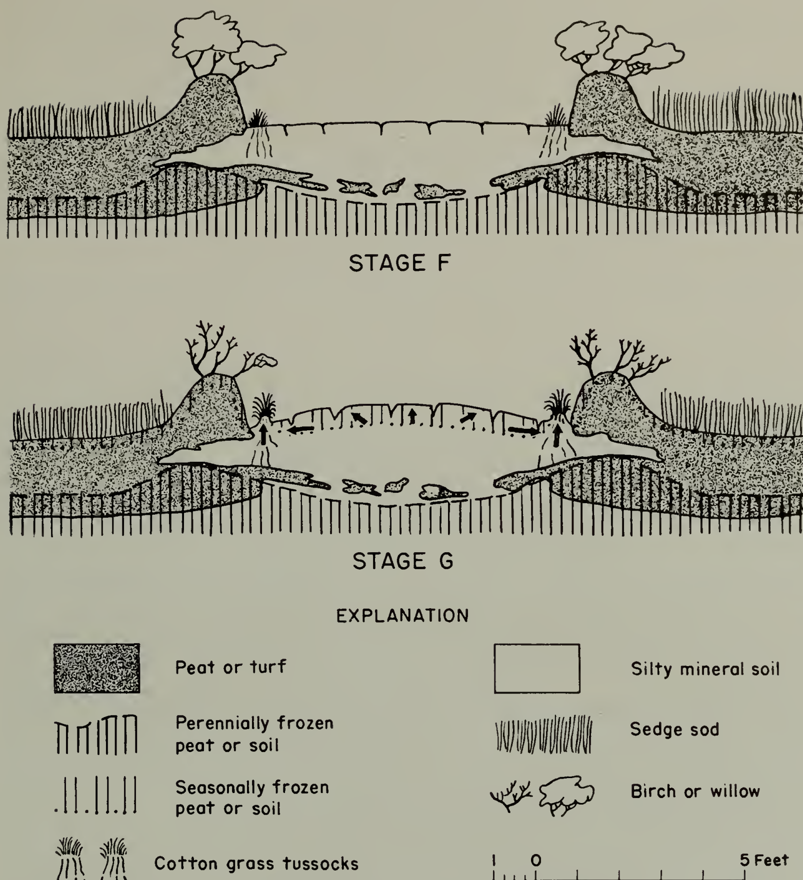


Figure 28.—Diagrammatic sketches showing evolution of a peat ring. Stage *A*, Unusually warm summer. In most areas depth of thaw does not extend below base of peat, but mineral soil is thawed in a few areas where peat is exceptionally thin. Stage *B*, Late autumn, same year. Thawed mineral soil expands upon freezing and breaks overlying thin cover of peat, initiating a frost scar. Stage *C*, Early autumn, several years later. Frost scar has been enlarged by shoving aside of peat at margins of bare soil area. Surface of scar expands upward as surface layers of soil freeze and expand. Dilation cracks (miniature zellenboden) are formed. Stage *D*, Late autumn, several years later. After surface layers of soil have frozen, a hard cover of frozen soil resists further uparching. Continued expansion resulting from freezing of deeper layers of soil is relieved by lateral thrusting. Ridge of peat is raised around bare soil center. Stage *E*, Late autumn, several years later. Ridge of perennially frozen ground beneath the peat ridge and thick layer of seasonally frozen ground in peat at the surface prevent further widening of the bare soil area by lateral thrusting. Instead, lateral expansion of soil center results in intrusion of masses of silt into peat of the ridges, forcing some of the peat to move in the opposite direction along the surface of the frozen ground beneath the frost scar. Stage *F*, Summer, several years later. Seedlings of cottongrass take root at inner edge of peat ridge. Stage *G*, Early autumn, same year. Bare soil has frozen to a depth of several inches, but soil beneath tussocks is still thawed. Lateral expansion forces freezing soil beneath tussocks, heaving them upward. Peat ridge no longer affected by lateral thrusting from soil center.

areas, but are no longer effective in increasing the length of the feature. Further elongation can result only from displacement of the peat ridge by down-slope frost thrusting within the soil center.

Movement in solifluction lobes consists chiefly of creep and viscous flow, but frost thrusting may be a minor factor. The origin and development of solifluction lobes will be discussed in a future paper.

TUSSOCK RINGS AND TUSSOCK GROUPS

A complete gradation exists between peat rings and tussock rings. Tussock rings consist of closely spaced plants of *Eriophorum vagina-*

FIGURE 29.—Small tussock ring. Scale is indicated by jackknife thrust into center of bare soil area. Note miniature zellenboden.

tum subsp. *spissum* surrounding a low mound of silty mineral soil, which, as in peat rings, is bare or covered with various amounts of *Eriophorum angustifolium* (fig. 29). Tussock rings occur in habitats similar to those in which peat rings are found, such as poorly drained lowlands, terraces, and hill summits where peat has accumulated to a depth of a few feet. No tussock rings were seen on slopes steeper than 1°.

The rings range from 4 to 12 feet in diameter and are spaced at intervals of 30 to 100 feet in the Imuruk Lake area. The surface of the mineral soil is distinctly convex and at the center stands 3 to 6 inches above the soil at the margin. The entire soil center extends slightly above the general level of the marsh. A network of miniature zellenboden invariably is present on the surface of the soil.

The low, relatively broad mound of mineral soil is surrounded by a ring of tussocks which grow on the inner margin of a low, inconspicuous ridge of peat. The peat ridge stands 4 to 8 inches above the general level of the surrounding marsh but only slightly above the soil at the center of the ring. Species of *Sphagnum* moss grow on the ridge and constitute part of its height. The ring of tussocks is 1 to 2 feet wide and stands 8 to 12 inches above the marsh and 4 to 6 inches above the soil center. Dwarf birch and heath grow in the *Sphagnum* and around the outside of the ring and around the individual tussocks.

In cross section the tussock rings are similar to peat rings. They occur on local mounds of silty mineral soil extending to the surface through the otherwise continuous mantle of peat. The soil centers are underlain by a 1-foot to 2-foot depression in the frost table, as in the peat rings. Fingerlike projections of silt extend into the peat at the margins, and contorted stringers of peat are strung out through the silt beneath the central part of the rings.

Recently initiated tussock rings were observed in 1948 on a broad hill summit in the Imuruk Lake area from which the vegetation had been cleared in 1945 with a bulldozer. All of the vegetation, as well as 6 to 12 inches of peat and mineral soil, was removed during the clearing. The hill summit apparently was rather well drained and supported a dense cover of tussock-birch-heath vegetation before clearing. Accelerated thaw followed removal of the original vegetation. The area became poorly drained, and in 1948 there were several small ponds.

Frost scars, peat rings, or tussock rings were present before the area was cleared, and the surface of the soil centers had undergone only slight modification 3 years later. Tractor tracks left in 1945 were still visible on the soil centers in 1948. New zellenboden had formed, adapting their pattern in part to the rectilinear indentations left by the cleats of the tractor treads. Young tussock rings were forming, and vegetation had begun to colonize the centers.

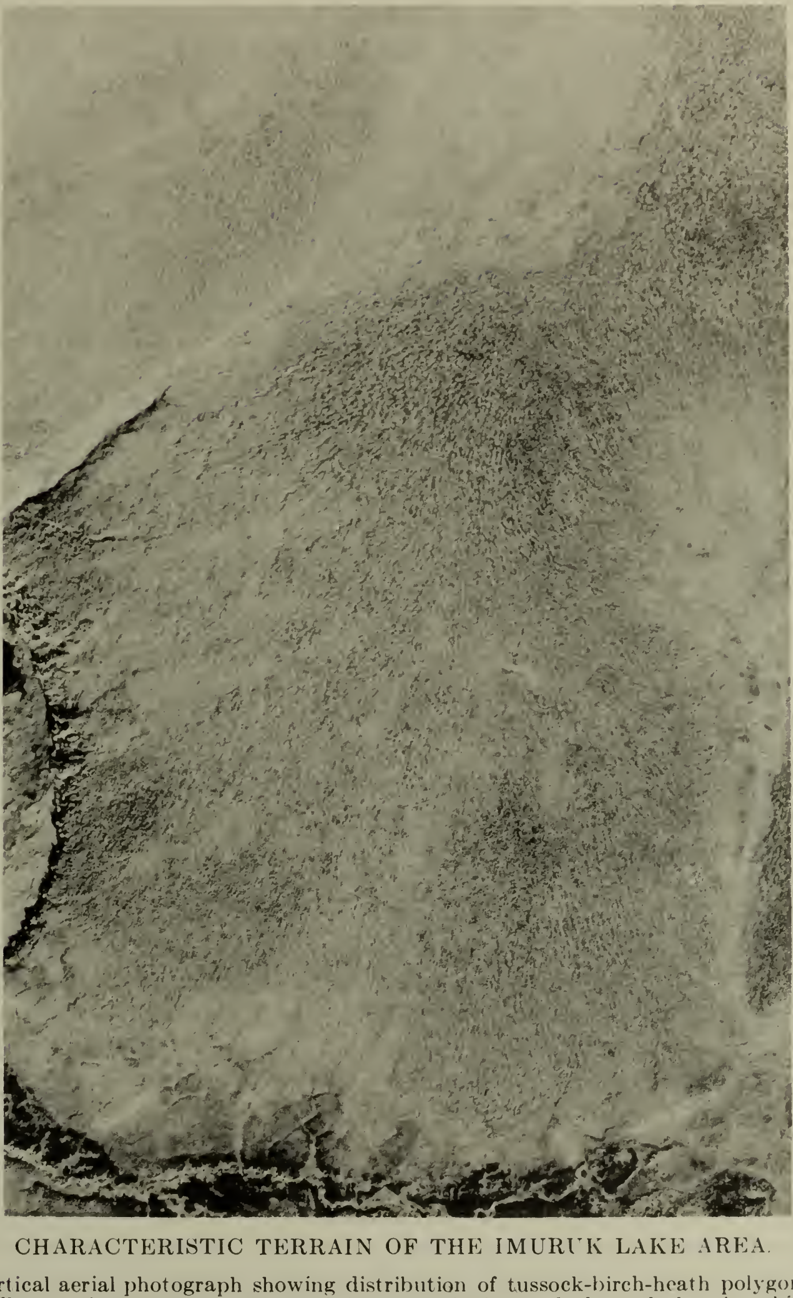
The rings consisted of widely spaced young tufts of cottongrass that were less than 1 year old when observed. The centers of most of the rings were bare, but a few supported small stands of *Eriophorum angustifolium*. Peat surrounded the rings and extended to the bare soil in the spaces between tufts of cottongrass. The age of the tufts was substantiated by the fact that no dead leaves were present at the base of the stems. Moreover, the plants had not developed the typical tussock form, and the stems rested on the mineral soil.

The ringlike pattern of the tussocks in the cleared area is due to the growth of tussocks on a frost scar formed by congeliturbation. At first it was thought that the tufts had been pushed or moved from random distribution on the centers of the scars, to their marginal positions by frost heaving somewhat in the manner that large stones migrate to the margins of stone polygons. The well-preserved tractor tracks and the undisturbed roots of the plants indicate, however, that the surface of the rings has not been sufficiently disturbed by frost to cause such a migration. Instead, conditions for the growth of *Eriophorum vaginatum* subsp. *spissum* are more favorable at the margins of the rings than at the centers. Drying winds, formation of needle ice, and heaving of seedlings from the soil are effective in preventing young plants from becoming established in the centers of the rings. At the margins, however, the small amount of peat on the surface may insulate the soil sufficiently to inhibit frost action and may lessen the water loss from the soil, so that seedlings can develop into mature tussocks.

Development of tussock rings on frost scars or peat rings in areas undisturbed by human activities probably proceeds in similar fashion. At the inside edge of the peat ring, where thin peat overlies the bare soil, a seed bed exists similar to that in the "artificial" frost scar described above. Scattered small tussocks have been observed on this inner margin in some rings; with the growth of more cotton grass plants, a complete ring of tussocks will be formed (fig. 28, *F*).

Once a complete circle of tussocks has developed, autumn frost thrusting ceases to affect the peat ridges, because a zone of thawed soil beneath the young tussocks intervenes between the ridge and the soil center. Instead, frost thrusting forces soil from the freezing centers into the thawed areas beneath the tussocks, and the tussocks are heaved upward (fig 28, *G*). Repeated cycles of heaving eventually raise the tussocks higher than the adjoining peat ridge, and a typical tussock ring is formed. Few tilted or overturned plants are seen, which indicates that the tussocks themselves are not moved outward but only upward. Outward movement would not be expected, because the compact tufted part of the tussock stands entirely above the soil, and the thrusting goes on several inches below the soil surface.

Certain tussock rings are two tussocks wide, and in those rings the outer tussocks are higher than the inner ones. The "two-storied" rings represent a later stage in the interaction of congeliturbation and plant growth. After a complete ring has developed, or perhaps while it is still developing, additional seedlings start on the mineral soil just inside the older rings. The relief between the two rings is maintained, because both rings are forced upward by frost thrusting and heaving continued over several years.



CHARACTERISTIC TERRAIN OF THE IMURUK LAKE AREA.

Vertical aerial photograph showing distribution of tussock-birch-heath polygons. These polygons are represented by the stipples and short dashes in white. Larger polygons are ice wedge polygons (lower left and upper right). Note partly drained thaw lake at right margin, small stream with angular course determined by trenches of ice wedge polygons at botton margin, and swale overgrown with sedge sod at right center. Photograph by U. S. Air Force.

Isolated circular groups of tussocks are present in some sedge marshes and seem to be related to tussock rings. All characteristics of site and soil are similar in both features, and the tussock groups differ from tussock rings only in the nature of the vegetative cover of the soil centers. In the tussock groups the centers are entirely covered with tussocks, whereas in the tussock rings the centers are bare or covered with *Eriophorum angustifolium.*

The development of two banks of tussocks in some sites and of circular clusters of tussocks in others suggests the mechanism by which some tussock rings become colonized by *Eriophorum vaginatum* subsp. *spissum* and by which the intensity of congeliturbation is reduced within the soil centers. The bare centers of some rings may become covered with tussocks by inward advance. The addition of successive rows of tussocks at the inner edge of the rings eventually may result in covering the surface of the low mound of mineral soil. Each new row of tussocks reduces the central area subject to early freezing (fig. 28, *G*). As the bare soil area becomes smaller, frost thrusting at the margins becomes less intense, and with the addition of the final tussocks at the center, congeliturbation reaches a minimum. Even in this comparatively stable state, however, congeliturbation is more active beneath the tussocks than in the adjacent areas covered with a thick peat layer.

Tussock rings with centers initially covered with *Eriophorum angustifolium* may become covered with tussocks by the growth of seedlings in random distribution throughout the centers. Scattered cottongrass tussocks are found among the *E. angustifolium* in some rings; with continued growth and development of the tussocks, *E. angustifolium* eventually could be replaced. It should be emphasized that not all peat and tussock rings pass through the sequences outlined above. On some sites, peat or tussock rings surrounding areas of *E. angustifolium* or bare soil appear to represent the vegetation of the feature in equilibrium with the present climate. Even when the cover of cottongrass tussocks is complete, congeliturbation is more intense in the mineral soil than in the adjoining peat. During a severe winter isolated tussocks can be overturned and new frost scars initiated on the site of the old peat rings.

TUSSOCK-BIRCH-HEATH POLYGONS

Tussock-birch-heath polygons in the Imuruk Lake area consist of dwarf, shrubby, woody plants growing in a network of peat-filled channels. The channels enclose areas of mineral soil covered by closely spaced cottongrass tussocks. The tops of most of the tussocks are level with the peat in the channels, so that the features have no obvious relief. During the summer the pattern in the vegetation and soil is striking from the air (pl. 3) but is not immediately obvious to the casual observer on the ground. In autumn, however, the contrast between the rows of red birch and heath and the intervening areas of yellow-green cottongrass becomes striking.

Tussock-birch-heath polygons occur on sites that are better drained than those on which peat rings, tussock rings, and tussock groups are found. The polygons occur on relatively dry uplands and on moderately well drained interfluves on slopes. On slopes of less than 3° the polygons are equidimensional and range in diameter from 7 to 15 feet. On slopes of 4° to 5° the nets become elongate, and the downslope axes are as much as 100 feet in length. On still steeper slopes the peat-filled channels extending across the slope disappear completely, and the pattern consists of continuous alternating stripes of birch-heath and cottongrass tussocks extending down slope. Tussock-birch-heath nets commonly are present throughout broad dome-shaped hills with a thick mantle of soil. The lineation of the elongate polygons resembles a flow pattern in aerial photographs (pl. 3). The direction and degree of maximum slope on any part of the hill can be estimated from the pattern of the polygons.

In cross section the polygons consist of closely spaced dome-shaped mounds in the mineral soil, each underlain by a discrete basin in the frost table (fig. 30). Thick layers of peat are present in the gullies between the domes in the mineral soil and are underlain by ridges in the frost table that commonly rise high enough to intersect the base of the peat. Thus each polygon is a closed cell of mineral soil, at least until late August or early September, when the entire partition of peat may become thawed. Involutions of mineral soil extend into the peat, and stringers of peat extend into the mineral soil along the base of the annually thawed zone.

The soil centers are composed of blue-gray and reddish-brown silty soil (fig. 30). The reddish-brown soil is found in a well-defined zone an inch or less thick beneath the humic materials at the surface and adjacent to the peat at the margins and in a poorly defined, ragged zone a foot or more thick extending along the frost table at the base of the soil center. The basal zone consists of mixed and involuted masses of reddish-brown soil, blue-gray soil, humic material, and peat. Stringers of reddish-brown soil extend upward into the blue-gray soil, which composes the remainder of the center. The reddish-brown color is most intense in the surface zone, in the zone adjacent to the marginal peat, and at depth in zones adjacent to masses of peat and living and dead cottongrass roots.

In the absence of chemical analyses the writers assume that iron is present in the blue-gray soil as FeO and in the reddish-brown soil as Fe_2O_3. An alternative possibility would be that iron is present as

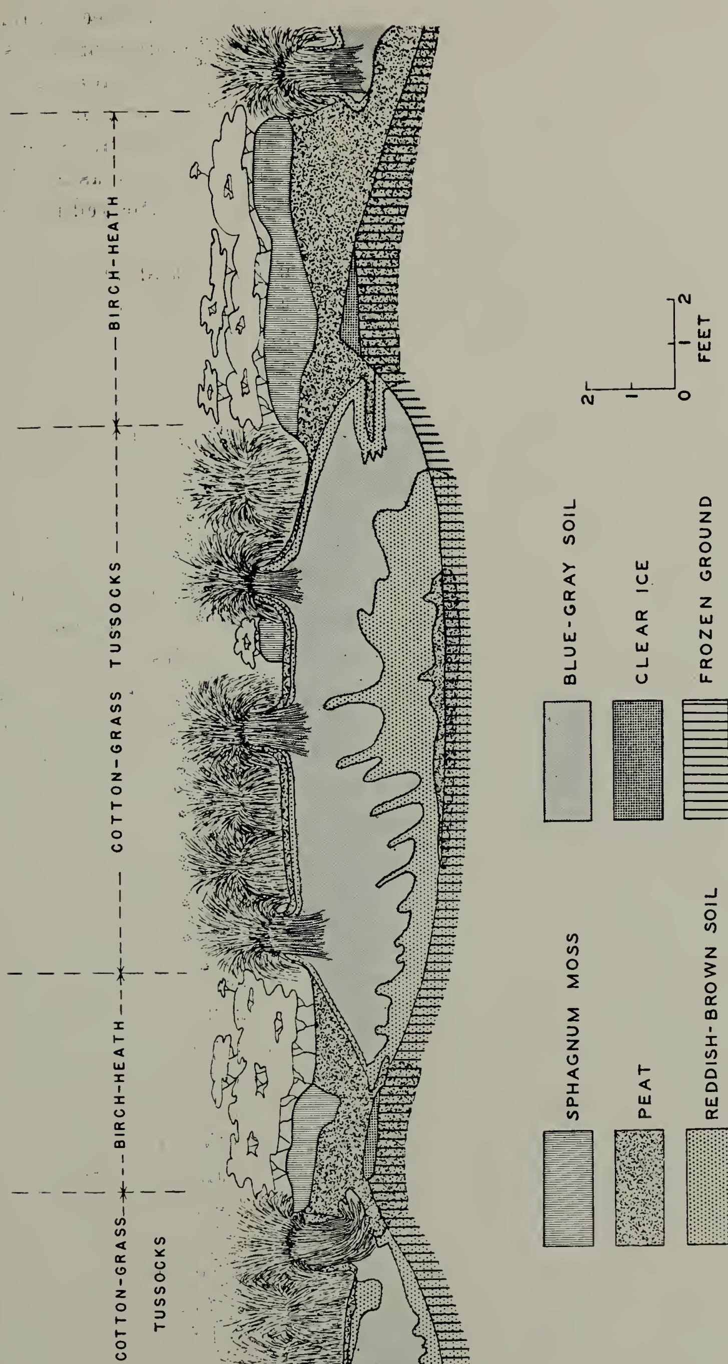


FIGURE 30.—Cross section through a tussock-birch-heath polygon.

Fe_2O_3 in both soil types but that most of the iron has been leached from the blue-gray soil and redeposited in the reddish-brown soil. Reddish humic acids also may contribute to the pigmentation. In any case, the close association of the reddish color of soil with living and dead vegetation suggests a genetic relationship. The writers believe that the reddish color of the soil originates adjacent to masses of organic matter, and that congeliturbation later mixes the reddish soil with the surrounding blue-gray soil.

Tussock-birch-heath polygons probably originate and develop much as tussock rings do. The mounds of mineral soil represent frost scars that have been colonized and partly stabilized by cottongrass tussocks, and the peat in the surrounding channels represents the remnants of a once fairly continuous thin layer of turf, which now constitutes a favorable site for the growth of birch, heath, and *Sphagnum*.

In most areas the polygonal or striped pattern in cottongrass-birch-heath vegetation appears to be very old and in equilibrium with the present environment. The polygons cannot be regarded as "inactive," however, because from time to time the pattern is altered in detail by the development of new frost scars, which later become colonized by vegetation and once more become an integral part of the reticulate pattern. The features are in equilibrium, nevertheless, because both the initial and the final pattern in this developmental sequence is the tussock-birch-heath polygon. In most areas the polygonal pattern originated in the past in response to small environmental changes.

It is possible that new polygons can originate in areas of structureless cottongrass-birch-heath vegetation growing on fairly well drained slopes covered with a nearly continuous mantle of turf. Where this takes place, polygon development is believed to involve the following sequence of events. Scattered frost scars disrupt the thin turf cover. In the early stages the scars are closely spaced but not continuous. The isolated frost scars acquire rings of cottongrass tussocks about their margins much as the tussock rings described above do. By growth of additional tussocks around the inner margin of the rings the surface of the frost scar becomes covered. *Eriophorum angustifolium* invades many of the centers. The insulating effect of the plants and dead leaves and the stabilizing effect of the roots lessens the intensity of congeliturbation. This plant cover then is invaded by *E. vaginatum* subsp. *spissum*, and a cluster of tussocks is formed.

In the meantime new frost scars form in areas between the original scars. When the scars become closely spaced, drainage is concentrated in the network of marginal channels. Peat shoved from the centers of the scars fills many of the channels, and on the peat *Sphagnum* mosses grow, adding to the thickness of the peat and forming a habitat in which dwarf birch and heaths can grow. The internal structure of the peat in the birch-heath areas indicates that the peat ridges owe their relief almost entirely to differential peat accumulation. The involutions in the peat ridges reflect lateral thrusting from the soil centers, but the effect of the thrusting seems to be to fold the peat deeper into the soil rather than to raise it above the surface.

The distribution of decomposed fragments of peat in the mineral soil of the polygons along the base of the annually thawed layer and upward at the center (fig. 30) suggests a sort of convective circulation of material within individual polygons. A similar pattern was noted within peat rings and tussock rings (fig. 28, *B*). For the origin of stone polygons, Low (1925) and Gripp and Simon (1933, 1934a, 1934b) proposed a theory of convection currents in a suspension of soil in water at temperatures near the freezing point. The Low-Gripp theory is generally discredited by geologists for a variety of reasons (Sharp, 1942, pp. 286–287) and can readily be ruled out here because of the undistributed state of the tussocks and because the soil centers of the tussock-birch-heath polygons always are relatively dry and well-drained. The distribution of the peat in the mineral soil suggests, however, that material is moved from the peat ridges at the margins, along the frost table, to the centers of the polygons, and at the centers, from the frost table toward the surface.

The movement of peat toward the centers of the polygons probably represents a reactive movement in response to the intrusion of mineral soil into the peat-filled channels. After several autumn frosts a thick surface layer of frozen ground is present throughout the soil centers except beneath the tussocks. The surrounding peat consists of a rigid, frozen surface layer, strengthened and anchored to the adjoining mineral soil be a dense tangle of stems and roots of birch and heath, and an underlying layer of thawed peat. As freezing progresses downward the mineral soil expands laterally into the peat; the channels are compressed by lateral thrusting from the freezing soil centers on both sides, and part of the peat is squeezed outward and downward into the thawed ground underlying the soil areas. Heaving of the peat between the two mounds is not accomplished because the rigid layer of frozen peat, reinforced by living stems, is sufficiently strong to resists upward movement. With repeated cycles of thrusting the peat moves by small annual increments to the center of the soil areas. Each increment of movement must be accompanied by a slight uparching of the surface of the mound. The upward projecting stringers probably originate after the peat has become widely distributed beneath the soil centers. During the early part of the freezing cycle, while cottongrass is being heaved, peat becomes involved in upward movements in the zones beneath the tussocks.

On slopes the development of the polygons is affected by the down-slope movement of soil, elongate polygons being formed on gentle slopes and stripes on steeper slopes. Frost thrusting and creep due to dilation and subsidence are the chief factors in down-slope movement. The observations of the writers indicate that the moisture present is insufficient to permit viscous flow in tussock-birch-heath polygons or stripes during summer and autumn. Meltwater from snow furnishes adequate moisture during early spring, but only a thin layer of soil is affected during that period because of the shallow depth of thaw, which ranges from 1 to 6 inches at that time of year.

AGE OF THE FEATURES

The cryopedologic features described above are active at the present time, and the discussion of their origin is actually a discussion of their perpetuation. New frost scars form and old frost scars are stabilized, but the total number that are present in a given site remains about the same as long as environmental conditions do not change. Local changes in drainage conditions related to lateral shifts in the positions of major streams on their flood plains or to the formation or destruction by thaw lakes (Hopkins, 1949) are reflected by small changes in the distribution of frost scars, peat rings, tussock rings, and tussock-birch-heath polygons. In general, however, the distribution of these features has remained nearly constant as long as the present climate has prevailed. Small changes in the climate probably have resulted in the initiation of new areas, variations in the degree of activity in some preexisting areas, and the destruction of other preexisting areas. Greater changes in the climate may have resulted in the complete elimination of some of the features.

There is evidence of major climatic fluctuations within Quaternary time in many parts of Seward Peninsula. At least two stages of glaciation can be distinguished in the Kigluaik and Bendeleben Mountains. The younger stage is subdivided tentatively into several substages. Present knowledge in Alaska is inadequate for an attempt to correlate the glacial stages on Seward Peninsula with the chronologies established elsewhere, but the age of the younger glaciation is thought to be about the same as that of the Wisconsin glaciation in the United States. The climate of Seward Peninsula was warmer than at present during some parts of Quaternary time. Spruce and birch logs and bones of extinct mammals are found together in deposits of Quaternary age as much as 50 miles west of the present timber line.

Widespread stabilized rubble fields, stone polygons, and stone stripes testify to the existence of a past climate even more rigorous than the present in the Imuruk Lake area. Most of these features are believed to have been active during the younger glaciation and during earlier cold periods.

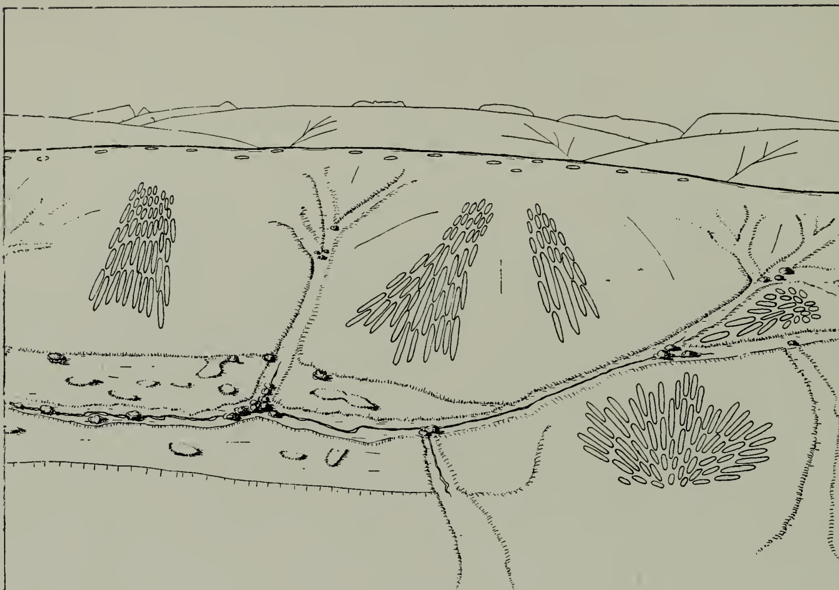
Evidence concerning the character of "postglacial"[3] climates is scanty. Low terraces and beach lines at Imuruk Lake and several smaller lakes suggest the following: Lake levels lower than the present levels (subaerial peat is found several feet below the present lake level in some terraces); a slow rise in water levels to an elevation 3 to 7 feet above the present lake levels; and a slow drop to the present level. The fluctuations in lake levels may have taken place in response to fluctuations in the balance of precipitation, runoff, and evaporation. If this is true, the low lake levels represent a period warmer than the present during which the rate of evaporation was high relative to precipitation and surface runoff, and the later high lake levels represent a period slightly colder than the present during which the evaporation rate was low. Lowering of the lakes to their present levels would have taken place in response to a gradual warming of the climate with a consequent rise in the rate of evaporation relative to precipitation and runoff. Bones of extinct mammals are absent in the low terraces, although they are abundant in older higher terraces; hence, the sequence of events outlined above is believed to have taken place after the extinction of those mammals and after the last local glaciation.

Other evidence supports the view that recently the climate has been growing warmer on Seward Peninsula. Small actively growing gullies in some swales suggest that in favorable localities soil movements due to congeliturbation have been retarted or have ceased, and that stream erosion has become important. Areas of alder are expanding in the region northeast of Imuruk Lake. The area of spruce is expanding on the Fox River, southwest of Council, and spruce is growing vigorously on all favorable sites in that area.

Under ordinary conditions later congeliturbation rapidly destroys evidence of past generations of frost scars, peat rings, tussock rings, and tussock-birch-heath polygons; consequently, speculations on the past distribution of these features is, at best, an intelligent guess. Present knowledge does permit speculation upon the effects of past climates upon depth of thaw and drainage conditions in various sites, however, and the resulting distribution of cryopedologic features can be inferred.

All four features, as well as most of the same plant species, probably have been present in the Imuruk Lake area throughout postglacial time and perhaps throughout the period of the last glaciation on Seward Peninsula. The distribution, abundance, and degree of activity of the features probably has varied, however, with varying climate.

[3] "Postglacial" is used here in an informal sense to indicate the period of time which has elapsed since the younger glaciation on Seward Peninsula.



STAGE A

STAGE B

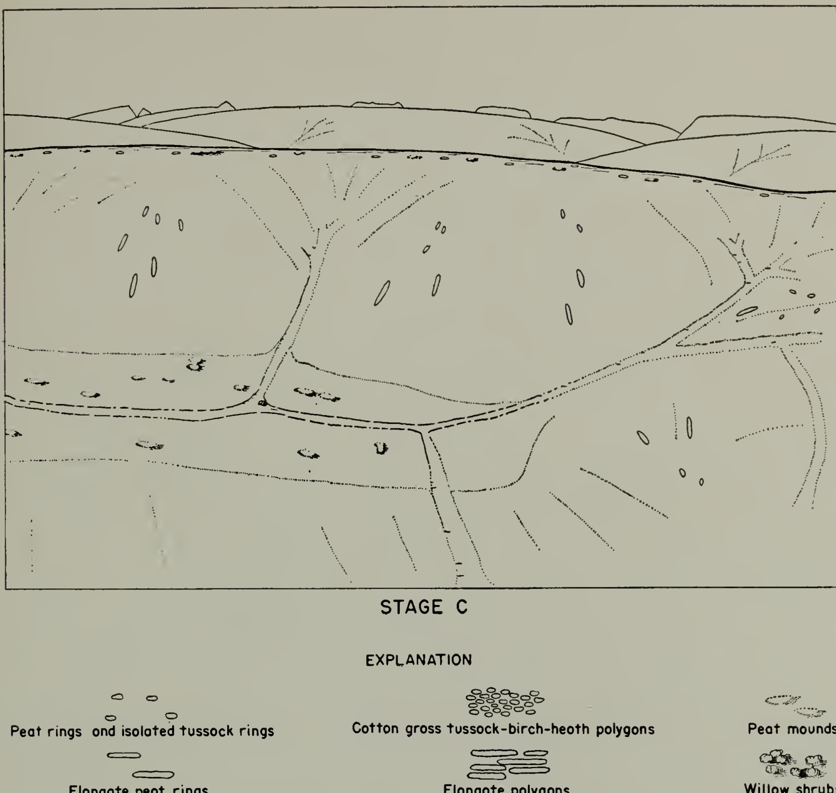


FIGURE 31.—Diagrammatic sketches illustrating the effects of change in climate upon the distribution of cryopedologic features. Stage *A*, Distribution at the present time. Peat mounds are largely confined to low-lying swampy areas mantled by a thick layer of peat. Peat rings are present on poorly drained uplands and summits. Tussock-birch-heath polygons are present on slightly drained summits and slopes. Large willows and birch shrubs are confined to swales containing well-defined streams. Stage *B*, Distribution of features if the climate were warmer than the present time. Drainage is much better because summer thaw extends to greater depths and because gullies are incised into swales and drainage lines. Birch and willow shrubs cover drainage courses and lower parts of slopes. Vegetation polygons are restricted to poorly drained summits, and peat rings are almost completely eliminated. Stage *C*, Distribution if the climate were colder than at present. Drainage is much poorer because summer thaw extends to shallower depth and because definite stream channels are lacking in swales and drainage lines. Peat mounds are present on poorly drained lowlands and summits. Vegetation polygons are restricted to steeper exceptionally well drained slopes (not shown). Large willow and birch shrubs are restricted to the flood plains of major streams (not shown).

During the altithermal period ("postglacial optimum," Antevs, 1948), the depth of summer thaw probably was greater and drainage better than at present at nearly all sites. Frost action was less intense throughout most of the areas but more intense in certain sites. Depergelation caused the summer frost table to retreat into the underlying mineral soil in areas mantled by several feet of peat. Peat rings probably were eliminated from most of their present sites and may have disappeared from the region (fig. 31, *B*).

Frost scars become more closely spaced on areas mantled by a thinner layer of peat, and tussock-birch-heath polygons developed where peat rings or tussock rings had existed before. Slopes at present covered with vegetation polygons or stripes may have become so well-drained that congeliturbation ceased, and cryopedologic features were entirely lacking or completely stabilized. The vegetation on these sites probably was dominated by birch and willow shrubs similar to the vegetation now growing on steep banks and exceptionally well drained slopes.

During the following cold cycle the depth of thaw was notably shallower than at present, and the drainage was poorer in most sites (fig. 31, *C*). Congeliturbation and congelifraction were more active throughout most of the area but less intense in certain sites. In areas mantled by 2 to 3 feet of peat, the frost table rose above the base of the peat and no new frost scars could be initiated, although preexisting peat rings and tussock rings in these areas probably continued to be active. A shallower depth of thaw produced conditions that favored the growth of sedge sod on areas that had been covered with tussock-birch-heath polygons; peat rings and tussock rings may have been the only cryopedologic features present on these surfaces. Vegetation polygons probably could exist on only a few of the most favorable, best-drained surfaces.

The distribution of active cryopedologic features approached the present pattern with renewed warming of the climate. New frost scars formed in areas mantled with 2 to 3 feet of peat. Cottongrass tussocks colonized the surfaces of peat and tussock rings on areas mantled with a thinner layer of peat (fig. 31, *A*). Continued vigorous congeliturbation on these surfaces resulted in the formation of new closely spaced frost scars, which later were colonized by tussocks. Eventually the sedge sod was destroyed, and the present polygons became dominant on the sites on which they are found today.

CONCLUSIONS

Frost scars, peat rings, tussock rings, tussock groups, and tussock-birch-heath polygons are characteristic features in areas where silty mineral soil is present beneath a mantle of peat or turf less than 3 feet thick. These features represent stages in several developmental series, all of which start with the frost scar as the initial form. Each feature represents the equilibrium feature for certain environments and supports the vegetation which is in equilibrium with that environment.

Closely spaced frost scars in relatively well drained areas where the soil is mantled by a thin, discontinuous layer of peat or turf evolve into tussock-birth-heath polygons. A different developmental series is encountered in poorly drained areas where the peat mantle is approximately equal in thickness to the depth of annual thaw. Here, frost scars are initiated only at the widely separated points where summer thaw extends through the peat into the underlying mineral soil. Such frost scars evolve into peat rings, and in certain marshes the peat rings evolve further into tussock rings. The tussock rings in a few sites ultimately become completely colonized by cottongrass, and tussock groups are formed. In many marshes, however, tussock rings or peat rings appear to represent the ultimate, equilibrium forms, with which the developmental sequence ends.

Frost scars initiated in rocky soils evolve into forms that lie beyond the scope of this discussion. If rocks are sufficiently abundant, segregation of coarse and fine material forms stone polygons or with the growth of vegetation on slopes forms turf-banked terraces.

Frost scars are lacking in areas mantled by a layer of peat that is thicker than the depth of annual thaw. Frost heaving in these areas occurs entirely within the peat and results in the formation of peat mounds of irregular shape.

It is apparent that even the most liberal concept of "climax vegetation" (Cain, 1947, p. 193) must be modified when applied to much of the vegetation in regions of intensive frost action (Sigafoos, 1949). Disturbance of the substratum is an environmental factor that generally is disregarded in theoretical discussions of the development of vegetation into climax communities. In temperate regions most plant succession proceeds upon an essentially stable substratum, and disturbances are rare in the time required to attain the climax vegetation. Repeated disturbance of the substratum is an important environmental factor, however, in most plant communities in tundra regions. Plant succession on frost scars proceeds upon a substratum that rarely becomes completely immobile, and the succession may be arrested at any point by continued mild heaving, or it may be interrupted by renewed heaving sufficiently violent to create a new bare spot. The final stage in the succession on many frost scars consists of a complete cover of cottongrass tussocks, but even this final stage exists on a mobile surface the instability of which contributes to the exclusion of possible later successional stages. The vegetation in areas of frost scars, peat rings, tussock rings, and tussock-birch-heath polygons can be regarded as an equilibrium assemblage adjusted to the environment in which it exists but differs from a climax assemblage because areas of bare soil and areas being actively colonized by pioneer plants always constitute important elements in the vegetation, interspersed among larger areas covered by vegetation which represents the highest stage in the succession.

Palmer and Rouse (1945) believe that a plant cover consisting predominantly of lichens is a later developmental stage in areas characterized at present by tussock-birch-heath vegetation. They state that reindeer are effective in destroying the lichen-dominated vegetation, which then is replaced by cottongrass tussocks. If the tussock vegetation is proteced from grazing, however, it will be replaced again by lichens, according to Palmer and Rouse. We have seen polygons of birch and heath within a lichen-dominated vegetation, but the area in which these polygons were found was better drained than most areas in which tussock-birch-heath vegetation is present. Therefore, it is believed that continued congeliturbation prevents tussock-birch-heath polygons from evolving into lichen-dominated vegetation, and thus the polygons can be regarded as the equilibrium feature covered by the equilibrium vegetation in most areas in which the polygons are found. During periods of warmer climate, when better-drained soils were more widespread, lichen-dominated vegetation probably occurred within areas where tussock-birch-heath polygons now exist. Lichen-dominated vegetation may have been an intermediate stage in the development of willow-birch-heath shrub vegetation on better-drained soils and probably persisted on a few sites throughout the warm period.

Some of the cryopedologic features described in this paper eventually may be recognized in "fossil" form in northern United States or Europe. Peat rings and vegetation polygons are the features most likely to be preserved in recognizable and distinctive forms; even these are likely to be recognized only where exposed in cross section. Chances of preservation would be best if the features were buried beneath a mantle of loess or alluvium. Some of the "involutions" and "plications" described by previous authors may represent ancient peat rings or tussock-birch-heath polygons. In "fossil" form peat rings would consist of isolated stubby columns of silt in a layer of peat. Tussock-birch-heath polygons would consist of a crudely polygonal network of peat masses surrounding stubby columns of mineral soil. They could be distinguished from ancient ice wedge polygons ("Taimyr polygons") by their small vertical and horizontal dimensions. Ice wedge polygons generally are 25 to 100 feet in diameter (Leffingwell, 1919, pp. 205–212), although polygons as small as 15 feet in diameter are not uncommon (Black, R. F., personal communication). Tussock-birch-heath polygons generally are less than 15 feet in diameter. Ice wedges of ice wedge polygons generally have a vertical extent in excess of 5 feet. Structureless masses of peat, soil, or till occupy the former sites of the ice wedges, and these also generally have vertical dimensions in excess of 5 feet (Schafer, 1949, pp. 165–169; Horberg, 1949, pp. 132–134). The peat masses of tussock-birch-heath polygons, on the other hand, range from 1 to 3 feet in vertical dimension.

The peat rings, tussock rings, and tussock-birch-heath polygons studied by the writers were found in areas where perennially frozen ground lies at shallow depth; the presence of perennially frozen ground appears to be an essential factor in their origin. It can be assumed that "fossil" forms of these features indicate the former presence of perennially frozen ground. In modern rings and polygons, perennially frozen ground lies a few inches above the base of the peat at the margins of the soil centers. Stringers and lenses of humic material are concentrated at the base of the annually thawed zone within the soil centers. The vertical position of these features in fossil rings and polygons should afford a reliable measure of the former depth of summer thaw.

Recognition of the cryopedologic features described here is useful to the photointerpreter in predicting trafficability and foundation problems. Peat rings, tussock rings, tussock groups, and tussock-birch-heath polygons can be recognized on aerial photographs with a scale of 1:10,000 or larger. Peat rings, tussock rings, and tussock groups generally cannot be distinguished from one another on these photographs, but these three features can be distinguished from tussock-birch-heath polygons or stripes. The presence of any of these features indicates the probable presence of fine-grained soil in which perennially frozen ground is present at shallow depth. The thickness of peat at the surface and the moisture conditions of the surface can be estimated if the polygons can be distinguished from the rings. Maximum degree of slope can be estimated from the degree of elongation of the features.

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