THE OHIO JOURNAL OF SCIENCE

VOL. LI NOVEMBER 1951 No. 6

SOIL INSTABILITY IN TUNDRA VEGETATION*

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Movement of the substratum and thawing of perennially frozen ground are of primary importance in northern latitudes in controlling the microdistribution of tundra vegetation. In middle latitudes, however, soil movement receives only minor attention in studies of vegetation, except in specialized habitats. Griggs (1934, pp. 168–170) drew an analogy between vegetation of rocky arctic slopes and weeds of plowed fields of temperate regions. Raup (1947, p. 50) classified the vegetation of the Brintnell Lake region and Polunin (1934, p. 346) classified the vegetation of Akpatok Island according to habitat, rather than according to recognized ecological schemes. Polunin (1935, pp. 192–194) stated that soil movement on Akpatok Island in eastern arctic Canada has retarded the development of the vegetation since the island was freed of continental ice. Thawing of perennially frozen ground under existing climates is unique to regions of high latitudes where it has a profound effect upon local water tables, thus upon vegetation.

The effects of unstable soils upon vegetation were studied on Seward Peninsula, which extends west of central Alaska between the Arctic Ocean and the Bering Sea. The peninsula, lies between 161° and 168° west longitude and between 64° north latitude and the Arctic Circle (fig. 1).

This paper is the byproduct of field studies made during the summers of 1948 and 1949 for the permafrost program of the United States Geological Survey in cooperation with the Engineer Intelligence Division, Office of the Chief of Engineers, United States Army.

Special appreciation is expressed to Mary D. Sigafoos for assistance in the field. For helpful criticism in writing this paper I wish to thank Kirk Bryan, D. M. Hopkins, H. M. Raup, L. L. Ray, and J. N. Wolfe.

GEOGRAPHIC SETTING

Topography

Four types of topography are represented on the Seward Peninsula: coastal plain, dissected uplands, interior lowlands, and mountains. The coast is bordered by a series of low plains, in places narrow and broken by upland prominences extending to the shore, in other places the plains are 1 to 10 miles wide. Dissected uplands occupy the southern and northern thirds of the peninsula and are characterized by rounded summits and convex slopes. Relief varies from 800 to 2,000 feet. A crescent-shaped system of mountains separates the dissected uplands. The mountains, from west to east, consist of the Kigluaik, Bendeleben, and Darby ranges (fig. 1). Summit altitudes average 2,500 feet, but some peaks exceed

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*Publication authorized by the Director, U. S. Geological Survey.

THE OHIO JOURNAL OF SCIENCE 51(6): 281, November, 1951.

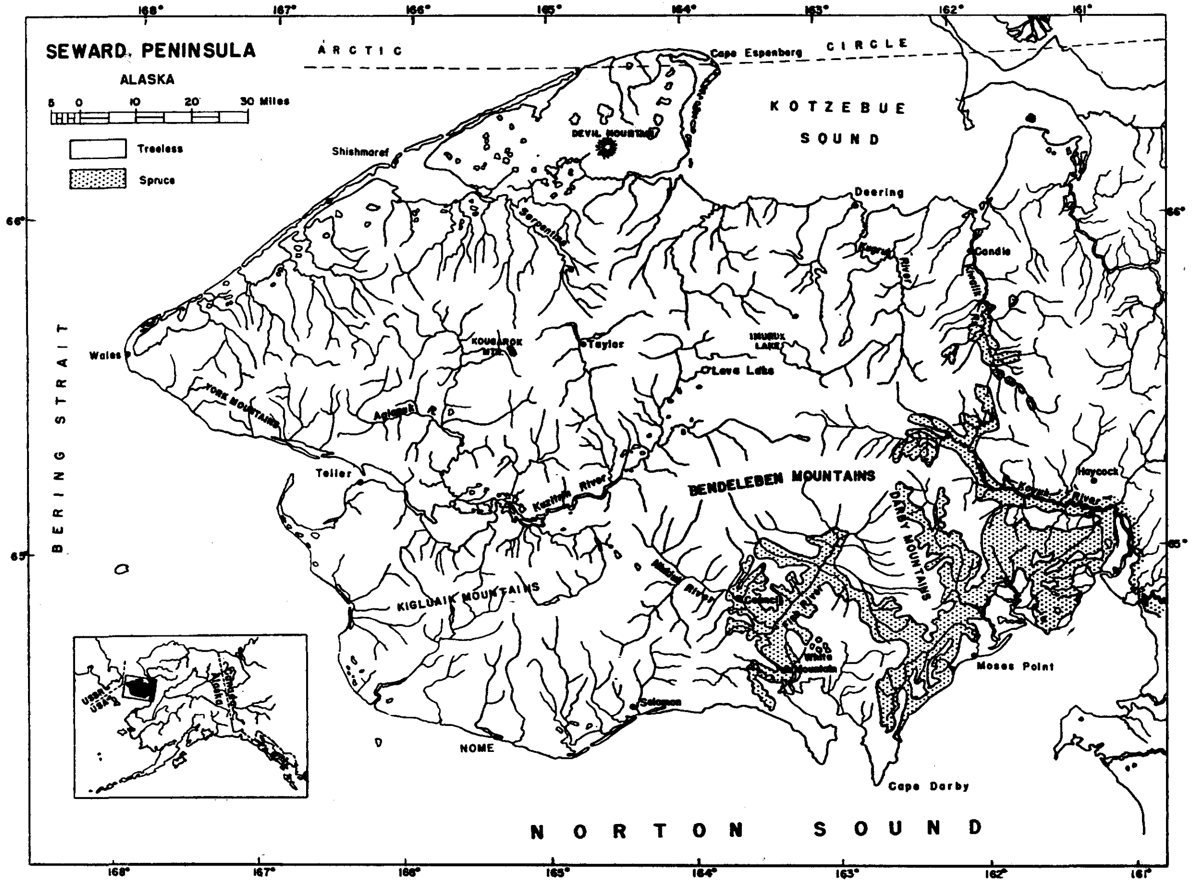

FIGURE 1. Index map of Seward Peninsula, Alaska.

4,000 feet. Valleys in the mountains are U-shaped, slopes are steep, and glacial cirques occur at the heads of most valleys. Interior lowlands are most extensive north of the Kigluaik Mountains. There relief is low, drainage is poor, and many lakes are present.

Vegetation

Most of the peninsula is treeless and is characterized by assemblages of shrubs and herbaceous plants which collectively are called "tundra." Willow shrubs, 10 to 12 feet high, grow along nearly all streams, and at sites of most ground-water seeps. Alder thickets are characteristic of steep well-drained slopes in the mountains and locally in the dissected uplands. Poplar occurs in small patches on the lower slopes in the dissected uplands and along stream valleys at the eastern end of the mountains. Spruce is found at intermediate elevations in the east and southeast sections of the peninsula (fig. 1).

Climate

The climate on Seward Peninsula is characterized by long, cold winters and short, cool, wet summers. Periods of several days to a week with temperatures below freezing alternate with similar periods with temperatures above freezing during spring and fall. The mean annual temperature at Candle, in the northeastern part of the Peninsula, is 20.2° F; the minimum temperature recorded is −60° F. The mean annual temperature at Nome, on the southwest coast, is 25.9° F; at White Mountain, within the spruce forest, 27.2° F. Minimum temperatures at Nome and White Mountain are not as low as at Candle (Taber, 1943, pp. 1440–1443; U. S. W. B. Climatic Summary, 1943). Temperatures of plants, soil, and rocks are more extreme than air temperatures recorded by the U. S. Weather Bureau, because plant, soil, and rock surfaces lose and absorb more heat than does air.

At Nome, during the summer of 1949, only 12 days were without rain in the 92 days of July, August, and September. For 35 consecutive days, August 1 to September 5, precipitation fell every day. Most of the precipitation is light drizzle of long duration, but heavy showers are not uncommon. Because of low temperatures and high atmospheric vapor pressures, evaporation rates are low.

Perennially Frozen Ground

Perennially frozen ground occurs nearly everywhere north of the mountains except under rivers and most lakes. Larger areas of unfrozen ground exist in the dissected uplands south of the mountains. For the most part, the unconsolidated deposits of the coastal plain are perennially frozen from 1 to 10 feet below the surface to bedrock, but thawed ground is present under streams. Depths of summer thawing depend upon the density and kind of vegetation cover, soil type, topography, and drainage conditions. Gravel tailing piles near Nome have become perennially frozen in 7 years from near the surface at least to bedrock at a depth of 60 feet.

Congeliturbation

Congeliturbation involves the processes that stir and mix the surface layers of soil in cold climates where freezing and thawing is intense. The material so moved is a congeliturbate (Bryan, 1946, p. 633). On Seward Peninsula it is a major geomorphic process and a dominant factor affecting vegetation. Some of the effects of congeliturbation upon the development of vegetation and upon modification of the land surface have been described by Hopkins and Sigafoos (1951, pp. 59–63).

Taber (1930) has shown that freezing silty soils in the presence of abundant moisture absorb a quantity of water in excess of the natural porosity of the unfrozen material. The excess water is present as segregations of small clear ice lenses and stringers, and large wedges 1 to 4 feet wide and 4 to 15 feet long. Individual grains of unconsolidated deposits are cemented with ice in the interstices which are invisible to the naked eye.

The intensity of heaving or amount of movement in the soil upon freezing is determined by the abundance of clear ice formed and upon the binding effects of vegetation. Any variations in the depth of annual freeze and thaw, in the insulating effects of the plant cover, in the amount of moisture and in the thickness of snow in autumn, result in variations in the quantity of ice formed, and thus in the intensity of congeliturbation. Dilation of the soil surface layers is not uniform, and differential heaving is a general phenomenon, not an exceptional one. Congeliturbation affects all parts of the soil surface layers in depth and horizontal extent in high latitude regions.

Plants grow and develop within and on the congeliturbates while the soil is in motion. The structure and form of the vegetation is determined by the interaction of plant growth and the intensity and kind of soil movement. Congeliturbation, which sorts coarse and fine fragments in soil, acts on vegetation as well. Thus rings, nets, garlands, stripes, mounds, hummocks, and ridges, which are common microrelief features formed by frost action (Sharp, 1942b), also are common patterns in the microdistribution of plants.

EFFECTS OF CONGELITURBATION UPON VEGETATION

It is practically impossible to separate cause and effect in the interrelationship between congeliturbation and vegetation without describing the development of microrelief features in which plant growth is an important factor. Congeliturbation, however, affects plants by: (1) burying them beneath soil; (2) damaging roots and stems by breaking or bending them; and (3) by changing soil-water relations by moving the plants with respect to water table or by blocking surface-water flow. These effects result from spring and fall movement of the upper 1 to 3 feet of soil.

Congeliturbation on Horizontal Surfaces

Congeliturbation is expressed in vertical heave and horizontal thrust; on flat-lying surfaces these movements produce nearly circular patterns and mounds.

Congeliturbation breaks the turf destroying the plants, or it heaves the turf above the general surface altering the soil-water relations. Where the turf is thin or discontinuous, it is broken by congeliturbation. Where turf is thick or consists of a tight tangle of stems and roots in peat, it remains intact and is heaved upward.

Frost, scars, peat rings, tussock rings and groups, and tussock-birch-heath polygons. Frost scars, peat rings, tussock rings and groups, and tussock-birch-heath polygons form in areas where turf or peat is thin relative to the depth of annual thaw—the layer of soil subject to congeliturbation (Hopkins and Sigafoos, 1951, pp. 66–87). Formation of frost scars—"mud spots" of Washburn (1947, p. 99) and "spot medallions" of some Russian workers (Poire, 1949)—is the initial result of congeliturbation on most sites (fig. 2). Peat rings (Fleckentundra, Troll, 1944, p. 631) develop from frost scars in dense sedge sod growing on peat in wet areas where water stands around the base of the plants. Continued congeliturbation forces the marginal peat into ridges surrounding the scar, forming a ring. If the bare soil areas are numerous and close together, vegetation on the marginal ridges, forms a netlike pattern (Troll, 1944). Cottongrass plants germinate in the mineral soil adjacent to the peat ridge, and form a tussock ring. Growth of additional tussocks within the center of the ring forms a tussock group. Frost scars in areas of thin peat form centers of mineral soil upon which cottongrass tussocks grow. These low barely perceptible mounds of mineral soil are surrounded by shallow peat-filled channels in which birch-heath grows. When closely spaced the features become tussock-birch-heath polygons. Isolated frost scars more or less continuously form over broad areas; thus the tussock-birch-heath polygons in a given area may be in varying stages of development. Low mounds of turf-covered mineral soil surrounded by wet marshy areas in Siberia, described by Nikiforoff (1928, p. 70), are unlike the tussock-birch-heath polygons on Seward Peninsula. Nikiforoff believes that the features he described are formed by the movement of moist soil upward beneath the mounds; differential freezing and thawing occurs between the mounds and the lower swampy areas. The mounds persist because of continued differential heaving. Tussock-birch-heath polygons owe their existence to the interaction of plant growth and congeliturbation.

The formation and development of these microrelief features represents the widespread importance of congeliturbation upon tundra vegetation where soils appear to be stable upon casual observation.

FIGURE 2. Dark frost scars in area of intense heaving in sedge sod; white square is 10 inches on a side.

Ground-ice mounds. Oval, elongate ground-ice mounds (Sharp, 1942a) are common in arctic, sub-arctic, and some alpine areas. Ground-ice mounds were studied near a large lake in the central part of Seward Peninsula. The mounds, 20–40 feet long and 3 to 5 feet high, are located in a sedge marsh on a sand plain bordering the lake. The mounds consist of a central core of ice overlain by a layer of sand and a tight sod mat, 6 to 8 inches thick. The sod is split for the entire length of most mounds but is unbroken on some mounds; piles of folded sod characterize sites of former mounds. The mounds are pushed upward by rapid vertical and lateral growth of ice above the perennially frozen ground, breaking the sod (Sharp, 1942a, pp. 420–422). Subsequent thawing of the ice mass, because of loss of insulation, causes the mounds to collapse. Growth and collapse of mounds occurs in one year.

The vegetation in the marsh, on the mounds with the split sod, and on the piles of folded turf is composed of the following species:

PRIMARY SPECIES: *Carex aquatilis, C. rotundata, C. membranacea, Scirpus cespitosus.*

SECONDARY SPECIES: *Eriophorum angustifolium.*[1]

Carex aquatilis and *C. rotundata* produce strong stolons which, with the roots, form a tight sod resting on coarse sand. Water stands at the bases of the plants.

On the mounds with unbroken sod, the following additional species are present: *Luzula Wahlenbergii*, *Betula nana* ssp. *exilis*, *Andromeda Polifolia*. These species grow only in habitats drier than those of the sedge marsh. Because the ice core has been preserved by the insulating properties of the sod, the mounds with the unbroken sod, then, have been in a raised position for a period sufficiently long for *Luzula*, *Betula*, and *Andromeda* to become established.

With the accumulation of peat, mosses such as *Sphagnum* spp. and *Pleurozium schreberi* begin to grow and additional peat is deposited. The ice of the mound is further protected from thawing, and change in the vegetation continues.

Nikiforoff (1928, p. 71) has described mounds with a form similar to the ground-ice mounds but formed in a different manner. According to him, the ground-surface layers freeze, and unfrozen ground water above the perennially frozen ground is thereby put under pressure. As freezing continues, and especially if the ground water is flowing downslope, hydrostatic pressure forces the surface to uparch. Mounds so formed may be 20 feet high; water may spurt from them. Trees are tilted at angles, and occasionally the trunks are split. Nikiforoff stated that the mounds are preserved in winter by the formation of ice within them but collapse in the following summer when the ice melts. Trees that grow on the site are usually uprooted when the mounds collapse. Nikiforoff called these mounds "water blisters."

Pingos. Large ground-ice mounds, 40 to 100 feet high, called pingos (Porsild, 1938), are common in arctic lowlands. Mounds with a somewhat similar form occur in poorly drained areas about 6 miles west of Nome in broad stream channels and lake beds near the bases of hills. The mounds are about 15 feet high, steep sided, about 20 to 50 feet long, and oval in outline. They are formed by the uparching of the surface through the growth of ground-ice creating a deep crack in the tops of some mounds. The vegetation around the mounds west of Nome is a sedge sod consisting of *Eriophorum angustifolium* and *Carex aquatilis*. Farther from the mounds and in standing water is a zone of *Equisetum limosum* and *Potentilla palustris*. The banks of the stream and lake are ringed with shrubs of *Salix pulchra* and *S. Richardsonii*. The surface of the mounds is covered with the following species:

PRIMARY SPECIES: *Arctagrostis latifolia.*

SECONDARY SPECIES: *Arctagrostis latifolia* var. *arundinacea*, *Calamagrostis neglecta*, *Poa arctica*, *Aconitum delphinifolium*, *Polemonium acutiflorum*, *Rubus arcticus*, *Sedum Roseum* ssp. *intergifolium*, *Trientalis europea*, and *Petasites frigidus.*

Willow shrubs grow on the sides of the mounds, but it is not known whether they were present before the formation of the mounds; it is possible they grew on the stream and lake banks before the mounds were formed and have since persisted on the mound.

Elevation of the stream and lake beds 10 to 15 feet above the water surface created a new habitat for vegetation development. The pingo vegetation is not successionally related to the vegetation of surrounding areas. Caving of the sides of the pingos along with thawing and erosion of the core will eventually destroy the feature, again initiating a new site upon which plant succession will proceed.

Peat mounds. A different type of mound develops in bogs where greater thicknesses of peat have accumulated (fig. 3). Long, irregular peat mounds stand

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[1] Nomenclature is that of Hultén (1941–1949). All identifiable species were collected from every area. All species unknown to the writer and all species of critical groups were collected wherever found. Specimens are being studied and will be placed in the U. S. National Herbarium, Washington, D. C.

2 to 4 feet above the surface of many wet bogs. The vegetation of the bogs consists of a sedge sod in which are the following species:

PRIMARY SPECIES: *Eriophorum angustifolium, Carex aquatilis.*

SECONDARY SPECIES: *Scirpus cespitosus, Carex chordorrhiza, C. rotundata.* On the drier mounds a dense heath shrub is prominent, and the following species are present:

PRIMARY SPECIES: *Betula nana* ssp. *exilis, Vaccinium uliginosum, V. Vitis-Idaea* ssp. *minus, Ledum palustre* ssp *decumbens.*

SECONDARY SPECIES: *Poa arctica, Empetrum nigrum, Rubus Chamaemorus. Betula* and *Vaccinium uliginosum* form a dense shrub thicket, 2 feet high, and are the most prominent species.

The mounds begin as small hummocks of *Sphagnum;* their size is increased by the deposition of dead plant parts, which form peat, and by frost-heaving. In the small hummocks of *Sphagnum*, in addition to the sedges of the wet areas, grow *Rhododendron lapponicum* and *Andromeda Polifolia.* Troll (1944, pp. 633–634) has described similar mounds which, he believes, owe their height to differential growth of ice lenses in the peat because of unequal freezing of the bog surface. He stated that unequal snow cover on the surface of the bog, due to the projecting peat mounds and *Sphagnum* hummocks, causes the elevated areas to freeze more rapidly in the fall. Rapid freezing, according to Troll, causes more clear ice to form under the mounds than under the sedge of the bog, and a net rise of the mound surface results. Whether this mechanism has been the major cause of the mound formation on Seward Peninsula is not known, but a large part of the surface of bogs near Lava Lake and east of Nome has been elevated. The peat at the top of some mounds becomes dry and is removed by wind, suggesting a mechanism by which the mounds disappear. Hanson (1950, pp. 624–625) made similar observations of mounds near Kotzebue, Alaska, north of Seward Peninsula. The mounds are formed, he believes, by a number of processes, but owe their height largely to accumulation of peat. Congeliturbation and plant growth in thick, wet peat completely changes the environment and initiates conditions which result in a different succession without an accompanying climatic change. Some depressions in which peat mounds occur hold water because of perennially frozen

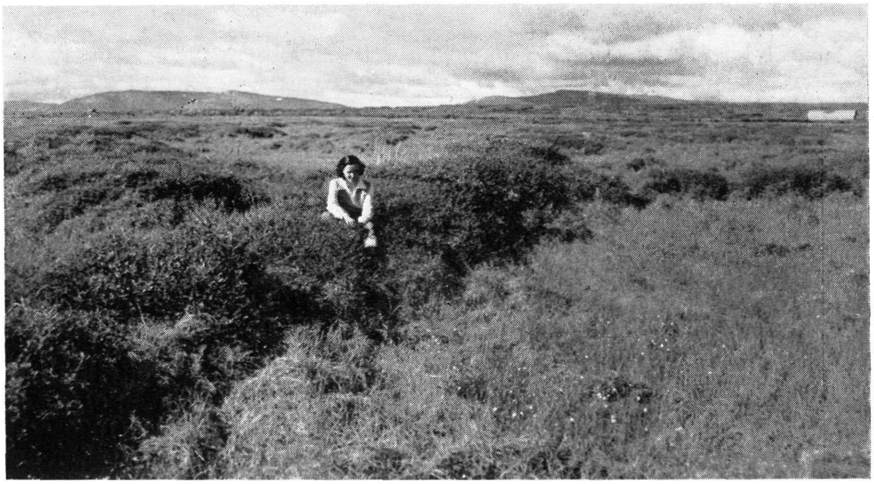

FIGURE 3. Dark shrub-covered peat mounds in marshy area near Nome.

banks and bottoms, and may drain if the banks thaw (Hopkins, 1949, pp. 124–127), inducing additional changes in the environment.

Ridges and depressions. Ridges and depressions occur locally on river flood plains of southern Seward Peninsula. The depressions are 3 to 4 feet wide and have rocky floors 2 to 4 feet in diameter. The ridges, 1 to 3 feet wide, 2 to 4 feet high, and steep walled, surround the depressions and form a reticulate pattern. The ridges consist of a layer of peat that ranges from 6 to 18 inches in thickness overlying mineral soil. Shrubs of *Salix pulchra* and *S. Richardsonii* cover most of the surface; but in a few places the ridges support the following species:

PRIMARY AND SECONDARY SPECIES: *Equisetum arvense, Arctagrostis latifolia, Festuca altaica, Carex membranacea, Salix reticulata, Polygonum Bistorta* ssp. *plumosum, Potentilla fruticosa, Sedum Roseum* ssp. *integrifolium, Dryas octopetala* sensu lat., *Empetrum nigrum, Vaccinium uliginosum, Pedicularis* spp., *Artemisia arctica,* and *Senecio lugens.*

Griggs (1936, pp. 395–397) described "hummocks and hollows of the heath" which are similar to ridges and depressions. Griggs believes that the ridges are raised upward by the lateral force of freezing water within the depressions; the soil within the ridge does not freeze as early as the water in the depression.

The ridges and depressions appear to be the mirror image of the earth hummocks described by Sharp (1942b, pp. 282–283)[2] Earth hummocks result from the differential freezing of the mounds and the surrounding low areas. The low areas freeze first because they are wetter, forcing unfrozen soil upward under the mound. The soil profile within the hummocks shows involutions of peat and mineral soil. In areas of ridges and depressions, early freezing of the bare soil in the bottoms of the holes would force unfrozen soil into the ridges, which would still be unfrozen because of the insulating effect of the vegetation and peat. Furthermore the tight mat of woody roots and stems would resist disruption by frost heaving. What determines whether earth hummocks or ridges and depressions are formed initially is not known. Earth hummocks and ridges and depressions are additional manifestations of frost heaving and further evidence that congeliturbation is an active and important environmental factor affecting the development of vegetation.

Earlier observations on frost-heaved patterns. Huxley and Odell (1924, pp. 212–216) described polygons occurring on nearly horizontal surfaces on Spitzbergen. Cracks or fissures, resembling drying cracks in mud, outline the polygons; the centers are bare of vegetation and are marked with smaller polygonally arranged cracks. These features the authors named "mud-flat polygons," and stated that they are similar to the *Zellenboden* of German authors. Channels surrounding mud-polygons (Elton, 1927, pp. 165–166) are filled with *Dryas octopetala* and *Salix polaris* plants. The polygons' surface structure is protected from erosion by running water, so Elton believes, because the water drains through the lower vegetation-filled channels. The tight mats further stabilize the polygons by inhibiting lateral soil movement. Elton (pp. 171–172) described frost-heaved mounds of soil in areas otherwise covered with dense turf. Some mounds are 2 feet high and 15 to 20 feet across, with surfaces bare of vegetation. Smaller spots of frost-heaved soil are frequent in the areas studied; newly formed ones occur as splits in the turf.

Washburn (1947, pp. 97–99) described mud polygons from Victoria Island in northwestern Canada. The features he described are similar to the polygons described by Elton; centers consist of bare soil separated by a reticulate pattern of peat-filled channels upon which the vegetation grows.

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[2] M. G. Rutten (1951, Polygon soils in Iceland. Geologie en Mijnbouw, 13: 161–167) has presented a new idea concerning the development of earth hummocks and stone nets in Iceland. Rutten's paper has only recently come to my attention; additional reference to it has not been made.

Lundqvist (1949, pp. 335–336) has classified surface features formed by congeliturbation according to amount of plant cover, boulder content of the soil, and degree of slope. On horizontal surfaces free of boulders, earth hummocks are formed when plant cover is heavy. Polygons, similar to the mud polygons of Elton, are formed on horizontal surfaces when plant cover is meager; these are termed "fissure polygons" by Lundquist. Hopkins and Sigafoos (1951) have shown that the type of plant cover, the method of plant reproduction, and the form of the plants are as important as the amount of cover in determining the form of the congeliturbate.

Congeliturbation on Slopes

Soil masses of varying size are moved downslope forming a variety of microrelief features. Steep slopes are characterized by small quantities of fine material and an abundance of coarse rock fragments. Downslope movement forms rock stripes alternating with thick mats of plants or with soil stripes. The thick plant mats block the downslopes movement of rock. Gentler slopes are characterized by lobes and terraces; terraces occur on slopes of lesser angle with greater accumulations of silt (Sigafoos and Hopkins, 1951). The vegetation on the slopes inhibits frost-heaving and thrusting and modifies and diverts downslope movement.

Vegetation Stripes. Sliding of coarse and fine materials on 30° slopes of weathered calcareous schist on the Seward Peninsula forms contrasting stripes of plants and rubble. The schist weathers into silt, coarse sand, and platy fragments which range from 1 to 12 inches in long dimension. The coarse and fine materials are crudely sorted into stripes parallel to the maximum angle of slope. The striping is accentuated by plants that grow in the fines and block the downslope movement of the coarse fragments. The silt moves downslope faster than the stones and overrides or pushes aside any stones that might be across the soil stripe (Sharp, 1942b, pp. 295–296). In vegetation stripes in calcareous schist, platy rock fragments move downward as a veneer over the entire slope with little sorting. Mats of *Dryas octopetala* ssp. *Hookeriana*, rooted in buried mineral soil and broken rock, form a dam against the movement. The mats are usually about a foot across at the upslope end, and narrow gradually or are broken into thin streamers downslope. Beneath the mat is a 1- to 5-inch layer of peat. Buried stems of *Dryas* extend upslope, acting as cables holding the aerial part of the plant in position; thus the mat acts as a barrier to downslope movement, causing the rock fragments to be slowed or diverted. Around the mats are the following species: *Carex glacialis*, *Silene acaulis*, *Smelowskia calycina* ssp. *integrifolia*, *Parrya nudicaulis*, *Papaver Walpolei*, *Saxifraga oppositifolia*, *Androsace Chamaejasme*, and *Artemisia senjaviensis*.

Burial by rock and pressure of stones kills the branches growing from the upslope part of the mat. The plant grows at the apex on the downslope side so that the mat slowly moves downhill. The scanty vegetation on this slope is constantly in a state of change; plants on the upslope end of the mat are destroyed while plant invasion takes place on the downslope end. If the *Dryas* stems break, the entire mat would suddenly slide downhill, destroying all of the plants. Raup (1947, pp. 54–55) described a similar habitat on weathered shale in the Brintnell Lake area, but some different species are involved.

Turf-banked terraces. On nearly smooth, convex slopes of less than 10°, weathered calcareous schist forms small turf-banked terraces similar to those described by Antevs (1932, pp. 56–61). The terraces are 1 to 3 inches high and 12 to 24 inches across. The scarps slope at angles ranging from 30° to 60°; the bare surfaces are gently sloping to nearly horizontal. The vegetation forms a mat on the low scarp, blocking the slow downslope movement of soil and fine rock debris. Plants characteristic of the mats are:

PRIMARY SPECIES: *Dryas octopetala* ssp. *Hookeriana, Carex glacialis.*

SECONDARY SPECIES: *Silene acaulis, Smelowskia calycina* ssp. *intergrifolia, Parrya nudicaulis, Papaver Walpolei, Saxifraga oppositifolia, Androsace Chamaejasme*, and *Artemisia senjavinensis.*

Beneath the centers of some mats covering the scarps is a layer of peat and humus 1 to 2 inches thick, but toward the edges of the mat, at the top and bottom of the low scarp, the stems of the mat rest directly on mineral soil. Solitary aerial stems of *Dryas* extend a few inches across the surface of some of the terraces, indicating that the rate of plant growth is faster than the disruption of the turf by congeliturbation. Under other terraces buried layers of humus indicate that congeliturbation has moved soil over the turf. Splits through the turf and into the soil indicate contraction of the soil by freezing. These splits kill many plants and create bare areas which are enlarged by congeliturbation.

Within an area with a radius of 5 feet all stages of development can be observed. Plants may be growing out over bare soil, the turf may be partially buried, and one terrace may slope directly to the next below through a break in the turf bank. The vegetation of the entire slope is unstable, though it appears more or less stable in any one spot. Downslope movement is slow, but sorting of mineral soil is continuous on a small scale, forming miniature stone and soil stripes on the surfaces of the terraces. These stripes measure 1 to 3 inches across and extend across the top of the small terraces parallel to the maximum angle of slope. Only the upper 1 to 3 inches of the soil moves downslope; turf banks are effective in modifying and diverting the movement. Huxley and Odell (1924, p. 225) believe that mats of vegetation can hold stones in stone stripes and form a rampart retarding downslope movement.

Terrace forms. Soil lobes, lobate terraces, soil terraces, and tundra mudflows were discussed by Sigafoos and Hopkins (1951). Movement of weathered materials downslope in tundra regions occurs mostly by congeliturbation and viscous flow. Rates and mechanics of movement and the resulting microrelief features depend upon the material, slope, amount of water available, and the type and density of plant cover. Isolated lobes form on steeper slopes mostly by viscous flow of nearly fluid soils. Viscous flow in spring, and creep by freezing and thawing in autumn, move soil on gentler slopes forming lobate terraces and soil terraces. Sudden spewing of fluid soils in mudflows moves material as much as several hundred feet downslope.

Creep and viscous flow are most effective in areas of bare soil and thin turf, because the ground cover only slightly restrains the moving soil. Soil moves slower in areas of thick turf and peat. Hanson (1950, p. 614) believes that ". . . seepage water, the flow capacity of the silt layer, and the weight of the water-saturated peat . . ." are important in moving materials downslope. Sigafoos and Hopkins (1951) believe that these factors, especially peat heavily weighted with water, are of less importance than are movement by freezing and thawing and by viscous flow of soil in areas of thin turf. They found that an increase in water content of soil can only increase the rate of viscous flow, because, by creep, wetter soils do not move faster than do drier soils. Viscous flow is most effective during wet spring thaws; and contrary to Hanson's hypothesis, movement is faster under thin turf. Peat is still frozen at a shallow depth and is bound in the surface layers by roots and stems of plants during the short time that viscous flow is effective. Washburn (1947, pp. 91–93) accurately measured the movement of a lobe on Queen Victoria Island, Canada. He found that stakes placed in the ground in June moved 1½ inches downslope in one month and a total of 1¾ inches in seven months from June to January.

Only lobate terraces will be discussed to show the effect of congeliturbation on slopes upon vegetation development. These terraces are characterized by festooned escarpments on slopes ranging from 7° to 20°. They consist of sloping steps or terraces of soil mantling the bedrock; at the terrace scarps and just above them the soil is relatively thick, varying from 4 to 6 feet, its thickness depending upon the height of the terrace. Below the scarp, the soil is thinner, and bedrock lies at depths ranging from a few inches to 2 feet. The vegetation of the surfaces and scarps of the terraces is a complex assemblage: *Festuca altaica*, *Dryas octopetala* ssp. *punctata*, and *Cassiope tetragona* are most abundant. Fifty to 75 species comprise those of secondary importance. On the face of the scarps and below them is a scattered stand of shrubby willows, 2 to 4 feet high, *Salix pulchra*, *S. Richardsonii*, and *S. glauca* varieties. With the willows, *Potentilla fruticosa* and *Spiraea Beauverdiana* are common. Many of the willow stems extend out from under the lobes as though the soil had over-ridden the shrubs. The surfaces of the terraces are hummocky, marked with cracks, folds of turf, numerous spots of bare soil, and small, poorly defined stone-rings, all of which are sites of intensive congeliturbation. On sides of hummocks and faces of scarps the underground stems of the matted, woody plants extend upslope, indicating that the terminal portions of the stems have been pushed or have dropped down the slope. Buried layers of humus and peaty soil occur in the terrace (fig. 4). Taber (1943, pp. 1460–1463) has described similar terraces and discussed their formation. He believes that such terraces exist because downslope movement of soil is retarded by the vegetation mat.

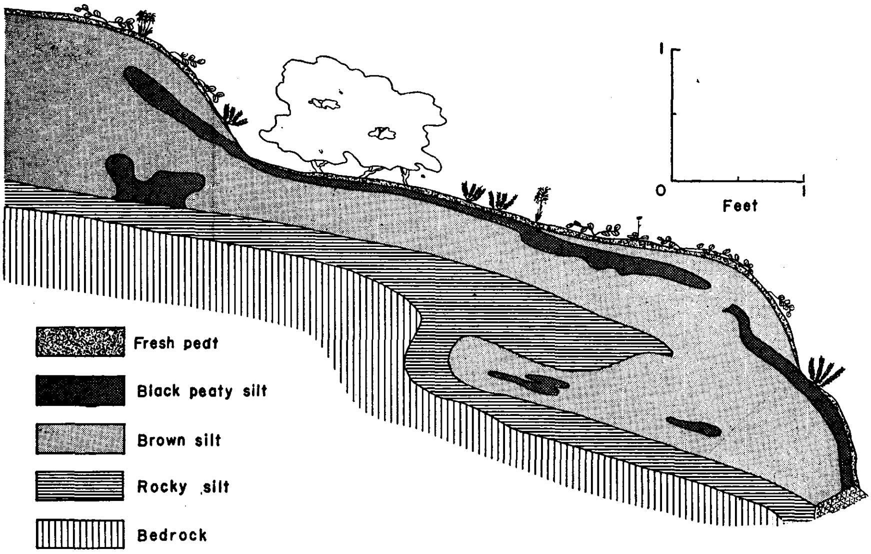

FIGURE 4. Section through solifluction lobe, shore of Lava Lake.

Downslope movement of soil in lobate terraces occurs by frost-heaving with burial of vegetation at isolated spots. Farther downslope, the turf is broken at widely spaced intervals; increased congeliturbation enlarges the spot by pushing the turf aside. Bare soil adjacent to the turf on the downslope side moves over the plants and buries them. On the upslope side of the terraces, the vegetation is discontinuous because congeliturbation is active, the soil is thin, and weathered bedrock is exposed at the surface.

Around the bare spots the plants are being destroyed or are advancing. The entire turf usually does not move downslope as a blanket, because the plants are firmly rooted in the soil and only part of the surface soil moves at one time. Thick layers of turf may be moved slowly downslope intact by heaving in an area a few tens of feet in diameter. The habitat, then, is one of alternating stability and instability; it is more or less stable where congeliturbation is less active and unstable where congeliturbation is intense.

Eakin (1916, pp. 78–82) described large terraces in the higher altitudes in west-central Alaska; these he called "altiplanation terraces." Similar features occur in the mountains of Seward Peninsula, especially around the lake at the head of the Kuzitrin River (fig. 1). The scarps, 10 to 25 feet high, are composed of large boulders. The surfaces of the terraces are broad, gently sloping, and range in width from 100 to 500 feet. The terraces described by Eakin are considerably larger; the blocks in the scarps measure 1 to 12 feet in diameter. Eakin believed that the terraces are formed by movement of boulders outward from the surface by congeliturbation and gravity; the fine materials of the surface are stirred by congeliturbation, and readjustment to forces of gravity causes the surface to form a gentle slope.

Other types of mass movement of soil on slopes have been described. Capps (1940, p. 169) described slow soil flow on slopes in central Alaska. He believed that the soil moves in mass down the slope. Because the movement is slow, the vegetation mat inhibits the movement resulting in the formation of terraces. Rapid flows occur, according to Capps, when the soil is extremely wet and the vegetation mat is broken by the great weight of the soil. Smith (1910, p. 97) described solifluction lobes on the uplands of Seward Peninsula. He believed that they are formed by downslope movement of soil in mass due to accumulated pressures of the weight of wet soil. Low slopes and high resistance, according to Smith, prevent the movement from being more rapid.

Swales. The formation of low ridges on poorly drained low-angle slopes and in sod-filled drainage lines affects the development of vegetation. Poorly drained gentle slopes are common northeast of Imuruk Lake; plant cover is dense, and perennially frozen ground is 6 to 18 inches below the surface. Well-defined drainage lines are absent on the summits of the hills and upper parts of the slopes. Water occurs at the surface and drainage lines occur on the lower parts of these slopes as well as on the steeper slopes of lower hills between Imuruk Lake and Lava Lake. The vegetation on the poorly drained summits, upper slopes, and in the drainage lines is a dense sod, overlying a 1- to 10-foot layer of peat. ***Eriophorum angustifolium*** and ***Carex aquatilis*** are of primary importance in the sod.

In drainage lines several tens of feet across and on upper slopes, low ridges extend roughly parallel to the contour. The exact mechanism of the formation of the ridges is not known, but they appear to be due to slow downslope movement of the sod. Gravity acting on sod resting on viscous underlying peat, and expansion of sod and peat in the wet areas between the ridges upon freezing, would result in downslope movement of the sod thus forming ridges. The following species are prominent on the ridges.

PRIMARY SPECIES: *Carex aquatilis*, *Salix pulchra*.

SECONDARY SPECIES: *Salix* cf. *flagellaris*, *Betula nana* ssp. *exilis*, *Rubus Chamaemorus*, *Rhododendron lapponicum*, *Vaccinium uliginosum*, *Ledum palustre* ssp. *decumbens*, and *Andromeda Polifolia*.

Willow thickets. Dense thickets of willows occur on steep banks of streams and lakes; their distribution accentuates the effects of slope movement. The willows are much branched, 6 to 12 feet tall, and form dense tangled thickets. The larger stems, 2 to 4 inches in diameter, are twisted and bent. They lie on or just below the surface on the ground, and small roots grow from scattered nodes. The shrubs appear to be resting on the surface of the soil. The following species comprise the thickets.

PRIMARY SPECIES: *Salix pulchra, Petasites frigidus.*

SECONDARY SPECIES: *Arctagrostis latifolia, Poa arctica, Salix alaxensis, Polemonium acutiflorum, Rubus arcticus, Spiraea Beauverdiana, Potentilla fruticosa.*

The thickets generally occur in slight depressions or reentrants in the banks and from a distance appear to be inhibiting soil movement on the slope. The willow thickets may grow, however, in a relatively stable depression, and active congeliturbation in adjacent areas may inhibit their spreading onto unstable soils. Of the above list, *Rubus, Spiraea, Potentilla,* and *Petasites* are the prominent plants on most better-drained slopes where congeliturbation or other soil disturbance is active.

THAW LAKE CYCLE

Local water tables are determined in many areas of deeply frozen silt by the proximity of perennially frozen ground to the surface. Lakes, ponds, streams, and swamps that owe their existence to perennially frozen banks are widespread on nearly level surfaces and on gently rolling uplands of Seward Peninsula. Such bodies of water are widespread elsewhere in northern Alaska where Black and Barksdale (1949, p. 116) estimated that 10,000 lakes occur in 25,000 square miles. Thawing of perennially frozen ground results in sudden changes in soil-water relations due to the collapse of soil because of the melting of ice masses. Sudden changes in soil-water relations have catastrophic effects upon plants.

FIGURE 5. Thaw lake near Nome. Opposite shore is caving. *Eriophorum angustifolium* and *Carex aquatilis* are moving into lake in foreground. Opposite bank is 5 feet high.

Origin and Development

Small ponds that develop in areas of deeply frozen silt on Seward Peninsula (Hopkins, 1949, p. 124) are initiated by (1) disruption of plant cover by congeliturbation and (2) accelerated thaw under pools in streams and on uplands. Wallace (1948, p. 180) believes that some thaw lakes in eastern Alaska are initiated when the vegetation cover is broken by overturning of trees. Lakes enlarge by continued thawing and caving of their banks. Some lakes are slowly migrating by caving of their banks on one side and filling by encroachment of vegetation on other sides (Hopkins, 1949, p. 127) (fig. 5). By studying annual rings of trees tilted by receding banks, Wallace (1948, p. 179) calculated that banks of lakes in eastern Alaska cave at a rate of 2.3 to 7.5 inches per year.

Vegetation

The vegetation around the small lake 4 miles north of Imuruk Lake (fig. 1) will illustrate the close correlation between vegetation types and soil-water relations. It is migrating downslope toward the southwest by caving on one side, by thawing of the bottom, and by filling with vegetation, peat, and sand on the other sides. The lake level is maintained by the banks that are perennially frozen within 10 inches of their surfaces. The insulating effect of thick peat maintains the shallow depth of thaw. A tight sod, across which the lake drains, effectively prevents erosion of the underlying thawed mineral soil and peat.

The vegetation surrounding the lake is best correlated with the drainage conditions of the soil, which are determined in part by the site location in relation to the lake surface. Vegetation on a few high banks, 10 to 15 feet above the water, is cottongrass tussock-birch-heath. On the lower banks around the lake is a sedge sod. On the downslope side, or lower surface of the hill on which the lake is located, are the following species:

PRIMARY SPECIES: *Carex aquatilis*, *C. rotundata*, *C. membranacea*.

SECONDARY SPECIES: *Eriophorum angustifolium*, *E. vaginatum*, ssp. *spissum*, *Betula nana* ssp. *exilis*, *Vaccinium uliginosum*, *V. Vitis-Idaea* ssp. *minus*, *Ledum palustre* ssp. *decumbens*.

The secondary species, some of which comprise the cottongrass tussock-birch-heath community, occur as scattered clusters or rings of tussocks on low, broad, barely perceptible mounds of mineral soil within the marsh. In this marsh, the sedge sod overlies peat ranging in depth from a few inches to more than 2 feet. Frozen ground in late July 1948 occurred at depth of 12 to 24 inches. On the upslope side or younger surface of the hill, which recently emerged from the lake, the following species are present:

PRIMARY SPECIES: *Eriophorum angustifolium*, *Carex aquatilis*, *Salix* cf. *flagellaris*.

SECONDARY SPECIES: *Saxifraga Hirculus*, *Potentilla palustris*, *Pedicularis* ssp.

The peat is 2 to 4 inches thick overlying sand derived from granite; perennially frozen ground occurs at depths of 20 to 60 inches.

When thaw lakes and ponds drain suddenly because of rapid thawing of their banks or bottoms (Hopkins, 1949, pp. 126–130), water relations of the soil and depth of annual thaw are changed in the area surrounding such a lake. Wet sedge marshes are drained, and the vegetation dies; communities favored by drier, better-drained soils become established. Cottongrass tussock-birch-heath communities is replaced on the higher banks by willow-birch shrub. The change in vegetation would further affect the depth of annual thaw.

The zonation of communities around thaw lakes, contrary to beliefs of Kellogg and Nygard (1951, pp. 35, 81), less represents upland plant succession than does zonation around ponds in temperate regions (Gleason, 1926, pp. 21–22). No genetic relationship exists between zones in the water of the adjacent caving banks, so that vegetation on banks is not successionally related to that in the water. Much of the vegetation in water along steep banks is that which has just caved with peat and soil. This vegetation is about to die and is not the initial stage of upland vegetation.

Thaw lakes, filled thaw lakes, and thaw sinks are common and widespread in the area around Imuruk Lake (Hopkins, 1949, p. 124). They occur on flood plains, on stream and lake terraces, and on areas mantled with silty mineral soil to depths of 10 to 20 feet. They are most abundant on level surfaces, but occur on slopes as steep as 5°.

The total amount of land surface modified by the thaw-lake cycle in regions of perennially frozen ground is not known. Thawing of at least some part of the banks of nearly all lakes and major streams occur, and it is an environmental factor that should be considered in vegetational studies. Further botanical and geological studies may show that the development of thaw lakes is one of the more important geomorphic processes modifying the land surface in areas of perennially frozen ground.

ENVIRONMENTAL DISTRIBUTION OF EFFECTS OF CONGELITURBATION

Peat rings, tussock rings, tussock groups, peat mounds, pingos, ground-ice mounds, swales, and some willow thickets develop on the wettest fine-grained soils that occur on broad, poorly drained terraces and uplands, gentle slopes, and parts of river flood plains. Swales and willow thickets occur where surface drainage in summer is concentrated. The remaining features characterize nearly horizontal surfaces, where runoff is extremely slow.

Tussock-birch-heath polygons, terrace forms, ridges and hollows, and some willow thickets develop on better-drained fine-grained soils. Tussock-birch-heath polygons form on better-drained interfluves of gently sloping uplands underlain with wet, silty soils. They are associated with the features that occur on the wettest soils. Terrace forms develop in shallow deposits of silty soil and rock that mantle well-drained slopes. The soils are generally drier than those in which tussock-birch-heath polygons develop but are wet locally during part of the thawing season. Some willow thickets grow on better-drained steep river and lake banks underlain by silty soils. Ridges and hollows form on better-drained areas of river flood plains adjacent to and within willow thickets that line the banks.

Turf-banked terraces and vegetation stripes form on the best-drained slopes on hills where bedrock is close to the surface and in terrace gravels. Turf-banked terraces form on the more gentle slopes where some fine material has accumulated, and where movement of soil is slow. Vegetation stripes reach their best development on slopes of 30° upon which movement of platy fragments is rapid and only small quantities of fines have accumulated.

Thaw lakes and accompanying phenomena are abundant on lowlands and gently rolling uplands underlain by thick, perennially frozen silt.

An almost infinite number of different microrelief features formed by congeliturbation occur in tundra regions. The effects of unstable soils on vegetation described are typical of much of the tundra vegetation of Seward Peninsula; all habitats with the possible exception of sand dunes and beaches exhibit evidence of soil movement. Microrelief features involving only fine and coarse rock materials are abundant.

CLIMAX VEGETATION PROBLEM

Discussions of the validity of the climax concept in vegetation as advanced by Clements are abundant in the literature (see Just, 1939). The climax is that stage of vegetation that is stable; its characteristics result from the effects of climate upon the available species. The generally accepted understanding of the "climatic" climax was stated by Cain (1939, pp. 150–152) to be that ultimate stage of vegetation that is limited only by the effects of climate on the plants and that will be reached regardless of differences in topography, soil, and microclimates. True climax will be reached only after the sites have been made nearly uniform by geomorphological change through geologic time (Cain, 1947, p. 193). It is believed by many, according to Cain (1947, p. 192), that edaphic and physiographic climaxes are merely stages in the vegetational development toward the true climax of the region. Edaphic and physiographic climaxes owe their existence to the limitations imposed by local variations in soil, microclimates, topographic position, and history of the area upon the hereditary potential of the plants.

These concepts carry a number of assumptions pertaining to the interrelationship between the land surface and vegetation: (1) the substrata are stable or undergoing only slow, uniform, and unidirectional changes (Gleason, 1917, p. 479), (2) succession results from slow change in the substrata or from changes in the habitat due to the growth of the plants, and (3) changes in the land surface are slow in terms of the life of the plants. These assumptions are invalid in at least the treeless areas of high latitudes. Substrata are unstable; the upper layers undergo constant churning by freezing and thawing greatly masking slow unidirectional changes. Succession, starting on bare soil, is frequently repeated because constant churning periodically destroys the plant cover. Much of the vegetation is in the initial stage so that the plants have reacted too little upon the habitat to affect much change in "forming a seed bed." Furthermore, individual plants are locally separated by bare soil, so that they have little affect upon one another (Raup, 1947, p. 49). On nearly all sites the plants are of first generation and only at isolated sites do they die of old age or because of unsuccessful competition with succeeding species.

The temporal nature of most microrelief features must be understood, for many are so short-lived that their destruction may occur during the time that the initial plant cover is becoming established. The relatively stable sites are restricted in areal extent and of little significance in the entire botanical landscape. They too are subject to sudden change in regional geomorphic development. Some of the most stable sites in high latitude regions are on stream banks which are, in temperate regions, among the most unstable sites (Raup, 1950, p. 12). Thaw lake phenomena are examples of these types of sudden changes. The vegetation associated with the more or less stable features cannot be thought of as climax for the region because the region will not develop characteristics of the stable sites.

Vegetation of high latitudes must be described and understood in terms of the unstable substratum; and climax concepts should not be used. It is merely an academic exercise to state that certain vegetation in treeless areas of high latitudes is "climax." The vegetation on each site is in equilibrium with geomorphic processes which vary in intensity according to the site, so that most vegetation types are in successional systems unique to themselves and unrelated to each other.

Listing the zonation of communities about ponds or on uplands in order to describe succession is invalid because of different history, process, and soil characteristics at each site. Raup (1941, pp. 219, 232–238) discussed this problem as well as others in describing plant succession in boreal vegetation. He noted also that no two lists of species from different sites are the same, although, from all outward appearances, the habitats are equivalent.

CONCLUSIONS

Congeliturbation and the thaw-lake cycle have been effective in modifying the botanical landscape since before the last glacial maximum. It is likely that the present vegetation of part of the Seward Peninsula is similar to that which grew in ice-free areas of the peninsula during maximum ice advance. Flint (1947, pp. 455–456) quoted estimates of the reduction of the mean annual temperature during the glacial maxima for several areas; the estimates range from 9° F to 14° F. The present mean annual temperatures recorded by the U. S. Weather Bureau, range from 20.2° F at Candle to 27.2° F at White Mountain. The weather recording station at Candle is close to several buildings in a protected valley; undoubtedly a great many areas on Seward Peninsula are characterized by mean annual temperatures lower than that at Candle, so that the range in mean annual temperatures on the peninsula is at least as great as the estimated reductions for the glacial maxima. Therefore, mean annual temperatures during maximum ice advance were present in ice free areas on the peninsula. Furthermore, persistent banks of snow and nèvè exist in cirques in the Kigluaik and Bendeleben Mountains;

yet vegetation similar to that described in preceding paragraphs occurs on many of the adjacent slopes and valley floors. The "phytoclimate" of the peninsula north of the mountains at the present time cannot be much different from periglacial climates on Seward Peninsula. Lakes remain frozen well into June, first frost probably occurs in late August, and snow banks persist throughout the year in protected coves on all north-facing slopes and on other exposures as well. All of the vegetation seen on the peninsula, except spruce and poplar forests, occurs near the severe habitats of the mountains.

Recent work has shown that intense congeliturbation disturbed the soil in parts of United States during glacial periods (Smith, 1949; Denny, 1950; see also Jour. Geol., 1949, 57 (2)). How intense soil movement in low-latitude periglacial regions was during the glacial maxima is not completely known.

In regions where congeliturbation has been active, a recorded change in vegetation does not necessarily mean a change in climate. It is possible that some of the changes in vegetation recorded in bogs about the termini of the last ice sheet are due to the effects of periglacial congeliturbation and thaw-lake phenomena. Further investigation may show that the movement of the soil must be considered in all studies pertaining to post-glacial plant migrations.

SUMMARY

The form and microdistribution of plants and the development of vegetation in a climate producing perennially frozen ground are greatly affected by congeliturbation, or stirring of the soil by freezing and thawing. The vegetation does not reach "climatic" climax because of the actively moving substratum, whether it is peat, soil, or rock. New concepts of vegetational development must be considered if a true picture is to be had.

Congeliturbation on horizontal surfaces forms circular or polygonal patterns and mounds that rapidly alter the environment, causing variations in many other edaphic factors. Many surface features have forms characteristic of this process.

Congeliturbation on slopes moves masses of soil and rock downslope, forming stripes and terraces. Growth of plants on these sloping sites is greatly affected.

Many lakes and ponds in areas of perennially frozen ground are short-lived, owing their existence to frozen banks. Many of the lakes suddenly drain when the perennially frozen ground thaws. Drainage of the lakes lowers the local water table, greatly affecting the vegetation.

The vegetation on the Seward Peninsula during the maximum glacial stages probably was similar to the present vegetation.

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The Ohio Journal of Science will make an award of $150 for an outstanding paper in the field of chemistry received before January 1, 1952. Further details may be found on page 168 of the July, 1951, number of the Ohio Journal of Science.