MEDDELELSER OM GRØNLAND
UDGIVNE AF
KOMMISSIONEN FOR VIDENSKABELIGE UNDERSØGELSER I GRØNLAND
Bd. 166 · Nr. 3

THE STRUCTURE AND DEVELOPMENT OF TURF HUMMOCKS IN THE MESTERS VIG DISTRICT, NORTHEAST GREENLAND

BY

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WITH 40 FIGURES IN THE TEXT
AND 1 PLATE

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1965

Abstract.

Turf hummocks in the Mesters Vig district of Northeast Greenland are composed primarily of mosses which form a substratum for several species of vascular plants. Well-defined, growing hummocks are found only on sites abundantly supplied with gently flowing surface water throughout most of the summer season. They may be common on drier sites, but here they are always in some stage of disintegration. They develop on any kind of soil, and on slopes of from 1° to 15°. They may or may not have upward projections of mineral soil beneath them. The vascular flora is characterized by the woody plants of the adjacent tundra, and by a few herbaceous species associated with them. Most of this flora is rooted in the turf, but a few species, notably *Salix arctica*, are firmly established in the mineral soil beneath, commonly with long horizontal taproots reaching far beyond the limits of the individual hummocks.

Observations indicate that the hummocks begin their development with aquatic mosses. They begin to show appreciable enlargement only when more mesophytic mosses appear on them. These, in turn, occur only when "micro-elevations" appear above the general level of the surrounding, continually saturated surfaces. Such micro-elevations may be cobbles, small boulders, or local sand and silt deposits in shallow stream beds; they may be small moss polsters in extreme snow-bed environments; they may be upfrozen stones in fine-textured soils; they may be pre-existing microrelief features formed by gelifluction; or they may be due to normally irregular and slightly hummocky surfaces in the mats of aquatic mosses themselves. Most of the hummocks in the Mesters Vig district appear to have been initiated in the last of these various situations.

A specific case of hummock development and deterioration is described in detail. A transect is analyzed, showing all stages from aquatic mosses to final disintegration and disappearance of the hummocks, with accompanying changes in water supply, insulation, frost action in the soils, and faunal activity. Evidence is presented that individual plants of *Salix arctica* germinate on the hummocks during incipient stages of development, live through the entire sequence of growth and degradation, and survive long after the mosses have disappeared. Annual growth layers in these willows serve to calibrate the process, and by their variations indicate some of the major events in the sequence. The abundance of deteriorating hummocks in the Mesters Vig district, and of willows that show by their form that they have been through a hummock sequence, strongly suggests that many slopes have been subjected to recent desiccation, due largely to reduction of perennial snowdrifts. The age of the willows indicates that most of this desiccation has occurred within the last 75 years, a figure consistent with the recent general warming in the North Atlantic region.

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INTRODUCTION

A common and striking microrelief feature of the landscape in the Mesters Vig district is formed of low hummocks which are densely covered by vegetation, and which may or may not contain a core of mineral soil. In the following discussion they will be called "turf hummocks", for they are made up predominantly of living and dead vegetation. Their tops vary in height above the surrounding surfaces from 2–3 cm to as much as 50 cm. In areal outline and topography they are equally variable, from nearly circular and more or less regularly domed, to complete asymmetry in all dimensions. In many situations they coalesce to form systems of ridges.

Most of the mass of living vegetation and organic turf which forms a typical hummock is of mosses. The living portion of the mosses commonly forms a cap 4–5 cm thick over the whole surface. Beneath this there is a gradual transition downward through dying and recently dead fronds of the moss to dark brown or black, partially decayed remains; and finally, just above the mineral horizons there commonly is a layer of finely comminuted, greasy humus. Depending upon local sources for it, and means for its transport, varying amounts of fine sand or silt may be found mixed with the turf and humus.

The moss and turf form a substratum for several species of vascular plants and a few lichens. Consequently both are interlaced with the stem and root systems of vascular species, notably of those with woody stems and roots. Some species are rooted only in the turf, while others, especially the willows (*Salix arctica*), penetrate the mineral soil beneath the hummocks. The vascular flora is variable, in some cases primarily of sedges and grasses, and in others of willows and heaths.

Turf hummocks occur on gentle to moderate slopes (1°–15°). They occur only in situations that have, or have had in comparatively recent time, an abundant supply of surface water throughout the growing season. They are common features of areas of sheet runoff or of the broad networks of shallow channels on till and gelifluction[1]) deposits. Their most extensive development is on the long gentle slopes extending

[1]) The term "gelifluction" is here used to mean solifluction in association with frozen ground.

from the shore of Kong Oscars Fjord to the bases of the sandstone and trap hills of the Labben and Nyhavn peninsulas and of the neighboring mountains to the south (see Plate 1). Many of these slopes are underlain by a stony marine silt or loam while others are predominantly of sand or gravel. In all places the source of the necessary moisture is melt-water from perennial snowdrifts or thawing ground. Although no attempt was made to map the distribution of turf hummocks in the Mesters Vig district, it is safe to say that many hundreds of hectares are covered with them.

Turf hummocks have been described both in botanical literature and in that of geomorphology. Emphasis upon them in the latter field stems from their being considered "patterned ground", conditioned in their developmental processes by frost action. They are widespread, in one form or another, in the arctic, antarctic, and alpine lands of the world. Several names have been used for them, some restricted to particular kinds of hummocks and others of more general meaning: "*Bülten*" (THORODDSEN, 1913); "*Rasenhügeln*" (TROLL, 1944); "*Hügelboden*" (BESKOW, 1930); "*Moorhügeln*" (BESKOW, 1930); "*buttes gazonnes*" (CAILLEUX, 1948; CAILLEUX & TAYLOR, 1954); "*Mottes de terre*" (DE LESSE, 1952); "*thufur*" (JÓNSSON, 1909; THORODDSEN, 1914; TROLL, 1944; THORARINSSON, 1951); "*earth hummocks*" (SHARP, 1942; WASHBURN, 1956); "*knolls*" (SØRENSEN, 1937; STEINDORSSON, 1945); "*tundra ridges*" (GRIGGS, 1936); "*tussocks*" (POLUNIN, 1948; BÖCHER, 1954); "*moss-tufts*" (BÖCHER, 1933; HARMSEN, 1933); "*frost hummocks*" (BILLINGS & MOONEY, 1959; WILLIAMS, 1959).

Turf hummocks in the Arctic appear to be of two kinds, the differences between them being highly conditioned if not determined by the kinds of plants that form them. One has a "tussock-form" and is made up of caespitose species of *Cyperaceae* or sometimes *Gramineae.* An individual tussock is formed by the proliferation, over a period of years, of a single plant. This plant gradually grows upward on a columnar mass of its own dead leaf bases and roots, around which moss and peat accumulate. Beneath this mass fine-textured mineral soils are domed up by frost action. Hummocks of this type are widespread in both temperate and arctic regions. In the Arctic they are particularly well-developed in western arctic North America where, in Alaska, they give the local name to "nigger-head tundra." Their structure and developmental processes have been described in detail by HOPKINS and SIGAFOOS (1951 a, 1954; SIGAFOOS and HOPKINS, 1951 b). The second major type of turf hummocks is composed basically of mosses. Vascular plants may play a part in the initial stages of growth of these hummocks, but they appear to serve only as nuclei for the accumulation of the mosses; later the higher plants may form a large part of the surficial vegetative cover, but their substratum is the moss and the moss peat beneath it.

In the Mesters Vig flora there are no tussock-forming species of *Eriophorum* or *Scirpus*, and no large caespitose grasses or *Carex* capable of forming the tussock type of hummock. The present paper is concerned, therefore, only with the second type of hummocks mentioned above. It is possible to distinguish two kinds of moss hummocks in the literature, but the distinction is not always clear. In general, geomorphological students have dealt only with hummocks that had some kind of earth core rising beneath them. This is reflected in the names used: "*earth hummocks*," "*Hügelboden*," "*mottes de terre*." According to THORODDSON the Icelandic term "*thufur*" should be restricted to hummocks with mineral earth cores. BESKOW (1930) apparently felt the need for a name for hummocks without cores, and called them "*Moorhügeln*" in sharp distinction to "*Hügeln mit Kernen von Mineralerde*."

A further subdivision of hummocks without cores may be made into those developed on deep deposits of peat in bogs, and those on mineral soil or very thin organic horizons. No organic deposits more than 5–10 cm thick were seen in the Mesters Vig district; consequently the following discussion will deal only with the second of these types.

Botanists who have described mossy hummocks of this kind usually have limited themselves to the vegetation, and have written little or nothing about the anatomy of the structures. There are a few notable exceptions to this, such as GRIGGS (1936), HANSON (1950), and BILLINGS and MOONEY (1959). If they have used terms for the hummocks they have been as a rule non-committal ones such as "*knolls*," or merely "*hummocks*." There has been no uniformity among botanists in the placing of the turf hummocks in schematic organizations of vegetation, though this may be due more to semantic variations in terminology than to real differences in viewpoint. OOSTING (1948), HANSON (1950), GRIGGS (1936) and DE LESSE (1952) (in part) considered them a part of the tundra "heath" vegetation, or at least the wetter phases of the heath. BÖCHER (1933) and STEINDORSSON (1945) thought of them for the most part, as "moor," presumably "low moor." POLUNIN (1948) included them in the drier phases of his "marsh" series. Those who have tried to describe micro-communities in the vegetation of the tundra (HANSON, 1950; BÖCHER, 1933, 1954; HARMSEN, 1933; DE LESSE, 1952; FRIES, 1913, and many others) have found that the common vascular species form a great variety of combinations which appear on different hummocks, and that often several can be described on the same hummock. The description of hummocks most directly applicable to the Mesters Vig situation was written by SØRENSEN (in SEIDENFADEN and

SØRENSEN, 1937). He called the terrain in which they were most abundant "knolly bog," and placed them in a single "ecosystem" which he related to "constantly irrigated fields."

TROLL (1944) recommended that the Icelandic term "*thufur*" be used internationally for hummocks that were recognized as products, at least in part, of frost action processes. This has not been followed, although the basic idea that these hummocks should have earth cores seems to have been adhered to, at least among geomorphologists. As will be shown in the following discussion, the Mesters Vig hummocks may be without earth cores, and if they have cores the latter may be of varied origin and manner of development. It is not unusual to find those with and without earth cores existing in close proximity. Under these circumstances it has seemed proper to use a term that would cover all of them—"turf hummocks," for they all have a well-defined horizon of fibrous, peaty turf under their caps of living moss. Whether or not they answer to the definition of "earth hummocks" or "thufur," it is highly probable that they are greatly affected at one time or another in the course of their growth or decay by the processes of frost action and mass wasting that are currently active around and under them.

ACKNOWLEDGMENTS

I am greatly indebted to my field companions for assistance in the preparation of the present paper. This applies particularly to Dr. A. L. WASHBURN in whose company, and with whose active collaboration, nearly all of the field work was done. Most of the ideas presented here concerning the Mesters Vig turf hummocks were threshed out while the materials were fresh before us, and a large measure of whatever rigor could be inserted into the reasoning must be credited to him. Later he generously gave me his personal field notes on the hummocks, and greatly improved my manuscript by a critical reading. He is entirely absolved, however, from any errors in which I may have persisted. My wife, LUCY G. RAUP, was my constant companion and assistant in the field. She collected most of the "perched" willows that eventually figured so prominently in the history of the hummocks. Prof. I. W. BAILEY of Harvard University made the first sections of willow stems and roots for me, and helped with the initial interpretations. Dr. JAMES L. RIOPEL, at that time a graduate student at Harvard, made the sections of the 1958 collections, and Miss JANE LEE sectioned those collected in 1960. I am indebted to these people for their painstaking care in making usable preparations. Dr. MARTIN H. ZIMMERMANN of the Cabot Foundation at Harvard very kindly made the microphotographs of the willow stems and root sections, and Dr. ERNEST M. GOULD, Jr. of the Harvard Forest gave me much useful advice on the graphic presentation of data on the willows. Dr. HOWARD CRUM very kindly determined my specimens of mosses.

Financial support for this study has come from the several sources which have supplied funds for all our Greenland work. I am particularly grateful to the Milton Fund at Harvard, and to the National Science Foundation for generous grants which paid our travel expenses to and from Iceland or Copenhagen. Dr. WASHBURN very kindly met our travel costs from these points to Mesters Vig, and our living expense while there, from general expedition funds.

REVIEW OF LITERATURE

The most comprehensive reviews of the literature on turf hummocks published to date are those of Troll (1944), Sharp (1942), and Washburn (1956). In all of these the hummocks are considered primarily as patterned ground. In the following treatment an effort is made to bring together the more pertinent references not only to the geomorphological literature on the hummocks, but also to the botanical literature. It does not attempt to cover, however, the rather extensive literature dealing with hummocks that develop on the thicker organic deposits of bogs (mires). For this references may be found in the works of Sjörs (1946 a & b, 1948, 1950), Dahl (1956, p. 322) and others.

To find the earliest descriptions of turf hummocks would be a difficult task, and probably would yield nothing of significance for the present study. Such early accounts might well be looked for in Icelandic literature, for the hummocks of Iceland have been observed and studied for many years because they have considerable importance in agriculture and soil management.

Although some of the most significant early observations of turf hummocks were made in Iceland, one of the earliest attempts to explain their origin and development was by M. P. Porsild (1902), on Disko, West Greenland. He termed the hummock terrain "mesh-vegetation" ("Maske-vegetation"), and related the origin of the hummocks to the retreat of snowdrifts. He was impressed by a certain amount of parallelism that he detected between the arrangement of the hummocks or mossy ridges and the margins of the snowbanks on level to gently sloping land, and thought that the bases of the moss growths that started the hummocks originated at these margins. The bases were assumed to be accumulations of dead vegetable litter blown over the the snow and lodged at its wet melting edge. He accounted for the "net" arrangement of much of the terrain by differential erosion of the ridges and knolls thus formed, the differences being determined in large measure by the steepness of the slope. Apparently he believed the hummocks to be at least a century old as he found them, and although he thought his explanation of their origin was adequate he did not believe it accounted for their remaining unchanged for so long.

Assuming a source for an abundance of vegetable debris postulated by PORSILD, and winds to carry it at the proper time, his idea is reasonable that it could form minor surface relief at the lower margin of a snowdrift. This surface relief could then form nuclei for the development of mosses, and eventually moss hummocks.

THORODDSEN (1914) dealt with turf hummocks at some length in his treatise on the physical geography of Iceland, describing their local and general geographic distribution, their structure, and the conditions under which they occur. The Icelandic hummocks in typical form, known as "thufur," occur on wet clayey or silty soils in flat or gently sloping areas. They are 25–50 cm high and 50–200 cm in average basal diameter. Though most commonly appearing as individual hummocks they are sometimes connected in ridges or netlike arrangements. According to THORODDSEN they form only on the above soils in the presence of abundant soil moisture, very poor drainage, and commonly subsurface frozen ground. They have well-developed, knollike earth cores which are capped with peaty turf and living vegetation. He believed that the "thufur" are not formed in areas where a snow covering lies late in the spring and protects the ground against frost action during that period. Farmers' "home fields" are cleared of hummocks with great labour, but if the soil is not thoroughly drained the "thufur" develop again within a few years.

The doming up of the surface of the mineral soil beneath many turf hummocks presents difficult problems. Whatever the cause of the doming, the fact of its occurrence has seemed indisputable, for, as pointed out by THORODDSEN (1914), layers of volcanic ash present before the hummocks were formed have been found domed upward to conform with the shapes of the earth cores that contained them. THORODDSEN proposed that clay soil particles were gradually concentrated and moved upward under hummocks, in part by pressures due to freezing in the channels between the hummocks, and in part by the movement upward of capillary water in the central areas of the hummocks. He thought that the capillary movement was induced by the loss of water by evaporation from the upper surfaces in the centers. There is recent experimental evidence (BREWER and HALDANE, 1957) that clay-size particles do move upward in capillary streams through columns of sand or silt.

Appararently THORODDSEN was unable to define the initial stages of "thufur" development. Although he thought the mechanism of their growth was closely related to that of sorted nets ("rudemark"; cf. WASHBURN, 1956, for terminology used here) in clayey soils in Iceland, and although he found the clayey centers of some nets bulging upward slightly in spring, he stated that "not until they are plant-covered and clad with greensward do they bulge and retain their convexity." He recognized more than one origin for turf hummocks, but he seems to have restricted the term "thufur" to those with clayey earth cores. He mentioned that "Upon mountainsides small eminences of various kinds may sometimes be observed which are due to underlying stones or ridged mud-flows, etc., but never 'thufur' proper." Again, "where the ground water stands very high, as in many extensive boggy tracts, so that the entire surface freezes into an icecake, only small knolls of organic material are seen, formed of moss and Carices."

HOLTTUM (1922, p. 98–99) in a study of vegetation succession in West Greenland, described turf hummocks in the Disko Region. For a discussion of how they probably formed he drew largely upon the work of RIKLI (1910). Although he did not mention excavations of hummocks, he wrote that "the raised parts of the soil consist essentially of masses of raw humus penetrated by the roots and stems of living plants." He considered that the essential characteristic of the habitat in which the hummocks could develop was wet, undrained soil. He described them under a type of vegetation that he called "Moss Bogs," and found them as much as 90 cm high. He thought they were kept separated by the flowage of melt water in the spring, and mentioned seeing in one area spaces between hummocks that were covered only by crusts of liverworts. Following RIKLI, he thought the hummocks began as low moss cushions, on which "The first phanerogam to appear is often *Salix groenlandica* . . . its horizontal stems half buried in the moss . . . various Carices also occur, forming compact cushions (*C. alpina*, *C. rariflora* and others), small species of *Juncus*, and occasionally the two common species of *Eriophorum* . . . These various plants begin to form, with the mosses, compact cushions; their dead remains from previous seasons accumulate, decay being exceedingly slow. On the raised parts of the bog so formed plants requiring less moist conditions can develop . . . Later the ordinary heath plants can gain a footing . . ." HOLTTUM was uncertain about the position of the moss bogs in his successional scheme, but thought they probably were "stabilized pre-climaxes." He regarded the heath as the climatic climax.

Many references to the turf hummocks of Iceland are found in the works of HANSEN (1930) in his "Studies on the vegetation of Iceland," of GRÖNTVED (1942) in the general part of his paper on the vascular flora of that country, and of STEINDORSSON (1945) in his work on the vegetation of the Central Highland. All of these authors used, with only minor modifications, a basic classification of Icelandic vegetation which had been set up by THORODDSEN (1914). THORODDSEN outlined the types of vegetation mainly on the basis of their external environments, but in part upon physiognomic grounds. Because this classification is essential to the understanding of the above authors' comments on turf hummocks, it will be summarized as follows:

1. The vegetation of the coast line (rocks; sandy shores; salt marsh, etc.).
2. The vegetation of fresh water (running streams; lakes and pools).
3. The vegetation around cold springs ("dy" vegetation).
4. The vegetation around hot springs ("laugar" vegetation).
5. The vegetation on wet soil (includes "flói," in which the water table is at or above the surface and the substratum is loose and not coherent; and "mýri," in which the surface soil is saturated but seldom flooded, and the substratum is a firm mat of turf).
6. The vegetation of rocky flats (includes "melar," or fell-field; the vegetation of gravelly or stony flats; "holt," the vegetation of gravelly ridges; "urd," vegetation of river gravels; "hamrar," vegetation on bouldery surfaces; "eyrar," and "Flag," vegetation of clayey flats).
7. The vegetation of mountain slopes ("Li" vegetation).
8. Psammophilous vegetations (includes "sandar," sand-covered tracts; and dunes).
9. The vegetation of lava streams.
10. The *grimmia* heath vegetation ("mosathemba" vegetation).
11. Grassland (includes grassy slopes; "grass mó" or "jaðar," knolly grassland; "vallendi," dry grassland without knolls; and home fields on farms).
12. Heathermoors ("Heather mó").
13. Willow copses.
14. Birch copses and birch forests.

According to Hansen knolls have been found in "mýri," "jaðar," and "heather mó." He also stated that in "flag" vegetation "the surface is a bare clayey flat with scattered knolls and stones." Two of his photographs (Pl. VI, Figs. 12, 13) show this, the knolls appearing as small turf hummocks partially covered by grasses or grass-like plants. The largest knolls are found in the "jaðar" type, where they sometimes reach a meter in height. In further describing the environments of these types Hansen wrote (p. 179–180), "The mó vegetation . . . is characterized by a normal snow-covering and by the fact that it is unaffected by the ground water. The surface is knolly and covered with vegetation." "The jaðar vegetation like the mó has a normal snow-covering but is confined to moderately moist soils, i. e., soils dry in summer and wet in winter. The surface has large knolls and is covered with a dense vegetation . . ." "The Mýri vegetation is peculiar to moist soil which must not, however, be covered with water all the year round. The surface is knolly." Because two of the types come under the heading of "mó" vegetation it will be well to define the use of the term "mó" in the Icelandic literature. This usage is a peculiar one because it seems to apply to parts of at least three of THORODDSEN's types and thus to confuse the definitions of all of them. It has a great deal of significance because the "mó" vegetation has been said to cover more area than any other in Icelandic lowlands. In HANSEN's work (1930, p. 47) the term "includes all such formations as are normally covered with snow in the winter, whose degree of moisture is exclusively determined by the precipitation, not by the ground water, the soil of which is not in motion, uncultivated, and not covered with forest or copse-wood." "The soil of the mo is always more or less covered with knolls . . ."

HANSEN wrote the following remarks about the forms of knolls on slopes (p. 47): "Where the surface is level or slightly inclined, the knolls are almost polygonal, half a metre high and broad, and separated from each other by narrow furrows. Where the soil is more inclined, the knolls grow smaller and arrange themselves in longitudinal rows parallel to the edge of the slope. The form of the knoll undergoes a change, not only in that it becomes more elongated, but also it begins to move downwards. This occurs by a displacement of the material of the knoll itself, apparent by its bulging in the middle of the more or less vertical side facing the valley, and becoming flattened on the upper side. Sometimes the upper side is bare, devoid of vegetation. If all the knolls become flat and bare on the upper side, and outwardly delimited by a vegetation curve, we get typical solifluction, which is especially well developed on melar in the highland tracts.

"If the slope becomes still steeper, the solifluction will assume the character of a landslip. Then it is no longer the single knolls but the substratum that slips, and in consequence the vegetable covering may be preserved intact." HANSEN seems to have described the transition from earth hummocks to small terraces that was seen later by SHARP (1942) in Yukon, and by many others.

The Icelandic turf hummocks, according to HANSEN, occur over fine-textured soils that are moist to saturated but not flooded, and they may be on soils that are relatively dry in summer. They occur on level ground or gentle to moderate slopes. HANSEN had a great deal to say about their relation to snow cover (see below), but he agreed with THORODDSEN that they did not develop where there was a heavy, long-lasting snow cover.

Both HANSEN (1930) and GRÖNTVED (1942) followed JÓNSSON (1895) in describing certain types of grassy hummocks in Iceland which might be interpreted as being in stages of deterioration. In their organization of the vegetation these types are in the general category of "mó," and three kinds of "grass-mó" were noted: *Kobresia* mó, *Juncus* mó, and grass mó. In all of these there is a marked difference between the vegetation on the dry tops of the knolls and in the intervening depressions. The characteristic species or species groups which give names to the three types are those on the upper surfaces. In some cases the vegetation of the depressions is of mosses and sedges, and in others (*Juncus* mó) it is of grasses. It is probable that the grassy nature of the summit vegetation on these knolls reflects a drying-out process that presages the eventual decay of the structures. Hansen (l. c., p. 83–84) described the dehydration and removal of the tops of knolls exposed to strong winds, and the final removal of the knolls together with the fine-textured soils beneath them.

Nieland (1930) described turf hummock areas in West Greenland and attempted to explain them as developments from sorted nets. He was impressed by the apparent regularity in their areal patterns, and though he made no dissections to verify his theory, he thought the wet muddy trenches between the mossy hummocks were the result of sinking of the marginal stony ramparts of the nets. He supposed that this occurred after the nets were fully formed and movement of the stones had essentially stopped; then in a particularly warm summer of deep thaw and saturated soils the stones could not be supported and would sink to deeper levels leaving trench-like depressions. At the same time he proposed a process for the invasion by mosses and the initial development of hummocks that was similar to that of Oosting (1948) and several other observers, calling attention to the fact that it resembled the process by which "bulten" were formed on the North German plain. However, he did not make clear how this process applied to his sorted net theory of origin, nor did he clarify the relationship between his theory and M. P. Porsild's ideas (1902) on the origin of hummocks, which he also cited. Further, he did not present evidence of coincidence between the distribution of the hummocks and that of preexisting net structures.

Beskow (1930) proposed the following explanation of the formation of earth cores in turf hummocks. He though the insulation of the thick turf prevented early freezing under the centers of the hummocks, while freezing occurred sooner and more rapidly around the sides and bases. This, he thought, set up pressures due to freezing in the mineral cores under the centers which forced material upward in them and thus made them higher. Because he thought that vegetation cover made possible the formation of the earth cores he had, perforce, to conceive of their having initial stages under vegetative cover. To accomplish this he relied upon chance variations in soil surfaces or in the vegetative cover itself. In the first instance he suggested that unevenness of flowage in moving soil would give the necessary relief, and in the latter that breakage in the turf due to soil flowage, or perhaps the development of grass hummocks would start the necessary accumulations. He suggested that turf hummocks of the "thufur" type could reach a maximum height and thickness. This would be achieved when, according to his theory of their formation, the lateral penetration of frost would be so reduced that upward pressures could no longer be effective.

The mosses and liverworts collected by BÖCHER (1933) on the occasion of the Scoresby Sound Committee's second expedition to East Greenland in 1932 were studied by HARMSEN, who published an account of them (1933). On p. 30–38 of his report he related the local distribution of these plants to the various plant communities that were described by BÖCHER. In his discussion of "Moor Vegetation" he described the distribution of mosses below a melting snow drift at Cape Daussy, saying that "there was a very distinct formation of zones from the very wet soil nearest the snow and outwards."

"Nearest the snow there was a *Sphagnum plumosum* — *Calliergon stramineum* — Association with *Drepanocladus revolvens*; the next zone was moist heath, passing into lichen—heath; the last zone was a moss—tuft vegetation . . . with tufts 20–30 cm in height, the top of which consisted of a *Sphagnum plumosum* – *Aulacomnium palustre* – Association, whereas the sides consisted of a *Paludella squarrosa* – Association which passed gradually into a *Calliergon stramineum* – Association in the hollows; here and there in the hollows there were also associations of *Oncophorus Wahlenbergii*. The dominating phanerogams on the tufts were: *Salix herbacea*, *Carex rigida*, and *Polygonum viviparum*; further *Empetrum nigrum*, *Vaccinium uliginosum*, *Salix arctophila* × *glauca* were found and in scattered occurrence *Pedicularis hirsuta* and *P. flammea*. The chief species found in the hollows were *Equisetum arvense* var. *rivulare* and scattered specimens of *Carex rigida*."

Judging by BÖCHER's description and photographs of this situation (1933, p. 7–8), together with HARMSEN's (l. c.), the area just below the snowdrift was one of moving soil in the form of sorted nets, and the "lichen-heath" mentioned above was located there. Otherwise, and allowing for the absence of *Sphagnum* from some areas, there is a resemblance between the general pattern here and that described in similar situations by OOSTING (1948), HANSON (1950), and others.

GRIGGS (1936) published an excellent description of the turf hummocks in the Katmai district of Alaska. He considered them a characteristic microrelief feature of the "Heath" vegetation of that district, in which *Empetrum nigrum*, *Vaccinium uliginosum*, *Betula nana* ssp.

exilis (*B. rotundifolia*), *Ledum decumbens*, *Vaccinium vitis-idaea* var. *minus*, *Salix arctica*, and *Arctostaphylos uva-ursi* are prominent species. He thought that the most important factor in the development of the heath was lack of drainage and the presence of stagnant water.

Griggs speculated as to the causes of the hummocky nature of the heath in the Katmai region, suggesting that snow and water in the hollows, remaining late in the spring, greatly shortened the growing season for plants, thus giving advantage to plants growing on the higher ground. Further, he proposed that expanding ice in the hollows would tend to squeeze the hummocks higher, particularly in the autumn when insulation on the hummocks would keep their interiors unfrozen while water in the holes between them had turned to ice. He considered that the Katmai heaths were very old, dating from shortly after the disappearance of the last glacial ice. He could see many forms of transition between the heaths and other types of vegetation, but he thought these were "static variations in the conditions of the habitat which affect drainage, etc., rather than dynamic moving vegetation fronts." He conceived the heath to be a "permanent subclimax due to lack of drainage."

Sørensen (1937) described the hummock areas below perennial snowdrifts as "constantly irrigated fields," and distinguished two types of them in the fjord region of Northeast Greenland. In the region to the north of Sabine Ø he found the hummock vegetation composed mainly of grasses and sedges and called the areas "denuded bogs." Farther south, in the Franz Josephs Fjord region and presumably also in the region of Kong Oscars Fjord, he called them "knolly bogs" in which the knolls, or hummocks, were covered with "dense moss, grass, and dwarf-shrub vegetation." In both areas, he distinguished infra- and supra-aquatic phases in these bogs, the former for the "paths" between the hummocks, and the latter for the hummocks themselves. He did not describe the internal anatomy of the hummocks, nor did he propose a process by which they might have developed.

Sharp (1942) described extensive areas of turf hummocks in the vicinity of Wolf Creek glacier, St. Elias Range, in southwestern Yukon. He designated them "earth hummocks," and noted them as "low rounded knobs of fine material covered by a tight mat of moss, grass and scrubby plants." He stated that they were "most abundant on slopes and flats covered by a thick growth of tundra-type vegetation, but closely related phenomena are reported in bogs and swamps." They were 1–2 feet high, with ground-plan dimensions of 1 to 5 feet. On flats and on slopes of less than 5° they tended to be rounded and domed, but on steeper slopes (up to 20°) they sometimes formed ridge-like structures more or less parallel to the contours. When arranged in this way the lower side was the steepest, and in some cases the upper side graded so gradually back into the hillside that a small terrace was formed.

SHARP considered that the hummocks were formed primarily by frost action, but that the process was highly conditioned by the cover of vegetation and turf. He reviewed the theories that had been advanced to explain them, notably those of FRIES (1913), BESKOW (1930), and HAMBERG (1915). The following is his outline of the processes that he thought probably produced the hummocks along Wolf Creek. "Since . . . (they) . . . have no frozen cores in summer, earthy material must have been introduced, probably by forces arising from differential freeze and thaw. These mounds are located in the less deeply frozen spots, for the deeply frozen areas are centers of pressure from which force is exerted outward on surrounding unfrozen material. If the surficial crust is not too deeply frozen, upward movement of the unfrozen material beneath domes it up to form mounds. The unfrozen debris cannot move downward to any degree owing to the underlying perennially frozen zone. If the crust is so deeply frozen as to be rigid and not subject to updoming, involutions will be developed by squeezing between the rigid crust and the underlying frozen ground. Once the mounds are formed their air-filled vegetative cover affords better insulation than the water-soaked grass and moss of the low areas between, so that freezing occurs first in the low areas forcing more material into the mounds. LUKASCHEW's (1940) analysis resembles that just outlined, and his treatment of mound height shows that it is dependent upon thickness of the frozen crust, depth to perennially frozen ground, pressure developed by freezing, and specific weights of the materials involved. The uniform size of the mounds at any particular locality suggests that the limiting conditions are remarkably uniform over small areas at least.

"On slopes the updriven earth partakes to some degree in downhill movement with a consequent steepening and even overturning of the downslope side of the hummock. Greater downhill movement produces a transition into turf-banked terraces (Wulstböden)."

The terrace-like hummocks described here as affected by gelifluction on slopes appear to be similar to those noted by HANSON in Alaska (1950).

TROLL (1944) discussed turf hummocks of many kinds, with and without earth cores, and formed with various kinds of cores. He also gave an account of their occurrence in many parts of the world. His review of the work of GREGOR'EV (1925) indicated that those in northern Eurasia closely resemble those of northwestern Europe and Iceland. For those in the Vosges Mountains he drew upon the studies of REMPP and ROTHE (1934, 1935) and ISSLER (1942). There the Icelandic type of "thufur" are common, as well as hummocks formed entirely of moss grown over stones, anthills, animal droppings, or grown up merely as isolated hummocks of *Sphagnum*. There are also hummocks that grade into solifluction forms, some of which involve only the humus layers while others include the mineral horizons. Similar forms have been described in the Alps by Sölch (1922), Stiny (1931), Stäger (1913), and Gams (1941).

Steindorsson (1945), in his description of the vegetation of the Central Highland of Iceland, made repeated reference to "knolls" or "knolly" land. His observations on the occurrence and distribution of knolls throughout the various types of vegetation were in substantial agreement with those of Hansen (1930) and Gröntved (1942). However, he noted that knolls were far less abundant in the Highlands than at altitudes below 500 m, and thus substantiated the observations of Thorarinsson and others. He found some knolls in "mýri" and "jaðar," but almost none in the Highland "mó" or heather types. "Flag" vegetation as defined by Hansen appears to be absent from the Highlands. It may be of interest that in one place he saw small Sphagnum knolls in "flói" vegetation, in which they have not usually been described. He made a rather thorough study of the vegetation of the "Flá," in which "rústs," or palsen, have developed in Iceland. In doing so he utilized in part the work of Hannesson (1928) who had expressed the opinion that "Rústs and knolls are of the same nature. Where flá and mó meet, they pass into each other without any sharp limits, and all kinds of intermediate forms between rústs and knolls are found. Steindorsson expressed no opinion of his own on this matter, but it should be noted that Thorarinsson (1951) also thought that the rústs and knolls were similar in nature.

Oosting (1948, p. 246–263) in attempting to outline vegetational successions in the fjord region of Northeast Greenland, published several remarks that illuminate the early development of hummocks. He wrote (p. 252) that in this region "all habitats with sufficient moisture eventually develop a moss mat in some form. Regardless of whether it is the bank of a stream, a drainage line, seepage area, or snow patch, the mosses eventually accumulate in mats which continue to spread as long as the moisture conditions prevail." He described two situations that are particularly significant to the present study.

One of these was on the "boggy," gradually sloping margins of shallow ponds on outwash plains and terraces and sometimes on new moraines. Here a mat of mosses developed, including *Funaria hygrometrica*, *Tortula* sp., and *Didymodon recurvirostris*. In older, more stable ponds, the bottom and margins were covered with *Drepanocladus aduncus*, and eventually *Aulacomnium palustre* and *A. turgidum* are added. Sedges and rushes were abundant at the outer pond margins, and Oosting had the following remarks concerning these areas (p. 251): "The larger species . . . may grow in clumps and when they do, the bases of the culms accumulating year after year with the mosses spreading over them initiate a condition which eventually produces a hummocky surface. The hummocks provide a habitat for species which could not grow in the younger, wetter bog . . . The raised portions of the older bogs show all characteristics of typical ericaceous heath." He regarded this heath as approaching the "climax" vegetation of the tundra of this region, and thought it might come about through improved drainage or by the building up of organic soil. Other mosses were added during this stage of development: *Blindia acuta*, *Drepanocladus revolvens*, and *Campylium stellatum*.

Another situation, or rather a complex of situations described by him involved drainage systems and seepage areas some of which remained wet throughout the open season. He did not outline sequences for these sites as concisely as he did for the pond margins, but he stated that the development of their vegetation "varies only slightly from that of bogs." He gave a somewhat more detailed description here of the later stages in the development of the heath "climax," but did not discuss further the hummocky nature of the surface; nor is there any indication that he saw the degrading hummocks.

POLUNIN (1948) described turf hummocks at several places in the Eastern Canadian Arctic, using for the most part the term "hillock tundra" for the whole vegetation in which he found them, and the word "tussocks" for the hummocks themselves. He considered the "hillock tundra" to be a drier kind of "marsh," the wetter phase of which he characterized by grasses and sedges, notably *Arctagrostis*, *Eriophorum*, and several species of *Carex*.

In the Cape Dorset district, southern Baffin Island, he described a transect of the vegetation below a perennial snowdrift (l. c., p. 171–172, pl. LXVIII), but although the accompanying photograph suggests a wet grass-sedge meadow with a hummocky area below it, the description does not give enough detail to make this clear. POLUNIN regarded the heath tundra, in general, as approaching a "regional climax" vegetation. He thought that the heath on the tussocks in some of the "hillock tundra" "indicated some tendency toward" this climax. In all cases, however, he considered the turf hummocks to be a phase of "snowpatch" vegetation.

HANSON (1950) recorded several observations in Alaska on the development of turf hummocks in wet meadows. He thought the mosses invaded sedge marshes "to form low mounds," and that conditions would then become "suitable on these low mounds for the invasion of other kinds of mosses and *Sphagnum*, followed by a variety of heath plants, willows, birch, and sedges adapted to drier ground, a few grasses, and a variety of forbs." His observations of hummocks near Kotzebue, Alaska (1950, p. 624), suggest that the presence of earth cores is sporadic in that area, and that they are more apt to occur on silty soils than on sands or gravels. He described a hummock in Mt. McKinley Park, Alaska (1950, p. 621, Fig. 6), which appears to have formed on the frontal margin of a small gelifluction lobe. In this case he was able to find continuity in the fibrous turf from the upper part of the hummock down its lower side and thence back under the mass of fine-textured silt that formed the front of the lobe.

Hanson thought that as the Alaskan hummocks grew progressively higher their tops became more and more exposed to wind, and their surface materials became dry. This would eventually kill off the plants growing on the tops and cause deterioration of much of the structure beneath. He did not cite clear evidence for this progression, or for its causes.

Large "peat mounds" were described by Sigafoos (1951) on the Seward Peninsula of Alaska. These occur in wet bogs and are noted as long and irregular in form, 60–120 cm high, and apparently composed entirely of peat and the living plants that grow on it. The surrounding bog vegetation is of sedges, primarily species of *Eriophorum* and *Carex*; but on the mounds there are dense thickets of dwarf *Betula*, *Vaccinium*, *Ledum* and *Empetrum*. Sigafoos proposed that the mounds began their development as small hummocks of *Sphagnum* in the bogs, where, in addition to the sedges, *Rhododendron lapponicum* and *Andromeda Polifolia* are found. He thought that once started they grew by simple peat accumulation, but probably were accentuated by differential frost heaving. He cited Troll (1944) who thought such mounds owed their height to differential growth of ice lenses in the peat because of unequal freezing of the bog surface. Troll suggested that unequal snow cover on the surface of the bog, due to the projecting peat mounds and *Sphagnum* hummocks, caused the elevated areas to freeze more rapidly in the fall. Rapid freezing, according to Troll, caused more clear ice to form under the mounds than under the sedge of the bog, and a net rise of the mound surface resulted.

Sigafoos observed as did Hanson at Kotzebue, that the peat at the tops of some of the mounds he saw on the Seward Peninsula had become dry and was being removed by wind. He thought this might be a mechanism for the disappearance of the mounds. He also suggested that changes in drainage patterns due to local thawing in the permafrost, or local soil movements due to frost action, could alter the course of development of the mounds.

The processes by which the mineral soil is domed upward beneath mounds of turf were studied rather intensively by Hopkins and Siga-

FOOS (1951, 1954; SIGAFOOS and HOPKINS, 1951). Although they were working with mounds made by tussock-forming sedges and grasses, the basic principles of frost action involved appear to be similar to those effective under moss hummocks. Assuming a cover of vegetation uneven in texture from place to place, isolated or thicker patches would insulate the ground and cause it to freeze later than bare patches or patches under thinner cover. The result would be a tendency for the earlier-frozen ground at the margins of the more thickly vegetated areas to exert a lateral thrust toward the latter, which would thus be forced upward. Because the downward-freezing surfaces beneath them would become convex upward, cryostatic pressures might also be involved in increasing the relief of the hummocks (HOPKINS and SIGAFOOS, 1954).

THORARINSSON (1951) discussed turf hummocks ("thufur") only briefly in his study of Icelandic patterned ground. He grouped them with palsen ("rústs" in Icelandic terminology) in a general category of "Vegetation-covered" patterned ground, and considered them the dominant surface formation of such ground up to altitudes of 400–500 m. His remarks about them, though brief, are useful: "generally speaking, *thufur* may be said to occur on wet as well as dry ground. On boggy ground, *thufur* are more scattered the wetter the ground is, and are occasionally wholly absent in its wettest parts. They are likewise absent from regions where the snow cover is particularly thick and does not melt until late in the spring. In bogs on strongly sloping ground they often float together into ridges, '*flytralkar*.' *Thufur* usually grow larger with increasing altitude, and merge without any sharp boundaries into a form of patterned vegetation . . . called "flá." "Flá" is the Icelandic term for the upland bogs in which "rústs" develop.

THORARINSSON investigated the "rústs" in considerable detail, and one of his main conclusions is of interest to the present study. He found clear evidence that the "flás" were diminishing rather rapidly and that the "rústs" which have formed on them have been disappearing during "the last few decades." He could cite personal experience over a period of 25 years in support of this, and also that of other observers familiar with the region. He correlated it with a general depergelation in Iceland. It has already been noted that he considered "thufur" to merge imperceptibly at their higher levels into the patterned ground of the "flá." Presumably the same factors which have caused the decline of "rústs" could be expected to affect the development also of Icelandic turf hummocks.

DE LESSE (1952), in his studies of the vegetation of the Eqe district in West Greenland, published notes on the plants and soil structures of several hummocks. He termed them "mottes de terre" and made this name synonymous with "Thufur." Though he did not discuss their origin, he evidently included forms of different origin under the same term. In his Fig. 4, p. 57 (l. c.) he shows mounds of nearly pure sand on the shore of a pond. These mounds have a vegetation of grasses and sedges, with a few other species of vascular plants. In Fig. 8, p. 68, are well-defined turf hummocks of moss, heaths, willows, and dwarf birch. The descriptions on p. 70–74, and the soil sections in Fig. 9, suggest hummocks that have grown up in sedge marshes. In all of these cases the terms "earth mound" and "thufur" are applied. Although De Lesse gives sections of soil in the hummocks, his descriptions are not sufficiently complete to afford 3-dimensional concepts of the structures.

In Böcher's analyses of vegetation (1933, 1954) in both East and West Greenland he distinguished several different types of hummocks, but his basis for a classification of them was almost entirely in terms of their living plants. His published papers contain very little on their internal structure, and even in a profile transect through some hummocks (1954, Fig. 65) he shows only the living flora. In one place, at Pâ, he described "tussocks" that he thought had been formed primarily by solifluction and secondarily by melt water that gathered and flowed away between them in spring. But he did not enlarge upon this idea, nor did he develop any general theory for the growth of hummocks except to conceive of them as a phase of "snow patch" vegetation.

P'yavchenko (1955) has published the results of rather extensive research on peat bogs in the northern parts of the U.S.S.R., and has discussed the structure and origin of hummocks. Unfortunately, however, his paper has not been translated from the Russian except for chapter headings, text-figure legends, and general conclusions. From the last it is evident that he did not think the frost in the peat mounds he studied was active. Rather, he thought it "a passive factor which is gradually degrading at the present time." Also he considered that "the most widespread hypothesis of the formation of peat mounds at the present time which connects this process with local projections of the mineral soil and peat under the influence of mechanical stress created by the force of the frost" was not confirmed. His arguments for these conclusions will be of great interest when they become more readily accessible. Studies at Mesters Vig indicated that hummocks do form without earth cores, and there is good evidence that earth cores may have origins other than those connected with contemporary frost-heaving; but none of these observations detracts from the apparent significance of frost-heaving in the formation or accentuation of many cores.

Washburn (1956, p. 830–831) considered turf hummocks, at least those known to have earth cores, as a "particular type of nonsorted net with a mesh characterized by a 3-dimensional knob-like shape and cover of vegetation." He followed SHARP (1942) in calling them "earth hummocks." He believed that although they were almost certainly related to frost action, their distribution in Iceland where permafrost is sporadic, particularly their prevalence in the southern coastal region where permafrost is absent, indicated that they were not necessarily associated with permafrost.

WILLIAMS (1959), in a study of solifluction and patterned ground in the Rondane mountain district of Norway, noted the occurrence of several forms of "frost hummocks" "in all parts of Rondane where there is a soil layer with more than a few centimetres of humus." He also observed that "they are invariably associated with high ground water and may cover wide areas . . . they may grade into irregular hummocks at the foot of solifluction slopes." His descriptions indicate that some of these are dome-shaped, with an unbroken cover vegetation of grass-like and ericaceous plants, and have earth cores in them. In other places, which he notes as "typical bog communities," he saw what he presumed to be "considerable erosion around the hummocks such that bare and wet peat is exposed." He thought the erosion produced the "pillar-like form" of the hummocks seen in these places. Such may have been the case, but plates 8 and 9 in his paper suggest that the "eroded" hummocks were in reality formed in a way quite different from that of the dome-shaped ones. They look like the tussocks commonly formed by the caespitose species of *Eriophorum* in the western arctic tundra of America, and if this is the case they may have been formed without appreciable erosion (see HOPKINS and SIGAFOOS, 1950, p. 70–76; SIGAFOOS and HOPKINS, 1951).

BILLINGS and MOONEY (1959) have described what they conceived to be "an apparent frost hummock–sorted polygon cycle" in the alpine tundra of the Rocky Mountains of southern Wyoming. They dissected a series of sorted nets and peaty hummocks that appeared to form a sequence involving the growth of the hummocks by accumulation of peat, their degradation by wind erosion and frost thrusting, and the development of "frost boils" in their centers by which stony silt would rise to the surface and the stones would be concentrated to form the centers of accumulation for new hummocks. Judging by their descriptions and text figures the hummocks they worked with were 60–70 cm high (at maximum), and upwards of 80 cm in basal diameter. Some were composed entirely of peat (turf), while in others the turf seemed to have grown up around pebbles and cobbles. In two of the excavations they showed hummocks that had silty earth cores beneath them. Another section indicated what appeared to be incipient hummocks of peat on stony accumulations at the margins of sorted nets.

The validity of the cyclic sequence proposed by BILLINGS and MOONEY depends largely upon the behavior of the water supply to the area they studied, for the turf hummocks could accumulate to the heights measured only in the presence of an abundance of moisture. The authors were obviously concerned about this for they discussed it at some length, and postulated a fluctuating water table to account for the phenomena. They suggested that some small hummocks might form without abundant surface water, but that the growth of larger ones probably required it. They were unable to estimate time intervals for these fluctuations, or rates of peat accumulation, or rates of movement in the soils that would form the frost boils and sorted nets. They had some evidence of fluctuation of the water table over a small number of years (they cite the years 1954 to 1957, inclusive). In 1957 the sorted nets were flooded to depths of 1–2 dm, but on this occasion the plants on the rocky intervals were killed and the accumulated peat (the incipient hummocks) was entirely washed away.

Under these circumstances, and considering the uncertainties in present understanding of the nature and calibration of the processes involved, it would be simpler and more in accord with the observed facts to regard these authors' data as suggesting a general deterioration of a turf hummock vegetation due fundamentally to progressive desiccation. In a long period of heavy snows, short summer seasons, and abundant surface water throughout the growing seasons the hummocks could grow freely and perhaps quite rapidly. Losses by wind erosion from the summits could be recovered in relatively short times, before they led to serious breaks in the insulation. Gradual lengthening and warming of open seasons, with less snow, would bring less surface water, drier upper surfaces on the hummocks, deeper erosion, and eventually breaks in the insulation that would allow more intensive frost action in the silts beneath. From this time on the breakup of the hummocks probably would be accelerated by the formation of frost scars and "frost boils," as BILLINGS and MOONEY propose. The process of frost action could be expected to go on only so long as the water supply remained adequate at the critical times of year to activate it. In some cases it and wind erosion have completely eliminated the hummocks and in others only partially so. Small peaty accumulations on the stony borders of sorted nets could under these circumstances be interpreted as relics of old hummocks, or ephemeral accumulations due to temporary, short-term rises of water level such as the authors have noted in recent years, or combinations of both of these things.

A recent paper by BILLINGS and MARK (1961) on a vegetational analysis of some patterned ground features in the mountains of the South Island of New Zealand may be discussed here. The principal features concerned are "hummocks and stripes," which the authors describe as follows: "The true hummock areas, as opposed to stripes, are almost level and occur on the top of the range (Old Man Range) to the north and south of the rocky highest point. The hummocks range from about 20–40 cm high and are about 1–1.5 m in base diameter. At first glance, they resemble the frost hummocks of peat described from North America and Europe by Troll (1944), Hanson (1950), Billings and Mooney (1959), and others. However, instead of the ubiquitous *Carex* spp. of the northern hemisphere, these hummocks are almost entirely covered with low cushion plants typified by *Dracophyllum muscoides* and *Raoulia hectori.* Moreover, the hummocks do not consist of peat but of mineral soil.

"The stripes appear to be greatly elongated hummocks. There is no readily apparent difference in vegetation pattern between stripes and hummocks, and the soil profiles across the stripes are essentially like those of the hummocks.

"The stripes are confined to gentle slopes (4°–7°) as opposed to the near-level areas of hummock occurrences. On intermediate slopes (2°–3°), intermediate forms between hummocks and stripes are found." Also the authors have described forms intermediate between "stripes" and small solifluction terraces, the materials of which do not differ from those of hummocks.

The hummocks and stripes were found to be entirely of stone-free sandy loams which overlay a very stony sandy loam whose surface showed almost no relief. The upper part of the loam in the hummocks and stripes was dark brown and ranged from 5 to 20 cm in thickness, with the thickest part at the top. It had 12–16 $^0/_0$ organic matter. Beneath this was a light brown loam with only 4–6 $^0/_0$ organic matter.

The authors cited a description of this area by Cockayne published in 1928 in which the latter stated that the surface of the ground at that time was "peaty." Nevertheless, Billings and Mark doubted that there was ever enough surface vegetation and turf there greatly to affect the hummock formation. They therefore attempted to account for the development of the hummocks without benefit of a thick covering turf. They proposed three possible physical origins: "(1) accumulation of wind-blown soil in old snow-tussock clumps or in cushion plants, (2) polygonal frost heaving due to relatively shallow annual freezing *above* the rocky C horizon and additional sorting on the hummock crests due to diurnal needle ice, or (3) a combination of wind accumulation and shallow annual and diurnal frost-sorting." Of these three possibilities they thought the last was the most promising.

The similarity in form between the mineral horizons of these hummocks and many of the earth cores of hummocks described in the

Northern Hemisphere is at once striking. The simple removal of the living vegetation and peaty materials from many surfaces such as those described by Sharp (1942) would produce a microtopography closely similar to that described by Billings and Mark. Troll (1944 transl. p. 79–80), citing the work of Rempp and Rothe (1935), described mineral soil profiles under a cover of vegetation in the Vosges that strongly suggest those on the New Zealand mountains: "... there is a very stone-poor and mobile fine soil under the hummocks, and a much more stable stone-rich soil in the furrows between. The soil becomes uniform only at 10 or 20 cm beneath the surface of the furrows." The arrangement of ridges (stripes) in relation to slope, however, appears to differ from that in the North. It seems to be more frequently oriented up and down slope than parallel to the contours. According to the authors' analysis of the situation, and the probable factors affecting it, the trends of the stripes are a resultant of slope and prevailing wind effects.

Drury (1962) described "hummock polygons" on Bylot Island in the Canadian Arctic Archipelago. He found these in three kinds of sites. The most pronounced hummocks were on a south-facing slope of 15°–20°, sheltered from easterly winds, and in shadow at 4 P. M. They were "of moss growth around an earth center ... 5–15 inches high, averaging 18–24 inches across." The mineral soil core was 1–10 inches high, and in some cases erupted through the top. Above the core there was a "3–8 inch transition level of increasingly organic material," and the top of the hummock was "usually capped by lichen growth except where mineral soil bursts through." The second situation was on steep south- or west-facing deposition slopes, such as below terrace banks. Here were found hummock polygons 18–24 inches wide separated by cracks 3–10 inches deep. These hummocks were found to be especially high on the edges of persistent snowbanks. Third, hummocks appeared on the lower parts of unstable and nearly vegetation-free slopes, where the vegetation first began to come in. As the plant cover became more dense the hummocks were higher and "better integrated." These hummocks had a mineral soil core, with a "humus layer," and were "colonized chiefly by Arctic Willow."

Thus Drury found some hummocks separated by cracks in the mineral soil which he called "hummock polygons." Others not separated in this way he apparently called merely "hummocks." He seems to have believed, however, that the two forms were "similar in origin, both dependent upon the formation of contraction cracks and differential growth of plants." He thought that the hummocks containing mineral cores were formed by differential freezing and thawing, citing the works of Thoroddsen (1913) and Tanttu (1915). However, he did not discuss the problem of their initial stages. He thought that the origin of hummocks on drier surfaces was "associated with the appearance of perennial contraction cracks, as the depositional slope builds up . . ." "The cracks form every year and plant growth thickens on the top and sides of the polygon. Then the hummock grows as above." The problem of water supply on these drier sites gives rise to questions, as it does in the case studied by BILLINGS and MOONEY in Wyoming (1959). It is not impossible that these hummocks are deteriorating rather than growing.

MÜLLER (1962) has attempted recently to explain the development of Icelandic thufur-type hummocks by a combination of processes. These involve local differentials in desiccation, frost heaving, and pressures exerted by the trampling of grazing animals guided into the interhummock trenches by the local microrelief. He does not deal adequately with the problem of initial stages in the development of hummocks; and although in many parts of Iceland the interhummock depressions are doubtless accentuated by grazing animals, this process cannot be generally applied to the formation of hummocks of the thufur type.

Some students of arctic vegetation already quoted (BÖCHER, 1933, 1954; POLUNIN, 1948) have considered the turf hummocks they described as phases of "snow-patch" vegetation. By this they have meant that the hummock vegetation must have been protected by heavy snow that lasted throughout the winter. The botanists who have investigated Icelandic vegetation, on the other hand, have said that turf hummocks (knolls) do not develop in snow-patch vegetation (HANSEN, 1930; STEINDORSSON, 1945; THORODDSEN, 1914). In fact the absence of knolls in certain kinds of situations seems to have become an indicator of "snow-patch" conditions. Thus there is an apparent contradiction that should be resolved; but to do this will require examination of the definition of "snow-patch."

The definition of "snow-patch" as applied to vegetational environments appears to have varied during the past 60 years. WARMING (1909, p. 257) considered the "snow-patch flora" to be that which developed in depressions where snow remained for a long time, and where a "greasy mud" accumulated which supported a vegetation of its own. He thought that the ecological conditions of this habitat were "(1) The characteristic soil, which owes its origin to the melting of the snow; (2) Brevity of the vegetative season; (3) Humidity." He proposed (p. 72) that the "greasy mud" soil was a product, in part at least, of the release of organic and inorganic particles by the melting snow.

A. E. PORSILD (1955), discussing "Snow Patch Vegetation" in the western Canadian Arctic, wrote (p. 66) that "In the high-arctic landscape, snow cover is a necessity to plants as a protection from desiccation and as a source of water during the latter part of the growing season for a number of species that in the Arctic Archipelago otherwise succeed only in slight depressions in the landscape or in the lee of protruding obstacles where not too deep snowdrifts form in winter. The plants growing in such places . . . require the full length of the short growing season. In the Archipelago all species with woody aerial stems are confined to snow patch habitats."

Thus the term "snow-patch" has come to have two quite different meanings, both of which appear in recent literature. Both involve accumulations of snow, but the difference lies in the length of time in the spring during which the snow continues to lie before it melts. This in turn determines the length of the growing season available to plants on the exposed soil. As used by PORSILD, BÖCHER and POLUNIN the term meant a modest covering of snow: enough to protect the plants during the winter but not enough greatly to shorten the growing season. HANSEN, STEINDORSSON, and GRÖNTVED, on the other hand, seem to have used it more in the sense of WARMING, for snow that lasted long enough in the spring to alter the vegetation. According to the interpretations of THORODDSEN and THORARINSSON it also stayed on the ground late enough to prevent the development of "knolls" in areas of Iceland where it occurred.

Many students now use a second term, "snow-bed," which carries the earlier (WARMING) meaning of "snow-patch." PORSILD (l. c., p. 65–66) used it in describing some western Canadian Arctic habitats, but found only small examples of these habitats in that region. A recent study of snow-bed vegetation, and an extensive review of the literature of the field, is that of GJAEREVOLL (1956) on snow-beds in the Scandinavian mountains. The term "snow-patch" as used in the more recent literature on Icelandic vegetation then (HANSEN, 1930; STEINDORSSON, 1945; GRÖNTVED, 1942) is approximately equivalent to "snow-bed" in the sense of GJAEREVOLL (1956).

It is apparent that HANSEN (1930) realized the significance of differences in depth and length of period in the snow cover of Iceland, for in his final attempt at classification of vegetation types (p. 178–179) he used variations in snow cover as main divisions:

I. "Vegetation bare of snow" (Moss heaths; fell-fields).

II. "Vegetation with normal snow-covering" (mó; vallendi; Jaðar; Flag; Mýri; Flói; Fén, vegetation of running water; Dý).

III. "Vegetation with a constant and deep snow-covering" (Geiri, or snow-patch; Forest ground).

In any ordinary arctic or alpine landscape, given the usual variety of relief, there will be found every conceivable gradation between snow cover that disappears early in spring and that which lies so late that plants do not have time enough for an effective growing season. It follows that precise definitions of "snow-patch" and "snow-bed," depending as they must upon measured divisions in this time interval, are impossible with present knowledge except in a few limited localities. HANSEN (1930, p. 7) had "no observations on the depth and duration of snow-covering in the various regions of Iceland," and therefore could not define what he meant by "normal" in the above classification. GJAEREVOLL (l. c., p. 16–20) could give no exact definition of "snow-bed," and relied heavily upon the behavior of various plant communities to determine the boundaries of snow-bed areas in specific localities. Even then he had great difficulty in establishing obligate relationships in the lower and middle altitudes of the Scandinavian mountains, and realized that what he had worked out for these altitudes would not apply directly to the higher alpine areas. His three-way division (p. 400) of the actual snow conditions that he thought caused the snow-bed vegetations was reminiscent of HANSEN's subdivisions of snow covering in Iceland: "Late snow-free . . ."; "Very late snow-free . . ."; "Extremely late snow-free . . .".

It appears that continuous snow cover in winter may be essential to the formation of turf hummocks in some regions but not in others. It is probable that in many areas the hummocks could not withstand the rigors of desiccation and erosion by the winter and spring winds if they were not covered with snow. On the other hand there are parts of southern Iceland in which the snow cover is not continuous throughout the winter, though turf hummocks are abundant there (HANSEN, 1930). WILLIAMS (1959) reported that the winter snow cover of hummocks in the Rondane mountain district of Norway was complete in some years but not in others. It seems clear that the presence of turf hummocks can not, of itself, be regarded as clear proof of snow-patch conditions in the sense of PORSILD (1955; see above). THORODDSEN (1914) and THORARINSSON (1951) related the absence of knolls of the "thufur" type in Iceland to late-lying snow (snow-beds in the sense of GJAEREVOLL, 1956), presuming that the ground was thus protected from frost heaving during the spring season. But much frost heaving could also be expected to occur in the autumn, particularly in soils as damp as those under "geiri" vegetation are described to be (HANSEN, 1930). These things at least raise a question as to whether some factors other than the depth and duration of snow cover may be effective in determining the presence or absence of knolls in these parts of the Icelandic landscape. This question is particularly pointed because actual data on the snow cover have been lacking, and because evidence of its depth and duration seems to have been inferred from the behavior of the knolls and the vegetation.

SUMMARY OF THE FIELD DATA

Field data for the ensuing discussion were accumulated in the following manner. General notes on the occurrence and local distribution of the hummocks were made on several occasions during summer visits to the Mesters Vig district in 1956–1958 and 1960. Their local distribution was studied in a broad channel among the emerged delta remnants (at approximately the 110-m level) near the northeast base of Hesteskoen west of Tunnelelv in July of 1957. Similar local studies were made in 1958 in an area near the base of the sandstone and trap hills north of experimental site 5 on the Labben peninsula, and in 1960 in a wet meadow a short distance north of experimental site 15 in the Nyhavn hills. These studies attempted merely to place the hummocks in their appropriate topographic position, and relate them areally to neighboring vegetation.

A few notes on the flora of the hummocks were made in July 1956, but most of the data on their flora were accumulated in 1957. These came from general collections and from detailed descriptions of experimental sites, notably from the target lines of sites 6, 7 and 8, and from the vegetation map area which embraces sites 7 and 8, all in the Nyhavn hills. Certain of the quadrats used in July 1958 to assess the percent of ground coverage by plants yielded floristic data on hummocks, and notes on plant cover were made for all hummocks that were dissected.

Dissections, with more or less detailed descriptions, were made of 11 turf hummocks. Three of these were done in 1957 and 1958: one in the vicinity of experimental site 16, one in the map area of experimental sites 7 and 8 (pit no. 6), and the third on the Labben slope just north of experimental site 5. The remaining eight were done in July 1960: four in the vicinity of experimental site 6, two in the "110-m" delta remnants west of Tunnelelv, one in a wet meadow just west of experimental sites 2, 3 and 9, and one in the wet meadow at the base of the sandstone and trap hills north of experimental site 5.

The first observations of "perched" willows (*Salix arctica*), which figure significantly in the developmental history of the hummocks, were made in July 1957 on the Labben slopes in the vicinity of experimental sites 2, 3, 5 and 9. In 1958 the collecting of these willows was continued and greatly enlarged, and a few additions were made in July 1960.

The descriptions and analyses to follow are based mainly upon the data referred to above. However, miscellaneous notes on the nature and distribution of turf hummocks were made on many other occasions during the course of the field operations, and many more dissections were made than there was time to describe in detail. These miscellaneous observations, and the ideas derived from them, are significant because they affected the selection of material for more detailed study.

THE STRUCTURE OF THE TURF HUMMOCKS

The photograph in Figure 1 gives the approximate locations of four turf hummocks excavated in the vicinity of experimental site 6, in the Nyhavn hills. The target line of site 6 extends along line A–B in this photograph. The surface in the vicinity of site 6 has a slope of 2.5° to 3°. Most of the moisture supply for the portion of the area on the lower part of the slope, below the target line, comes from a large snow-drift at the left. This drift is in the lee of a trap outcrop similar to that at the right, and only on rare occasions entirely disappears during the summer. Water for the upper part of the slope comes from drifts and thawing ground farther back in the hills, some of it by sheet runoff from nearby sources, and some brought by a shallow stream with several interlocking channels that can be seen in the photograph. The hummocks illustrated in Figures 2 and 3 were located in area C of Figure 1, while those shown in Figures 4 and 5 were located in area D.

The hummock shown in Figure 2 extended 25 cm above the general level, was approximately circular in outline, and about 55 cm in diameter at the base. The living mat of mosses was 2.5 to 4 cm thick on the top, over a layer of dark brown to black, root-filled turf 7.5 to 12 cm thick. At the base of the turf the latter gradually merged into a greasy, fine-textured humus which formed a layer 2–3 cm thick. Beneath this humus, and forming a roughly conical core to the hummock, was a mass of stony loam similar to that underlying the surrounding surfaces. This loam was stained a yellowish color to a depth of about 5 cm, but otherwise was pale gray. All of the above measurements refer to the top of the hummock. They are reduced on the side slopes.

The vascular flora of this hummock formed a rather dense cover in which the primary species were *Vaccinium uliginosum*, *Salix arctica*, and *Carex Bigelowii*. Secondary species listed were *Cassiope tetragona* and *Polygonum viviparum* (see Fig. 42). The hummock is one of many in this vicinity that have approximately the same vegetation and size. They differ greatly in shape and areal configuration, and many are separated by shallow pools or slowly flowing meltwater from the nearby snowdrift.

The section through the hummock was oriented approximately N–S. Although the earth core was about in the center, the highest point

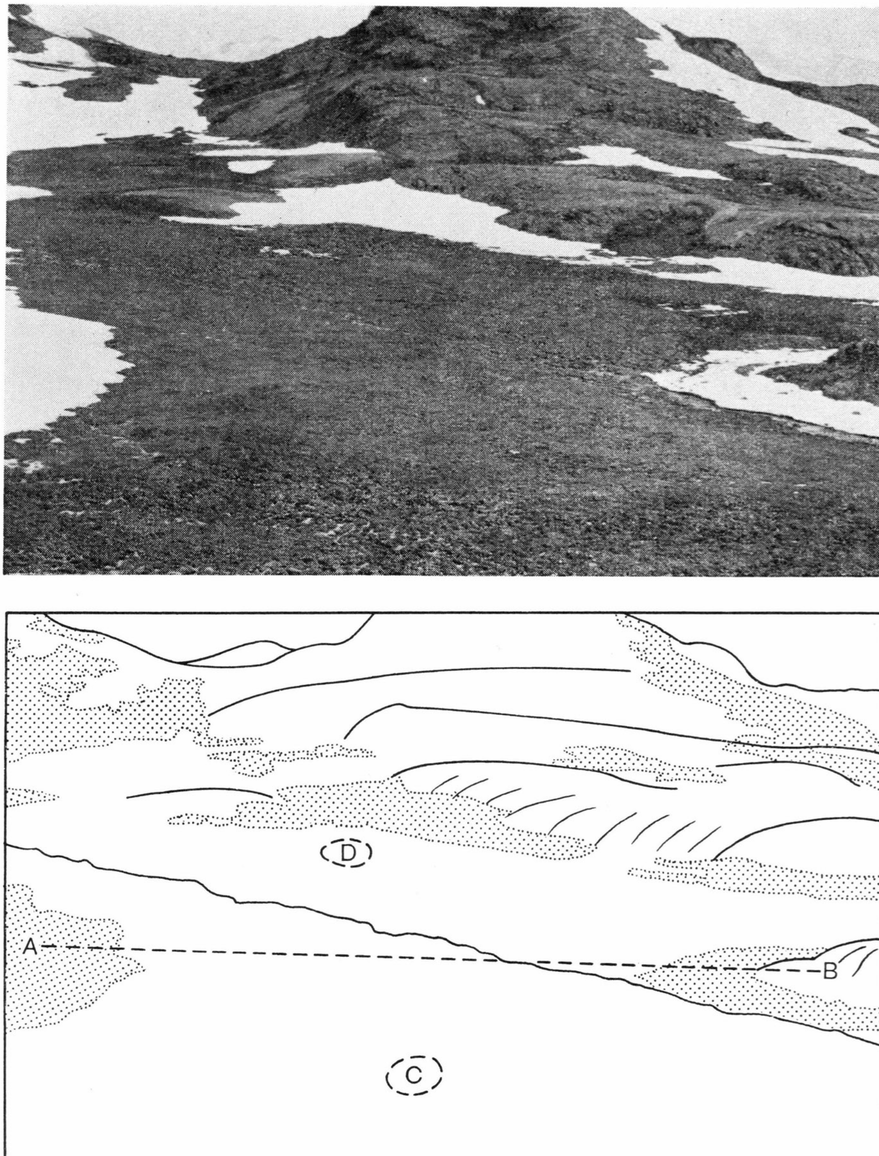


Fig. 1. View of experimental site 6 and vicinity, showing location of turf hummocks illustrated in Figs. 2–5, incl.

on it was south of the center, making the turf accumulation slightly asymmetrical, with the larger part of the mass on the north side.

Figure 3 shows a hummock complex about 18 cm high in an area characterized by rather low microrelief. Also there was a strong tendency for the hummocks to be connected with each other to form irregular

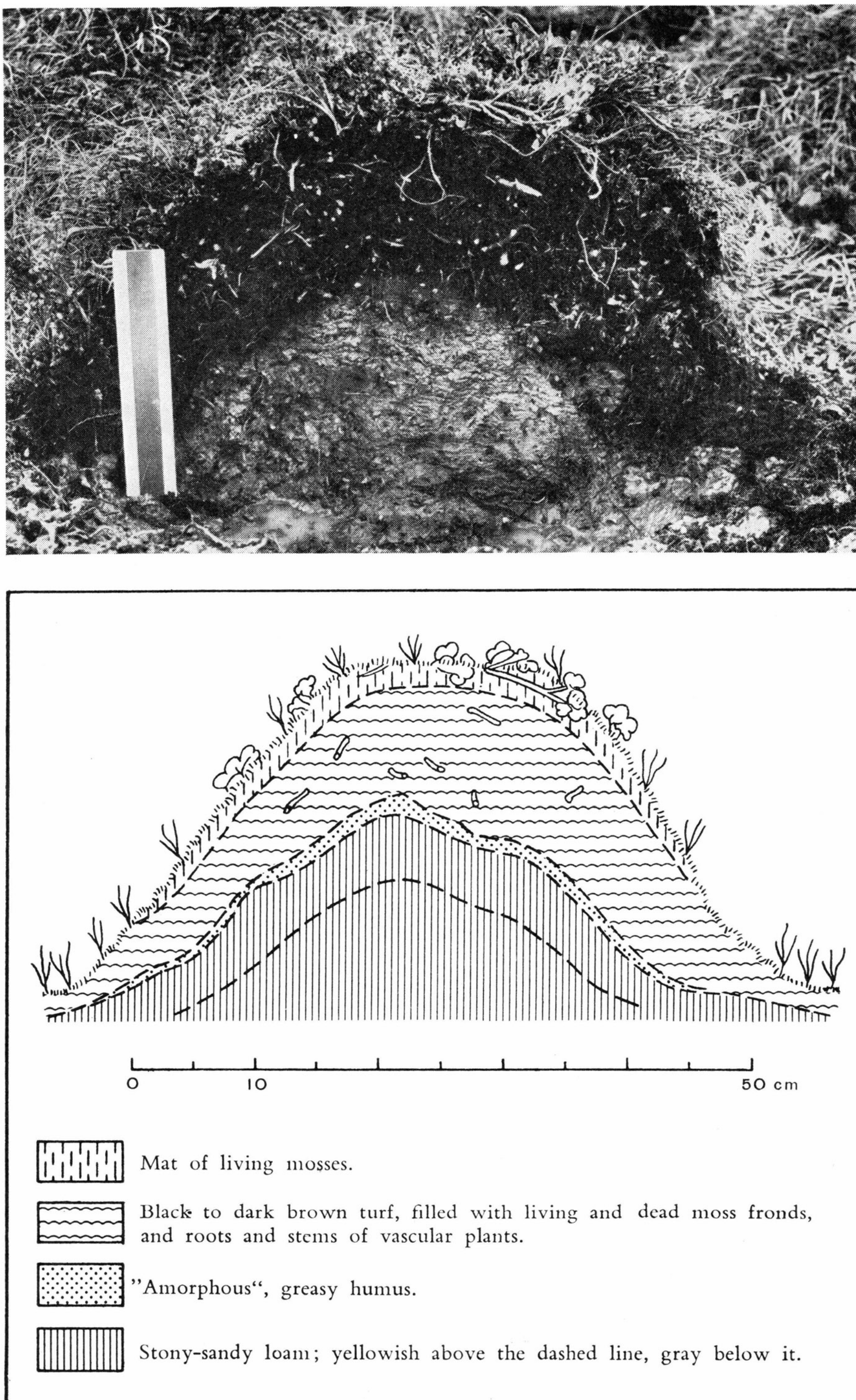


Fig. 2. Turf hummock dissected in area C, below target line of experimental site 6.

and discontinuous ridges. The excavation was carried to some distance on either side of the hummocks to show their relationship to the surrounding surface.

The living portion of the moss mat on the top of the larger hummock was about 5 cm thick, and there was a thinner living mat on the smaller, adjacent hummock at the side of the main one. The turf layer was continuous under the two hummocks, but was thickest under the smaller one. It also extended widely under the neighboring more or less level tundra. The living moss mat was present in these more nearly level areas, but was much thinner. The layer of "amorphous," greasy humus overlying the mineral horizons was conspicuous under the two hummocks, but if present under the turf on either side of them it was too thin to be noticeable.

Immediately below the turf and humus the stony loam had a yellowish stain, but this gave way to brown at a few centimeters depth. The upper surface of the loam showed a small elevation just to the left of the main hummock, beneath a slight depression in the tundra surface (Fig. 3). The excavation was oriented approximately NW–SE; consequently this depression was at the northwest base of the hummock. Under the main hummock the surface of the loam rose to form a low knoll, or part of an irregular ridge, the top of which was about 5–8 cm above the general level of the mineral soil. Southeastward the surface of the knoll dropped off rather steeply, with irregularities in its slope, to a depression which lay beneath the smaller adjacent hummock. The total relief on this side was about 10 cm. Beyond this depression the surface of the loam gradually rose until it was only 2–3 cm below the tundra surface.

Within the loam it was possible clearly to distinguish two horizons, largely on the basis of color. Beneath the turf and humus was a continuous horizon of brown loam. It was this horizon that had the yellowish stain in the upper part, and its brown color was undoubtedly due to humic materials. Below it was a light brown to gray loam containing much less humus. This light brown horizon appeared under the relatively thin turf and dark brown loam in the northwest part of the excavation, and became thicker upward under the main hummock. Under the southeast slope of this hummock, however, it disappeared at the bottom of the excavation. Before doing so it appeared to overlie a portion of the thicker, dark brown loam which was continuous under the smaller hummock and under the tundra southeast of it.

The hummock area shown in Figure 3 can be characterized floristically in two phases. On the hummocks themselves, and on minor elevations in the surrounding tundra the primary species of vascular plants were *Vaccinium uliginosum* and *Carex Bigelowii*, while common

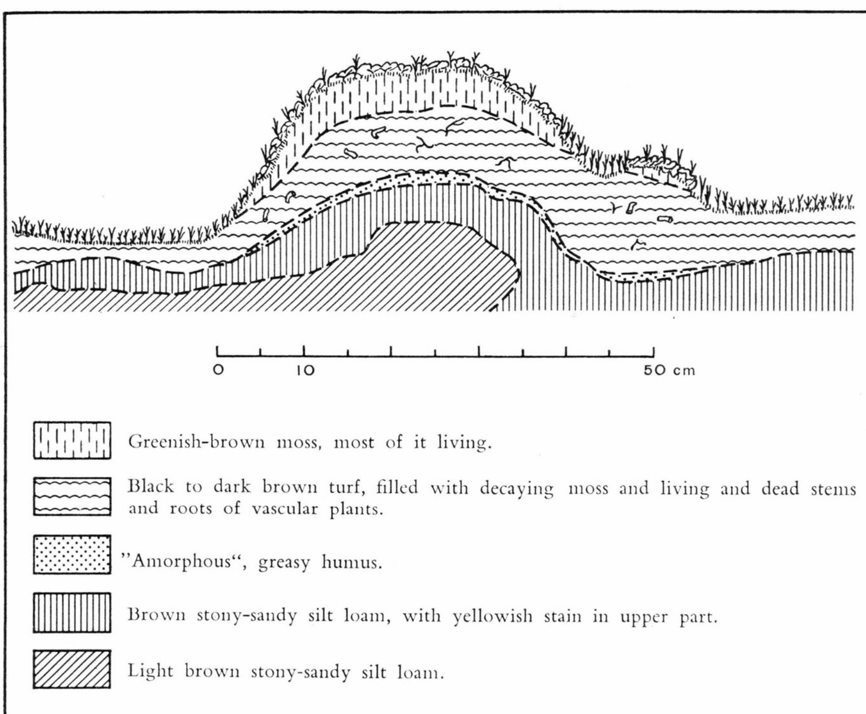


Fig. 3. Turf hummock dissected in area C, below target line of experimental site 6.

secondary species were *Poa arctica* and *Polygonum viviparum*. In depressions the mat of living mosses was very thin, and the sedges, *Carex Bigelowii*, etc., became primary. In the wettest spots the sedges were much scattered, with an organic crust between them. The winter snow had melted off only a few days before the observations were made, so that it was impossible to make a complete description of the vegetation.

Figure 4 illustrates a rather broadly domed turf hummock in area D, Figure 1. Its top stood about 45 cm above the level of most of the depressions between it and the neighboring hummocks, and its basal diameter was about 110 cm along the line of the excavation, which was oriented roughly north and south. It will be noted that the hummock had a broadly dome-shaped earth core which was symmetrical in the section exposed, but that the center of mass of the turf about it was 10–15 cm to the north. This, with a steeper slope on the north side of the hummock, resulted in a certain amount of asymmetry. The mat of living mosses remained thick farther down on the north side than it did on the south.

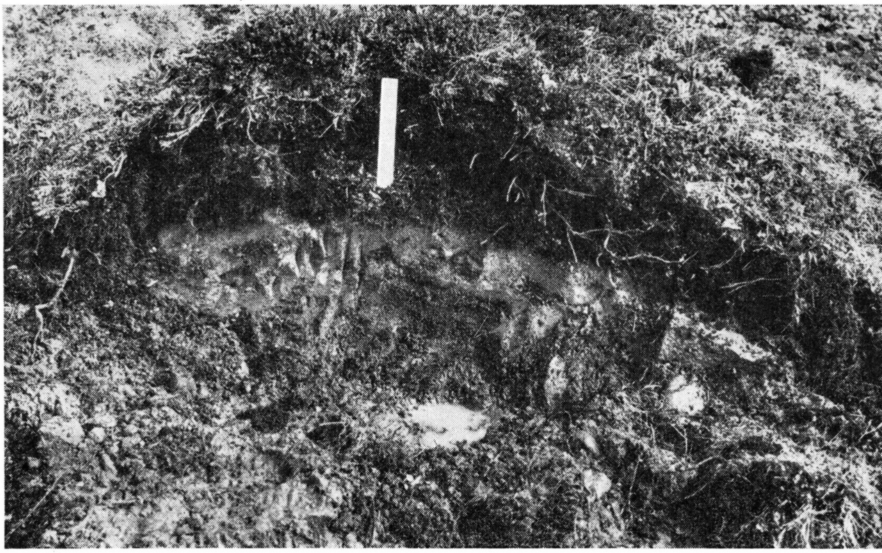
The core of mineral soil was composed of a pale brownish-gray loam that was increasingly sandy with depth, and merged with gravel at the bottom of the excavation. The upper horizons, in the loam, were still frozen when the digging was done on July 15, 1960, but the lower sandy and gravelly horizons were thawing. There were occasional lemming burrows in and around the core.

This hummock differed notably from those shown in Figures 2 and 3 in not having a well-defined layer of greasy, "amorphous" humus at the base of the thick turf layer. Nor was there a noticeable yellowish stain in the upper part of the loam immediately beneath the turf.

The vascular flora formed a dense cover over nearly the whole surface of the hummock. The primary species in the cover were *Vaccinium uliginosum* and *Salix arctica*. Secondary species observed at this early date, before the summer flora had scarcely more than started to develop, were *Luzula confusa*, *Carex Bigelowii*, and *Silene acaulis*.

The hummock illustrated in Figure 5, though smaller than that shown in Figure 4, was similar to it in general topography and orientation. Its top was only about 15 cm above the general level, and the hummock was only about 60 cm in diameter along the line of excavation (approximately N–S). It had its steepest slope on the north side and was therefore somewhat asymmetrical, but its mat of living mosses retained about equal thickness on both sides.

This hummock did not have a well-defined core of mineral soil. It was underlain by grayish-brown rather sandy loam, greasy with included humic materials, and streaked brown and black horizontally. There were occasional pockets of light brown loam in it. The loam formed



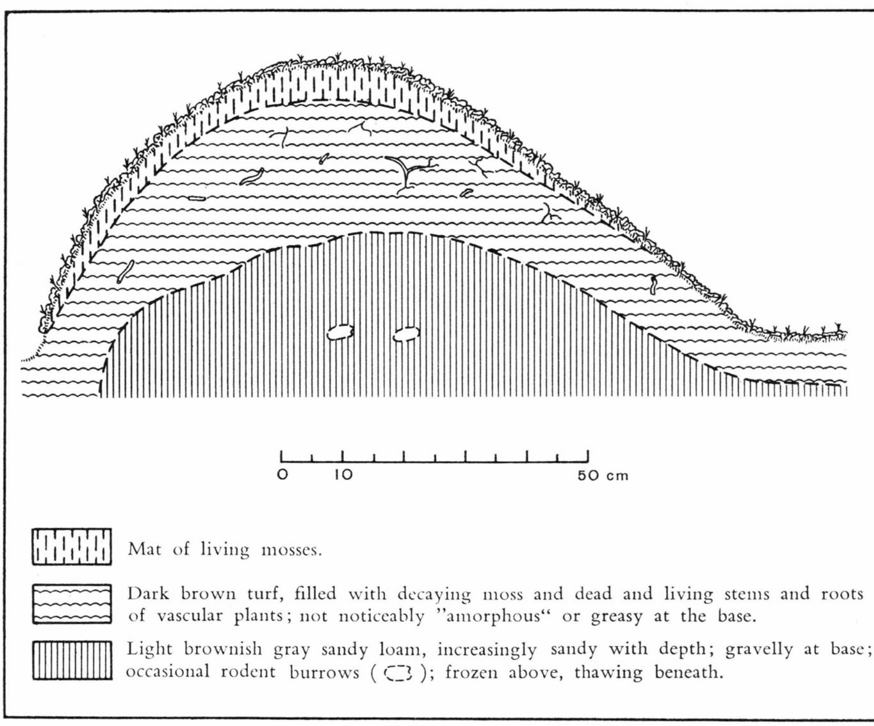


Fig. 4. Turf hummock dissected in area D, above target line of experimental site 6.

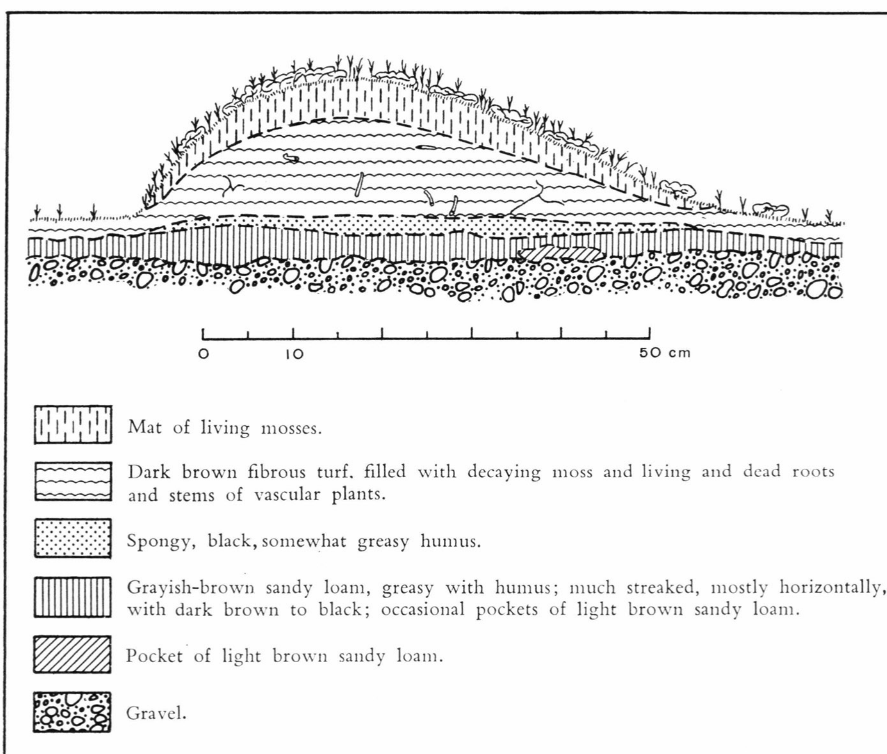


Fig. 5. Turf hummock dissected in area D, above target line of experimental site 6.

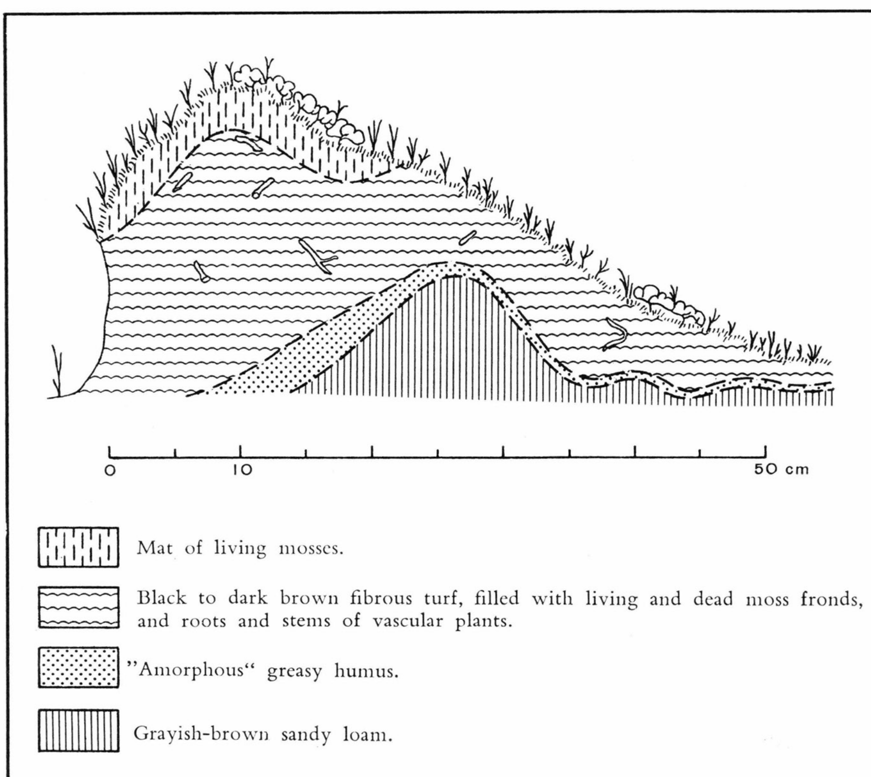


Fig. 6. Turf hummock along small stream in delta remnants at approx. alt. 110 m, 1 km west of Tunnelelv.

a layer 2–5 cm thick that appeared to be continuous. Beneath it was gravel. The turf of the hummock was, of course, increasingly decayed with depth; and just above the loam it merged into a layer of spongy, black, somewhat greasy humus, apparently the counterpart of similar horizons seen in Figures 2 and 3.

The cover of vascular plants was a dense one, in which *Vaccinium uliginosum* and *Carex Bigelowii* were the most prominent species. *Cassiope tetragona* and *Dryas octopetala* were present but less abundant. Areas immediately bordering the hummock were covered with a thin tundra of mosses and lichens (*Cladonia* sp., *Cetraria* sp.), with occasional plants of *Luzula* sp.

Several other hummocks resting on the gravel, some of them larger than the one described here, were excavated and also found to contain no earth cores. In a few of the larger ones there appeared to be a slight upward bulging of the gravel immediately beneath them, and in this gravel there was considerable clear ice at the time of excavation. The bulging may have been due to this ice, and if so it probably was seasonal.

Several turf hummocks were investigated in a wet meadow area along a small drainage channel (Fig. 14) among the delta remnants about 1 km west of Tunnelelv and near the base of the northeast slope of Hesteskoen. This area is approximately at the 110-m level. Excavations were made on July 14, 1960, but only two of the hummocks were described in detail (Figs. 6 + 7). In both of them the orientation of the excavations was roughly N–S.

Figure 6 shows a small hummock about 20 cm high and 50 cm wide. It was asymmetrical, with the north side apparently eroded away to form a nearly vertical face about 10 cm high. The thick part of the living moss mat was on the top of the hummock, and appeared to extend farthest down on the north side.

A core of mineral soil projected upward into the hummock, but well to the south of the center of its mass. The core was of grayish-brown loam. The dark brown to black turf above it graded downward into a layer of black, greasy humus which was thickest under the northerly, thickest mass of turf.

The vascular flora formed a dense cover in which the primary species were *Vaccinium uliginosum* and *Carex Bigelowii.*

A more complex structure was found in the hummock illustrated in Figure 7. The usual mat of living moss was present over the whole surface, but was thickest on the upper parts (3–4 cm). The hummock as a whole was more or less round in outline, about 60 cm in basal diameter on the N–S axis, and about 20 cm high. Its steepest side, however, was on the south, so that its asymmetry was the reverse of that exhibited by the nearby hummock shown in Figure 6. The center

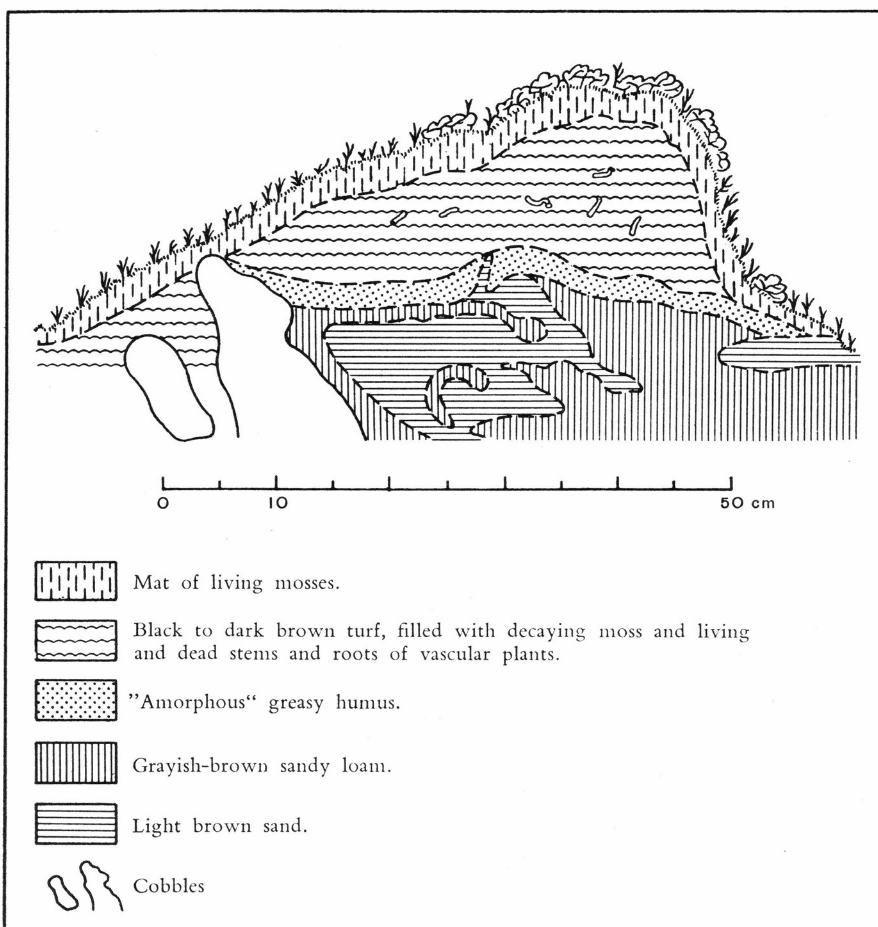


Fig. 7. Turf hummock along small stream in delta remnants at approx. alt. 110 m, 1 km west of Tunnelelv.

of mass in the dark brown to black turf was also on the south side. At the base of the turf, and overlying the mineral soil, was a relatively thick layer of blackened greasy humus (2–3 cm).

Beneath the north side of the hummock, near its base, were two granite cobbles, neither of which appeared at the surface or seemed to have any effect upon the surface configuration of the hummock. Adjacent to these cobbles on the south, and extending under the remainder of the hummock was a grayish-brown sandy loam which projected upward only slightly under the hummock. It reached its highest point not under the center of mass of the turf, but 8–10 cm to the north of this point, under the north slope. Included in the loam were irregular masses of light brown sand. The general outlines of these can be seen in the photograph (Fig. 7), and the principal ones are shown in the accompanying sketch. The section also shows a small projection of the sand into the greasy humus beneath the turf. It is notable that the included sand was at the highest level of the mineral horizon.

Primary species in the vascular flora of the hummock were *Vaccinium uliginosum*, *Cassiope tetragona*, and *Carex Bigelowii*. A rather common secondary species was *Poa arctica*. The vascular flora formed a dense cover of vegetation over the entire surface of the moss.

A dissection was made of a larger, broadly domed turf hummock situated in a shallow valley among trap knobs in the Nyhavn hills on July 28, 1957. This hummock was at the base of a steep rock slope adjacent to experimental site 16, in the vicinity of Map Summit 112 m. Figure 8 shows two sections approximately at right angles to each other, one on the longest axis of the hummock (SE–NW; approximately 150 cm) and the other on the shortest (SW–NE; approximately 100 cm). The top of the hummock was only about 20 cm above the general level. It was selected because it contained a pair of caribou antlers, and because most of the turf of the hummock lay *over* the antlers. This gave a minimum time span for the accumulation for most of the turf, since it was known that the caribou had disappeared from this part of Greenland about 60 years previously.

This was the first hummock dissected in the course of the Greenland field work, and only its general structure is shown in Figure 8. No distinction among organic horizons was made, though a layer of living mosses formed the surface mat over the whole. These graded downward into the dark brown to black, root- and stem-filled turf that overlay the mineral horizon. The latter was made of sandy silt, and was still frozen nearly to the surface at the time of digging. The mineral soil beneath the central part of the hummock bulged upward approximately 15 cm above the general level of the surrounding surface. At the northeasterly base of the hummock the sandy silt was largely re-

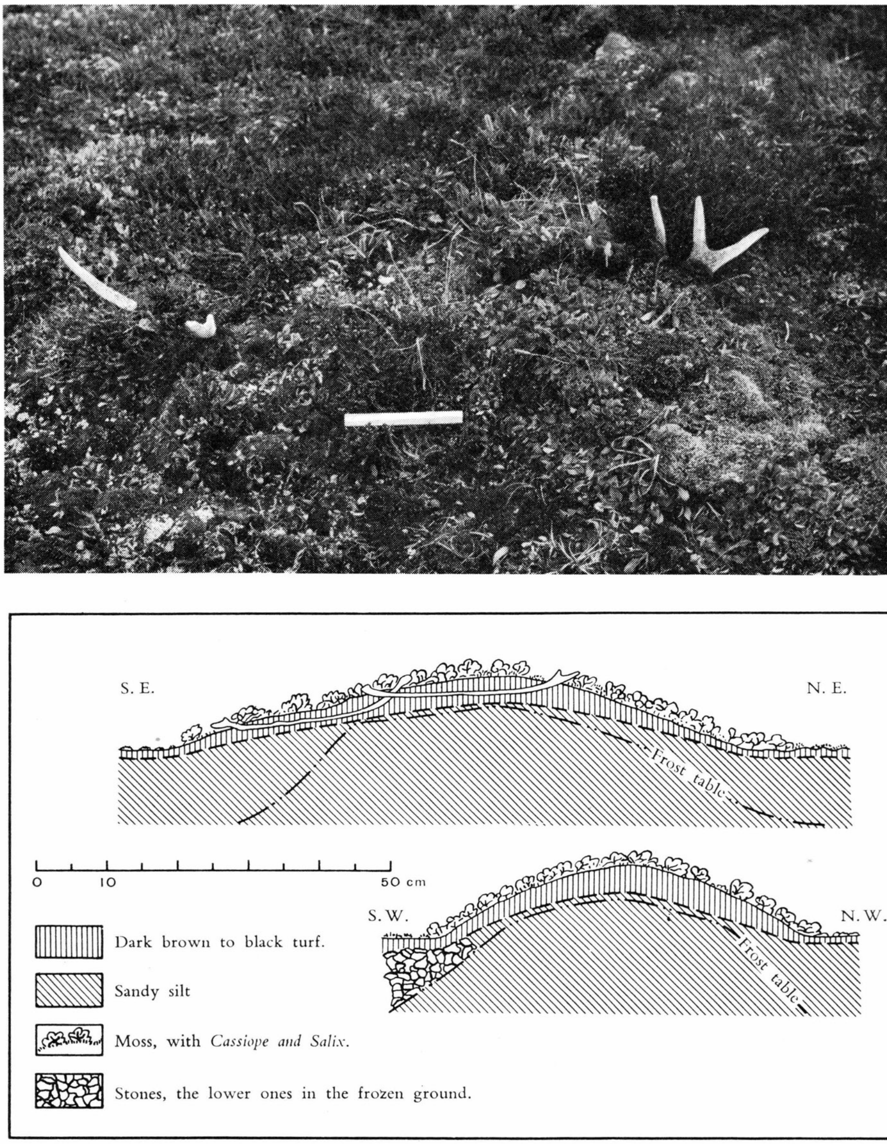


Fig. 8. Turf hummock containing caribou antlers, vicinity of experimental site 16, Nyhavn hills.

placed by a mass of pebbles and small cobbles. The frost table was highest under the center of the hummock, where it was scarcely more than 10 cm beneath the surface of the living moss. Under the side slopes, however, especially under the southerly ones, it dropped rapidly to much greater depths. At the south–east margin it was 40 cm below the top surface of the hummock.

The surface of the hummock was only partially covered by vascular plants, and there were considerable areas of exposed living moss in dense mats. Primary species among the vascular plants were *Cassiope tetragona* and *Salix arctica*. Common secondary species were *Trisetum spicatum*, *Polygonum viviparum*, and the lichens *Cetraria islandica*, *Cladonia pyxidata* and *Peltigera* sp. Occasional species listed were *Draba alpina*, *Stellaria Edwardsii* and *Cladonia* sp. The lichen *Stereocaulon* was common around the base of the hummock. Immediately about the base the above vegetation was greatly reduced, and the surface was covered for the most part by dead moss and small mats of *Cassiope tetragona* in which there was high mortality.

The turf hummock shown in Figure 9 was located in the map area of experimental sites 7 and 8, in the Nyhavn hills. It is situated on an 11° slope about 20 m below the vicinity of targets 33–35 of site. 7. It was in the vegetation described as "hummock meadow in which the hummocks are prominent features, but in which the intervening black organic crusts have sedges growing on the them." The dissection was made on July 29, 1958.

The hummocks on this slope are highly irregular in shape and size, and many are connected to form a discontinuously reticulate system. It is possible that Figure 9 shows a main hummock and part of another at the right. The excavation was oriented approximately N–S, and the hummock was about 150 cm in diameter on this axis. Its top reached a height of about 10 cm above the general level. The different organic horizons were not described in detail, but a mat of living moss formed the surface material. The main mass of the hummock was of dark brown to black fibrous turf, full of living and dead roots and rhizomes. This turf formed a continuous layer over the mineral horizons, but had its greatest thickness under the central part of the main mass of the hummock.

The principal mineral soil beneath the turf, extending to the bottom of the excavation, was a grayish-brown loam which was rather sandy and had many pebbles and cobbles in it. The water table was within about 10 cm of the top of this at the time the digging was done. Immediately beneath the turf of the hummock, and overlying the grayish-brown loam, was a dark grayish-brown, more silty loam with enough humic material in it to make it greasy. This silty loam showed a low ridge or knoll under the north slope of the hummock, and also an extension at an angle downslope so that it appeared to be partially interbedded with the sandier loam beneath. A lens of the darker silty loam some 40 cm wide on the axis of the excavation was entirely enclosed in the sandy loam at about 35 cm below the top of the hummock. The dark-colored silty loam thickened notably under the southern margin

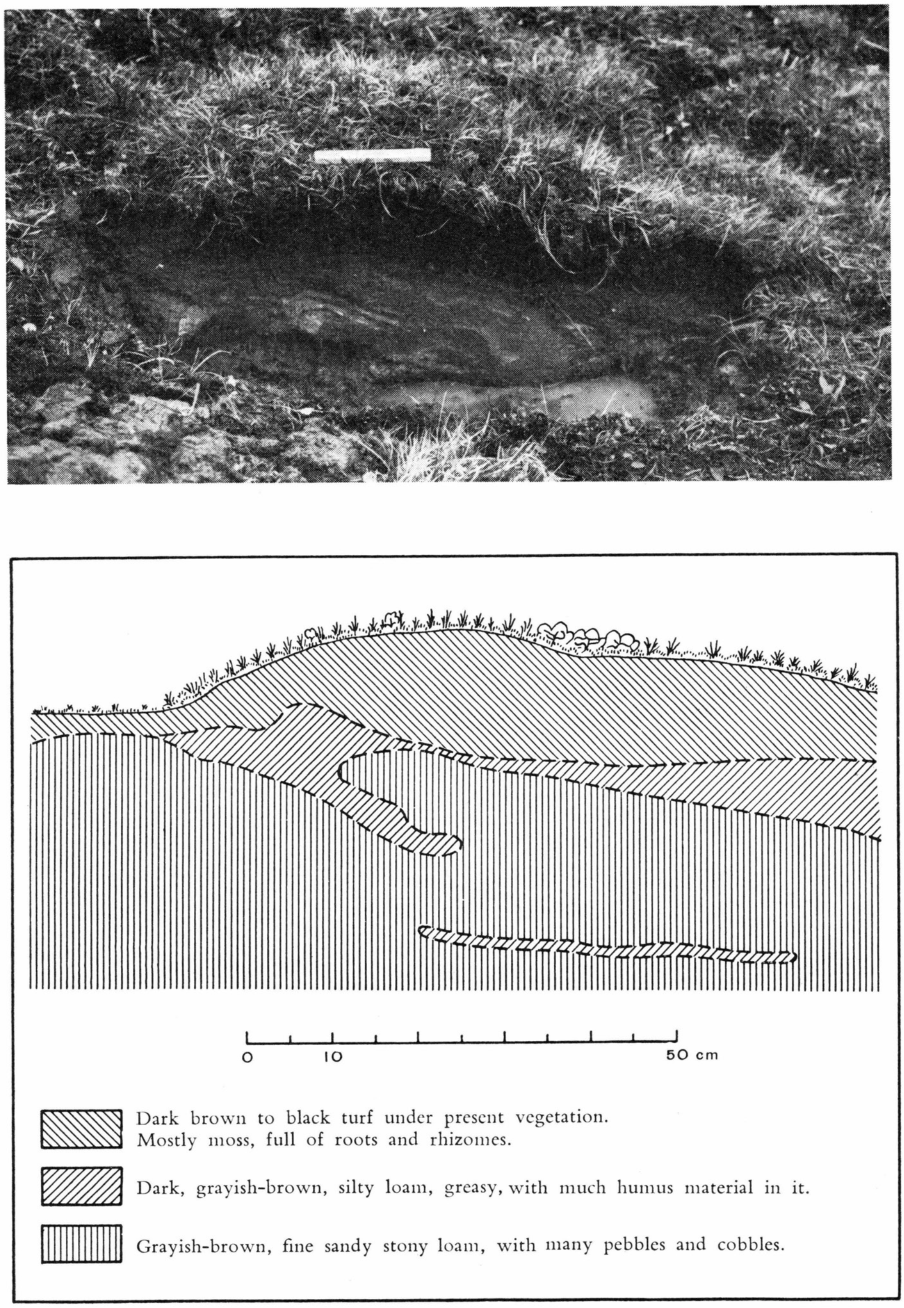


Fig. 9. Turf hummock on slope between target lines of experimental sites 7 and 8, Nyhavn hills.

of the hummock, but no attempt was made to relate it to other hummocks in that direction.

The mineral soil horizon under this hummock showed a total variation in relief of approximately 5 cm. Its upper surface was above its general level by only 3 or 4 cm, with the highest portion a small bulge under the north slope of the hummock. Under the thickest mass of turf there was a broad, shallow depression in the surface of the mineral soil.

The vascular plant cover on the hummock was nearly complete. The primary species were *Carex Bigelowii*, *Vaccinium uliginosum*, and *Salix arctica*. Secondary species were *Dryas octopetala*, *Pedicularis flammea*, and *Polygonum viviparum*. Most of the roots of these planats are in the turf or in the dark grayish-brown silty loam. A few were seen to depths of 3–5 cm in the sandy loam.

At the base of the southeasterly slope of a sandstone and trap ridge on the Labben peninsula noted as Map Summit 83 m is a wet meadow area containing a variety of turf hummocks. The soils show a mixture of sandy areas with fragmented angular sandstone pebbles and cobbles that are sometimes arranged in stripes or poorly formed nets. Intermingled with the sandy areas are nonsorted circles of stony silt, some of them wet and some dry and cracked on the surface. Water is supplied from snowdrifts and thawing ground in the hill area to the northwest. The meadow is in the vicinity of experimental sites 2, 3 and 9.

Several hummocks, large and small, were excavated here on July 19, 1960 but only one was described in detail (Fig. 10). It was round in outline, approximately 60 cm in diameter at the base and about 30 cm high. The excavation was oriented roughly N–S. It will be seen from the photograph that the hummock was composed almost entirely of dark brown to black fibrous turf, with a living mat of mosses over nearly all of its upper surface. The turf was underlain first by a greasy, sandy-silty humic horizon that was only 1–2 cm thick under the north side of the hummock, but upwards of 12 cm under the south side. The upper surface of the humic horizon sloped upward, so that near the southerly base of the hummock it was only about 5 cm below the surface at one point. Under the main mass of the turf it varied from 2 to 4 or 5 cm in thickness, but reached its greatest thickness where the turf was thin. Beneath the humic horizon was a light gray pebbly silt which dipped downward under the southerly side of the hummock.

The hummock was well covered with vascular plants, among which *Salix arctica*, *Cassiope tetragona* and *Carex Bigelowii* were primary species. The prominent root and stem system of a plant of *Salix arctica* can be seen in the photograph (Fig. 10). It twined through the turf, and the root disappeared in the mineral soil below.

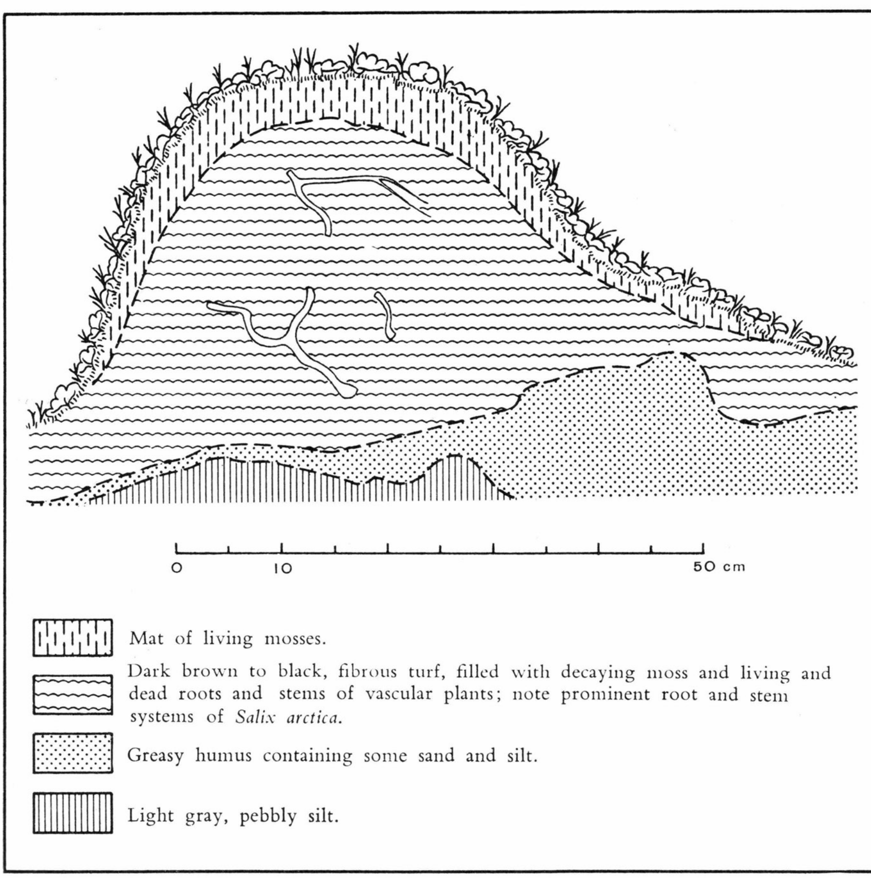


Fig. 10. Turf hummock in wet meadow area at base of sandstone and trap ridge just north of experimental sites 2, 3 and 9, Labben peninsula.

Two turf hummocks were dissected in the drainage system that lies north of experimental site 5. This is on a long gentle slope the northerly part of which is kept moist throughout the summer season by perennial snowdrifts and thawing ground in the hills involving Map Summits 65 m and 83 m. Figure 11 shows the uppermost of these hummocks, which was located in a hummocky meadow, in the uppermost part of zone C of the transect shown in Figure 20. Figure 19 gives the general appearance of the area.

This hummock was more or less round in outline, about 70 cm in diameter on the axis of excavation (N–S), and about 25 cm high. The mat of living moss on its surface was continuous and quite thick except on the lower north slope. It reached a thickness of more than 5 cm on the top. The hummock rested upon coarse gravel, which appeared to be general under the meadow, judging by several similar excavations made in the vicinity. Standing upright from the surface of the gravel, a little to the north of the center of the hummock, was an angular cobble about 13 cm long. There was a barely perceptible upward bulge in the surface of the gravel under the hummock. Between the gravel and the fibrous turf, and merging into the latter, was a greasy humic horizon containing some sand and silt. This reached a thickness of about 10 cm in the vicinity of the large cobble, but thinned out on either side of it, rapidly to the northward and more gradually southward.

The surface of the hummock was fairly well covered by vascular plants, though a few patches of moss were evident. Primary species were *Carex Bigelowii* and *Carex scirpoidea*, while prominent secondary species were *Vaccinium uliginosum* and *Salix arctica*. The predominance of the sedges over the woody plants was notable.

The second hummock dissected in the area north of experimental site 5 was located in the lower, drier part of the drainage system where the soils become dry at the surface in the latter part of the summer. This is in the lower part of zone C of the transect shown in Figure 20, in which the hummocks are reduced in size and widely separated from each other by expanses of barren or nearly barren mineral soil.

This hummock, illustrated by the photograph and sketch in Figure 12, was a mound of moss about 10 cm high and 40 cm in average diameter at the base. It was asymmetrical in form, with a steep slope to the north and a more gradual slope to the south. The only vascular plant growing on it was a single *Salix arctica*, but this plant was obviously thriving. The moss beneath it was moist but by no means wet, and it was dying around the lower margins of the hummock. The hummock was dissected not so much to determine its internal structure as to study the anatomy of the willow growing on it.

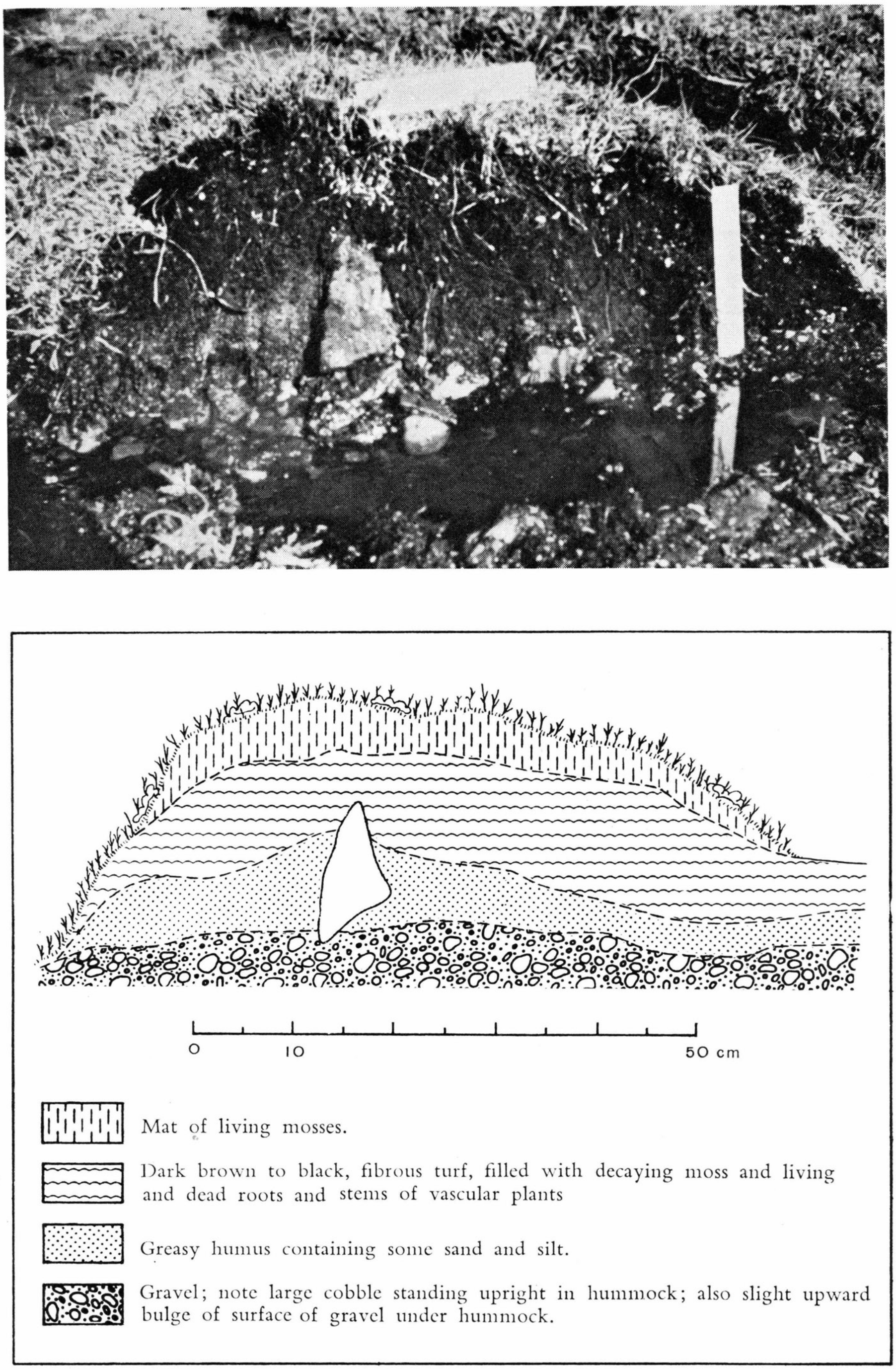


Fig. 11. Turf hummock in wet meadow area below snowdrift north of experimental site 5 (in upper part of zone C of transect in Fig. 19).

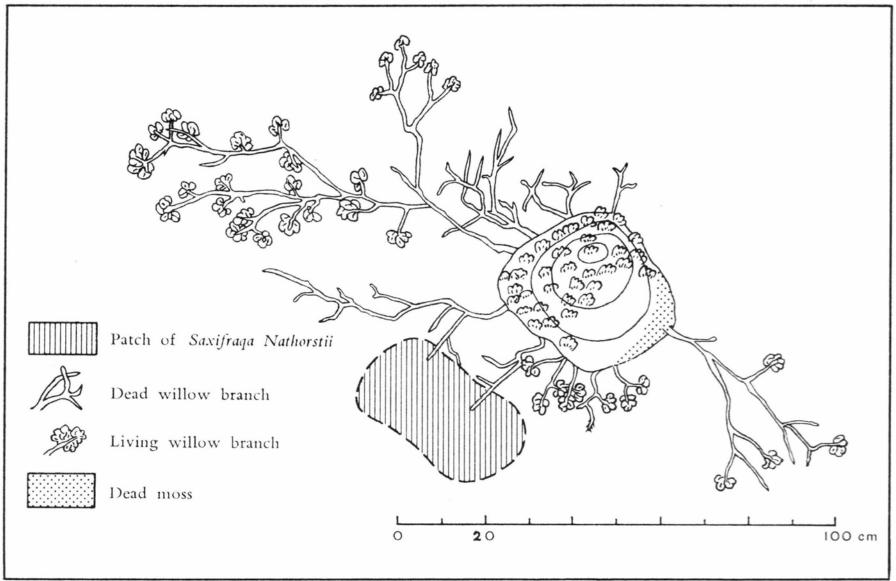


Fig. 12. Turf hummock dissected to show structure of stem and root systems of the willow, *Salix arctica* (see Fig. 29).

The mineral soil here is a stony and sandy silt, which is washed for a short time each spring by meltwater that flows in sheets or broad, shallow channels over the slope. There was no conspicuous upward bulging of the surface of the silt beneath the hummock, though there may have been a slight one that was not detected. No vertical section was cut which would have exposed a bulge more clearly. The base of the willow stem system was in the living moss mat in the upper surface of the hummock. From this point the stem system was greatly ramified, with main branches arching downward through the moss and turf to the surface of the mineral soil at the borders of the hummock, thence trailing outward in various directions for as much as a meter beyond the base. The stem system within the turf was an intricate tangle, though the main root was rather simple. It was about 1 cm in diameter, had a few bends in it, and one nearly right angle, but it ran fairly directly into stony silt beneath the higher part of the hummock. The base of the stem was sectioned for a ring-count, and found to be about 80 years old. Figure 30 shows the willow with the mass of its stem system turned over to expose the main root.

The major kinds of hummocks noted in the preceding pages have all been described at one time or another by earlier students. Those with well-defined earth cores that are composed almost entirely of fine-textured materials and are more or less central under the turf masses (Figs. 2, 4, 8) closely resemble those that have been described repeatedly in Iceland and are known there at the "thufur" type (Jónsson, 1909; Thoroddsen, 1913, 1914; Thorarinsson, 1951). They are similar in structure to the "Heath" microrelief described by Griggs (1936) in the Katmai district of Alaska, and to the "earth hummocks" of Sharp (1942) in southwestern Yukon. Billings and Mooney (1959) described hummocks of similar nature in the alpine tundra of the Rocky Mountains in southern Wyoming. Troll's studies (1944) indicated that the type is widespread in the subpolar and alpine lands of the world.

Fewer descriptions are found for hummocks without earth cores (Figs. 6, 12). The "Moorhügeln" of Beskow (1930) are a case in point, though it is presumed that these occurred on a substratum of peat. Troll (1944) noted isolated hummocks composed entirely of *Sphagnum* in the Vosges Mountains. Hanson's observations on hummocks in Alaska (1950) indicated that he found them without cores when developed over sands and gravels. Billings and Mooney (1959) described hummocks both with and without earth cores in the area they studied in Wyoming.

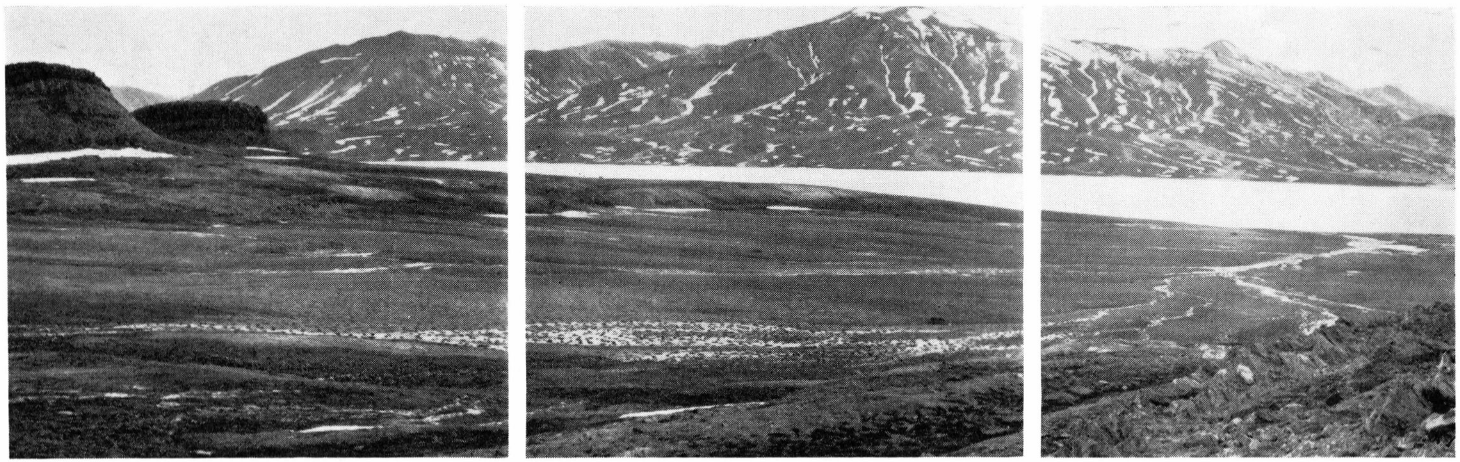


Fig. 13. Landscape on Labben peninsula, showing abundance of turf hummocks. View south and southwest, across Noret to Korsbjerg and Blyryggen.

OBSERVATIONS ON THE ORIGIN AND DEVELOPMENT OF TURF HUMMOCKS

The initial stages of hummock growth.

Turf hummocks occur in such abundance in the Mesters Vig district, and in such a variety of forms and sizes, that one is constrained to attempt a classification of them. This leads inevitably to problems relating to their origin and their evolutionary changes. Some idea of their abundance and variety may be gained from Figure 13, which is a view southward from near Map Summit 80 m on the Labben peninsula, looking across the small bay called Noret, with Map Summits 120 m and 105 m at the left.

Judging by the dissections of the Mesters Vig hummocks, there is every evidence that all or nearly all of them began their development with moss. It is equally obvious that such a development has required abundant surface water throughout the growing season over whatever period of years it has taken to grow the hummocks to their present size. A further condition has been that the water be relatively slow-flowing and spread widely over the slopes. If it were confined to narrow channels and subject to rapid flow in flood seasons it would remove the mosses before they could grow into large accumulations.

These conditions are met to some extent on the lower slopes of the mountains and in the broader drainage basins among the delta remnants at the base of the mountains. However, in all of these areas the water is partially channeled, and the mosses are subject to a certain amount of erosion. Usually the resulting hummocks are relatively small, commonly impregnated with sand and silt, and highly asymmetric (Fig. 14). The necessary conditions are much better developed on the broad, gentle to moderate slopes at the north base of Hesteskoen and on the Nyhavn and Labben peninsulas up to altitudes of approximately 80 m. Here the meltwater from snow and thawing ground is widely dispersed, and finds only a few channels where the flow is rapid enough to interfere with the development of mosses (see Fig. 13).

Provided the conditions outlined above are met, the initial stage in the formation of a hummock is a growth of aquatic moss. As this moss proliferates and becomes thicker, its upper horizons become pro-

Fig. 14. Meadow and hummocks along small stream in delta remnants at approx. alt. 110 m, 1 km west of Tunnelelv, July 14, 1960.

gressively less wet, and less hygrophytic mosses invade it. Further, it forms a substratum for increasingly mesophytic vascular plants, the roots and stems of which develop in the moss mat. The mesophytic mosses then grow upward and outward, their lower parts dying off to form the turf and humic horizons of the hummocks in which the living and dead stems and roots of vascular plants are increasingly abundant.

Fundamental questions that arise regarding this process are whether hummocks so formed can and do start from isolated moss polsters and grow to large dimensions as separate entities, or whether they grow from more or less continuous moss mats and become isolated in later stages of their development. In the event that both kinds of development occur, which one will best account for most of the hummocks in the landscape? In either case, before the "hummock-form" can begin to develop there have to be some kind of small "eminences," or "micro-elevations" upon which the more mesophytic mosses can grow. These must rise above the uniformly saturated surfaces, whether the latter be in stream channels or in sheet flow areas.

Although much is to be found in the literature about the internal structure and surface vegetation of hummocks, only a few students have ventured opinions on the initial stages of their development. Those who have attempted to explain the growth of earth cores have been able to rationalize the latter to good advantage only after a cover of vegetation has appeared. And then it has been necessary to conceive of inequalities in the density or thickness of the vegetation to account for differential effects upon the substratum. THORODDSEN (1914) for example could find no evidence of permanent bulging of the surface without a cover of vegetation. BESKOW (1930) seems to have realized the difficulty of getting the hummocks and their earth cores started, and suggested ways in which irregularities in the surfaces of the mineral soil or the vegetation might be produced.

The problem of initial microrelief.

The investigation of the Mesters Vig turf hummocks began with the assumption that they were of the "thufur" type, with earth cores formed primarily by differential frost heaving. Reference to the descriptions of the dissected hummocks will show that five of them had well-defined upward bulges of the mineral soil immediately beneath them, while two had none and four had very poorly defined ones. In three of the five cases where bulges were present there was reasonably good correspondence between the form of the earth core and the form of the hummock (Figs. 2, 4, 8), while in the other two (Figs. 3, 6) there was notable asymmetry.

It was at once clear that in the Mesters Vig landscape the hummocks can and do develop without earth cores, and a great many more were dissected not only to determine whether or not they had earth cores, but also what their substrates were and how the hummocks might have formed over them. Coincident studies of the local distribution of turf hummocks, and of the nature of their development from early stages to maturity, emphasized the significance of the initial microrelief upon which they began their growth.

All of these studies led to the conclusion that the hummocks, although they all began with mosses in saturated sites, were in reality of multiple origin because of the various ways in which their essential growing conditions could be produced. Further, it became obvious that the origin of their earth cores, if the latter were present, was in some cases closely related to the origin of the initial microrelief upon which they started their growth.

Observations on the distribution of the different kinds of hummocks supported these conclusions. Other excavations in the immediate neighborhoods of those dissected and described in detail showed that the hummocks in any one area tended to be similar with regard to substrata and to the presence or absence of earth cores; and if the latter were present, with regard to their form. In the vicinity of the one shown Figure 2 there were several more with closely similar earth cores; and this was likewise true in the case of the vicinity of the hummock shown

Fig. 15. Turf hummock developed over large stone in stream channel; delta remnants about 1 km west of Tunnelelv, alt. approx. 110 m, August 1, 1957.

in Figure 3. On the stony substratum about 200 m north of the target line of experimental site 6, where the hummock in Figure 5 was excavated, there were several more that revealed the same structure. In a wet hummocky meadow in the Nyhavn hills a short distance north of experimental site 15, where the hummocks and the terrain generally closely resembled that in the vicinity of the excavations in Figures 2 and 3, the interior of the hummocks and their earth cores also resembled the ones in Figs. 2 and 3.

Most of the hummocks that were studied were found to contain more or less sand and silt throughout their living moss, turf and humus horizons. Some of this was probably blown into them by wind, but more came from meltwater as sheet runoff brought materials from higher on the slopes. Where hummocks occur along streams, or scattered about braided channel systems on the slopes and mountainsides, they commonly become thoroughly impregnated with sand and silt. These hummocks apparently start on small deposits of sand or silt in eddies. The first small mats of aquatic mosses enlarge and become filled with more mineral material to form the cores of hummocks that gradually grow to large size. Excavations of impregnated hummocks along the small stream that flows through experimental site 6, in the channel system at the 110-m level in the delta remnants, and on the lower north slopes of Hesteskoen illustrated both the initial impregnation and further development of such hummocks. It is probable that the eccentric sandy

Fig. 16. Small hummocks developed on moss polsters in snowbed (zone A of transect shown in Fig. 19), July 15, 1957.

core of the hummock shown in Figure 6 originated in this way, and possibly also the more complex structure of the sand and loam base of the hummock in Figure 7. The core of the hummock shown in Figure 4 was of sandy loam, increasingly sandy with depth. This hummock was in the neighborhood of that shown in Figure 5 which had no core, and both were in the shallow channel system that marks the eastern part of experimental site 6.

It was thought for a time that in stony soils the hummocks might have formed around nuclei of large cobbles or small boulders, and that this may have been illustrated by the one sectioned in Figure 11. Others were found that were somewhat similar to this, but many were turned over that showed only stones of pebble size under them, like that shown in Figure 5, even where larger stones were present in the material of the area. Mossy hummocks do form over cobbles and boulders in stream channels, but these are rather easily identified as such (Fig. 15). Among many hummocks dissected in a study area in the 110-m delta remnants west of Tunnelelv, only about one in ten was found to have a central stone over and around which it might have formed. Careful search was made in all sites of this nature for evidence of incipient hummocks. In the upper reaches of the stony channels among the delta remnants, and on mountain slopes where water appeared from thawing ground or snowdrifts, moss polsters could be found among the stones; but only occasional polsters appeared to be forming small hummocks.

Fig. 17. Turf hummock ridges; vicinity of experimental site 6. Nyhavn hills, July 15, 1960.

A few species of mosses form more or less hemispheric polsters in snow-bed environments. Figure 16 illustrates this, in the drainage area of a large snowdrift north of experimental site 5. Similar situations are to be seen in the latter part of the summer below many drifts. The surface of the ground is continuously wet throughout the thaw season, the water flowing slowly or standing in small pools. The polsters are more or less isolated from each other and occasionally grow into the small hummocks seen in Figure 16. The areal extent of sites like this is relatively small, and in terms of the total area of land covered by turf hummocks it is insignificant.

The upfreezing of stones from fines is a common process in the Mesters Vig tundra in the finer-textured soils such as the silts and silty sands. Before a stone appears at the surface it can dome the surface locally, and the dome might thus form the basis for the growth of a hummock. Probably the latter would, by its presence, further the process. A diligent search for possible cases of this sort was carried on, and a few were found. But there were not enough of them to make this explanation of the origin of initial microrelief or of earth cores generally applicable.

It has already been noted that some hummocks show local patterns of arrangement. They are, in places, connected with each other to form ridges, and occasionally the ridges are set in arcuate patterns. Figure 17 illustrates this in the area D shown on the photograph in Figure 1, north of the target line of experimental site 6. These arrangements suggest that the position of some hummocks, and possibly also the presence or absence of earth cores, are partially controlled by mass-wasting processes. The surface configuration of the mineral soil in Figure 3 shows a "steplike" structure, with an upward bulge on the front of the "tread," and a rather steep "riser" whose front is distinctly uneven. The bulged "tread" is the earth core of the hummock, although the thickest mass of turf is not over this, but over the neighboring *depression* in the mineral horizon downslope from the "riser." Within the "earth core" itself a brown loam, which immediately underlies the humic horizons, is stratigraphically both above and below a pale brown loam that appears to intrude into the "step" from the upslope side. This structure bears a striking resemblance to that found on the fronts of small gelifluction lobes that are now forming, or have very recently formed, in the thinly vegetated stony loam of the Mesters Vig district. Such lobes are of common occurrence in the district. Experimental site 15 was established on an active one in the summer of 1957 and its movement was observed each year through 1961. Others were seen in the meadow at the base of the hill just northwest of sites 2, 3 and 9, and on the gently rounded slopes of the hill above and to the north of experimental site 15. The wet meadow system in the latter place is watered by large perennial snowdrifts on the steep easterly slopes of the trap knob, Map Summit 112 m. A large proportion of the hummocks in this meadow were developed on the fronts of small gelifluction lobes similar to those found on the adjacent surfaces but not covered by meadow.

It is probable also that the mineral horizons shown in Figures 9 and 10 of the present paper acquired their surface forms and general profile structures primarily by gelifluction processes.

From the observations at Mesters Vig it seems clear that at least a portion of the earth cores predated the development of the turf hummocks over them. Once the hummocks had grown to considerable size over whatever minor elevations occurred in the substratum, whatever the origin of this microrelief, it is probable that frost action would tend to accentuate the cores.

The relation of turf hummocks to mass wasting has been noted several times in the literature. Hansen, in 1930, attempted to describe its effects upon the structure of hummocks on Icelandic hillsides, and Sharp (1942) described the same phenomena in southwestern Yukon. The way in which hummocks grade into mass-wasting microrelief in the Alps has been described by Sölch (1922), Stiny (1931), Stäger (1913), and Gams (1941). Hanson's notes (1950) on a hummock formed on the front of a small gelifluction lobe in Mt. McKinley Park, Alaska, appear applicable in the Mesters Vig area.

Hummocks that have developed around large stones in stream channels with or without the accumulation of sand and silt, or those whose mineral cores may have been initiated or emphasized by the ejection of a boulder or cobble from surrounding fines, have been previously described scantily or not at all. It is possible that some of those noted by REMPP and ROTHE (1934, 1935) and by ISSLER (1942) in the Vosges would be in one or another of these categories.

Certain characteristics of hummocks, the origins of which have been discussed thus far, should be emphasized. They are usually rather widely and irregularly spaced, or if they are more closely spaced they are more likely to be arranged in ridges or arcuate patterns than in reticulate systems. The wide spacing is evident among small, newly developed hummocks as well as among older ones. Earth cores are commonly lacking in these hummocks; but if present they may be of sandy or silty materials. If made of the finer materials the cores are likely to be highly asymmetric with respect to the main mass of hummock turf, and may be small gelifluction microrelief features that predate, at least in embryo, the development of the hummocks. There is a general coincidence between the nature of the substratum and the presence or absence of the earth cores. The most pronounced cores are made of fine-textured silty materials, while hummocks with poorly defined cores or none are on more gravelly materials. Exceptions to this, where found, usually can be accounted for in terms of the variations in hummock origin that have already been described.

The modes of origin for turf hummocks discussed thus far, though they account for a great many, do not account for most of those that occur in the Mesters Vig district. A large residual group, yet to be dealt with, covers wide areas in which the hummocks, both newly developed and maturing, are densely aggregated in reticulate patterns. They include those that most closely resemble the "thufur" of Iceland, with their frost-induced cores of fine-textured mineral soil. These hummocks appear to have developed in a manner quite different from those described above. They are most abundant on ground surfaces where no physical microrelief is available to give raised starting points for initial hummock growth. They overlie sandy soils or fine-textured silt loams, and over the latter they commonly have bulged-up cores beneath them without admixtures of sand that could have been washed in by streams or sheet flow. These cores bear no relation to recognizable mass-wasting features. This large group of hummocks will be treated in the following section.

Fig. 18. Scene of transect shown in Fig. 19; Labben peninsula north of experimental site 5.

Transect of a wet-meadow–turf hummock system.

Hummocks form in large numbers and in dense aggregations in a context entirely different from those just described. This is in wet meadows, which occur in areas of sheet runoff downslope from snowdrifts and thawing ground. Examples of it are numerous in the Mesters Vig district, and were illstrated by several transects made during the course of the field work. Figure 19 is a schematic diagram of a transect running

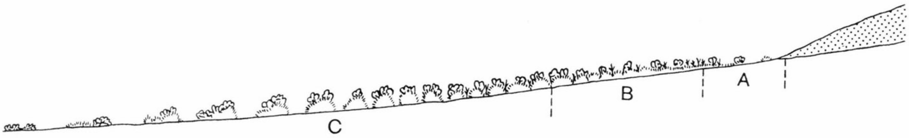


Fig. 19. Transect of vegetation on slope below snowdrift shown at right in Fig. 18.

approximately north-south through a snowdrift and the meadow-hummock area below it. This transect was taken at the base of the hills immediately north of experimental site 5, and because it is typical of many others it will be described in some detail. Figure 18 shows the scene of the transect.

The snowdrift and area of thawing ground that supply water to the slope are below the sandstone and trap ridge of which Map Summits 65 m and 83 m are the highest points. The drift shown in the transect

Fig. 20. Moss-sedge meadow with incipient hummocks (upper part of zone B, Fig. 19), August 1, 1957.

lies in the gap between these two summits, with its lower margin approximately at altitude 40 m. The lower portion of the transect is about 25 m above sea level, but the following discussion of the turf hummocks will extend the area downslope to somewhat lower altitudes. The slope is underlain by a pebbly-clayey marine silt which, toward the north, is mingled with sandy materials derived from sandstone of the hills in that direction. The silt is the principal surface material on the lower parts of the slope, where it is so wet as to be mire-like in spring and early summer. Its surface becomes dry, brittle, and very hard in mid- and late summer, though it retains some moisture at a depth of only 2–3 cm below the surface. The surface of the silt is formed into nonsorted polygons commonly 0.5 to 1.5 m in diameter, separated by deep cracks, and dome-shaped at their centers. These large polygons in turn are cracked into smaller ones 1–2 dm in diameter, each slightly domed and sometimes containing lesser cracks that are irregularly arranged. Near the base of the hills the sandy material appears to have been spread out over the silts, and the latter to have been pushed up through the sandy material by frost action to form irregular bare patches in the sandy area which is, itself, rather thinly vegetated. These bare patches have the same surface characteristics as does the silt farther downslope. Wherever pits have been dug to sufficient depth on the slope (approximately 1 m), or cave-ins have occurred to expose it, clear ice has been found in or beneath the silt.

Fig. 21. Small hummocks partially segregated by channeling of meltwater (lower part of zone B, Fig. 19), July 20, 1960.

Zone A of the transect, immediately below the snowdrift, is illustrated in Figure 16, already discussed in part. Surfaces nearest the melting snow are quite barren or have a thin cover of organic crust and living mosses, for not enough of the short growing season is left, after the snow has melted this far back, to allow vascular plants to become established and maintain themselves even by vegetative means. Only a little farther down slope, however, a few moss polsters can live, but no vascular plants. Still farther down, with a little more of the season available, *Salix arctica* is established on the larger polsters of moss, which now have the appearance of small turf hummocks. These hummocks are widely spaced, and though they have characteristic turf horizons within them, they do not have earth cores.

Zone A gives way rather gradually to Zone B, the upper part of which is a sedge-grass meadow growing in a nearly continuous mat of aquatic mosses. The substratum is essentially saturated, with water standing in shallow pools or flowing slowly through it. In a few places, notably toward the upper levels near Zone A, there is very little microrelief in the surface of the vegetation, and the grass-like plants form a sward: *Carex Bigelowii*, *Carex misandra*, *Luzula arctica*, *Luzula confusa*, *Arctagrostis latifolia*, *Poa glauca*, *Carex parallela*, *Juncus biglumis*, *Eriophorum triste*. More characteristic of the lower part of Zone B, where the moss mat has reached a thickness of 5–10 cm, is a slightly hummocky area in which the mosses form many convex mounds that rise

Fig. 22. Hummocks well formed, with channeling between them complete or nearly so (upper part of zone C, Fig. 19). The hummock shown in Fig. 12 was dissected in this zone, July 20, 1960.

a little above the general level (see Fig. 20). These mounds have more mesophytic mosses on them, and are the substratum for several species of vascular plants that are common on turf hummocks: *Salix arctica*, *Dryas octopetala*, *Vaccinium uliginosum*, *Polygonum viviparum*, *Cassiope tetragona*, *Saxifraga oppositifolia*, *Pedicularis hirsuta*. All of the grasses and sedges mentioned above also occur, though such species as *Eriophorum* and *Juncus biglumis* are mainly in the low areas between the mounds. The water is rather evenly spread through Zone B, but toward the lower part it begins to be more distinctly confined to channels among the mounds.

This mossy meadow below the snow-bed appears to be a crucial one in the genesis of the turf hummocks. Minor elevations in the mineral soil surface easily give rise to a few of the low mounds of moss, but there are not nearly enough of these elevations to account for all that develop. Where the vascular plants occur they become centers for the accumulation of humus, and thus raise a few low mounds. But other mounds seem to be due merely to irregularities in the growth rates of the aquatic mosses themselves.

In Zone C, progressively downslope, the hummocks gradually become better defined as separate units, and gradually become farther apart. The water becomes dispersed over a wider area, and when it flows abundantly during the most active thaw season in spring it is confined to channels between the hummocks. Later in the summer season

Fig. 23. Hummocks showing effects of summer desiccation and erosion. Interhummock areas dry in late summer (middle part of zone C, Fig. 19), July 13, 1960. Upslope is to the right.

these channels commonly are damp to dry because water from later snow melt does not reach this far down the slope. The hummocks toward the middle part of Zone C show the beginnings of degradation. They are more asymmetric than those farther up, with their upper sides steeper and apparently eroded by the spring flow of meltwater. This erosion is no doubt facilitated by weakening of the surface moss structure resulting from partial desiccation in the latter part of each season. By the same processes small hummocks or moss accumulations of low relief among the larger ones are entirely removed, so that the larger masses remain as isolated hummocks.

Aquatic mosses commonly found in seepage areas and running streams are *Drepanocladus vernicosus*, *Calliergon sarmentosum* and *C. stramineum*. Where small elevations rise above the general level of the water such species as the following appear: *Drepanocladus uncinatus*, *Dicranum angustum*, *Pogonatum alpinum*, *Oncophorus Wahlenbergii*, *Tritomaria quinquedentata*, *Catoscopium nigritum*, *Blepharostoma trichophyllum*, etc. As the hummocks grow, a few of these mosses remain about the wet bases, but others become more abundant to form the main masses. In the Mesters Vig district the most common moss in the hummocks appears to be *Tomenthypnum nitens*. With it are usually associated, mostly toward the lower parts of the hummocks, *Distichium capillaceum*, *Campylium stellatum*, *C. hispidulum*, *Bryum pseudotriquetrum*, *Pogonatum alpinum*, etc.

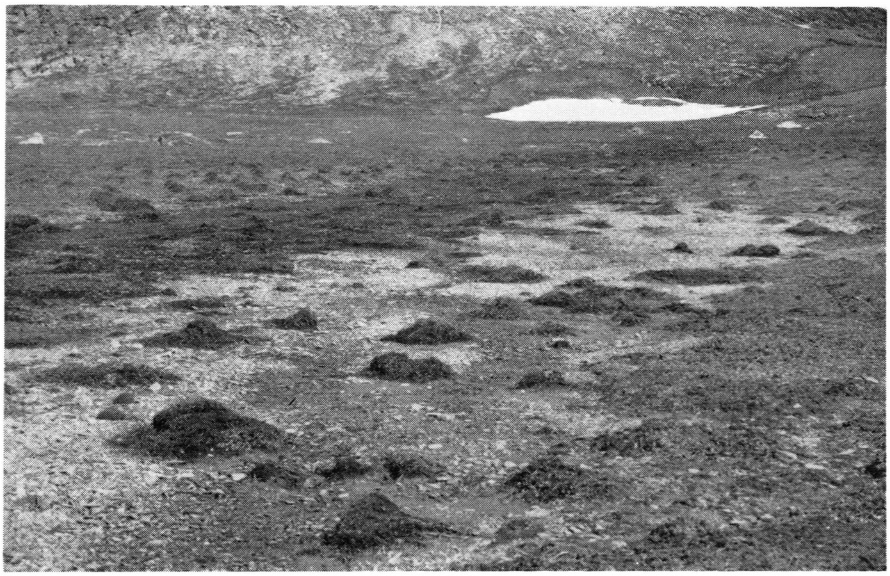


Fig. 24. Hummocks in later stages of deterioration (lower part of zone C, Fig. 19), August 3, 1958.

The vascular flora on the hummocks is much the same as in Zone B, except that the woody plants are relatively more prominent, commonly forming a dense cover of *Salix arctica* and *Vaccinium uliginosum*. This is variable, however, and many hummocks have a large admixture of *Carex Bigelowii* and *Carex misandra*. *Eriophorum triste* is abundant in the intervals between the hummocks, but nowhere does it make continuous cover.

In the lower part of Zone C the hummocks are obviously in process of disintegration (see Figs. 24, 25). Here they are often 1–3 m apart, separated by barren pebbly silt or sandy material, or by a thin tundra consisting of much-scattered vascular plants, mosses, liverworts, and lichens. Small shallow channels meander through the area carrying broad, braided streams during the thaw season, but drying out in mid-summer. The individual hummocks are in various states of degradation, apparently due to desiccation and erosion. The erosion seems to be due almost entirely to running water during the spring thaw season, for the eccentricity of the hummocks is consistently oriented to this process rather than to wind erosion. Each hummock is worn away on its upstream side. A dissection of one of them has been described (see Fig. 12).

A notable feature of the isolated, degrading hummocks is the reduction of their shrub flora to essentially a single species, *Salix arctica*. It is the only one of the shrubby species that has long roots penetrating the mineral soil beneath the hummocks. These roots extend, in some

Fig. 25. Deteriorating hummocks, some reduced to low piles of organic debris with living willows in them (lower part of zone C, Fig. 19).

cases, 2–3 meters out from the bases of the hummocks, usually within 10–15 cm of the surface of the ground, and sparingly branched. As a rule most of them extend upslope from their origins. Other species commonly found on these hummocks are: *Polygonum viviparum*, *Saxifraga oppositifolia*, *Carex misandra*, *Equisetum arvense*, *E. variegatum*, *Silene acaulis*, *Melandrium apetalum*. There are a few lichens, among which *Stereocaulon* sp. is most conspicuous. On the open ground between the hummocks the following species are scattered thinly: *Silene acaulis*, *Carex misandra*, *Polygonum viviparum*, *Salix arctica*, *Poa glauca*, *Saxifraga Nathorstii*, *Pedicularis hirsuta*, *Juncus biglumis*, *Oxyria digyna*, *Saxifraga oppositifolia*, *Saxifraga cernua*, *Draba alpina*, *Draba lactea*. Here and there are thin black organic crusts, and there is abundant evidence of high mortality among all the species.

The areas of degrading hummocks extend farthest downslope in the broad, shallow stream channels. In the lowest sites noted in Zone C of the schematic diagram, along these channels or lateral to them on the slightly higher bordering ground, the deterioration of the hummocks reaches a still more extreme stage. Here the turf and moss are reduced to low piles of organic rubble, or have disappeared altogether. In the latter case the only things left to mark the former presence of the hummocks are the willows that formerly grew on them. These willows usually are still alive (Figs. 26, 27), and often appear to be thriving. That they had, their origin in former hummocks is shown by the arrangement and form of their root and stem systems with relation to the surface of the ground.

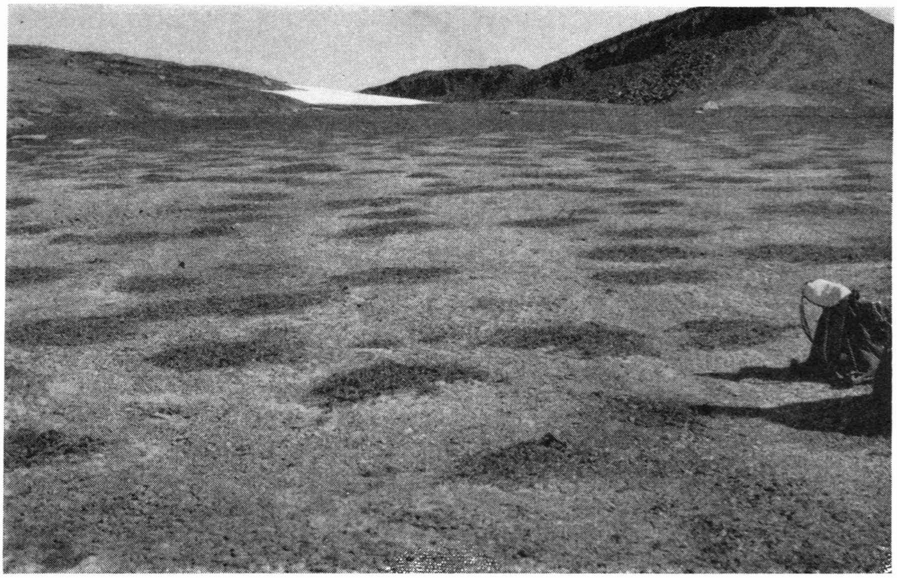


Fig. 26. Hummocks eliminated entirely, leaving "perched" willows growing as mats. Labben slope northeast of experimental site 5, July 11, 1958.

The bases of the stems are well above the ground level, so that the roots are exposed to varying lengths (commonly 10–15 cm) before entering the mineral soil. In many cases the exposed roots are slender, and not stiff enough to hold up the stems; then they are in reclining positions, often intertwined with parts of the stems. *Salix arctica* plants having stem and root arrangements of this nature are called "perched" willows in the present study, and will be discussed more fully in another place.

The thermal regimes in a transect such as that just described should be considered, at least in outline. Before doing so it is necessary to review the process by which earth cores are formed under turf hummocks (BESKOW, 1930; LUKASCHEW, 1940; SHARP, 1942; HOPKINS and SIGAFOOS, 1941, 1954).

It is now generally agreed that these cores can develop or be accentuated under turf hummocks as the latter grow in size, and that the major process involved is differential freezing and thawing. Because the soil under the thicker layers of moss and turf in the central parts of the hummocks freezes considerably later in the autumn than the bare or thinly covered soil between the hummocks, and because the latter soil freezes from the surface downward in the presence of a firm subsurface horizon such as frozen ground or bedrock, lateral pressures are set up which force material upward in the still unfrozen areas under the thick turf layers. It is probable that under suitable conditions the

Fig. 27. Mat of *Salix arctica* showing base of stem "perched" on projecting root at lower right. Labben slope northeast of experimental site 5, July 11, 1958.

size of the cores may also be increased by the upward movement of clay-size particles, as proposed by THORODDSEN (1913).

It is assumed that differential frost heaving is more likely to form cores under hummocks in fine-textured materials such as silts or clayey silts than in coarser mineral soil. Figures 2, 4 and 8 probably illustrate, at least in part, this influence of finer material.

The frost table remains high in the hummocks into the summer. Most of the cores that were dissected in mid-July 1960 were found to be at least partially frozen, and the core of the hummock containing caribou antlers (Fig. 8) was found to be frozen to within 1–2 cm of its top at the end of July 1957. The ice in the cores is in the form of lenses parallel to the surface. Freezing tends to swell the cores and keep them swollen, and some of them appear to become part of the permanently frozen subsoil of the region. The presence of these "micronunataks" of permafrost in areas otherwise subject to erosion has a tendency further to accentuate the cores and the height of the hummocks, particularly in silty soils.

In the sequence of hummock development suggested by the transect nothing could be expected to happen in the production of earth cores by frost until there were pronounced differentials in the thickness of the insulating moss and turf, and until drainage channels had clearly defined the hummocks and broken the continuity of the moss mat. It is significant that no trace of earth cores could be found under small hummocks 10–15 cm high formed in the lower parts of the continuous moss-sedge meadows or in the upper parts of the channeled areas.

With the thinning and eventual removal of vegetation in the inter-hummock channels, differential freezing and thawing could become increasingly effective, and the earth cores could begin to grow upward under the hummocks. Presumably this process of bulging up the cores, once started, could go on so long as there was enough moisture in the soil for freezing and consequent pressure effects. In this instance the process certainly would be decreasingly effective downslope due to the wider dispersal of available water in that direction, and to the loss of some of the moisture to the plants and to simple evaporation. The point on the slope at which it would cease to function at all would be determined by a complex of interacting factors: the degree of slope, the permeability of the soil, the size of the initial water supply, the amount of insolation, etc.

One of the effects of raising earth cores is to increase the height of the hummocks and thus to increase the rate of desiccation of the mosses of which they are composed. Thus the mortality in the mosses is increased, and their erosion by spring meltwater accelerated, leading to even greater asymmetry than would otherwise develop. Another effect of the thermal regime produced as the cores grow is the physical disturbance of plants rooted in the mineral soils. This applies particularly to those in the inter-hummock areas, and to those on the hummocks that have their roots penetrating the soils beneath. Among the latter it applies especially to the willows (*Salix arctica*) whose roots not only enter the mineral soil but extend horizontally far beyond the margins of the hummocks.

Field observations on the slopes below perennial snowdrifts, and the application of what is known of thermal regimes on these slopes, indicate therefore that there are portions of the slopes that are subject to especially intense physical disturbance due to frost action. In the transect described above (Fig. 19) these are represented in a segment the upper edge of which is in the area where the channeling of the meltwater is nearly or quite complete (upper part of zone C), the continuous mat of aquatic mosses characteristic of the upper slope is broken up, and the turf hummocks appear as well-defined separate units. The lower margins of the segment are more difficult to define, though they are probably in the area where the mature hummocks are still closely aggregated while the inter-hummock soils are just beginning to dry out in late summer (the middle part of zone C as it is suggested in Fig. 19). At some point in the gradient the intensity of the disturbance must reach a peak, but with present information the exact place is conjectural. It would vary with the kind of soil, probably being greatest in fine-textured material.

Although no systematic studies were made in the matter, faunal changes along the transect should also be expected. Lemming burrows were found in the earth cores of well-developed, mature hummocks, but none was seen in the many smaller hummocks that were dissected. Burrowing rodents would not be expected in the saturated moss-sedge meadow, but could appear in the system as soon as the channeling was complete and the hummocks were definite entities. Thus their advent probably would be coincident with the beginning of differential freeze-thaw activity in the soils. Larger rodent populations might not appear, however, until the deterioration of the hummocks was further advanced, with greater desiccation and deeper thaw of the earth cores in summer.

The turf hummocks have been most completely reduced on the driest parts of the slopes, and desiccation appears to have been the major factor in their reduction. Nonetheless, ancillary factors have been effective at certain times. Erosion has carried away the smaller hummocks and reduced the size of the larger ones during the early stages of deterioration. Later, much of the dead moss of the isolated, disintegrating hummocks was removed by spring meltwater flowing downslope. The most barren dry surfaces give abundant evidence of having had their soils disturbed by frost. This evidence is in flat stones heaved to vertical positions, in the formation of nonsorted circles in the silt of the upper parts of the slopes, and in the distortion of horizons in the soil profiles. It is possible that some of the disturbances, such as the formation of the silt circles, antedate the turf hummock sequence described here, but others probably occurred during the period in the sequence when frost heaving and the formation of earth cores was at its height. The effects of these disturbances upon the eventual deterioration of the hummocks can only be conjectured. It undoubtedly played a role, even if only in raising the height of hummocks and increasing their rate of desiccation.

Various phases of the wet meadow—turf hummock system just described have been found in the literature, but not the whole sequence.

The early stages of hummock development in saturated moss mats have been suggested by several students. Holttum (1922) proposed a sequence of early development for hummocks on Disko island, West Greenland, which is closely similar to that at Mesters Vig. Oosting's notes (1948) on the development of "boggy" vegetation in the fjord region of Northeast Greenland indicate that he was describing something very like the early stages of hummock growth. Harmsen (1933), describing the bryophytic collections of Böcher (1933) in Southeast Greenland, outlined the function of the various species of mosses in the progressive growth of hummocks ("moss-tufts") in that region. Hanson (1950), working in Alaska, proposed that the hummocks began their development with the invasion of sedge marshes by mosses which formed low mounds.

Although THORODDSEN (1914) discussed variations in the forms and origins of hummocks in Iceland, such students of Icelandic vegetation as HANSEN (1930), GRÖNTVED (1942) and STEINDORSSON (1945) described only differences in surface plant cover without regard to internal structure or possible status in developmental sequences. They merely called hummocks "knolls," and it is impossible to tell from their descriptions whether the knolls had earth cores or were formed entirely of turf. Further, the sites of the knolls were not "placed" in the local landscapes with enough precision to permit analyses of attendant water regimes or geomorphic processes.

It is tempting to suggest that the Icelandic turf hummocks described by the several students who observed them might be segregated into groups representing stages in developmental sequences. To do so, however, without more complete knowledge of their local water supply and frost regimes is speculative. Judging by the descriptions they have much in common with the hummocks studied at Mesters Vig. In both regions they have been formed in several different kinds of situations, and with different initial stages; but in both they are most densely aggregated on gentle slopes of fine-textured materials that contain abundant water. In the Mesters Vig district, and so far as is known also in Iceland, the commonest origin for them appears to be on surfaces that are already covered with some kind of wet meadow vegetation. A question could be raised as to whether the knolls in the drier forms of "mó" vegetation are not late stages in the sequences, with no current development of new hummocks. The fact that knolls do not develop in "home fields" if the soil is drained artificially (THORODDSEN, 1914) is, in effect, experimental evidence that a very high water table is essential to their formation.

There are several references in the literature to the disintegration, and even to the eventual destruction of mossy turf hummocks by desiccation and wind action. Special cases of their destruction by water erosion and solifluction processes are occasionally mentioned (HANSEN, 1930; TROLL, 1944; SHARP, 1942). TROLL (1944) stated that in the tundra of northern Europe, "In the advanced stages, the turf cover on top of the little hummocks is usually frost heaved, so that loosening of the fines and ablation is beginning." In discussing hummock formations in the Vosges he wrote, "the growth of hummocks leads finally to a conversion to heather and to removal by water and wind." Destruction by desiccation and wind was noted by HANSEN (1930) in Iceland, and by SIGAFOOS (1951) and HANSON (1950) in Alaska. BILLINGS and MOONEY (1959) believed that the hummocks they studied in the mountains of

Divisions of transect	Topography and vegetation	Water supply	Insulation	Frost action	Faunal activity
Snow-drift					
A	Ground surface relatively even, with crust of dead, blackened moss and few polsters of living moss with *Salix arctica*	Sheet flow from melting snowdrift. Continuous through summer.	None, or a thin crust of dead moss, except for a few scattered living moss polsters.	Disturbance of soil by frost action intense at autumn freeze-up.	Rodents few or none.
B	Continuous mat of aquatic mosses, with sedges, grasses, and rushes.	Sheet flow and seepage through moss mat. Continuous through summer.	Continuous cover of moss, of fairly uniform thickness.		Rodents few or none.
	Continuous moss mat, with low mounds forming in moss. *Salix* and heaths on mounds. Grasses, sedges and rushes.		Moss mat continuous, but insulation probably greatest under low mounds of moss.	Disturbance by frost action relatively minor, with probable slight increase in the incipient interhummock channels toward the lower part of B.	
	Mounds forming low hummocks. Channels between hummocks partially formed.	Flow partially channeled among low moss hummocks. Continuous through summer.	Moss mat continuous, but insulation thinner in interhummock areas, and thicker in the low hummocks.		Probable slight increase in rodent activity.
C	Channels complete and hummocks separated. Salix, heaths, sedges, grasses, etc.	Flow continuous in interhummock areas through most of summer.	Insulation discontinuous. Thick in hummocks. Bare mineral soil exposed in interhummock channels.	Disturbance by frost action increasingly intense, forming cores in the hummocks over fine-textured soils.	Moderate increase in rodent activity.
	Hummocks larger in height and diameter than those upslope. Interhummoch areas wider. Flora as above,	Interhummock areas merely damp in latter part of summer and autumn.	Insulation discontinuous, increasing in thickness on hummocks as the latter increase in size. Interhummock bare areas progressively larger downslope.		Marked increase in rodent activity.
	Hummocks increasingly asymmetric. Flora as above.	Flooded in spring and early summer. Interhummock areas dry in late summer.		Probable decline of disturbance by frost action.	
	Hummocks becoming widely spaced. Mosses and turf deteriorating. Flora partially reduced.	Flooded in spring. Interhummock areas dry by mid-summer.	Wide interhummock areas with no insulation or very thin plant cover.	Soils relatively stable except for minor disturbance by frost action in spring and autumn.	
	Hummocks disintegrating to organic rubble. Flora reduced to *Salix arctica*.	Watered only by local snowmelt in spring. Dry by early summer.		Slight disturbance by frost action in spring and autumn.	
	Hummocks eradicated; their former positions marked by living, perched *Salix arctica*.	Watered only by local snowmelt in spring. Dry by early summer.	No insulation or only thin and scattered plant cover among mats of *Salix arctica*	Slight disturbance by frost action in spring and autumn.	

Fig. 28. Chart showing correlation of vegetation and site conditions at various levels of the transect in Fig. 19.

southern Wyoming were degraded by wind, water erosion, and frost thrusting.

No evidence was found in the Mesters Vig district to support the suggestion of M. P. PORSILD (1902) that the bases of hummocks on Disko were formed of vegetable debris blown by wind to the melting margins of snowdrifts. Nor was any evidence found that would relate the local distribution and genesis of the hummocks to the formation of sorted or nonsorted net features in the mineral soils beneath them. THORODDSEN (1914) proposed that the development of Icelandic "thufur" was closely related to that of sorted nets in clayey soils, and NIELAND (1930) made a similar proposal, with modifications, in West Greenland. DRURY (1962), working on Bylot Island in Arctic Canada, described hummocks the margins of which were closely correlated with cracks in the mineral substratum. He did not suggest early stages for the development of these hummocks, but a mineral soil surface cracked by desiccation or other causes would present a microrelief upon which they would readily form provided an adequate supply of moisture became available. Although a diligent search was made for structures such as cracks in the mineral horizons between hummocks in the Mesters Vig district, none were found.

The problem of development and deterioration in individual turf hummocks.

The transect described in the preceding pages merely places adjacent to one another in space a series of apparent stages of development in vegetation and microrelief. Although its continuity suggests sequential development, it does nothing to prove genetic relationship between adjacent stages. The fact that most of the Mesters Vig hummocks merge insensibly into this series or into others like it lends weight to its significance, and requires that it be studied further.

If it is assumed that the transect representents an actual process, the latter may be summarized as shown in Figure 28.

It seems evident that the summer water supplies are the primary factors governing the presence or absence of these wet meadow–turf hummock systems, and that the gradients in the water supplies are closely related to the assumed developmental sequences. The effects upon the vegetation of variations in water supply may be direct, or indirect through the thermal, erosional, or faunal regimes. Because the concept of development involves time, it becomes necessary to consider the possible effects of variation in water supply over time as well as along gradients in space.

If only the upper parts of the meadow-hummock systems are considered, involving Zones A, B and the upper part of C of the transect in Figure 19, it is possible to conceive of a developmental sequence in the presence of a water supply that remained relatively stable over a long period of years. Under these conditions the margins of the snowdrifts, and the volumes of the latter, would be approximately stable year after year. How long such a state could last is conjectural. Something like it probably is a basic assumption made by those who have considered larger turf hummocks, with their heath-willow vegetation, as approaching the tundra "climax" (HOLTTUM, 1922; GRIGGS, 1936; OOSTING, 1948; POLUNIN, 1948). M. P. PORSILD (1902) thought that hummocks of this kind on Disko were a century old, and GRIGGS (1936) dated those in the Katmai region back to the disappearance of the last glacial ice.

When all of Zone C is considered, however, the assumptions made in the preceding paragraph, so far as they apply to the Mesters Vig hummock systems, are unrealistic. To form the hummocks now deteriorating, widely scattered and far removed from sources of abundant water, the water supplies must have been considerably greater at some time in the comparatively recent past. This suggests that the snowdrifts were formerly larger and that their fronts extended farther downslope. Warm summers, melting them back gradually, could then motivate the process illustrated in the whole transect.

Still another possibility should be considered: that the water supply has been increasing in recent years rather than decreasing. A very small increase would be difficult to detect in the vegetation, but if it had been going on for one or two decades its effects ought to appear among the hummocks in the upper parts of Zone C. Here the inter-hummock areas, recently denuded by erosion, frost heaving, and partial desiccation, would begin to acquire a new wet meadow vegetation. At the same time the neighboring hummocks would have a renewed water supply around their bases, and their flora would be greatly enriched by the appearance of appropriate species. No evidence for this kind of development was found on the slopes of the Labben peninsula. In fact only a single instance of it was seen among all the turf hummock areas examined in the Mesters Vig district (see below).

If developmental sequences in the hummocks have actually occurred, and if their development has been motivated by a decreasing water supply, as their structure and arrangement on the slopes suggest, it would be highly desirable to find some evidence for this development within individual hummocks. Only by such a method can the substitution of space for time in the reasoning be avoided. The perched willows briefly noted above appeared to have lived in their respective turf hummocks throughout at least the period of disintegration of the latter, and were therefore studied in detail for evidence of change in their habitat.

Fig. 29. Root and stem systems of willow (*Salix arctica*) dissected from hummock shown in Fig. 12. Specimen no. 135. August 3, 1958.

ON THE GROWTH OF *SALIX ARCTICA* IN TURF HUMMOCKS

Introduction.

Perched willows are extremely common on the long, gentle to moderate, lower slopes in the Mesters Vig district, particularly on the Nyhavn and Labben peninsulas. They are numbered in thousands, and indicate that turf hummocks were formerly considerably more numerous than they are now.

It was thought that the upper portions of the roots of these willows might have been exposed by frost heaving, and dissections of turf hummocks were made in order to compare the growth forms of the roots above and below ground. Figure 29 shows an example of the portion of a root that was above the mineral soil and exposed by the dissection of the hummock shown in Figure 12. Though heavier and simpler than the stem system with which it was entangled, it tended to display sharp angles and crooks in its direction of growth. In contrast, roots of *Salix arctica* that are beneath the surface of the soil usually are long and relatively straight. Figure 30 shows a group of them that were heaved out of the soil in an active sorted net area in the vicinity of experimental sites 1, 11 and 12. The lifting of these roots from the tundra soils is

Fig. 30. Roots of *Salix arctica* exposed by frost heaving in sorted net; vicinity of experimental sites 1, 11 and 12.

comparatively easy, for they are usually cord- or ropelike and within a few centimeters of the surface.

With a view to determining their usefulness in the hummock study a few specimens of perched willows were collected in the summer of 1957. Their roots were sectioned and the growth rings counted, showing that they had reached ages of 30 to 80 years. In the field season of 1958, 68 specimens of living willows were gathered on the Labben slopes (see Figs. 26, 31, 32). All of these were sectioned, and studies made of their growth patterns.

Specimen nos. 81–133, inclusive, came from the slopes immediately southwest, south and southeast of experimental sites 2, 3 and 9. They were collected on July 11, 1958, and were growing both in the silt and in the sandy soils among the nonsorted silt patches. Numbers 42–47, inclusive, collected on the same day, came from the drier parts of the silt farther downslope, in the vicinity of experimental site 5. The surface of the silt was dry and brittle at the time of collection, and nearly barren of vegetation except for the rather widely spaced willow mats, which ranged from 20 cm to 1.5 m in average diameter. The living parts of the willows were mat-like or were on low mossy hummocks 5 cm high or less. However, the base of the stem in these mats was commonly raised much higher above the silt, sometimes with arching, crooked roots standing up 10–20 cm. The exposed root systems were always on the uphill sides of the mats. Numbers 48–51, inclusive, were collected on

A

B

C

Fig. 31. Perched willows (*Salix arctica*), Labben slope between experimental site 5 and the vicinity of sites 2, 3 and 9, July 11, 1958. A is specimen no. 51 and B is specimen no. 52 (see Fig. 26). C is a detail of Fig. 27.

A

B

C

Fig. 32. Perched willows (*Salix arctica*), Labben slope between experimental site 5 and the vicinity of sites 2, 3 and 9, July 11, 1958. A is specimen no. 47 (see Fig. 26).

July 11, but on a somewhat wetter site in a shallow channel near experimental site 5. Numbers 48 and 49 had well-exposed roots, with the bases of the stems 10–20 cm above ground. Number 50 was a large root extending from the eroded, upslope side of a mossy hummock about 20 cm high. Numbers 40 and 41 were from mossy turf hummocks 1–3 m apart a short distance above site 5. Number 52 (Fig. 31 B) came from a dry silt area with low willow mats similar to the location of nos. 42–47, but from farther up the slope. Number 135 was the willow dissected from the turf hummock shown in Figure 12.

Age determination of the specimens.

Although the formation of spring and summer wood in the stems and roots is clearly seen, the arrangement of the growth in annual "rings" is highly irregular. Eccentricity of growth is the rule rather than the exception, and the "rings" are commonly discontinuous around the stem or root. The result is that counts of annual layers of wood on different radii in the same section will give several different ages, with variations of as much as 20 years in a plant that is no more than 40 years old. In many cases a root or stem stops growing entirely on one side, and continues on the other. The only recourse under these circumstances is to try to find the radius with the largest number of definable "zones" of growth, and use the total count of this as the age of the plant.

The sections were made as close as possible to the top of the root or the base of the stem. Most of the specimens from the 1958 collection were of roots, though eleven were of stems (nos. 39, 40, 43, 83, 95, 105, 109, 125, 128, 129, 133). The best evidence for the age of the plants no doubt came from the roots, which were the long, rather simple ones characteristic of *Salix arctica*, usually only one main one to each plant. Although care was taken to select what were thought to be main stems for sectioning, there was no certainty that these were not later shoots. However, judging by the size and growth patterns in the eleven stem specimens, it is believed that the error involved was not great.

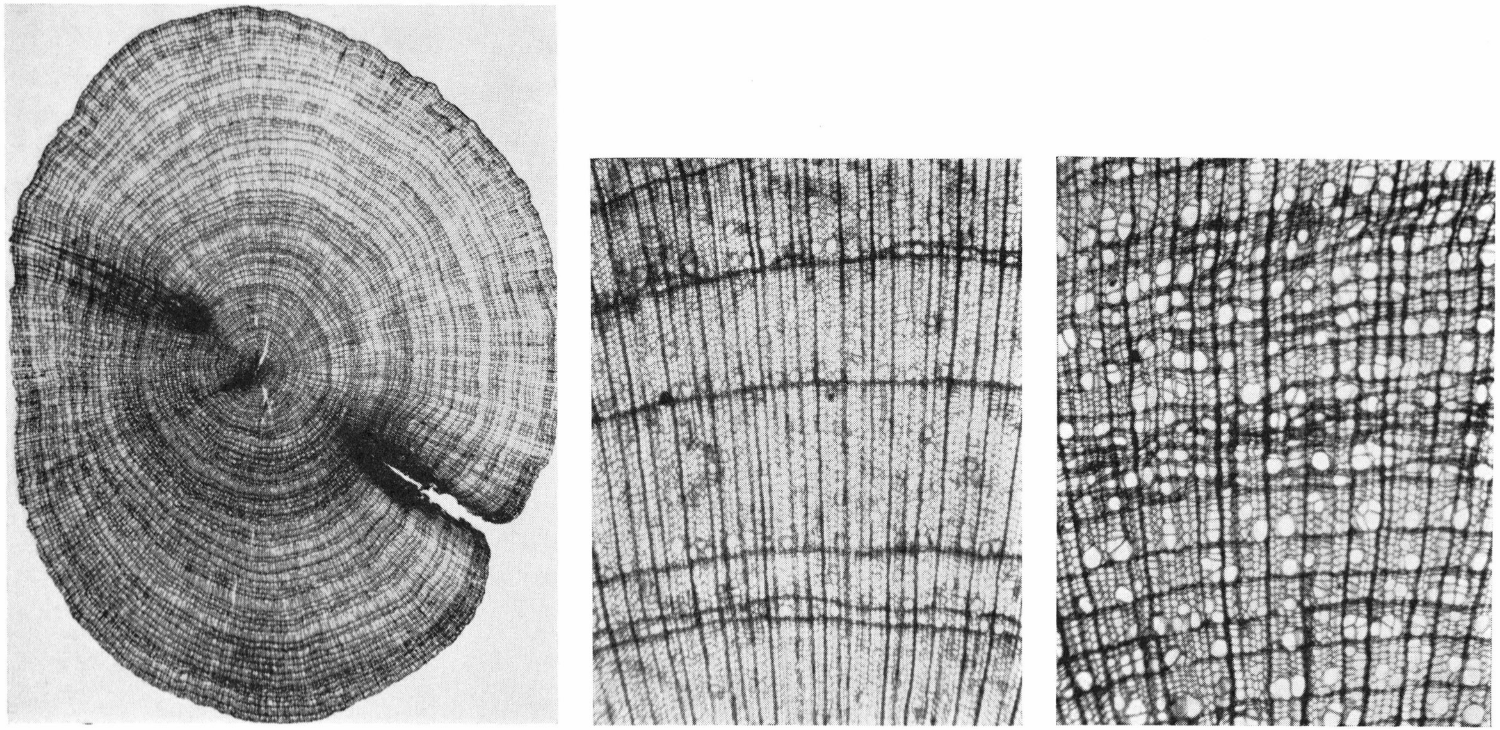
Most of the willows whose growth behavior is analyzed in this paper were 60 years old or younger. However, it is assumed that the life span of *Salix arctica* in Northeast Greenland is a great deal more than that. Fourteen of the specimens collected on the Labben slope exceeded this age, and one of them was at least 106 years old. About an equal number of willows collected elsewhere in the Mesters Vig district showed a similar proportion that were over 60 years old, one of them 175–180, one about 210, and another about 236 years. Considering the evidence of suppressions in their growth rates (see below), and the apparent mortality resulting from them, it seems reasonable to believe that these willows can go on living to ages much greater than 60 years if they are not periodically decimated by suppression.

Growth patterns shown by the annual layers of wood.

The interpretation of annual growth as shown by the layers of wood is a highly complex matter involving many factors for which only limited data are yet available, and requiring far more material for study than is at hand. Therefore the following discussion must be restricted to a few simple observations on phenomena that are outstanding in the overall appearance of the root and stem sections studied.

First, only one of the willows grew with fair regularity and rapidity throughout its life. By this is meant that its annual growth was approximately the same year after year except for occasional single poor years and that, as average growth of these plants goes in the tundra, it was relatively rapid. Second, and in contrast to this, the usual growth pattern over time showed great irregularity and unevenness. The commonest form of irregularity was in sudden suppressions of growth rate (Fig. 33 C), shown by sudden narrowing of growth "rings" or "zones." These suppressions were clearly different from the occasional "bad" years scattered among the regular zones (Fig. 33 B), for they usually involved a series of several years of slow growth after or during which the growth rate gradually increased again. Many of the plants showed several of these suppressions, after each of which they wholly or partially recovered.

Repeated decisions had to be made on what were suppressions and what were not. Finally a somewhat arbitrary definition was used: if the growth rate were suddenly reduced to a small fraction of its former rate, and remained so for 3 or 4 years or more with little or no increase, the reduction was regarded as a serious suppression. Reductions that lasted only 1 or 2 years were looked upon as due merely to occasional short growing seasons. A special problem arose in the case of stems. Stem shoots commonly grow rapidly in length and diameter during their first few years, and may even in this period be interrupted by suppressions. Usually, however, they grow rather regularly for 4 to 7 years (sometimes for 10 or 12 years), then much more slowly and irregularly thereafter. Commonly the reduction in growth rate at the end of the early period of rapid growth is rather sudden, though it is sometimes gradual. When sudden it closely resembles the suppressions that occur at intervals later in the life of the plant. Because this early reduction in the growth rate of most stems appeared to be a normal event in their



A B C

Fig. 33. Microphotographs of sections of roots of *Salix arctica.* A – specimen no. 122 showing periods of rapid and slow growth; B – specimen no. 48 showing relatively rapid growth with occasional narrow rings; C – specimen no. 135 showing pronounced suppressions lasting several years.

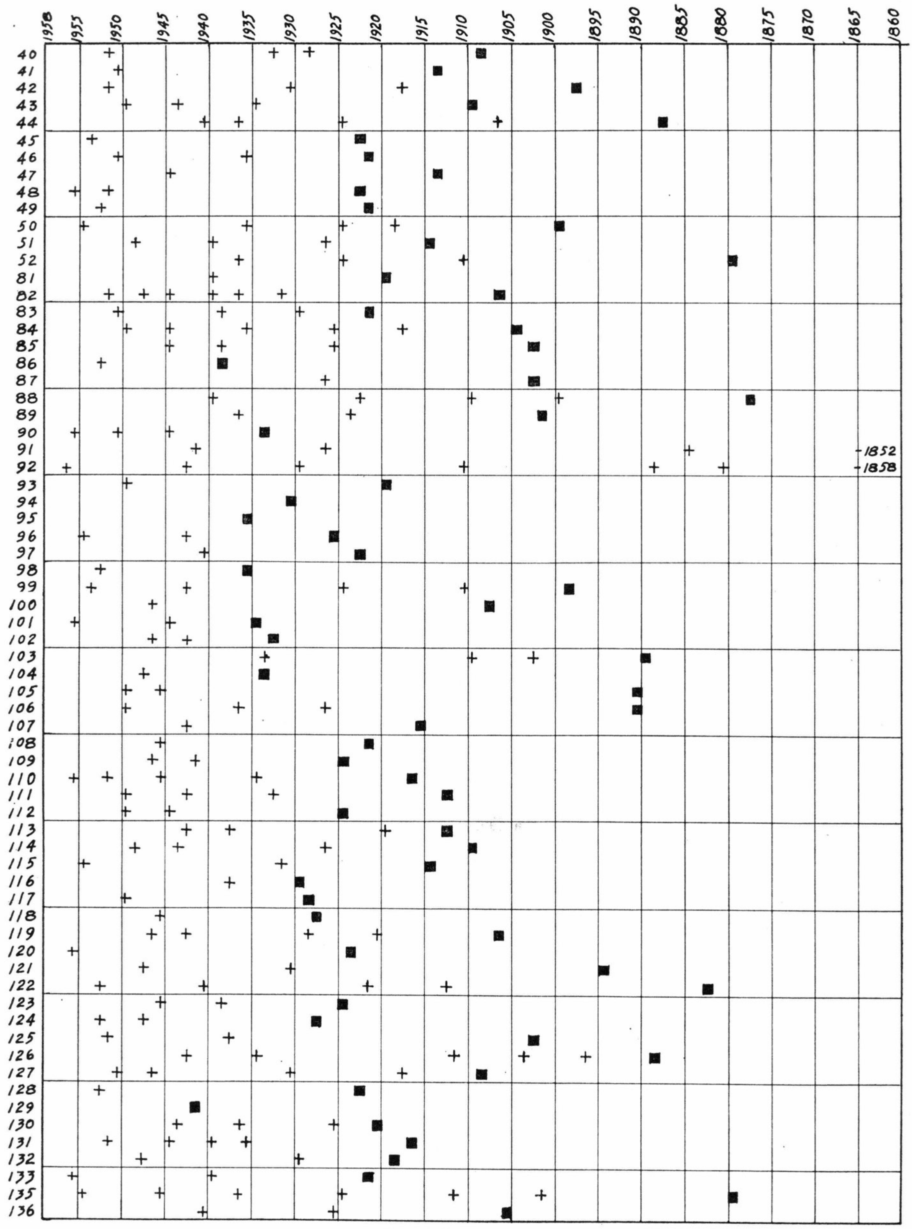


Fig. 34. Chart showing dates of origin of 68 living perched willows collected on the Labben peninsula in 1958 (solid blocks), and the dates of suppressions in their growth rates (plus signs).

development, apparent suppressions resulting from it were not counted in the following analysis. Sections of roots did not show periods of rapid growth at the start.

Causes of suppression and mortality in the perched willows.

Most of the suppressions of growth mentioned above were distinguished by their suddenness and by their persistence. Had they been caused by gradual changes in climate they would have been persistent but probably would not have been sudden. Had they been due to occasional years of unsuitable climate for the plants they might have been sudden in their effects, but not persistent beyond one or two years. Therefore most if not all of the observed suppressions are regarded as having been due to some kind of injuries to stems or roots.

The sources of these injuries are many in the arctic tundra. At present it is possible to do little more than list them in three general categories: 1) physical injuries due to movement of the soils by geomorphic processes: 2) desiccation; 3) gnawing by rodents. Injury, especially to the roots of the plants, is of extremely common occurrence. Not only is it evident upon superficial observation, but the transverse sections show it clearly in various forms of eccentricity and irregular growth patterns. Rodent burrows have been found in isolated or semi-isolated hummocks (see Fig. 4). If these animals ranged the wet meadows they apparently did small damage to the willows. But some of the roots and stems of the "perched" willows look as though they had been gnawed (see Fig. 32 A). With the postulated breakup of the meadows to form isolated hummocks, not only would rodent injury have become effective, but also injuries due to desiccation and the physical disturbance of the soils. Because the effects of desiccation probably would be more gradual than those of rodents and soil disturbance, the latter two are likely to have been the most significant.

An interpretation of the age and growth data from perched willows.

Figure 34 is a chart showing the dates of origin of each of the 68 willows collected on the Labben slopes in 1958, as well as the dates at which suppressions of growth rate occurred. Figure 35 A gives the numbers of the plants collected in 1958 that were living in any given year between 1860 and the date of collection. In 1910, for example, about 30 of them were in place and growing, but in 1900 there were only 15. It is obvious that the more valid interpretations are likely to come from the left side of the chart, where the numbers are greater. It should be noted that two of the willows were already present in 1860, with approximate dates of origin in 1852 and 1858. Invasion of the area by *Salix arctica* appears to have been slow until about 1900, for it took the preceding half century for 15 of these willows to become established.

Invasion seems to have been much more successful after about 1900, as shown by the steep rise in the curve. The period of most abundant establishment was between 1900 and 1935, during which time nearly 75 % of the plants appeared on the scene. However, the curve shows that there was a notable decline in the rate of establishment about 1923. There were no origins, among those collected, after 1941, and young willows were rarely seen on the slopes in the vicinity of those collected.

Figure 35 B was made by adding the number of suppressions indicated in the growth zones for each year, and charting the results on a time scale similar to that used in Figures 34 and 35 A. A total of 162 suppressions were recorded for all years. The chart indicates that suppressions occurred among the older willows beginning as early as 1880 when there were only five plants to record them. They were infrequent, however, and remained so (one to three per year) until the mid-1920's even though there were by that time about 55 plants available to show them. After the mid-1920's they came with increasing frequency (up to 8 or 9 per year). Thus in 1925, when over 80 % of the plants collected were already established, only about 21 % of all the suppressions recorded or to be recorded by their growth rings had occurred. The suppressions became most frequent after 1940. Nearly half of them (77, or about 48 %) were recorded after 1941, which was the year in which the last of the willows became established. The charts show only the dates of the beginnings of suppressions. If one were designed to show their duration it would accentuate the significance of the more recent suppressions, especially those dating in the 1950's and late 1940's. A large proportion of the plants suppressed in these years had not yet recovered when they were collected in 1958, even after 5–10 years of microscopically slow growth.

Another way of showing this is to chart the suppressions cumulatively, and compare the trends of their curve with those of the population curve (Fig. 36). The curve of suppressions remains relatively low, with only a gradual upward trend, until about 1923, at which time the curve of population increase had reached the end of its steepest pitch. Then the suppression curve begins to rise more rapidly, while the population curve begins to fall off. About 1935 the suppression curve is further steepened, and shortly thereafter the population curve becomes flat.

Reference to the chart in Figure 34 will show that the curves in Figures 35 and 36 can represent only general trends, for the suppressions are not much concentrated in time or space during the period between 1900 and 1958. Rather, each plant appears to have been answering to extremely local conditions. Field notes for the collection area, as for many others of similar nature, carry the expressions, "high mortality rate," or "as many dead willows as living ones." The evidence in the

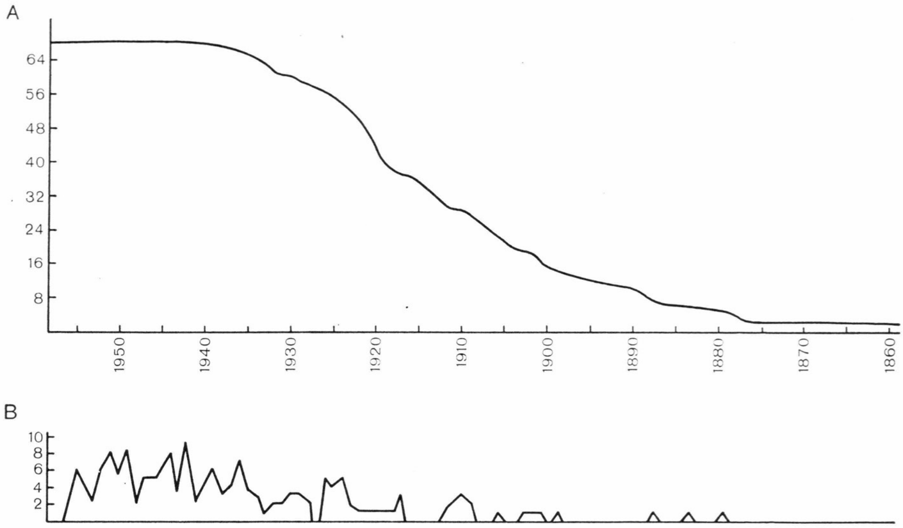


Fig. 35. Charts of cumulative population growth of the 68 plants represented in Fig. 34, and of the sums of their growth suppressions by years.

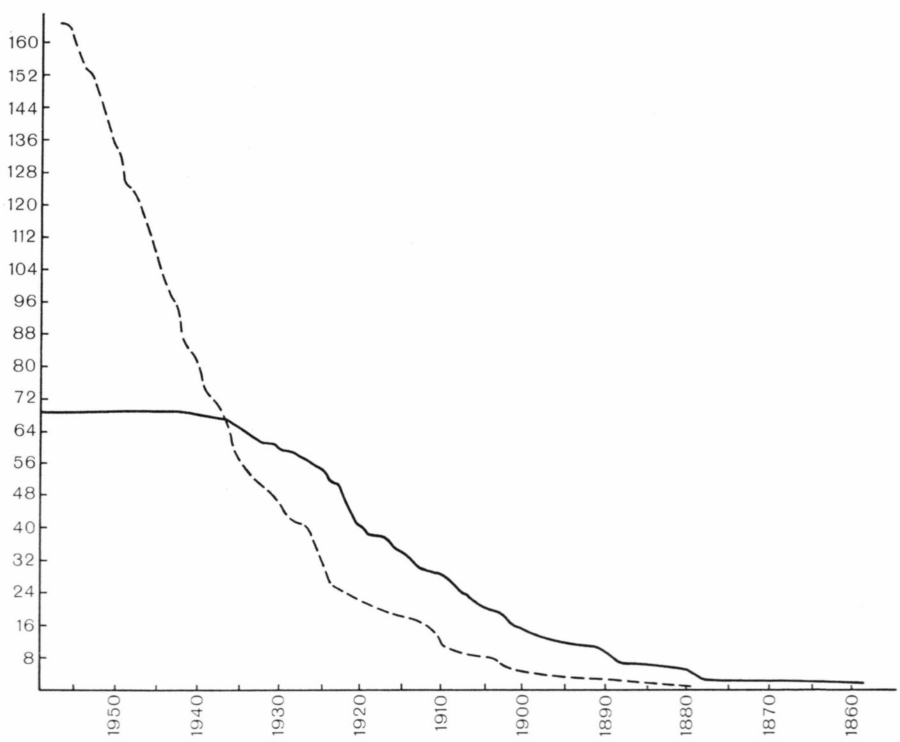


Fig. 36. Chart of suppressions added cumulatively, and the resulting curve compared to that of the cumulative population curve.

sections of the living plants, coupled with the obvious mortality seen on the ground, is that a certain percentage of the willows fail to survive the suppressions each time they occur, and that the population is now losing ground very rapidly indeed. Whatever the cause of the suppressions and mortality has been, it seems not to have become seriously restricting until the mid-1920's. By this time most of the willows discussed thus far were already there, but only a few of them had suffered any major suppression.

From the foregoing it can be postulated that the area of the Labben peninsula in which the 1958 collections were made was especially suitable for the establishment and relatively rapid, steady growth of *Salix arctica* during the period of years beginning about 1900 and ending between the mid-1920's and mid-1930's. Judging by what we know of the structure of these willows, with their projecting roots and "perched" stems, most of them germinated 5 to 10 (or 15) cm above the present ground level. The forms of their exposed roots indicate that they germinated and had their earliest growth in a turf similar to that now found in a saturated, mossy, somewhat hummocky meadow. This meadow must have extended widely over this slope. The unbroken sequence of many intermediate stages between willows still embedded in mature hummocks, and those of similar form growing as mats on essentially bare soil, together with the relatively close and regular spacing of these mats, strongly suggest that the vegetation of the whole slope has undergone changes analogous to those now seen in the transect described above (Fig. 19). In the period of rapid invasion by the willows there must have been an abundance of surface water throughout the growing seasons on the parts of the slope that are now dry in summer. Presumably this water came from much larger snow accumulations than now exist in the hills immediately to the northward.

The relation of *Salix arctica* to site variation in a turf hummock system.

Inherent in the data and interpretations presented above is evidence that individual plants of *Salix arctica* live through an extraordinarily wide range of habitat conditions. The wide tolerance of the species to site variation in East Greenland has been noted previously. SØRENSEN (1933, p. 72–73) mentioned "dry," "damp" and "bog" localities for it. GELTING (1937, p. 29–30) stated that the species "has an exceedingly great amplitude in the various ecological scales and occurs on nearly all kinds of soil from the driest to the dampest, from the deeply snow-covered to the snow-free soil . . ." He thought, judging by its relative

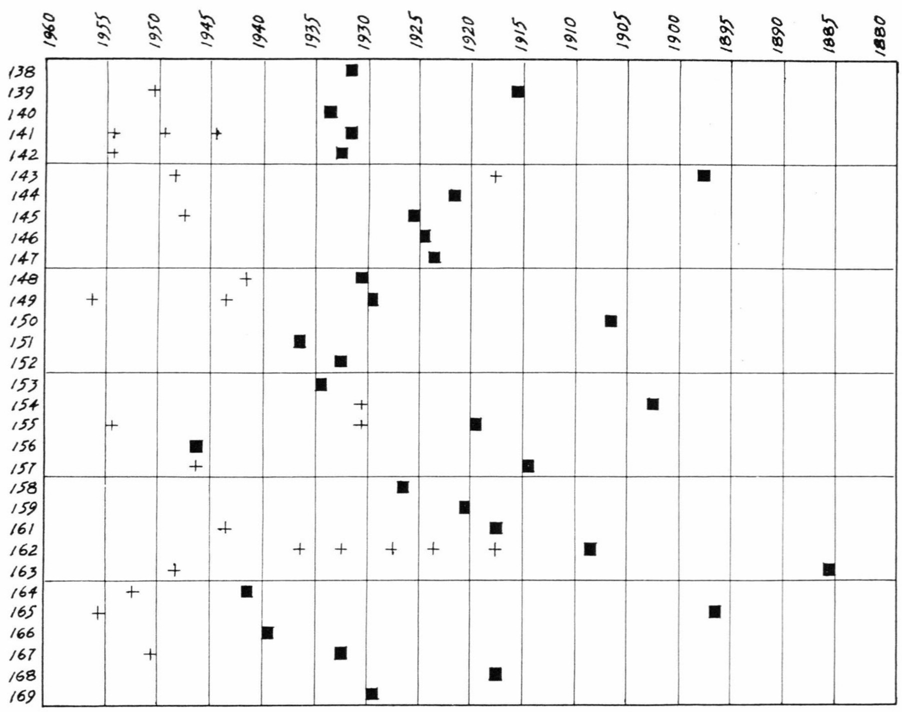


Fig. 37. Chart showing dates of origins and dates of suppressions of 31 living willows collected in the upper part of zone B of the transect shown in Fig. 19.

luxuriance on different sites, that it was "rather a hygrophyte." SØRENSEN (l. c.) reported it most frequent on damp soil.

On the moisture gradient in a turf hummock system like that described on the Labben slopes the willows start in a saturated, mossy meadow, and after experiencing a long period of gradual desiccation they still manage to persist in the hard, dry silts that are cracked and brittle at the surface in summer. In their association with other plants they may be alone among the mosses at the beginning, or among a loose mixture of grasses and sedges. On the developing hummocks they may be crowded together in dense tangles with *Cassiope*, *Vaccinium*, *Dryas*, or *Carex*, but their roots are unique, for they range much farther into the mineral soil than do the roots of the other plants. On the disintegrating hummocks the willows are again essentially alone with the now declining mosses. In the matter of physical disturbance, their roots probably remain relatively stable during the early and late periods in the hummock sequence, but during the middle period, when earth cores are being raised, and there is much frost heaving in the inter-hummock areas, their root systems must undergo a great deal of dislocation.

Further evidence that they live through the whole sequence, and also some corroborative evidence for the site changes that occur during the sequence, may be gleaned from their forms and growth patterns. If they had germinated on the tops of hummocks 20 to 40 or more cm high their now exposed roots would be much longer than they are. Consequently most of them must have become established when the hummocks were very small or almost nonexistent in the moss mats. Further, there is a correlation between the timing of the probable devel-

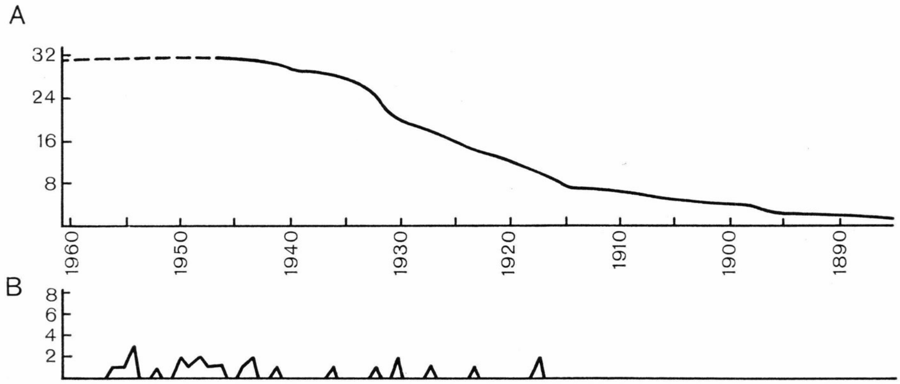


Fig. 38. Charts of cumulative population growth of the 31 willows represented in Fig. 37, and the sums of their growth suppressions by years.

opment of the hummocks as well-defined units and the rapid increase in number of effective suppressions. Evidence for this was checked in the following manner.

Thirty-one specimens of willow stems and roots were collected in July 1960 from a wet, hummocky moss-sedge meadow a short distance below the snowdrift shown in the transect in Figure 19. They came from the uppermost part of Zone C, an area where the water is channeled, the hummocks are fairly well defined (about 15 cm high), and the ground is wet throughout the growing season. It represents a site for willow establishment and growth which approximates that postulated for the lower slopes at some time between 1900 and the 1920's.

Figure 37 gives the dates of origin of these 31 willows, and Figure 38 A shows the numbers of them that were growing in any year since the first one appeared in 1885. It will be seen at once that invasion was slow until about 1915, at which time only 7 of the 31 had appeared. Then came a period of about 20 years, 1915–1935, when invasion was relatively rapid and during which about 65 % of the plants became established. The last of the 31 to come in appeared in 1946. Comparison of the curves in Figures 35 A and 38 A suggests that rapid invasion on this part of the slope began about 15 years later than it did farther down where the 1958 collections were made. The upper part of the curve is unrealistic and should continue to rise, for the collecting was confined to the larger willows. Smaller and apparently younger ones were present, and there was no obvious mortality. Had these smaller plants

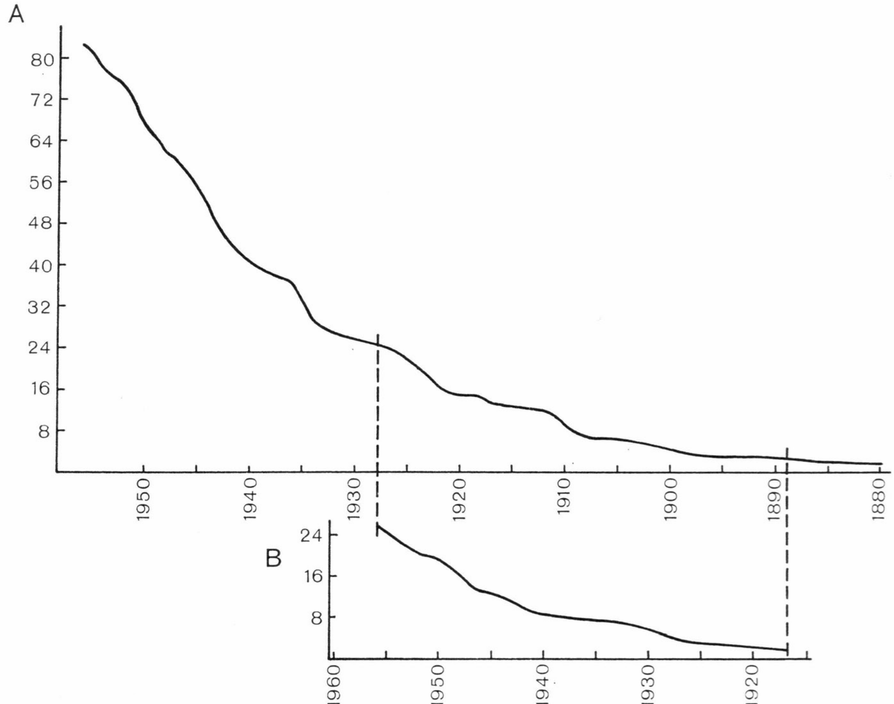


Fig. 39. A – Chart of suppressions in 31 perched willows selected from those shown in Fig. 34 and added cumulatively.
B – Suppressions in the 31 willows shown in Fig. 37 added cumulatively, and the curve compared with that of A.

been collected there would have been more origins dating after 1935 than the curve indicates.

Figure 38 B gives the sums of suppressions by years for these willows. They began in 1917, but occurred only sporadically until after 1940. Even then they were relatively infrequent.

In order to make a more valid comparison of the data on suppressions from willows of the 1958 and 1960 collections, 31 specimens were selected from the 68 collected in 1958. The selection was made by using alternate numbers in the list in Figure 34, beginning with no. 46. The greater frequency of suppressions in the willows of lower, dry slopes is at once apparent. The total number recorded by the growth rings of the 31 specimens from the drier slopes was 81, while the total in the 1960 specimens, from the wet hummocky meadow, was only 25.

Some indication of the position of the site of the 1960 collection in the time and developmental sequences of the turf hummock system can be gained by plotting these data in another way. In Figure 39 the suppressions in the 31 specimens of each collection are charted cumulatively, and the trends of the resulting curves are compared. This particular group from the 1958 collection showed very few suppressions until about 1909 when there began an increase which continued at approximately the same rate until about 1923. Then came another increase that continued to about 1935. Following this came the rapid rise that lasted until 1958, and is reflected in the curve for all 68 of the specimens collected in that year. The analogous curve for the 1960 collection follows rather closely the trend of the curve for the 1958 plants in the period between 1889 and 1928. There is a change in the direction of its trend that can be dated about 1940. This trend corresponds roughly to that which started about 1909 in the older specimens. There has been, as yet, no steep rise in the curve of suppressions for the willows of the wet meadow—a rise equivalent to that shown by the growth rings of the willows on the drier slopes after 1935. This is borne out by the absence of mortality among the willows of the meadow, and by the presence of young plants.

Thus the curve of suppressions in the willows collected in the wet, mossy meadow with its incipient hummocks, when compared to the curve of those from the drier slopes, gives further evidence that the drier area in which the "perched" willows were collected was covered as late as the 1920's or early 1930's by a similar wet mossy meadow. The close similarity of the curves in Figure 39 is additional evidence that individual willows live through the entire turf hummock sequence, for specimens collected in 1960 in an early segment of the sequence show a pattern of growth behavior predicted on the basis of the forms and growth patterns of older willows, collected in 1958, which appeared to have been through the sequence.

A question arises concerning the point in the turf hummock sequence at which the suppressions begin to become critical for the survival of the willows. Judging by the curves in Figure 36 it is the point at which the frequency of suppressions begins to increase very rapidly. The relevancy of the data at hand for this can be tested on the ground in only two areas, where the plants were collected in 1958 and 1960. In the former, as already noted, conditions were advanced far beyond the early critical stage for the willows. Mortality was high, and the population was obviously declining. In the 1960 collection area the channeling of the meltwater from the snowdrift was well advanced, and the continuous mat of mosses characteristic of the upper part of Zone B was in process of being broken. There was still some turf in the inter-hummock channels, but mineral soil was beginning to appear. Earth cores were not found under hummocks of this size and origin, either here or in similar situations elsewhere, indicating that the differential freezing and thawing upon which they depend in part for their growth had not yet become effective. There had not been enough desiccation or erosion of the small hummocks to cause appreciable asymmetry in their form.

If the analysis given for the curves in Figure 39 is valid, and if the upslope retreat of the water supply continues at about the same rate as in past years, the willows collected in 1960 were in an area that will, within 5 to 10 years, become much more hazardous for growth than it was in 1960. Though these willows were already undergoing suppressions, they seemed not to have suffered much from them, for they were growing vigorously in the continuously wet substratum. However, the curve in Figure 39 B shows that the suppressions had been gradually increasing in number, especially after 1940.

In the development of turf hummocks in a system such as that described in Figure 28, one of the most striking physical changes is that which occurs in the upper to middle parts of Zone C. In the local geography this area is just below that in which the 1960 willow collection was made, and in the time scale suggested by the curves in Figures 36 and 39 its growing conditions would appear in the 1960 collection area within a very few years. These growing conditions include those which appear to cause the greatest amount of injury to the willows—intense frost heaving in the soils, gnawing by rodents, and desiccation.

The evidence is strongly suggestive, therefore, that the suppressions become critical for the willows in the zone where frost heaving becomes intense. This is the zone in which the breakup of the moss-sedge meadows is complete, and there are bare inter-hummock areas devoid of insulation. The growth patterns indicate that the suppressions remain critical throughout the remainder of the lives of the willows, though the causes for them may change. It has already been argued that frost heaving in the hummock sequence is progressively reduced downslope. This occurs in spite of wider spacing of the hummocks, and is due to reduction of moisture in the soil during summer and autumn. Thus injuries due to frost heaving might well be displaced in part by those due to desiccation. It is probable also that the increasing desiccation leads to less frozen ground in the hummocks and their earth cores in summer, and makes the willow roots more accessible to gnawing rodents.

It is tempting to interpret also the breaks in the suppression curves that occur earlier—about 1909 in the 1958 collection and about 1940 in the 1960 collection. These are highly speculative, however, because they are based upon very few plants. It is possible that they mark the zones in which initial channeling began among the low mounds of moss in the wet meadows.

THE RELATION OF TURF HUMMOCK DEVELOPMENT TO CLIMATIC CHANGE

The development and deterioration of turf hummocks on the lower slopes of the Labben peninsula appear to have occurred within a relatively short time—30 to 60 years. Snowdrift retreat of a magnitude great enough to motivate the process presumably was a reflection of climatic change affecting a region much larger than the Mesters Vig district, and evidence of it should be found elsewhere.

It is now generally accepted among climatologists that a general warming trend in the climate became effective around the North Atlantic basin about the beginning of the present century. Evidence for this is cited in the general introduction to the present series of studies on the Mesters Vig district (Washburn, 1965) and need only be mentioned here. It is based first upon meteorological observations from the few stations in the North Atlantic region with records long enough to cover the period, and upon extrapolation from these. Second, it rests upon a great many careful observations and historical studies of the recent behavior of glaciers, sea ice, and of general weather conditions in the inhabited lands around the North Atlantic.

Specific meteorological data, continuous for the time span in question, are non-existent for the Northeast Greenland coast. Therefore a study by Dr. Lauge Koch (1945) of the northward retreat of the East Greenland sea ice after 1900 is of particular interest for the present investigation. He found that there had been exceptionally large quantities of ice along the coast southward from Scoresby Sund to Kap Farvel in the 300-year period from 1600 to 1900. This ice began to decrease about 1889, and continued to do so through 1939 which was the last year from which he had data. There were particularly small amounts of ice in the period 1920–1939 (Koch, 1945, p. 233–234; Fig. 104, p. 235). The success of summer shipping in Kong Oscars Fjord during the 1950's indicates that the scarcity of ice noted by Koch for the region south of Scoresby Sund has applied also in some measure to the southern part of the fjord region, and that the warming trend must have persisted, at least in some of its effects, through the 1940's and 1950's.

A warming trend of the magnitude described above would have the effect, on the slopes of the Labben peninsula, of reducing the size of the perennial snowdrifts available to supply meltwater during the summers, of eliminating others, and in general of promoting desiccation. The result in the vegetation would be a "migration" of wet meadow—turf hummock systems upslope below the retreating fronts of the snowdrifts. The most durable parts of the vegetation would be the mossy turf hummocks that were bound together by the root and stem systems of their woody plants, principally willows. It has already been noted that the last woody plants to survive in the degrading hummocks are the willows. Where upslope retreat has been relatively rapid, as it apparently has in the present instance, great numbers of turf hummocks or their relict willows could persist in the landscape and become a conspicuous feature of it.

The persistence of the turf hummocks in such numbers on many open slopes is evidence of the constancy of winter snow cover and general moderation of winter wind erosion in the Mesters Vig district. The hummocks could not resist the effects of such winds as are described in many other parts of the Arctic.

The summer climate of the Mesters Vig district during the period when the meadows covered the lower slopes is conjectural. The close correlation between the present meadows and their sources of water in snowdrifts and thawing ground indicates that at the present time the light and sporadic summer rain is of little consequence in the total supply. It is not impossible that summers under a somewhat colder climate, with large icefields offshore, would have been more stormy than now, with more precipitation at least some of which fell as rain. If this were the case the meadows would have been further enlarged by it, and the development of turf-hummock systems would have been accentuated.

Koch (1945) marshaled a great deal of corroborative evidence for these climatic changes from Icelandic history and from the Eskimo archaeology of Greenland. It is unnecessary to note this material here, but mention should be made of a paper by Thorarinsson (1951) already cited. This author emphasized the general decrease of frozen ground observed in Iceland during the second quarter of the present century, and related it to the disappearance of "rústs" noted by himself and others during the same period.

Caribou antlers are commonly found in the Mesters Vig tundra, but the last living caribou is reported to have been seen in the late 1890's. Koch (1945, p. 314) explored the possibility that known changes in caribou and musk-ox populations might reflect climatic trends. However, he concluded that "The periodical occurrence of these two animals

... says nothing about changes of the climate." It is worth noting that a major effect of the widespread desiccation on the lower mountain slopes of Northeast Greenland such as is suggested for the Mesters Vig district, would have been a large scale reduction in the feeding grounds available to these animals. The three cold centuries (1600–1900) probably were more favorable for them than were the subsequent warm years. It is known that the Eskimos hunted the caribou successfully on this coast from 1600 to 1800, and that the caribou were common between 1869 and about 1900. Musk-oxen, probably because they are more adaptable to extreme conditions, are still present in small numbers.

There is some evidence that the general warming trend previously noted may have been reversed. A study of an upward trend in global temperature, based on available recorded data up to 1939 was published by WILLETT in 1950. MITCHELL (1961) has revised and corrected WILLETT's analysis, adding certain data for the period prior to 1939 not available to WILLETT, and carrying the study forward through 1959. MITCHELL's analyses show that a cooling trend began in the early 1940's "at most latitudes," and that average global temperatures are now "comparable to those of the early 1920's" (MITCHELL, 1961, p. 249).

No evidence of increasing moisture on the Labben slopes during the last two decades was seen. Rather, the desiccation of the preceding decades appears to have continued. However, if the cooling noted by MITCHELL persists, the snow accumulations could be expected to enlarge and deliver meltwater to larger areas of the slopes.

The hummock chronology suggested by the case studied on the Labben slopes is not likely to apply widely, except that all or most of the hummock systems in the Mesters Vig district probably have developed within the climatic amelioration of the past 60 years. Within this period any stage or combination of stages could be prolonged or shortened by variations in slope, insolation, water supply, or the nature of the soils. Hummocks developed on other kinds of terrain will show different sequences. Shifts in drainage patterns due to various mass-wasting phenomena are frequent and sometimes violent in this district. Such a shift could stop the growth of a hummock system in mid-career, or rehabilitate one in a late stage of decay. Presumably a general enlargement of the snowdrifts would simply move the systems back down the slopes, expanding them at the same time.

Only one of the hummock areas at Mesters Vig could be interpreted as expanding. It was found in a valley among the Nyhavn hills west of Map Summit 162 m, and was characterized by large isolated hummocks that appeared to have suffered from desiccation and erosion. The intervening areas, however, contained a wet sedge meadow, and the hummocks seemed to be well supplied with water. Their vascular flora was the richest found on any hummocks in the district. A possible explanation for this situation is that the process of deterioration in the hummocks was arrested by a renewal of the water supply to the area. If this is the case, and if the renewed supply should continue, new hummocks could be expected to form among the old ones, but no instances of this were seen. The uniqueness of this situation among the otherwise prevailingly retreating hummock systems suggests that it has been caused by local factors.

THE VASCULAR FLORA OF THE TURF HUMMOCKS

Forty species of vascular plants were found growing on turf hummocks in the Mesters Vig district. The flora of individual hummocks usually was found to be small, commonly of not more than four to six species; but there was great variability in the occurrence of the species, particularly those of secondary significance in the plant cover. The density of the vascular plant cover was also extremely variable. Some hummocks were so densely covered that the moss of the substratum was scarcely visible, while in others large patches of moss occurred in nearly pure stands.

Data for the following analysis of the hummock flora were gathered from twenty areas of study. Eleven of these were the dissected hummocks that have already been described. The target line of experimental site 6 traversed hummocks that appeared to be in three different stages of development, and was therefore subdivided as follows: targets 9–13, 14–24, 25–28. General notes and collections were made in five areas where the hummocks were well developed and not extensively degraded. The first of these was in a valley west of Map Summit 162 m in the Nyhavn hills, and the second was in a wet hummocky meadow north of experimental site 15 and just east of Map Summit 112 m. The third lay between the target lines of experimental sites 7 and 8, and included the dissected hummock shown in Figure 9. The fourth was the hummocky meadow north of experimental site 5, illustrated in Figures 18, 22 (parts of Zones B and C, Fig. 19). This area included the dissected hummock shown in Figure 11. The fifth was near the north shore of a small lake between Map Summits 180 m and 186 m on the lower north slope of Hesteskoen. Finally some general notes were made in the area of deteriorating hummocks north of experimental site 5. This area is illustrated in Figures 24, 25 (lower part of Zone C, Fig. 19). The dissected hummock shown in Figure 12 was included here. The occurrence of the species on all of the dissected hummocks and in all of the hummock areas studied is assembled in Figure 40.

In Figure 40 the species are arranged in an order showing the relative frequency with which they were listed in the 20 situations studied. At the top are three species (*Carex Bigelowii*, *Salix arctica*, *Vaccinium*

+ = species present
⊕ = species primary

	Dissected hummock, Fig. 2	Dissected hummock, Fig. 3	Dissected hummock, Fig. 4	Dissected hummock, Fig. 5	Dissected hummock, Fig. 6	Dissected hummock, Fig. 7	Dissected hummock, Fig. 8	Dissected hummock, Fig. 9	Dissected hummock, Fig. 10	Dissected hummock, Fig. 11	Dissected hummock, Fig. 12	Targets 9–13, exp. site 6	Targets 14–24, exp. site 6	Targets 25–28, exp. site 6	Wet hummocky meadow N. of exp. site 7	Hummocky area between exp. sites 7 & 8	Hummocky meadow N. of exp. site 5	N. shore of lake between MS 180 & MS 186 m	In valley W. of MS 162 m, Nyhavn Hills	Degrading hummocks N. of exp. site 5
Carex Bigelowii	⊕	⊕	⊕	⊕	⊕	⊕	..	⊕	⊕	⊕	..	+	+	+	+	⊕	⊕	..	+	..
Salix arctica	⊕	..	⊕	..	..	..	⊕	⊕	⊕	+	⊕	⊕	+	+	⊕	⊕	⊕	+	+	⊕
Vaccinium uliginosum ssp. *microphyllum*	⊕	⊕	⊕	⊕	⊕	⊕	..	⊕	..	+	..	+	+	+	+	⊕	+	+	⊕	..
Polygonum viviparum	+	+	..	..	..	..	+	..	+	..	..	+	+	..	+	+	+	+	+	+
Dryas octopetala	..	..	..	+	..	..	..	..	..	..	..	+	+	+	+	+	+	⊕	+	..
Cassiope tetragona	+	..	..	+	..	⊕	⊕	..	⊕	..	..	..	+	..	⊕	..	+	..	+	..
Carex misandra	..	..	..	..	..	..	..	..	..	..	..	..	+	+	..	+	+	+	+	+
Carex scirpoidca	..	..	..	..	..	..	..	..	..	⊕	..	+	+	..	⊕	..	..	+	⊕	..
Silene acaulis	..	..	+	..	..	..	..	..	..	..	..	⊕	+	..	⊕	..	..	..	+	+
Poa arctica	..	+	..	..	..	+	..	..	+	..	..	+	..	..	..	..	..	..	+	..
Carex parallela	..	..	..	..	..	..	..	..	..	..	..	+	+	+	..	..	+	..	..	+
Pedicularis flammea	..	..	..	..	..	..	..	..	..	..	..	..	+	+	..	+	..	..	+	..
Equisetum arvense	..	..	..	..	..	..	..	..	..	..	..	+	..	..	..	..	..	..	+	+
Equisetum variegatum	..	..	..	..	..	..	..	..	..	..	..	+	..	..	..	..	..	..	+	+
Eriophorum triste	..	..	..	..	..	..	..	..	..	..	..	+	..	..	..	..	..	..	+	+
Saxifraga oppositifolia	..	..	..	..	..	..	..	..	..	..	..	..	..	+	..	..	+	..	..	+
Poa glauca	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	+	..	..	+
Carex capillaris	..	..	..	..	..	..	..	..	..	..	..	..	+	+	..	..	..	..	..	..
Oxyria digyna	..	..	..	..	..	..	..	..	..	..	..	+	..	..	..	..	..	..	+	..
Stellaria Edwardsii	..	..	..	..	..	..	+	..	..	..	..	..	..	..	..	..	..	..	+	..
Melandrium apetalum ssp. *arcticum*	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	+	..	+
Saxifraga cernua	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	+	+	..
Lycopodium Selago	..	..	..	..	..	..	..	..	..	..	..	..	..	..	+	..	..	..	..	..
Poa alpina	..	..	..	..	..	..	..	..	..	..	..	..	..	..	+	..	..	..	..	..
Trisetum spicatum	..	..	..	..	..	..	+	..	..	..	..	..	..	..	..	..	..	..	..	..
Eriophorum Scheuchzeri	..	..	..	..	..	..	..	..	..	..	..	+	..	..	..	..	..	..	..	..
Carex nardina	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	+	..
Luzula frigida	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	+	..
Luzula confusa	..	..	+	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Luzula arctica	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	+	..	..	..
Luzula spicata	..	..	..	..	..	..	..	..	..	..	..	..	..	..	+	..	..	..	..	..
Tofieldia pusilla	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	+	..
Minuartia biflora	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	+	..	..
Cerastium alpinum	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	+	..
Draba alpina	..	..	..	..	..	..	+	..	..	..	..	..	..	..	..	..	..	..	..	..
Draba lactea	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	+	..	..
Empetrum nigrum var. *hermaphroditum*	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	⊕	..
Epilobium latifolium	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	+	..
Pedicularis lapponica	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	+	..
Pedicularis hirsuta	..	..	..	..	..	..	..	..	..	..	..	+	..	..	..	..	..	..	..	..

Fig. 40. Chart showing the species of vascular plants found on turf hummocks in the Mesters Vig district.

uliginosum ssp. *microphyllum*) each of which was present in 16 of the localities. Next is *Polygonum viviparum* which was present in 12 situations. Thus the arrangement is in a descending order of frequency down to the last 18 species, each of which was seen in only one of the localities. Notes on relative local abundance were made in 18 of the 20 localities, and then only by ocular estimate. A single subdivision was made in these notes: between "primary" and "secondary" species, and the former are indicated in Figure 40. An analysis of the frequency with which the species were primary among the 18 cases shows that *Salix arctica* was so noted in 11 situations, *Carex Bigelowii* in 10, *Vaccinium uliginosum* ssp. *microphyllum* in 9, *Cassiope tetragona* in 4, *Carex scirpoidea* in 3, *Silene acaulis* in 2, and *Dryas octopetala* and *Empetrum nigrum* var. *hermaphroditum* each in 1.

It is obvious that the data from the various localities studied are not truly comparable because of differences in size of samples, particularly between those from dissected hummocks and those from larger areas involving groups of hummocks. This is clearly shown by the total numbers of species listed in the two kinds of situations. They average about 4 on the dissected hummocks and about 12 for the larger areas. In order to eliminate as much of this inequality as possible, the data for the two kinds of studies have been analyzed separately.

Carex Bigelowii was present on 9 of the 11 dissected hummocks and primary on 7 of them. *Vaccinium uliginosum* ssp. *microphyllum* was present on 8 and primary on 7; *Salix arctica*, present on 7 and primary on 6; *Cassiope tetragona*, present on 5 and primary on 3; *Polygonum viviparum*, present on 4; *Poa arctica*, present on 3; and the following present on 1 each: *Trisetum spicatum*, *Carex scirpoidea* (primary on 1 hummock), *Luzula confusa*, *Stellaria Edwardsii*, *Silene acaulis*, *Draba alpina*, *Dryas octopetala.*

Frequencies of species listings in the 9 larger areas were as follows:

Present in 9 areas: *Salix arctica* (primary in 5 areas)
– - 8 – *Polygonum viviparum*, *Dryas octopetala* (primary in 1 area), *Vaccinium uliginosum* ssp. *microphyllum* (primary in 1 area)
– - 7 – *Carex misandra*, *Carex Bigelowii* (primary in 3 areas)
– - 5 – *Carex scirpoidea* (primary in 2 areas), *Carex parallela*, *Silene acaulis* (primary in 2 areas)
– - 4 – *Cassiope tetragona* (primary in 2 areas), *Pedicularis flammea*
– - 3 – *Equisetum arvense*, *Equisetum variegatum*, *Eriophorum triste*, *Saxifraga oppositifolia*

Present in 2 areas: *Poa arctica*, *Poa glauca*, *Carex capillaris*, *Oxyria digyna*, *Melandrium apetalum* ssp. *arcticum*, *Saxifraga cernua*

– - 1 – *Lycopodium Selago*, *Poa alpina*, *Eriophorum Scheuchzeri*, *Carex nardina*, *Luzula frigida*, *Luzula arctica*, *Luzula spicata*, *Tofieldia pusilla*, *Minuartia biflora*, *Stellaria Edwardsii*, *Cerastium alpinum*, *Draba lactea*, *Empetrum nigrum* var. *hermaphroditum* (primary in 1 area), *Epilobium latifolium*, *Pedicularis lapponica*, *Pedicularis hirsuta*

In spite of a lack of strict comparability among the situations from which data were taken, all of the analyses show the same small group of species to be most frequently listed on turf hummocks, some of them most commonly noted as primary species. These are *Salix arctica*, *Vaccinium uliginosum* ssp. *microphyllum*, *Polygonum viviparum*, and *Carex Bigelowii*. Then comes another group, also appearing in all of the analyses, and made up of species extremely common but not so pervasive as the preceding four: *Dryas octopetala*, *Carex scirpoidea*, *Cassiope tetragona*, *Silene acaulis*. Four other species probably should be included here, although they fail to appear in one or the other of the two major groups of situations sampled: *Carex misandra*, *Carex parallela*, *Poa arctica*, and *Pedicularis flammea*. These species are common, and their absence from one or another group of lists is due to the nature of the sampling rather than to actual differences in their distribution.

Figure 40 indicates that the vascular flora of individual turf hummocks varies from one to six species, but this is based upon the limited sample of the eleven dissected hummocks. Actually the total number that can be found on a single hummock is considerably more than six, though no attempt was made to list the largest number possible. Young hummocks just appearing in wet moss mats commonly have only a single species on them, which may be a sedge such as *Eriophorum* or *Carex*, or a willow, *Salix arctica*. The same is true of hummocks growing over stones or other microrelief features in stream channels or sheet-flow areas. The hummocks with the richest vascular flora seen were those in a valley in the Nyhavn hills west of Map Summit 162 m. These hummocks appeared to be relatively old, about 50 cm high, and well segregated from each other. The total vascular flora for all the hummocks of the area was 24 species, considerably more than in any equivalent area studied.

It is proposed in the present paper that hummocks in the Mesters Vig district commonly experience a developmental sequence involving youth, maturity, deterioration, and finally complete elimination. Their vascular flora in the beginning stages is known to be extremely simple, often consisting of a single species; and in the final stages of deterioration it is also known to consist of a single species. Consequently one could postulate, at least in theory, a development and deterioration of the more elaborate vascular flora that exists in the intervening stages. It is tempting to try to arrange the 20 situations noted in Figure 40 to illustrate some of the stages in this sequence, but it soon becomes clear that various factors of time and geomorphic process have affected the areas in ways that do not seem to be reflected in the flora. Hence it is impossible with present knowledge to do much more than make the threefold sequence already mentioned: a very simple youth stage, a more complex vascular flora in the stages surrounding the "maturity" of a hummock, and a very simple flora in the late stages of deterioration. A notable feature of this sequence is that the "middle" segment covers large changes along moisture and disturbance gradients, while the flora remains relatively unaltered. This suggests that most of the vascular flora of the hummocks is endowed with wide tolerance.

SUMMARY OF OBSERVATIONS AND CONCLUSIONS ON THE STRUCTURE AND DEVELOPMENT OF TURF HUMMOCKS IN THE MESTERS VIG DISTRICT

Turf hummocks are abundant in the Mesters Vig landscape, and form a major feature of the terrain and vegetation. They occur in all stages of development, from small ones 5–10 cm high and broad, to mature ones 50 cm high and a meter broad at the base. Well-defined, growing hummocks are found only on sites abundantly supplied with gently flowing surface water throughout most of the summer season. They may be common on drier sites, but here they are always in some stage of disintegration. They are found on any kind of soil, from gravel to clayey silt or stony loam, and on slopes of from 1° to 15°. They may or may not have earth cores appearing as upward projections of mineral soil beneath them. If well-defined cores are present, the underlying mineral soils usually are fine-textured ones—silts or silt loams. If coarser sandy material is a prominent constituent in the cores, the cores usually contain organic fibrous materials, and the hummocks containing them are usually situated in stream channels where flood waters have partially submerged them and deposited the sand in the early stages of their growth.

There is marked asymmetry in well-developed hummocks, usually oriented to the direction of slope. Their upslope sides are steepest—in places almost vertical—while their lower sides taper off more gradually. Due to the insulating properties of the turf, the interiors of the hummocks freeze later in the autumn than the inter-hummock areas, and remain frozen much later in spring and early summer.

The basic structure of the Mesters Vig hummocks is of mosses. In a well-developed hummock the living portion of the moss forms a cap 2.5 to 5 cm thick on the top. This grades downward into a layer of dark brown to black, root-filled turf of varying thickness depending upon the size of the hummock. At the base of the turf the latter commonly merges into a greasy, fine-textured humus layer which usually is only 2–3 cm thick. Beneath this humus is the mineral soil.

The vascular flora of the larger hummocks is characterized by the woody plants of the local tundra and by the sedges and grasses associated with them: *Vaccinium uliginosum*, *Salix arctica*, *Dryas octopetala*, *Cassiope tetragona*, *Carex Bigelowii*, *Carex scirpoidea*, *Carex misandra*, *Poa arctica*, etc. Most of these species are rooted in the turf, but a few, notably *Salix arctica*, are firmly established in the mineral soil beneath. Usually the vascular plants form a rather dense cover, but on some hummocks the mosses are exposed.

Observations indicate that turf hummocks in the Mesters Vig district have several modes of origin and development. Because mosses form the basic component of all the hummocks, the characteristics of the mosses figure prominently in their development. Further, because the formation and growth of the hummocks is closely associated with abundant surface water, aquatic mosses are the most significant species in their incipient stages. The hummocks do not begin to develop appreciable volume or height until the more mesophytic mosses appear on them; and before this can occur there must first be formed some kind of "eminence," or "micro-elevation" above the general level of the continually wet surrounding surfaces. Judging by observations in the area of the present study, such small elevations for the more mesophytic mosses are achieved in the following situations.

A. On cobbles, small boulders, or on local sand and silt deposits in shallow stream beds that carry enough water throughout the summer to keep the sites wet but in which the currents are not strong enough to remove growing mosses. Similar situations may be found on occasional cobbles or boulders in areas of sheet-flow runoff below perennial snowdrifts.

B. In snow-bed environments, and in places where seepage issues from thawing ground, moss polsters form and occasionally develop into small hummocks. However, growth is exceedingly slow in these situations, due in the first instance to the short season available, and in the second to the variable nature of the water supply.

C. The rapid upfreezing of stones in fine-textured soils first domes the surface and eventually the stones break through. This is a valid source of small microrelief, and hummocks are occasionally found with such stones projecting into their turf.

D. In some areas initial stages of hummock growth may have occurred on microrelief features due to gelifluction, and in places embryo earth cores may be structures formed by gelifluction.

E. In wet meadows on gentle slopes supplied with abundant water by sheet runoff from snowdrifts and thawing ground, aquatic mosses form dense mats in which sedges and grasses are commonly found. The surfaces of the moss mats are never even and level, but are slightly hummocky. This may be due in part to the growth habits of the mosses, and in part to differential accumulation of humus and silt about the bases of the grasses and sedges. Whatever the cause, the small hummocks are extremely common in the wet meadows. They form nuclei for the growth of more mesophytic mosses, and for the development of the vascular flora.

The largest proportion of all the hummocks in the Mesters Vig district appears to have developed in the last of the above situations. It is most extensive on the long gentle slopes reaching from the shores of Kong Oscars Fjord up to the bases of the nearby hills and mountains. Apparent sequences of development in turf hummocks, from incipient stages through maturity to deterioration and final disintegration, can be seen on the gentle slopes immediately below snowdrifts. They may be interpreted in terms of the seasonal and longer-term regimes of water supply, erosion and frost action.

In the upper parts of such areas, where the water supply is abundant throughout the season, there is no desiccation and no erosion. Moss-sedge meadows form dense, vigorous cover through which meltwater flows in sheets. If the snow melts much farther back during the summer, the result is "snowbed," in which time is inadequate for vegetation to develop at all. The wet meadow mosses develop many small mounds which gradually rise above the water levels and begin to channel the flow of water, thus accentuating the hummock form. The mounds, even when very small, acquire the shrub flora characteristic of larger hummocks. The hummocks become progressively larger downslope, and the channels deeper. Gradually the hummocks become separated by areas of bare soil, and so much meltwater from the snowdrifts is lost en route by evaporation, infiltration to the now thawed soil, or to the plants, that by mid-summer there is pronounced desiccation of the vegetation and the surface soils. This leads to mortality in the mosses of the turf hummocks that were formed there, and among the higher plants growing in them. These dead mosses and other plant parts are then subject to easy erosion by the meltwater of the following spring, which is now firmly channeled among the hummocks and thus has a more rapid flow than if it came in a sheet. The hummocks now show pronounced asymmetry in form. Still farther downslope there is progressive deterioration of the hummocks, with a gradual "weeding out" which produces wider spacing. Finally, on the dry slopes beyond the reach of any appreciable summer moisture, the hummock mosses disappear completely.

Disturbance of the underlying soils by frost heaving probably does not become effective in the above sequences until after the continuous moss mats of the wet meadows are broken up by the channeling of the water. Its effect on the sequences probably remains intense only while the hummocks are actively growing in size, in the areas where the inter-hummock channels retain moisture throughout the summer. It then becomes progressively less effective downslope.

It is suspected that the rodent populations of such areas are relatively insignificant in the upper parts of the sequences, gradually increase during the period of rapid hummock growth and maximum influence of differential frost heaving, and probably reach their peak in the later parts of the sequences.

Evidence that these sequences illustrate actual developmental histories that have been passed through by individual turf hummocks is found in the root and stem systems of willows (*Salix arctica*) that grow in profusion on the hummocks. These willows appear when the hummocks first begin to take form as low mossy mounds in the wet meadows. They root in the mineral soil beneath, and persist not only throughout the life of the hummocks, but remain living long after all trace of moss and turf has vanished. They then appear with perched stems and partially exposed roots on the dry slopes far below the present sources of meltwater from the snowdrifts. A study was made of the growth patterns in 68 of these willows collected on a dry slope adjacent to the lower, deteriorating portion of one of the sequences described above. In effect these willows not only indicate that individual turf hummocks have passed through the stages described in a representative transect, but they also measure the time involved in the sequential changes.

The annual "rings" or "zones" of wood in the roots and stems indicate that most of these willows germinated and had relatively rapid, uninterrupted growth in a wet meadow that covered this slope between 1900 and sometime in the 1920's. The willows then began to suffer increasingly from periodic suppressions in their growth rates, apparently due to injuries. At the same time additions to their population by new germinations began to decline. There were no additions after 1941, and current mortality is high.

A study of 31 other willows, collected from a wet meadow approximating the conditions postulated for the dry slope late in the period between 1900 and the 1920's showed patterns of growth that duplicated the patterns found in the perched willows of the dry slope during that period. The position of this meadow in its wet meadow—turf hummock sequence suggests that the beginning of deep channeling, rapid hummock growth, intense frost heaving, and probably the advent of rodent populations, became effective in the perched willow area about the mid-1920's or early 1930's. Thus at least a portion of the hummocks in this area completed their development, from incipient stages to disintegration, in less than 40 years.

To produce the amount of surface water necessary to supply such large meadows, the snowdrifts presumably were much larger than they are now, indicating a climatic change of some magnitude during at least the past 40 years. This change is identified with a general warming trend around the North Atlantic basin which began about 1900. This trend would have the effect, in the Northeast Greenland coastal region, of causing the perennial snowdrifts to decrease in size, and in general of promoting desiccation.

The Mesters Vig turf hummocks look as though they were primarily vegetational phenomena, and their vegetation has the appearance of near-stability that has been attributed to similar structures elsewhere. But their natural history shows them to be only transient and perishable things. Their mesophytic mosses have a flash of success for a time, and actually account for most of the hummock volume; but they have to do this quickly before the erosional and thermal mechanisms that they produce through dense growth and by channeling of the water isolate them and raise them too high in the air. Desiccation then begins to injure them, making their erosion easier and more rapid. The hummocks are in part built by, and eventually destroyed by physical processes which they themselves by their presence help to set in motion. The seeds of their destruction are present from the earliest stages of their growth, for once the channeling, differential frost heaving and erosion start, given the overweening influence of the retreating water supply, destruction is inevitable.

The whole complex of interacting processes, from beginning stages to the dissolution of the hummocks, runs its course in time intervals that are well within the life spans of the longer-lived plants of the tundra. Under these circumstances biological succession in the hummocks is fragmentary. Most of the vascular plants concerned are drawn from that curious and surprisingly large group of arctic species that have wide tolerances with respect to environmental gradients, and most of them appear while the hummocks are quite small and saturated. They last as long as there is any appreciable moisture in the turf, but in the last stages of hummock decay the mosses and turf are thoroughly dry in summer, and there remain only the willows, the most tolerant of all.

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Færdig fra trykkeriet den 31. december 1965.

Map of Mesters Vig district, showing location of experimental sites.