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THE VEGETATIONAL RELATIONS OF WEATHERING, FROST ACTION, AND PATTERNED GROUND PROCESSES, IN THE MESTERS VIG DISTRICT NORTHEAST GREENLAND

BY

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WITH 47 FIGURES AND 11 TABLES
IN THE TEXT

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Abstract

Botanical descriptions and analyses presented in this paper apply to representative sites selected from those discussed by Washburn in "Weathering, frost action, and patterned ground in the Mesters Vig district, Northeast Greenland" (Meddr Grønland 1969, Bd. 176 No. 4). They deal with vegetation-site relations in the following habitat complexes: rocky hilltops, ledges, crevices and talus; simple and compound nonsorted circles and their included small nonsorted polygons; small sorted and nonsorted polygons on emerged delta remnants; large nonsorted polygons; debris islands; and large sorted nets. Site factors used are: coverage of the ground by vascular plants; moisture supply; and physical disturbance of the soil by frost- and nonfrost-induced geomorphic processes. The vegetations are analyzed with respect to their species' tolerance of variation and intensity in the factor gradients. A summary compares the sites in terms of the relative proportions of wide, intermediate and narrow tolerance shown by their vascular floras on each of the gradients.

The analyses presented show, as did those made for the mass-wasting sites, positive correlations between the local distribution of species tolerance and the local behavior of the site factors of coverage, moisture and physical disturbance. They suggest further that the ratings of species tolerance made from general observations are sufficiently valid to be useful as indicators of these site conditions.

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GENERAL INTRODUCTION

The present paper is intended as a botanical companion-piece to WASHBURN's study of "Weathering, frost action, and patterned ground in the Mesters Vig district, Northeast Greenland" (WASHBURN, 1969). Observations of the vegetation were made in varying detail at many of the sites discussed by Dr. WASHBURN in this paper, and at some of them none at all. Consequently, although the general order of presentation will parallel that of his paper, several parts of the latter will be treated cursorily.

Most of his section on "Weathering" is of botanical significance mainly as it applies to the origin and development of the soils (see UGOLINI, 1966 A, B for discussions of the Mesters Vig soils). Direct effects of weathering processes upon the present flora no doubt occur, but it was impossible with the time and facilities available to make precise studies of them. Processes due primarily to frost action, on the other hand, appear to be of immediate importance to the growth and survival of plants. Most significant of these are frost heaving and thrusting, though in localized areas mass displacement produces striking effects. Among the patterned ground features discussed by WASHBURN turf hummocks have already been treated at some length (RAUP, 1965 B). Nonsorted circles and related forms, small sorted and nonsorted polygons, large nonsorted polygons, debris islands, and large sorted nets and polygons were studied botanically in considerable detail and will be discussed below. All of these involve processes that directly affect the vegetation, though with varying intensities. Sorted and nonsorted stripes and nonsorted steps were given but little botanical study in the field, for their effects upon the flora closely resemble those found in the circles, polygons and nets.

Methods used in the analysis of the vegetation were those already described (RAUP, 1969 A) and applied to sites illustrative of mass-wasting processes (RAUP, 1969 B). They will be described briefly here, and the reader is referred to the above papers for more detail.

Each vascular species was assigned a "rating" based upon studies of some 300 sites representing a wide variety of habitats in the Mesters Vig district. These habitats were in turn classified with respect to their approximate positions on gradients of ground coverage by vascular plants, moisture supply, physical disturbance of the soil due to frost action, and physical disturbance due to nonfrost geomorphic processes. The ratings of the species, estimated by the presence or absence of the latter in these habitats, reflect their capacity to withstand variations in ground coverage and moisture and their adjustment to differing intensities of disturbance.

Three-fold divisions were used for the species rating and for the environmental gradients. The term "wide tolerance" refers to the capacity of a species to survive wide variation in one or other of the factors studied, and to occupy sites representing $^2/_3$ of the factor gradient or more. "Narrow tolerance" means that the species was found on $^1/_3$ of a factor gradient or less. "Intermediate tolerance" means the capacity to live in more than $^1/_3$ but less than $^2/_3$ of a gradient. Ratings of species on the coverage and moisture gradients give no indication of where on these gradients limited tolerances occur. Data on such preferences will be found in RAUP, 1969 A, Table 1 and Figs. 9, 10 and 11. On the disturbance gradients, with a few minor exceptions, progressively limited tolerances indicate progressively limited capacities to withstand disturbances.

In the vascular flora as a whole, 22 species were regarded as widely tolerant on all the gradients used, and 17 species were narrowly tolerant on all the gradients. For comparative studies of habitats and vegetations these 39 species were considered non-definitive. Base numbers for computing proportions of tolerance ratings were therefore made by subtracting the numbers of non-definitive species found in the habitats from the total floras of the latter.

The distribution of species tolerance on the factor gradients is given in percents of the base numbers (definitive species) occurring in the various habitats. Some of these data appear in the discussions under each site complex, and all of them are in the graphs presented in the Summary and Discussion (Figs. 44–47, incl.).

As in the analyses made for the mass-wasting sites, the results of the present ones are regarded as tests for the validity of the tolerance ratings, and of their relevance as indicators of environmental processes.

Fig. 1. Cliffs and talus of trap and sandstone, Labben near ES 2, 3, 9. 19 July, 1957.

THE VEGETATION OF ROCKY HILLTOPS, LEDGES, CREVICES AND TALUS

Introduction

Vegetation growing on soils derived from weathering processes is largely limited to rock faces, ledges, crevices and talus. In the Mesters Vig district the rocks are principally shales, sandstones, conglomerates, and basaltic intrusives. The sandstones and basalts are the most prominent in the local landscape (Fig. 1). On some of the higher mountains there are outcrops of limestone. The sedimentary rocks are considered to be of Paleozoic age, ranging from upper Carboniferous to (possibly) Lower Permian. The intrusives are believed to date from the Tertiary. At low elevations on the hills back of Nyhavn, on the Labben peninsula, and on the lower northerly slopes of Hesteskoen and Korsbjerg are many trap knobs with altitudes ranging from fjord level to about 180 m. In a few places the trap forms caps on sandstone hills. Similar situations are found at higher altitudes, as on Gorms Spids (525 m) and near the summit of Hesteskoen (1118 m).

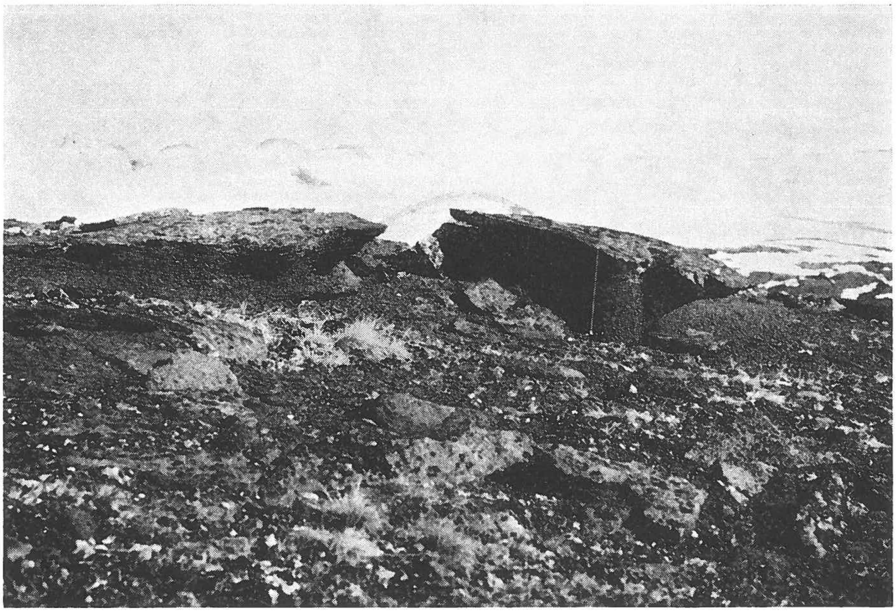

Fig. 2. Weathered and distintegrated trap bedrock on summit of trap knob MS 112 m, hills of back Nyhavn, 15 June, 1956. Local relief at hanging tape is 25 cm. Scattered vegetation in grus mainly *Carex rupestris*, *C. nardina*, *Poa glauca*. (From WASHBURN, 1969, Fig. 3).

Topography and soils

Plant habitats found on the tops of the rocky hills for the most part have thin, excessively drained soils (Lithosols: see UGOLINI, 1966 B, p. 8) composed of cobbles, pebbles and coarse sand (including the grus that weathers out of the trap). Occasionally, usually in depressions, there are pockets of glacial till or marine sediments containing finer textured material, but more characteristic are convex rock surfaces bare of fines or thinly mantled with grus. The grus is locally variable in texture, in some places containing higher proportions of fine sand (Fig. 2).

Closely related to this habitat are talus accumulations on ledges and around the bases of cliffs (Fig. 1). Some of these are small and fairly stable, while others are large and show evidence of dry creep (WASHBURN, 1967, p. 78–86; RAUP, 1969 B, p. 160–179).

Site factors

Coverage of ground by vascular plants

Density of vascular plant coverage is low throughout these habitats. It ranges from zero to about 20 %, but most of the sites observed had less than 10 % of the ground covered. Variation in coverage, therefore, is correspondingly low.

Moisture supply

Moisture supply to these sites is confined mainly to spring snow-melt. The soils become dry early in the summer and remain so throughout the open season except for occasional light rains. The latter dampen the surface materials but the moisture is quickly lost by drainage or evaporation. Cracks and crevices in the rounded hill tops hold somewhat more moisture, for a longer time. They also collect humus which increases their waterholding capacity. Shallow depressions collect drainage from the surrounding convex surfaces and in some places hold it through most or all of the summer. Their finer textured soils further their capacity to hold moisture. Soils adjacent to the bases of high cliffs, particularly at the upper margins of large talus accumulations, are commonly well watered by seepage derived from ice in the deeper crevices of the hills.

Seasonal variation in moisture supply to the thin sandy soils on hill tops and ledges, and on most of the talus, is relatively small in terms of plant requirements. Although there is an abundance for a very short time after snow-melt, it disappears too quickly to have much lasting effect upon plant establishment and growth. Therefore the sites remain relatively dry, without much variation.

Disturbance factors

Because of coarse texture, summer desiccation, and the lack of soil moisture at autumn freeze-up, most of the ledge, crevice and talus soils are very little disturbed by frost heaving. On the other hand, those on steep slopes are affected by dry creep, and those on the tops of the hills are frequently subject to wind deflation and deposition.

The vegetation

Forty-seven species of vascular plants were seen growing on convex rocky knolls, in crevices, and on dry talus. This number does not include the species found only in the more moist sites on the hills—depressions, damp ledges, and talus immediately below cliffs. These moist sites contain vegetation closely related to that of heath tundra or to that of organic crusts. Of the 47 species 29 (61.7 %) were found to be generally common to abundant in the Mesters Vig district, 17 (36.2 %) were occasional or locally common, and 1 (2.1 %) was rare.

The plants were much scattered, nowhere forming large aggregations. There were occasional small mats or clumps of *Dryas*, *Vaccinium* or *Cassiope*, and on some of the loose soils on the tops of knolls there were enough sedges and grasses to give the appearance, at a distance, of a pale green sward. These were in areas having finer textured grus. This vegetation was described, in part, in the analysis of ES 16 (RAUP, 1969 B, p. 169–173). A list of the flora is in Table 1.

Table 1. *Species found on rocky hilltops, ledges, crevices and talus.*

Woodsia glabella
Cystopteris fragilis
Festuca brachyphylla
Poa alpina
Poa glauca
Trisetum spicatum
Calamagrostis purpurascens
Kobresia myosuroides
Carex nardina
Carex scirpoidea
Carex glacialis
Carex supina ssp. *spaniocarpa*
Carex rupestris
Carex misandra
Luzula spicata
Luzula confusa
Salix arctica
Oxyria digyna
Polygonum viviparum
Cerastium alpinum
Arenaria pseudofrigida
Minuartia rubella
Silene acaulis
Melandrium affine
Papaver radicatum
Draba nivalis
Draba lactea
Draba fladnizensis
Draba subcapitata
Draba glabella
Draba cinerea
Sedum Rosea
Saxifraga oppositifolia
Saxifraga nivalis
Saxifraga tenuis
Saxifraga cernua
Saxifraga caespitosa
Potentilla nivea
Dryas octopetala
Epilobium latifolium
Cassiope tetragona
Vaccinium uliginosum ssp. *microphyllum*
Pedicularis hirsuta
Campanula rotundifolia
Antennaria canescens
Arnica alpina
Taraxacum phymatocarpum

Behavior of the vascular species on gradients of ground coverage, moisture, and physical disturbance

In the flora of these dry sites 18 species were widely tolerant on all the gradients studied, and one was narrowly tolerant on all of them. Eliminating these from the analysis, 28 species were regarded as definitive (see Figs. 44, 45, 46, 47).

The coverage gradient (Fig. 44)

Fifty percent of the definitive species were widely tolerant of variation on this gradient, about 14$^0/_0$ were narrowly tolerant, and about 36$^0/_0$ were intermediate (Fig. 44). Correlations of figures such as these with known coverage variations in specific site complexes have not been very satisfactory in the Mesters Vig district.

However, in most of the habitats analyzed there has been a great preponderance of species widely tolerant of coverage variation. Of 29 sites other than the present one the average percentage of widely tolerant species was 84, in a range of 60% to 100%. Only three of these sites showed percentages below 70%, and in six of them all of the species were widely tolerant. Thus the 50% wide coverage tolerance on knobs, ledges and talus is not only far below the average, but also below the range shown in other sites.

The average for narrow coverage tolerance in the same 29 sites was about 7%, in a range of 0% to 30%, 11 sites having no species with narrow tolerance, and only 5 with percentages over 14%. Therefore the 14% in the present analysis is regarded as relatively high.

A greater discrepancy was in the intermediates, where the average of the 29 sites was about 9% in a range of 0% to 24%. Thus the 36% of intermediates in the present analysis is much higher than either the average or the range.

These figures suggest that the flora has become adjusted to coverage conditions that vary considerably less than they do in other kinds of sites.

The moisture gradient (Fig. 45)

It was pointed out in an earlier paper (Raup, 1969 B, p. 175, Figs. 65, 71) that the habitats with least variation in moisture supply were those constantly very wet throughout the summer, and those that were very dry. Percentages of species widely tolerant on the moisture gradient ranged between 40% and 50% in these sites, while in habitats showing greater seasonal variation the range was between 55% and 80%. The least variable sites ranged between 35% and 55% of intermediately tolerant species while those with greater variation ranged from 40% down to about 7%. Average percentages of narrow tolerance in the two groups were about the same—approximately 8%, though a third of the sites with greater variation had no narrowly tolerant species at all.

The sites analyzed here were consistently dry except for ephemeral moisture supplies from spring-melt and from occasional light rain or snow in the open season. Their proportions of species tolerance were consistent with those of other sites having relatively small seasonal moisture variation (see Fig. 45).

The frost disturbance gradient (Fig. 46)

Only 14% of the definitive species were widely tolerant of disturbance due to frost action. The remaining 86% were about equally divided between intermediately and narrowly tolerant species (Fig. 46). These proportions are the expected ones in sites with very low soil moisture at the time of autumn freeze-up. There is a clear predominance of species sensitive to frost disturbance or only partially adjusted to it (see RAUP, 1969 B, Fig. 72).

The nonfrost disturbance gradient (Fig. 47)

Dry creep of soils, or their deflation and deposition by wind, are characteristic features of the rocky hill tops, crevices, ledges and talus. These processes are reflected in the low percentage of species sensitive to such disturbances (18%), and in the relatively high proportions of species very well adjusted or partially adjusted to them (36% and 46%, respectively) (Fig. 47). Thus the two kinds of disturbance, frost and nonfrost, show complimentary effects in the selection of species for these habitats.

SOME GENERAL OBSERVATIONS ON THE RELATIONS OF VEGETATION TO FROST ACTION

The most precise data on frost heaving in the Mesters Vig district were derived from target behavior in experimental sites. These data have been discussed in part, in preceding papers on mass-wasting (Washburn, 1967), on the vegetational effects of mass-wasting (Raup, 1969 B), and in Washburn's general discussion of frost action and patterned ground (1969). Further target data on heaving will be found in treatments of experimental sites in the present paper.

It is probable that nearly all soils in the district are disturbed in some measure by frost heaving and thrusting. In many soils the effects are minimal and have little or no influence upon the establishment and growth of plants, while in others the disturbances are lethal. The disturbances are caused by pressures generated in the soils when the contained moisture freezes. Resulting displacement upward is termed "heaving" while lateral movements are termed "thrusting". All phases of the process are not understood, but its effects are obvious (see Washburn, l. c. for further discussion).

Washburn (l. c.) has treated disturbance by frost action in two parts: surface and subsurface. He has confined the surface action to the uppermost few centimeters (1–5), and has stressed the work of needle ice which "probably disturbs the surface more thoroughly than any other frost action process if its frequency and distribution are taken into account. Upfreezing of stones and frost cracking break the surface, but these processes are essentially single episodes and affect small areas at any one time. On the other hand needle ice can affect relatively broad surfaces repeatedly. From the point of view of its effect on vegetation it is therefore particularly disruptive. Gentle deformation of the ground surface by heaving is certainly much more widespread than needle ice in the Mesters Vig district, but its disruptive influence is much less as shown by the continuous vegetation cover in many places where heaving must be recurring each year as the active layer freezes. Minute surface disturbance, such as those illustrated by gaps around stones and surface ice veinlets, if they develop in the spring may deter the growth of germinating plants, but would hardly seriously interfere with more mature plants whose roots extend more than a few centimeters beneath the surface. As indicated in the discussion of freeze-thaw cycles, short term cycles below a depth of 10 cm are infrequent in the Mesters Vig district, and are most probable in the autumn when plants are no longer germinating."

Evidence of heaving at depths to 20 cm was in the heaving of cone-targets and dowels. Those with 20-cm insertions were heaved much more than those with 10-cm pins. Involutions in the soils were seen in many excavations (Ugolini, 1966 B). The rapid upfreezing of large cobbles and boulders (Washburn, 1969, p. 52–58) indicated considerable frost action at depth, and large patterned ground features probably were products, in part, of deep seated frost action.

Washburn probably is correct in drawing a distinction, with respect to their effects upon plants, between surficial frost action and frost disturbance in deeper horizons. Most of the roots of the vascular plants were found in the uppermost 15 (20) cm of the soil. Consequently most mature or maturing vascular plants were not much affected by needle ice. Germinating plants, however, probably were injured or killed by it. It is possible that much of the low coverage density so common in the "fjaeld-mark" has been caused by needle ice disturbance of seedlings. Most of the observed needle ice work was in areas having very thin vascular plant cover. It was particularly conspicuous where the mineral soil was more or less covered by thin organic crusts. The crusts were commonly disrupted and torn, and the exposed mineral soil had a fluffy appearance. Further discussion of organic crusts and needle ice will be found in Washburn, 1969, p. 82–88 and Raup, 1969 B, p. 180–183.

That heaving deeper in the root zone has also been effective is shown by high mortality rates among mature plants in situations where intensitive disturbance has been demonstrated by target heaving. The intensity of this deeper heaving varies with the amount of moisture in the soil and with the amount and effect of insulating agents. Many such variations were seen in the development and deterioration of turf hummock systems (Raup, 1965 B) and in some of the experimental sites devoted to mass-wasting processes, notably in ES 6, 7 and 8 (Raup, 1969 B, p. 11–15).

Evidence from the experimental sites has shown that, in the absence or scarcity of freeze-thaw effects in the surficial soils, most of the injury to mature plants probably occurs at the major annual freeze-up in the autumn. If there is very little or no moisture in the soil at this time, heave injury is insignificant; but progressively greater amounts are accompanied by increases in the intensity of heave, and greater possibility of damage to roots and rhizomes.

Fig. 3. Nonsorted circles in the vicinity of ES 3 and 9, on the Nyhavn slope of Labben. 19 July, 1958.

VEGETATION OF NONSORTED CIRCLES AND RELATED FORMS

Introduction

Nonsorted circles and related forms have been discussed at length by Washburn (1969, p. 107 et seq.). The present account will deal primarily with their vegetational aspects, but will include information derived from Washburn's studies of the physical sites.

The most intensive studies of these forms were made in the vicinity of ES 3 and 9 on the Nyhavn slope of the Labben peninsula. General observations were made at the southeast base of a trap knob MS 120 m in the hills of back Nyhavn, and on the summit of a hill MS 266 m about

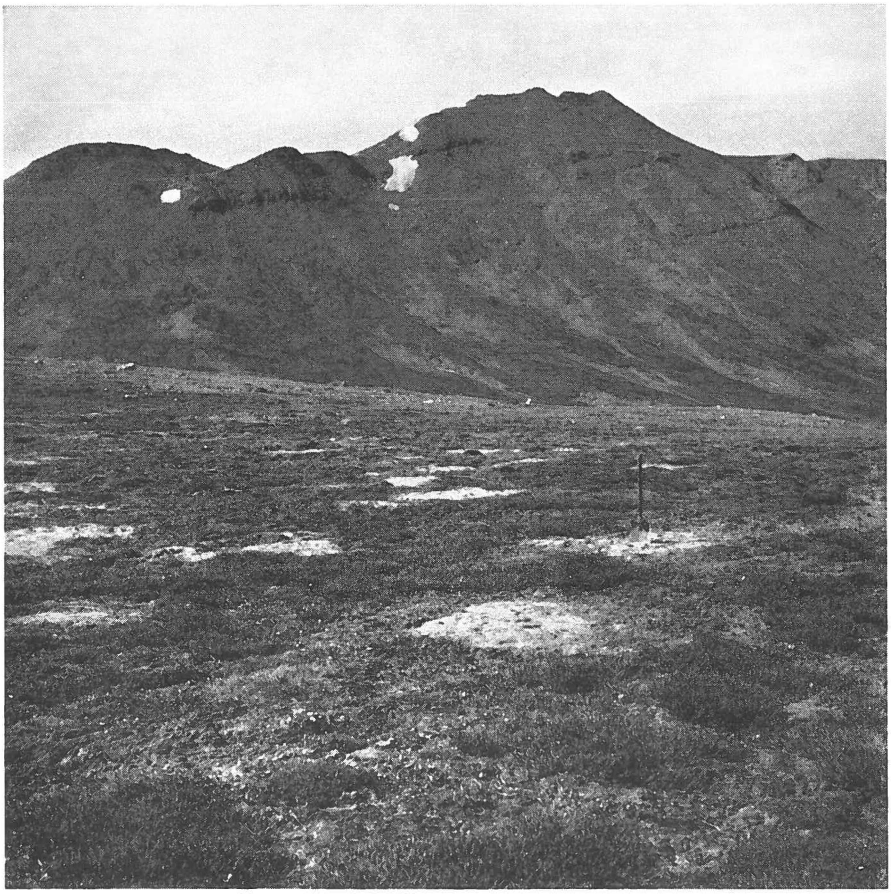

Fig. 4. Nonsorted circles on summit of hill northeast of Myggesø (MS 266 m). 25 July, 1958.

800 m northeast of Myggesø. Most of the vegetational data used here came from the Labben sites, though a few were derived from the hill near Myggesø and from occasional observations elsewhere.

Description of the sites

The nonsorted circles at the Labban and Myggesø sites were oval to circular patches of nearly barren sandy-silty clay surrounded by coarser-textured soils (Figs. 3, 4). The fines (silt and clay) in the circles ranged from 74 $^0/_0$ to 94 $^0/_0$, and liquid limits from 28 $^0/_0$ moisture to 34 $^0/_0$. The bordering soils were mainly of nonplastic gravelly sands with less than 10 $^0/_0$ of fines toward the surface but in some places increasing in fines below 30 cm. Fragments of shells were found in both fine and

Fig. 5. A developing nonsorted circle near ES 3 and 9. The silty clay was saturated, and dried only slightly at the surface during the summer. 19 July, 1957.

coarse soils. The coarser soils were vegetated with organic crusts and scattered vascular plants.

The surfaces of the circles had networks of small nonsorted polygons, usually pentagonal and convex upward (Fig. 3). They ranged in size from 7 × 11 cm to 18 × 20 cm, and were separated by cracks 1 to 2 cm wide at the top. These cracks were perennial features, reaching depths of at least 30 cm and persisting through annual alterations of soil saturation and intense surface desiccation. The surfaces of the small polygons varied from smooth to nubbly.

In a few places in the vicinity of ES 3 and 9 and of ES 11, 12 and 14, nonsorted circles were fresh and active (Figs. 5, 6). These circles were entirely barren of vegetation and remained wet throughout the summer. They varied greatly in size and in the height of the doming. Some had

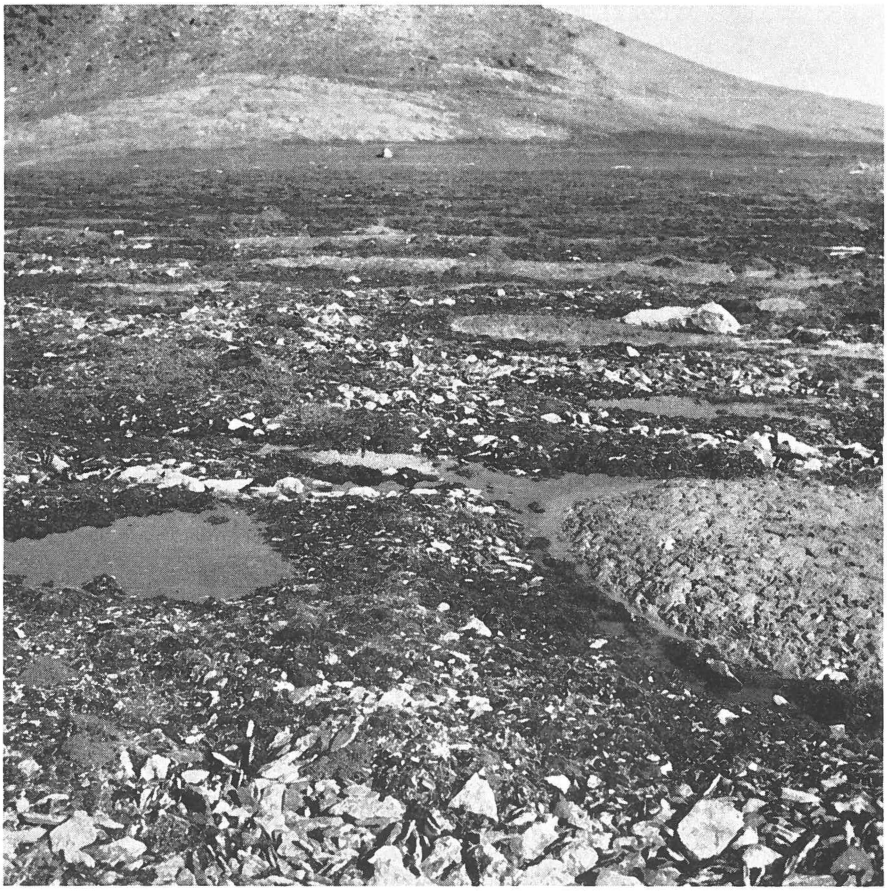

Fig. 6. Active nonsorted circles near ES 3 and 9. Some are partially dried at the surface and cracked to form small polygons. 19 July, 1957.

already begun to have well-formed small polygons (Fig. 6), while others had slightly wrinkled surfaces (Fig. 5). Occasional ones had nubbin-like projections of their surface materials. Most of these circles were near a small pond, and probably were supplied from the high water table in its vicinity (WASHBURN, 1969, p. 111).

Another form of nonsorted circles was found on a slope of about 3°, 50–100 m above the northwest end of ES 4 (Fig. 7). Some of these circles were nearly round, and all were distinguished by light gray color and no borders of sandy soil. Also they were nearly free of the smaller nonsorted polygons that characterized the circles described above. Though surficially dry, they appeared to be of recent origin, only slightly domed, and had a few scattered living plants on them that were partially inundated by clayey silt. They were probably formed "as a result of met-

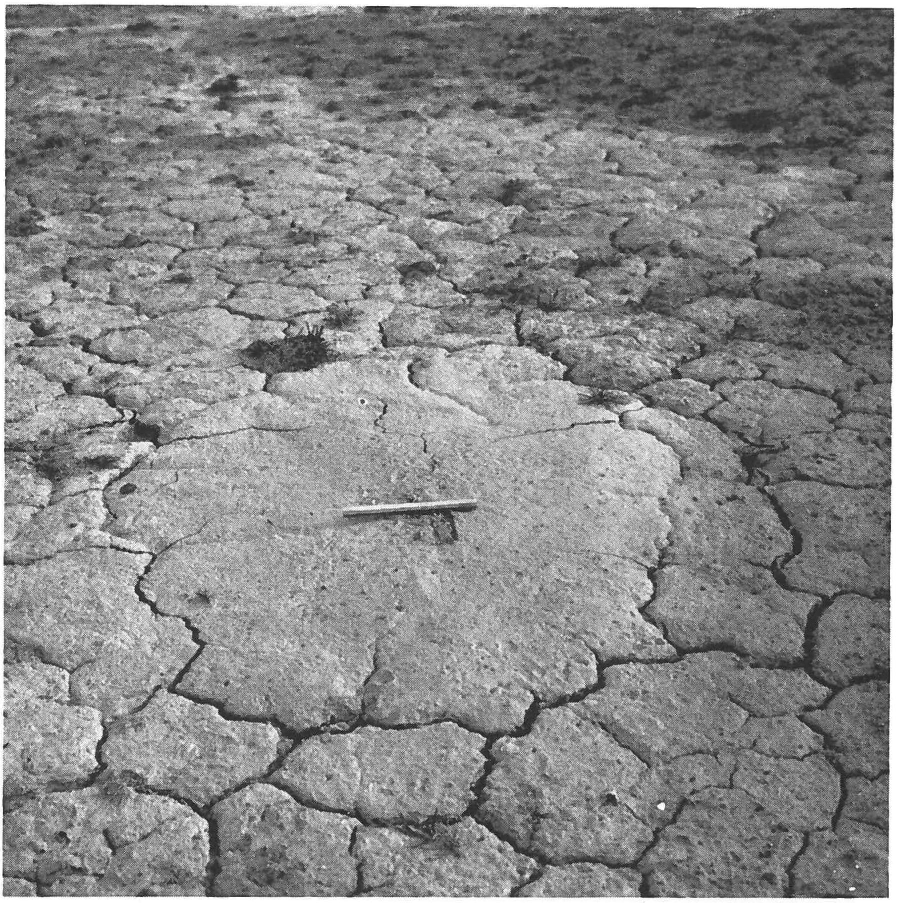

Fig. 7. Nonsorted circle north of ES 4, showing effect of recent deposit of surface silt from upslope. 1 Aug. 1958.

water, flowing from bare ground higher up the slope in the spring, having deposited fines in holes in the snow and in the basal ice that usually forms under snow" (Washburn, 1969, p. 118–123).

Downslope from ES 3 and 9, in the vicinity of ES 5, was a large area of compound polygons in shell-bearing soils ranging from sandy-silty clay to sandy-clayey silt (Fig. 8). The fines in these soils ranged from 78 $^0/_0$ to 93 $^0/_0$. The surface was composed of small domed nonsorted polygons 6×8 cm to 20×20 cm in diameter, grouped into a larger pattern, also domed, with average diameters ranging from 40 to 100 cm. Cracks separating the smaller polygons were 0.1 to 1.0 cm wide at the top, while those between the larger were 1–4 cm wide. Some cracks were open to depths of 15 cm or more. In general the pattern of cracks was polygonal (see Fig. 8).

Fig. 8. Compound nonsorted polygons in vicinity of ES 5. Shrubs are nearly all *Salix arctica*. 15 July, 1957.

Nonsorted circles near the shore of a small lake between map summits 180 m and 186 m, on the lower northeast slope of Hesteskoen, probably should be included here (Figs. 9, 10). They were in sandy silt, and nearly circular in outline, on a very gentle slope (2–3°), and 1–2 m from the lakeshore.

The circle described here was about 4 m in diameter, and had within it two smaller, irregular circles the largest of which was about 80 cm in average diameter (see Figs. 9, 10). The main circle was bordered by vegetation principally of mosses and lichens. Several turf hummocks made up parts of the marginal cover on the landward margins, the largest of them 25–30 cm high. The inner circles were raised 7–10 cm above the general level at their downslope margins. The upslope margins merged with the general level. These inner circles were bordered also by a vegetation mainly of mosses.

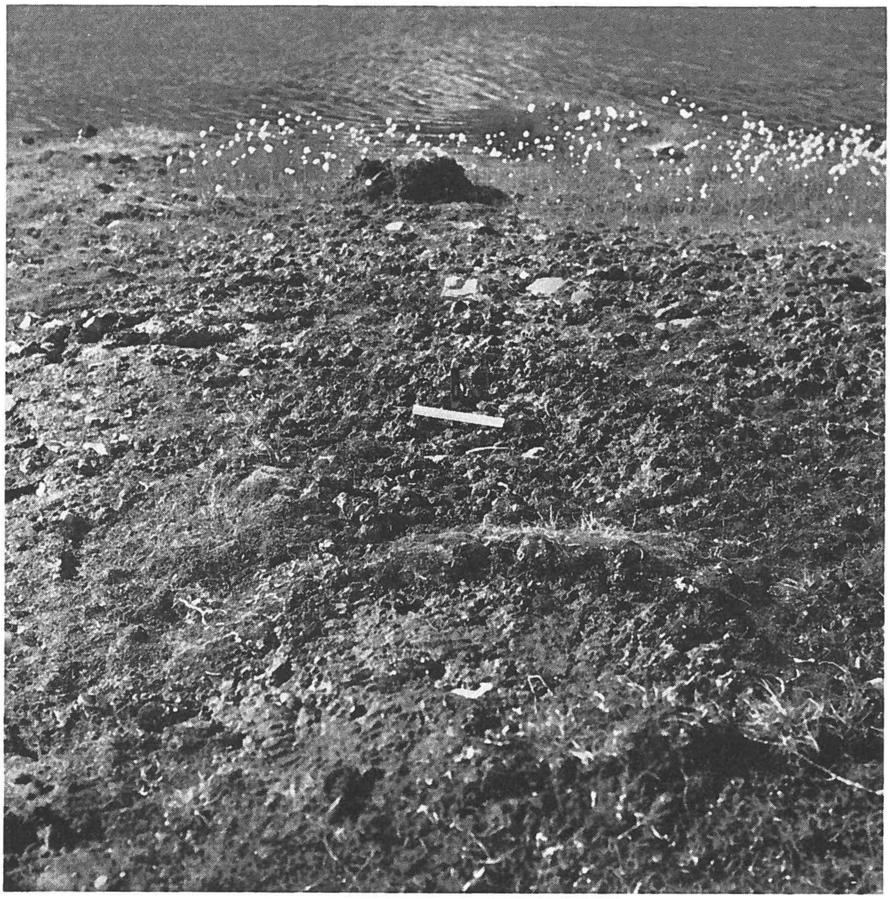

Fig. 9. Nonsorted circle near shore of small lake between MS 180 m and MS 186 m on the lower northwest slope of Hesteskoen. Scale is in outer circle. Smaller circle (80 cm) is in foreground. *Eriophorum Scheuchzeri* on lake shore. *Carex Lachenalii* on margin of circle. 4 Aug. 1957.

The ground surfaces of both inner and outer circles were partly bare of vegetation, and partly covered by thin organic crusts on which were scattered vascular plants: *Polygonum viviparum*, *Juncus biglumis*, *Cerastium alpinum*, *Carex Lachenalii*, *Equisetum arvense*, *Koenigia islandica*. The crusts showed a low microrelief composed of nubbins 1–2 cm high and up to 5 cm broad. The surface of the bare soil was much roughened and coarsely crumblike. The inner circles had proportionately somewhat more bare soil and fewer vascular plants than the outer. The mossy margins contained the following vascular plants, also scattered: *Equisetum arvense* (common), *Eriophorum Scheuchzeri* (a few culms), *Carex Lachenali* (common), *Juncus biglumis* (abundant), *Salix arctica*, *Polygo-*

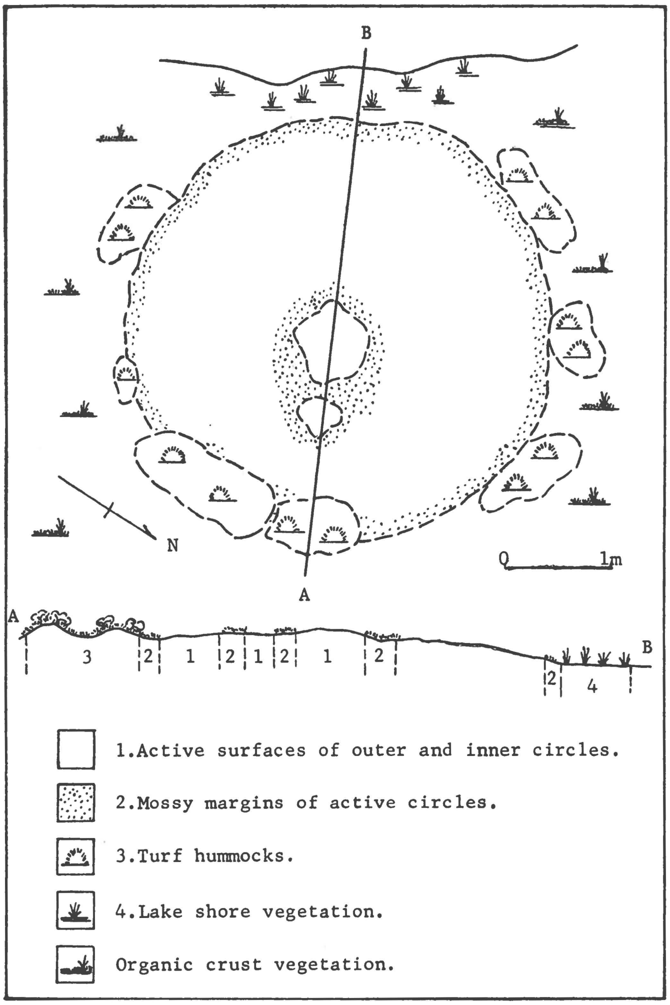

Fig. 10. Schematic diagram of nonsorted circle near shore of small lake between MS 180 m and MS 186 m, on lower northeast slope of Hesteskoen. 4 Aug. 1957.

num viviparum, *Saxifraga hieracifolia*, *Saxifraga caespitosa*. The soils were moist when examined on 4 Aug., 1957.

A nonsorted circle observed near MW 6 (see RAUP, 1969 B, Fig. 30 for location) was somewhat similar to those just described. Here a domed circle, about 2.5×2.7 m with its longer axis up and down slope, was bulged upward in its lower portion (Figs. 11, 12), while its upper margins merged with the surrounding slope. A turf border formed a low ridge at the upper margins. The general slope of the surrounding surface was about 4°, and the soil was moist when examined on 8 Aug., 1957. The circle was not more than 1–2 meters from the margin of the same

Fig. 11. Nonsorted circle near NW 6. 8 Aug. 1957.

snowdrift that supplied water to ES 6 (Raup, 1969 B, Figs. 30, 37), but most of its moisture appeared to be coming from upslope to the northward. The surface showed a net of small polygon cracks similar to those seen on the Labben slopes, but was nearly covered with organic crust on which were a few scattered vascular plants: *Carex nardina*, *Luzula confusa*, *Salix arctica*, *Polygonum viviparum*, *Saxifraga oppositifolia*, *Dryas octopetala.* The surrounding slope had a cover of organic crust and scattered vascular plants similar to that on the Labben slopes.

Site factors

The sites and their vegetation will be discussed in terms of three major habitat complexes: 1. the small nonsorted polygons and their associated cracks; 2. the vicinity of the cracks separating the larger

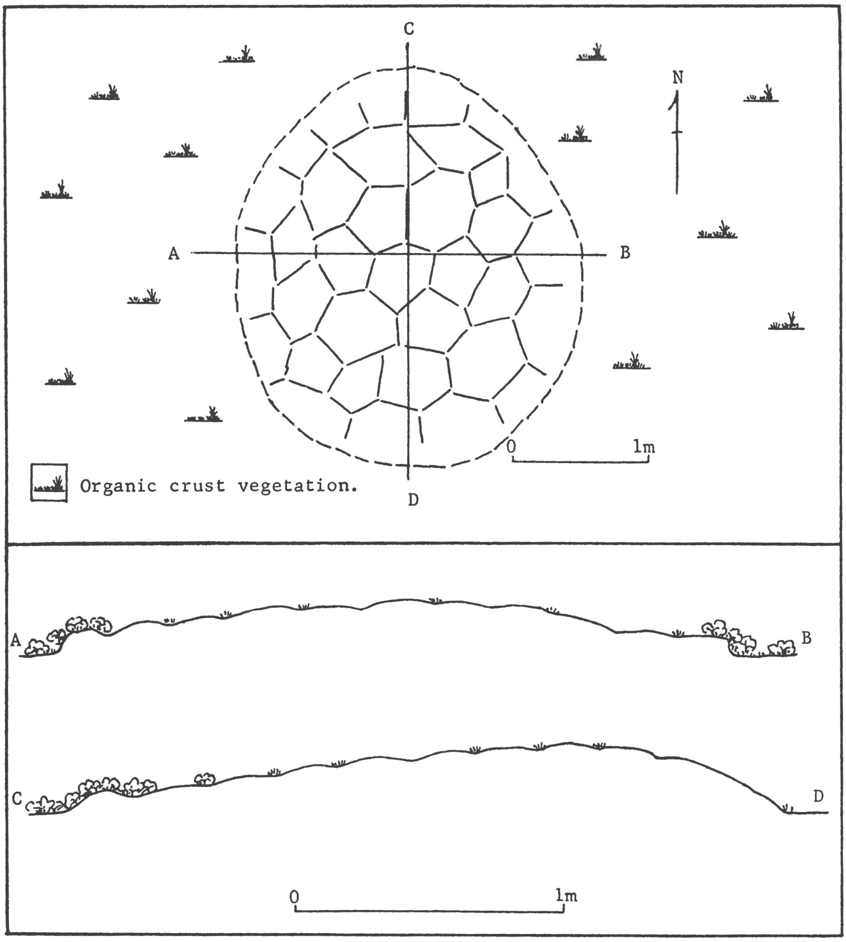

Fig. 12. Schematic diagrams of nonsorted circle near MW 6. 8 Aug. 1957.

polygons of the compound polygon systems; 3. the sandy soils separating the nonsorted circles.

Probable origins of the nonsorted circles and compound polygon systems have been discussed by Washburn (1969, p. 120–123). The reader is referred to his paper. The following treatment will deal primarily with processes in these areas which have more-or-less direct effects upon the lives of the plants.

Coverage of the ground by vascular plants

The soil of the nonsorted circles and related forms, except for the environs of the larger cracks that separated the larger compound polygons, was nearly barren of vegetation (Figs. 3, 4). Vascular plant coverages ranged from 0.4 % to 5.0 %, with an average of 2.2 %. Nonvascular plants were equally scarce. There was no evidence of an earlier more dense cover, suggesting that the coverage had been extremely sparse for a long time, with very little variation in density (see Figs. 3, 4). Most of the damp sandy soils among the nonsorted circles ranged in vascular coverage between 17% and 33%, with an average about 20%. The remainder of the surface was nearly covered by organic crusts with a few living bryophytes and lichens. Although the coverage varied from spot to spot the total effective range probably was still small (about 16%). Wider variation appeared in the main cracks between the compound nonsorted polygons, where it ranged from nearly zero to 50–60%.

Moisture supply

The nonsorted circles and polygons at Labben and Myggesø were saturated with moisture immediately after snow-melt. They lost their surficial moisture to a depth of 1–3 cm within a few days, by rapid evaporation from the fine-textured soil. Thus there was annually and within a short period of time, wide variation in their surficial moisture content. It is probable that in areas of compound nonsorted polygons there was a progression of desiccation from margins of the main cracks to the centers of the polygons, and within the latter from the margins to the centers of the small polygons. On the other hand moisture in the form of light rain during the summer would be most effective in the cracks, thus giving the crack margins a little more total moisture during the growing season than the centers, and at the same time making it locally a little more variable. Nonsorted circles immediately surrounded by sandy soils, without cracks separating them, were probably performing a "wick-like" function during the summer season, drawing moisture from the surrounding soils and evaporating it from their surfaces. In this case the marginal portions of the circles, being nearer the source, should have slightly more moisture than the centers, though rapid evaporation from the silt would render most of this moisture ineffective in the surface materials. Circles of this kind usually showed rather sharply defined vegetated margins with no concentrations of vegetation there.

The sandy loams between the nonsorted circles generally retained some moisture throughout the summer and into the autumn freeze-up. Thus there was much less seasonal variation in the moisture supply. Washburn (1969, Table D II) has published data from moisture analyses showing the contrasting surficial moisture in the circles and in the sandy marginal areas. On 11 July, 1958, surface samples in the vicinity of ES 3 and 9 ranged from 2% to 7% W $\left(W = \frac{\text{weight of water}}{\text{weigh of solids}}\right)$ (av. 4.7%) in the centers of the circles, while in the vegetated soils between the circles it ranged from 7 % to 121 % (av. 39.6 %). On 13 July 1958, surface moisture was 7 % in a circle and 61 % under marginal vegetation, and on 20 July 1960 the contrasting figures were 26 % and 100 %. Similar data for surface soils in late summer are incomplete, but on 30 August 1958 samples from a depth of 20 cm about 2 m west of ES 9 showed 17 % in a circle and about 86 % under marginal vegetation. At this place the surface moisture in the same circle was 7 %. Soil moisture tends to equalize in the circles and surrounding soils at greater depths beneath the surface (*cf.* WASHBURN, l.c.).

The moisture regimes of the nonsorted circles described on the lower northeast slope of Hesteskoen and near MW 6 differed from those at Labben and near Myggesø in retaining their moisture to late summer and probably into the autumn.

Disturbance by frost action

Frost heaving in the nonsorted circles and polygons appeared to be relatively weak. General heave data were derived from ES 5, situated in an area of compound polygons on the Labben slopes, mainly in sandy-clayey-silt (see WASHBURN, 1969, Fig. 34). Twenty-six cone-targets were used, 13 with 10-cm insertions alternating with 13 having 20-cm pins. Net heave of the 10-cm targets, 6 August 1956 to 5 August 1964, averaged 0.5 cm. The average for the 20-cm targets in the same period was 3.2 cm. These amounts are comparable with those found in other sites having similar dry clayey silt soils such as those in the "dry" sectors of ES 7 and 8 (RAUP, 1969 B, Table 1).

Wooden dowels were placed in the nonsorted circle at ES 9 on 24 August 1956 (Fig. 13). They were arranged in a grid pattern, 10 cm apart, and inserted to 10 cm. Heaves were measured on all dowels on 11 July, 1 August, and 10 September 1958; 3 August 1959; and 19 July 1960 (see Figs. 13, 14 and WASHBURN, 1969, Figs. 41, 42, Pl. E 2). Each measurement indicated how much a dowel was raised above its original position relative to the ground surface at the date of observation. Most of the measurements showed that the dowels had dropped back from former raised positions one or more times during the period of observation, usually 5 mm or less, but occasionally 5–10 mm. The largest single heave was 6 cm, but in general the heaving was from 0 to 3 cm, averaging 0.63 cm for all dowels. This is in sharp contrast to the intense heaving at ES 11 and 12 where most of the dowels were lifted out of the ground.

Evidence of heaving in surficial soil (1–3 cm) in the circles was from observation of small pebbles. Of 75 platy fragments in a circle near ES 9, and in a square 50 × 50 cm, all of them 1 cm or more in longest dimension, 14 (19 %) were standing on edge or at angles within 45° of vertical. In another circle, of 70 counted, 28 (40 %) were within 45° of

Fig. 13. Experimental site 9, on Labben, showing arrangement of dowell targets. 10 July, 1958.

vertical. In a third circle 25 stones were counted, 6 of them on edge (24 %). In the first of these samples only 11 pebbles (15 %) had any crustose lichens on them, while in the second and third none had lichens. In a 50×50 cm square in an area of compound polygons near ES 4, 117 platy stones 2 cm or more in largest dimension were counted. Of these, 29 were standing within 45° of vertical, and 15 (13 %) had small traces of crustose lichens on them. These data suggest that a small amount of heaving occurs in the surface materials, and that the turnover of pebbles is recent enough to preclude most of the growth of lichens.

To check the reliability of the lichen data two 50×50 cm squares in the vicinity of ES 7 and 8 were compared. One was on gravelly talus known to be nearly free of frost heaving, and the other was on pebbly silt where some significant target heaving was measured. Most of the pebbles in both cases were about 5 cm in average diameter or less. Of

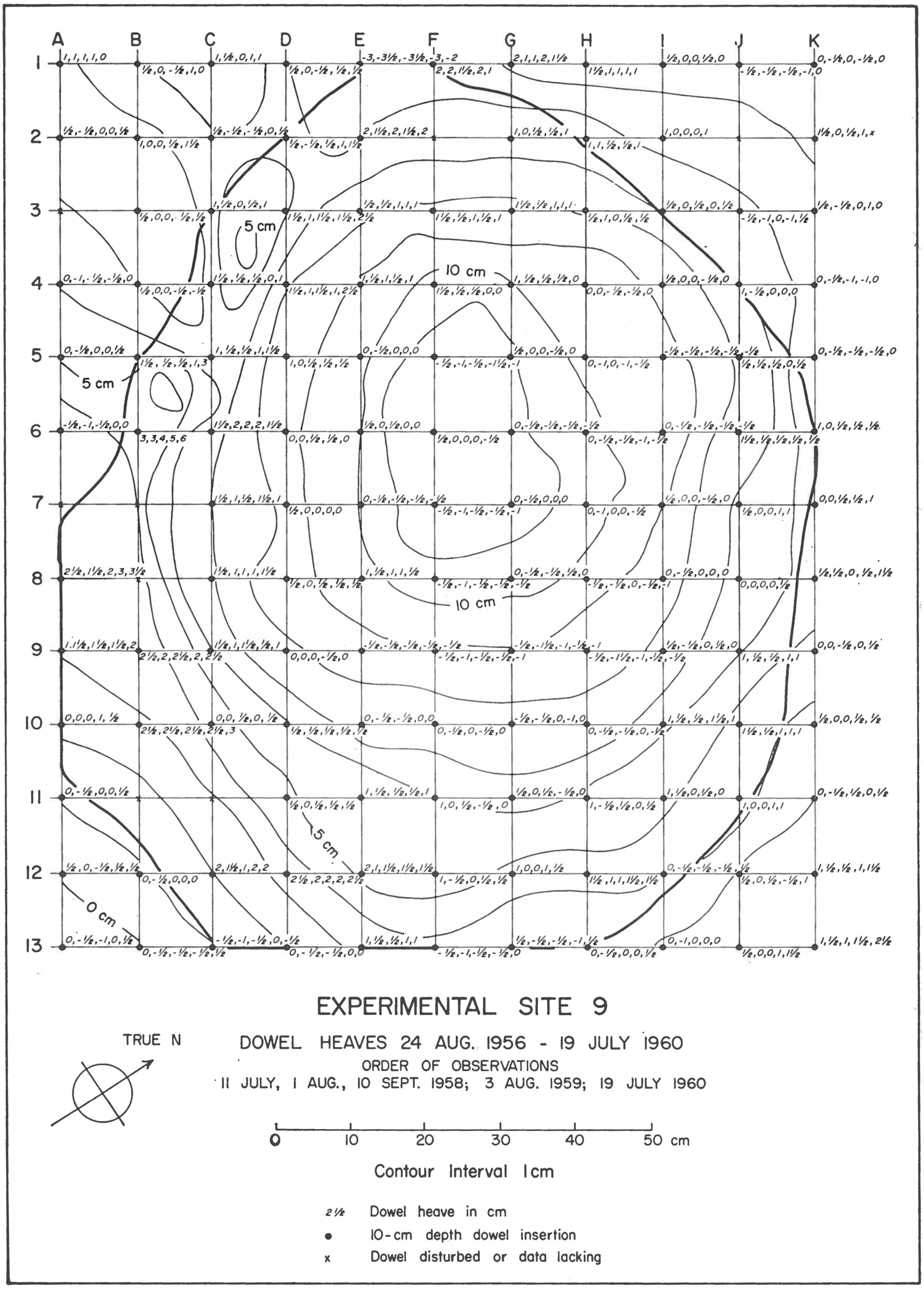

Fig. 14. Dowel heaves in ES 9, 24 Aug. 1956 to 19 July 1960. From WASHBURN, 1969, Pl. E 2.

Table 2. *Distribution of dowel heave intensity with respect to the contours of the nonsorted circle at ES 9.*

Contour interval	Dowel heave
cm	cm
11–12	0.42
10–11	0.44
9–10	0.42
8– 9	0.52
7– 8	0.54
6– 7	0.63
5– 6	0.77
4– 5	0.94
3– 4	1.01

141 stones counted on the gravel, 58 (41 %) had lichens growing on them. Of 108 counted on the silt, 20 (18 %) had lichens on them but only as very small bits of thallus.

Within the small range of dowel heave at ES 9, 0–3 (6) cm, there were differences related to topography. The site was a low-domed circle approximately 90×120 cm, with a total relief of about 12 cm (see map, Fig. 14). When the heave figures for dowels within each 1 cm contour interval are averaged, the results show progressively increased heave from the center to the margins of the circle (Table 2). This is consistent with the probability, already mentioned, that there is slightly more moisture toward the margins.

The low intensity of heave in the nonsorted circles and related forms probably was due to extreme desiccation in the summer. It is probable also that much of the heaving that occurred took place during a small number of freeze-thaw cycles while the ground was still wet in spring. After the summer drought, autumn heaving depended upon whatever light rain fell, or upon melt-water from ephemeral snow cover.

Very few target heave data are available for the sandy soils surrounding the circles. However, somewhat similar moist soils, with similar vegetation, showed intense heaving at ES 6, 7, and 8. Persistent moisture throughout the summer and into the autumn produced conditions conductive to heave during the autumn freeze-up. Excavations of the circles and their bordering soils showed much distorted horizons of organic layers intermingled with the sandy soils (see WASHBURN, 1969, Figs. 72, 73, 74). Many platy pebbles and cobbles were found partially heaved from the ground and standing on edge in the sandy soils.

Frost disturbance by needle ice was not seen in the circles and polygons at Labben and Myggesø, but disruptions of the organic crusts in the areas between the circles were frequently observed and attributed to needle ice. Small areas so disturbed showed the plant cover (usually thin moss mats, or organic crusts) torn up to form bare spots that appeared as wormy crumblike "fluffed" surfaces (Washburn, 1969, p. 85). No evidence was seen to suggest that needle ice seriously disturbed any vegetation other than the moss mats and crusts. It was noted primarily in sandy soils. The surfaces of the circles observed on the northeast slope of Hesteskoen appeared to have been intensively disturbed by needle ice (see Fig. 9). Their "fluffed" appearance was conspicuous, and in many places the organic crusts seemed to have been disrupted recently. Moisture persisting to late summer, added to that of autumn, probably made needle ice formation particularly effective.

Disturbance by nonfrost processes

Very little evidence of gelifluction was seen in the areas characterized by nonsorted circles and polygons. Most of the circles were more or less regularly domed, though they commonly had their long axes slightly ridged and oriented down slope. A study of surface pebble orientation was made on a slightly ridged nonsorted circle near ES 9. The circle was elongated downslope (N–S), but the general slope here was very slight. A 50×50 cm square (see Raup, 1969 A, p. 39) was set near the middle of the bare area, so that the slight ridging of the circle produced minor downward slopes (E–W) under it. There were 75 pebbles 1 cm or more in longest dimension; 42 (56 %) were oriented east and west and 33 (44 %) north and south, or respectively within 45° of these directions. Thus there appeared to be, even on this slightly domed surface, a measurable preference for the orientation of pebbles with their long axes of right angles to the contours. This suggests minor gelifluction in the surface soils, perhaps modified by frost creep. A related situation was seen in the orientation of small pebbles on a "step" of clayey silt in the "dry" sector of ES 7 and 8. In a 50×50 cm square 96 pebbles 2 cm or more in longest dimension were counted. Of these 74 (77 %) had their long axes oriented normal to the contours or within 45°.

Exceptions to the regular doming were seen in the circles on the northeast slope of Hesteskoen and at MW 6 (Figs. 11, 12). In the latter place the soil in the circle appeared to have flowed, leaving a low turf border at the upper margins and forming a bulge toward the lower border, with a relatively steep slope on the downhill side. The vegetated border on this side was being slowly inundated. Similar microrelief was seen in the circles on the northeast slope of Hesteskoen (Figs. 9, 10).

A small amount of erosion and sedimentation was seen in the fine-textured soils on Labben (see Washburn, 1969, p. 120). Some of this was in the fresh nonsorted circles near ES 4 (see above). It was more prominent along shallow drainage channels in the vicinity of ES 4 and 5. These channels dried out during the summer, leaving thin deposits of silty clay or clayey silt. They sometimes partially buried a few scattered living plants which seemed but little injured in the process (see Fig. 7). Erosion of deteriorating turf hummocks on the slope above ES 5 was described earlier (Raup, 1965 B, p. 65–70, Figs. 24, 25). The effects of erosion and deposition in the interhummock areas appeared to be minimal.

The above observations suggest that nonfrost disturbance in areas notable for nonsorted circles and polygons was of relatively small significance. It was highly localized, and seemed to have little restrictive effect upon the growth of vascular plants.

The vegetation

The flora

For purposes of analysis the vascular species found in all of the areas studied are grouped together. Table 4 contains 45 taxa. The distribution of these species among the frequency classes of Mesters Vig district as a whole is shown in Table 3.

Table 3. *Distribution of 45 species (found in nonsorted circles and polygon areas) among frequency classes of the Mesters Vig district as a whole.*

	%
Common or abundant	64.4
Occasional or locally common	28.9
Rare or locally occasional	6.7

Approximately 100 hectares were included in these areas of study, 40–50 times as much area as that covered in the ES 7 and 8 map. The latter yielded 88 vascular species, about twice as many as in the areas included here. It is probable that the small flora of the vicinity of the nonsorted circles is due to the intense desiccation of large parts of them, and to lack of much differentiation of habitats. The former restricts the flora in many areas to species capable of withstanding such drying of the soils. The latter eliminates most of the species dependent on large moisture supplies, and also species that prefer moist soils but are at the same time very sensitive to physical disturbance. This situation is reflected in part by the fact that 19 (42 %) of the 45 species proved to be widely tolerant of variation on all of the environmental gradients studied.

Table 4. *Vascular flora of nonsorted circles and related forms, and of immediately surrounding vegetation.*

	In nonsorted circles or polygans		
	In small nonsorted polygons or in cracks between them	In or near cracks compound nonsorted polygons	In damp sandy soils among nonsorted circles
Equisetum arvense			+
Equisetum varieqatum			+
Festuca vivipara	+	+	
Festuca rubra ssp. *cryophila*	+	+	
Colpodium Vahlianum			+
Puccinellia angustata	+		
Poa arctica		+	
Poa alpina		+	
Poa glauca	+	+	+
Trisetum spicatum	+	+	
Phippsia algida	+		
Carex nardina	+	+	+
Carex scirpoidea			+
Carex Lachenalii			+
Carex glacialis			+
Carex misandra			+
Juncus biglumis			+
Luzula arctica	+		+
Luzula confusa			+
Salix arctica		+	+
Koenigia islandica			+
Oxyria digyna	+	+	
Polygonum viviparum	+	+	+
Stellaria Edwardsii		+	
Cerastium alpinum	+	+	+
Minuartia Rossii			+
Minuartia biflora		+	
Silene acaulis	+	+	+
Melandrium apetalum			+
Melandrium affine			+
Draba alpina	+	+	
Draba lactea	+	+	
Draba oblongata			+
Draba glabella		+	
Eutrema Edwardsii			+
Saxifraga oppositifolia	+	+	+
Saxifraga nivalis			+
Saxifraga aizoides			+
Saxifraga cernua	+	+	+
Dryas octopetala		+	+
Cassiope tetragona			+
Pedicularis flammea			+
Pedicularis hirsuta			+
Campanula uniflora		+	
Taraxacum arcticum		+	

The vegetation of the principal habitats

The first of the three habitats mentioned above was in the small nonsorted polygons, and in or near the cracks separating them. These polygons were inside the margins of the circles and of the larger polygons in the compound patterns (see Figs. 3, 4, 8).

Sixteen vascular species were found in this habitat, 8 of which were widely tolerant on all the gradients, leaving 8 definitive species. Table 4 shows two species found here but not in the two remaining habitats: *Puccinellia angustata* and *Phippsia algida.* Both of these were occasional in the centers of the small polygons as well as at the cracks.

The second habitat was in or near the cracks separating the larger polygons in the compound patterns. The plants tended to be concentrated in the deeper depressions, which were at the meeting points of cracks at polygon corners (see Fig. 8).

Twenty-two species of vascular plants were found in this habitat, 12 of them widely tolerant on all the gradients, and 10 that were considered in some measure definitive in their habitat requirements. The commonest species probably was *Salix arctica* which formed mats in the angles between major polygons. Commonly associated with it were *Saxifraga oppositifolia*, *Cerastium alpinum*, *Draba alpina*, various grasses such as *Trisetum spicatum*, *Festuca vivipara*, *Festuca rubra* ssp. *cryophila*, and a few other species. Seven species listed in Table 4 were seen in neither of the other habitats: *Poa arctica*, *Poa alpina*, *Stellaria Edwardsii*, *Minuartia biflora*, *Draba glabella*, *Campanula uniflora*, and *Taraxacum arcticum.* Three of these, *Stellaria*, *Campanula* and *Taraxacum*, were seen only near a large boulder in the area of compound polygons.

The third habitat was in the sandy soils between and marginal to the nonsorted circles (see Figs. 3, 4). The surface of these soils showed minor relief composed of broad low domes 2–3 m wide and 12–25 cm high separated by shallow depressions of similar dimensions. In many areas this topography was scarcely visible, and the surface was essentially even. Most of the surface was covered with a dark gray to black organic crust and a scattered flora of vascular plants.

This habitat had the largest vascular flora of the three, with 30 species of which 15 proved to be widely tolerant of variation in all the gradients, leaving 15 definitive species. Minor differentiation in the local distribution of species could be loosely correlated with the low relief noted above. The low domes had more *Salix arctica* than the shallow depressions, with occasional loose clumps of *Cassiope tetragona. Pedicularis hirsuta*, *Luzula arctica* and *Carex scirpoidea* were more common on the domes than in the depressions. *Equisetum variegatum*, *Juncus biglu-*

mis, and *Eutrema Edwardsii* were most likely to be found in the shallow depressions where the soil was a little more moist than on the domes. Twenty of the species listed in Table 4 appeared to be restricted to this habitat: *Carex scirpoidea*, *C. Lachenalli*, *C. glacialis*, *C. misandra*, *Juncus biglumis*, *Luzula confusa*, *Koenigia islandica*, *Minuartia Rossii*, *Melandrium apetalum*, *M. affine*, *Draba oblongata*, *Eutrema Edwardsii*, *Saxifraga nivalis*, *S. aizoides*, *Cassiope tetragona*, *Pedicularis flammea*, *P. hirsuta.*

The floras of the circles described at MW 6 and on the northeast slope of Hesteskoen are included in the list from this habitat. The soils in these places remained moist through all or most of the summer, and they were characterized by at least a partial cover of organic crust. Those in the Hesteskoen circles appeared to be much disturbed by frost action and it is probable that the circle at MW 6 was likewise disturbed. These circles suggest what probably would happen if the Myggesø and Labben circles were supplied with continuous moisture instead of being dried out early in the summer.

Behavior of the species on gradients of coverage, moisture and physical disturbance

The coverage gradient (Fig. 44)

As do most of the Mesters Vig plants, those in the nonsorted circle areas show prevailingly wide tolerance on this gradient. Most of them were found in coverage densities ranging from less than 1 % to 50–60 %. The highest percentage of widely tolerant species, and the lowest of narrowly tolerant were in or near the cracks separating the larger compound polygons. Here the variation in cover density was greatest: 0–60 %. It probably was least in the central parts of the circles, and low to intermediate in the sandy soils bordering the circles. The percentages of widely and narrowly tolerant species suggest the low to intermediate variations in coverage exhibited by these two habitats, although a larger difference in percentages might have been expected in the damp sandy soils.

The moisture gradient (Fig. 45)

Two of the habitats, both of them in the circles having highly variable moisture supplies, had high percentages of plants widely tolerant of variation in moisture (87 %–100 %). It was suggested above that the larger polygon crack habitat probably had more moisture variation during the season than the small polygons. If this is the case it is reflected in the slightly higher proportion of widely tolerant plants there. The sites with persistent moisture including those at MW 6 and at the northeast base of Hesteskoen, were notably less variable in their supply, and have a correspondingly low percentage of species widely tolerant on this gradient. At the same time a measureable percentage of narrowly tolerant species appeared in these sites, whereas there were none in the dry circles.

The frost disturbance gradient (Fig. 46)

Frost disturbance, either by general frost heaving or the action of needle ice, was shown to be relatively small in the dry circles. Assuming its dependence on moisture supply in spring and autumn, there probably was a little more of it in the larger polygon crack habitats than among the small polygons. It was much greater in the bordering sandy soils and in the moist circles. These differences are reflected in the behavior of the plants on this gradient. Species narrowly tolerant of frost disturbance were most highly represented among the small polygons (50 %), and least in the moist sandy soils (13 %). An intermediate proportion (30 %) were in the large polygon crack sites. Widely tolerant species showed a relatively low percentage (25 %) among the small polygons, and a relatively high proportion (40 %) in the damp soils. The widely tolerant species are not as definitive for the larger polygon cracks as the narrowly tolerant ones, showing only 20 % where they should have a percentage a little higher than among the small polygons.

The nonfrost disturbance gradient (Fig. 47)

The generally high percentages of narrowly tolerant species, 1.5 to 5.5 times as many as widely tolerant ones, suggests the generally low intensity of this kind of disturbance in the nonsorted circle areas. What little occurred probably was mainly in the circles, and it was here that the percentages of narrow tolerance were lowest (60–63 %) and those of wide tolerance highest (25–40 %). In the damp sandy soils where surficial gelifluction appeared to be insignificant about 73 % of the plants were narrowly tolerant and only about 13 % were widely tolerant.

Earlier studies have shown that gelifluction, *per se*, probably is not seriously injurious to mature plants (RAUP, 1969 B, p. 199–202). However, even small gelifluction disturbance such as has occurred on the moist circles above described may have been injurious to small seedlings that germinated in spring while the soil was saturated. On the dry circles there was very little evidence of this movement, though the orientation of small pebbles with respect to contours suggested a slight amount of downslope movement by minor gelifluction and/or frost creep. If this movement did occur it probably was greatest on the marginal slopes of the larger domed polygons, where the moisture was greatest and persisted for a little longer time.

Erosion and sedimentation by spring snow-melt were not apparent in the damp sandy soil, but there was a small amount of it in the compound polygon areas. It was particularly apparent in the fresh polygons near ES 4, where light gray silt had been recently deposited in thin sheets. This material must have come from the slow erosion of more-or-less barren circles and polygons upslope. The erosion probably was most effective on the lower margins of the larger polygons and in their associated cracks, and much of the depositional activity probably ocurred in similar places.

If these observations and assumptions are correct, the species with least tolerance of nonfrost disturbance should be most numerous in the damp sandy soils between isolated circles, as they are. Within the circles and polygons they should be less numerous in general, and probably less numerous among the small polygons than in the depressions between the large compound polygons. The narrowly tolerant species show about the same percentage in these two habitats (62.5 and 60 % respectively), while the widely tolerant species show the expected larger proportion in the large polygon cracks (25 and 40 % respectively).

THE VEGETATION OF SMALL POLYGONS ON EMERGED DELTA REMNANTS

Introduction

The vegetation of small polygons was studied on low-level emerged delta remnants a short distance from the northwest end of the Mesters Vig airfield. These polygons were both nonsorted and sorted, and some appeared to be transitional. The following description of the sites is derived from WASHBURN (1969, p. 130–140), who has discussed in considerable detail their structure and probable origin.

Topography and soils

The polygons were located on the nearly level surfaces of terraces at varying altitudes above the present fjord. Those studied were near the 17-m and 25-m contours. The surfaces have a few broad shallow depressions and low knolls. Similar terraces elsewhere in the distributary system of Tunnelelv showed the same polygon forms and vegetation. The polygons ranged in diameter from 5 to 30 cm, with microrelief from 4 to 8 cm. The intervening cracks extended downward in the mineral soil from 3 to 12 cm.

The soil and vegetation on the 17-m level are illustrated in Figs. 15, 16, 17. The uppermost horizon in the soil was a moderate brown sand 14–18 cm thick containing isolated stones and stringers of humic material. The largest of these stringers reached downward from the main polygon cracks nearly or quite through the sand, and appeared in some places to curve under the polygons.

Figures 18, 19 illustrate a somewhat similar profile on the 25-m terrace. Here there were 10–13 cm of moderate brown silty sand with very few stones, humic material concentrated in the cracks, and living rootlets in the mineral soil mostly in the neighborhood of the cracks. WASHBURN distinguished two horizons in the underlying coarser material: a dark yellowish brown silty-sandy gravel 7–8 cm thick, and a light brown gravelly sand 20+cm thick. There were a few rootlets in the uppermost of these, but none in the lower. There was no reaction to HCl in

Fig. 15. Small nonsorted polygons on the 17-m level in the emerged delta remnants near the northwest end of the Mesters Vig airfield. Scale is a 17-cm rule. Note patch of *Cassiope tetragona* under pack sack. 21 July, 1960.

this profile. The pH ranged from 5.2 near the surface to 6.6 at a depth of 42 cm.

In both of the profiles described above there was only minor evidence of sorting, with a few stones occasionally found in the cracks. The least evidence was on the 17-m level, suggesting that the shorter time available may have been a factor. It is clear that the cracking and polygon formation were confined to the sand and silty sand, and that the cracks tended to extend to the bottom of it.

Another profile on the 25-m terrace level showed more evident sorting (Figs. 20, 21, 22). The surficial soil was a moderate brown silty sand 15–20 cm thick. It tended to be a little coarser toward the borders of the polygons. In the depressions surrounding the polygons, over the cracks, was black peaty humus mixed with sandy gravel to depths of

Fig. 16. Soil profile on 17-m level in the emerged delta remnants (excavation 60 – 7 – 21 A). Scale is a 17-cm rule. 21 July, 1960.

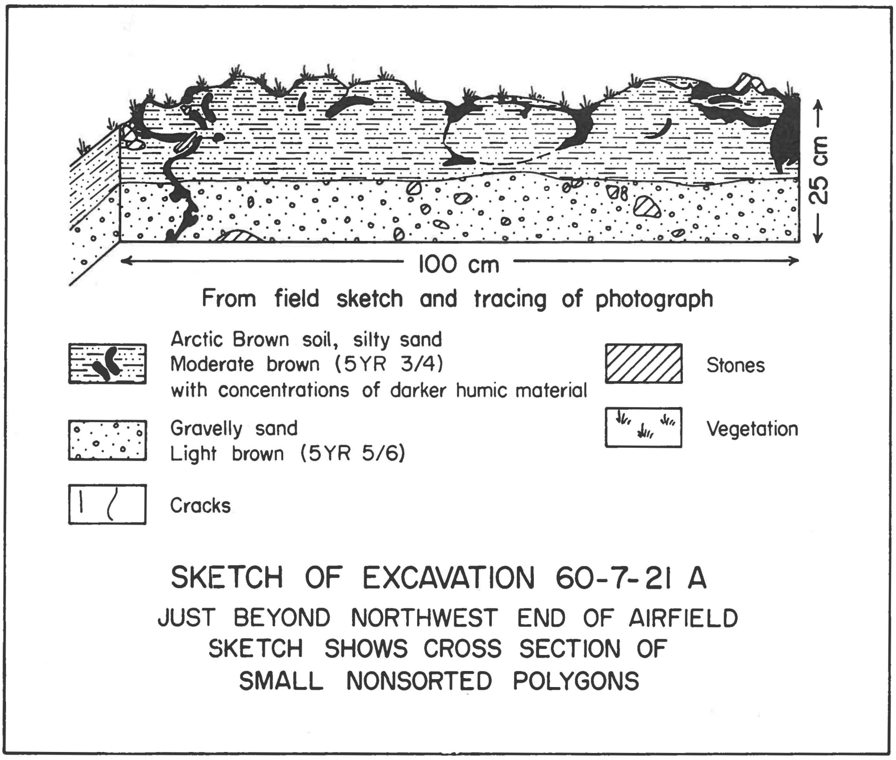

Fig. 17. Diagramatic sketch of profile shown in Fig. 16. 21 July, 1960 (from WASHBURN. 1969, Fig. 85).

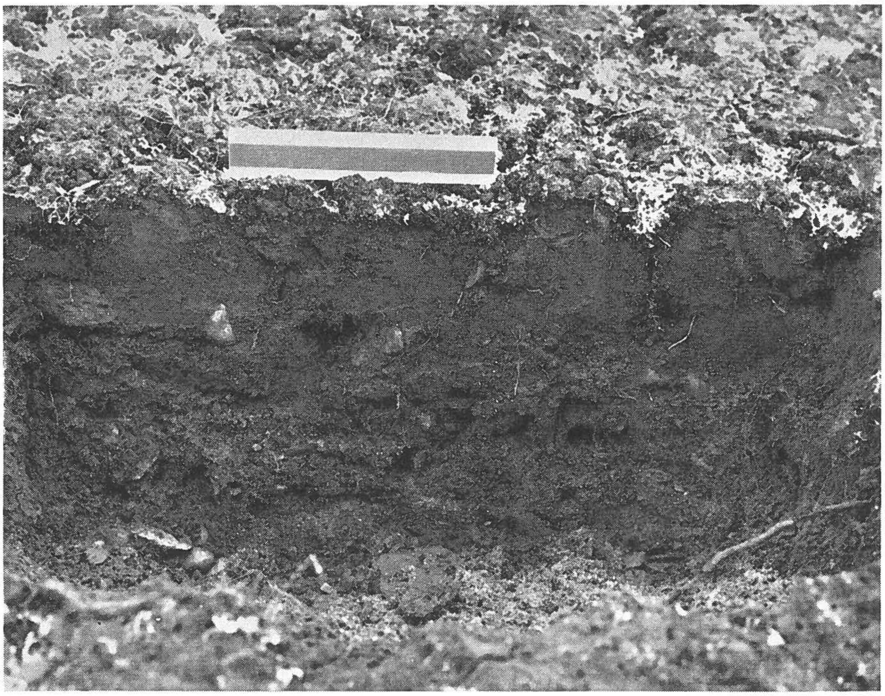

Fig. 18. Soil profile on 25-m level in emerged delta remnants (excavation 60 – 7 – 21 B). Scale is a 17-cm rule. 21 July, 1960.

as much as 5 cm. Below the silty sand, and extending to 30^{+}cm, was a pale brown to dark yellowish brown sandy gravel. The surface of this gravel showed shallow cup-like depressions beneath the polygons, with the high ridges separating the cups located beneath the main cracks. The humic material in the surface depressions, 5–15 cm wide and deep, also penetrated the narrow cracks below. Although a few roots were seen in the fines of the polygons, most were concentrated in or near the cracks.

The soils in the excavations described above have been described as "Arctic Browns" (UGOLINI, 1966 A; see also TEDROW and HILL, 1955). UGOLINI (l. c.) has reviewed the general distribution of Arctic Brown soil in the Mesters Vig district, and has shown that it appears in sites that have been relatively undisturbed by geomorphic processes for a long time. The length of time necessary for its formation is unknown.

Site factors

Coverage of the ground by vascular plants

Coverage by vascular plants ranged from 0–10 % over large areas of the polygons. Patches of *Cassiope* heath, in which were varying

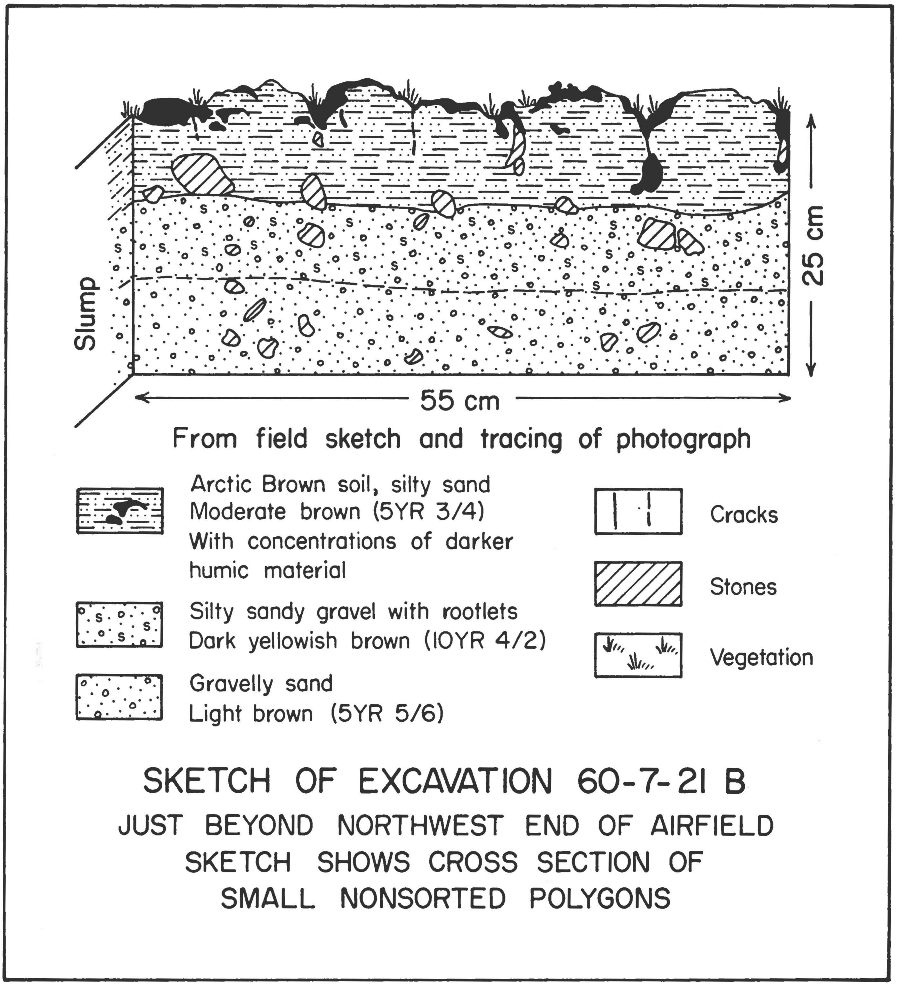

Fig. 19. Sketch of soil profile shown in Fig. 18. 21 July, 1960 (from WASHBURN, 1969, Fig. 86).

mixtures of *Salix arctica* and *Vaccinium uliginosum*, had 50 % to 80 % of the ground covered. Over most of the mineral soil was a rind of black organic crust.

Moisture supply

The emerged delta remnants considered here had no moisture supply other than the winter snow and occasional light summer rain. Although swept by winter winds, there were no obstructions behind which drifts could form. The silty sands of the surface soils were found to be damp when they were excavated on 21 and 23 July, 1960, and 21 Aug., 1964,

Fig. 20. Small sorted polygons on 25-m emerged delta remnant, adjacent to excavation 60 – 7 – 23. Vertical view of excavation in foreground. 23 July, 1960 (from WASHBURN, 1969, Fig. 102).

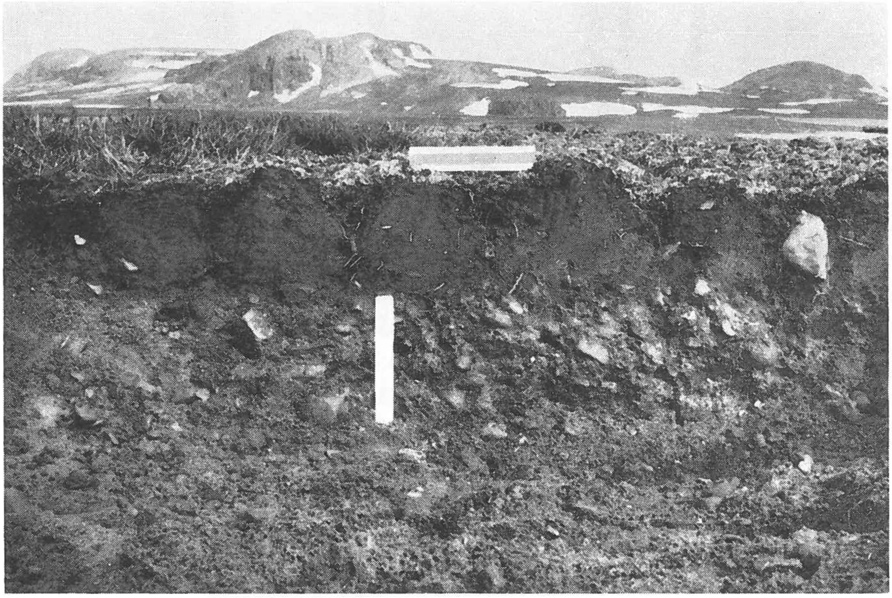

Fig. 21. Soil profile on 25-m emerged delta remnant, showing small sorted polygons (excavation 60 – 7 – 23). Scales are 17-cm rules. 23 July, 1960 (from WASHBURN, 1969, Fig. 100).

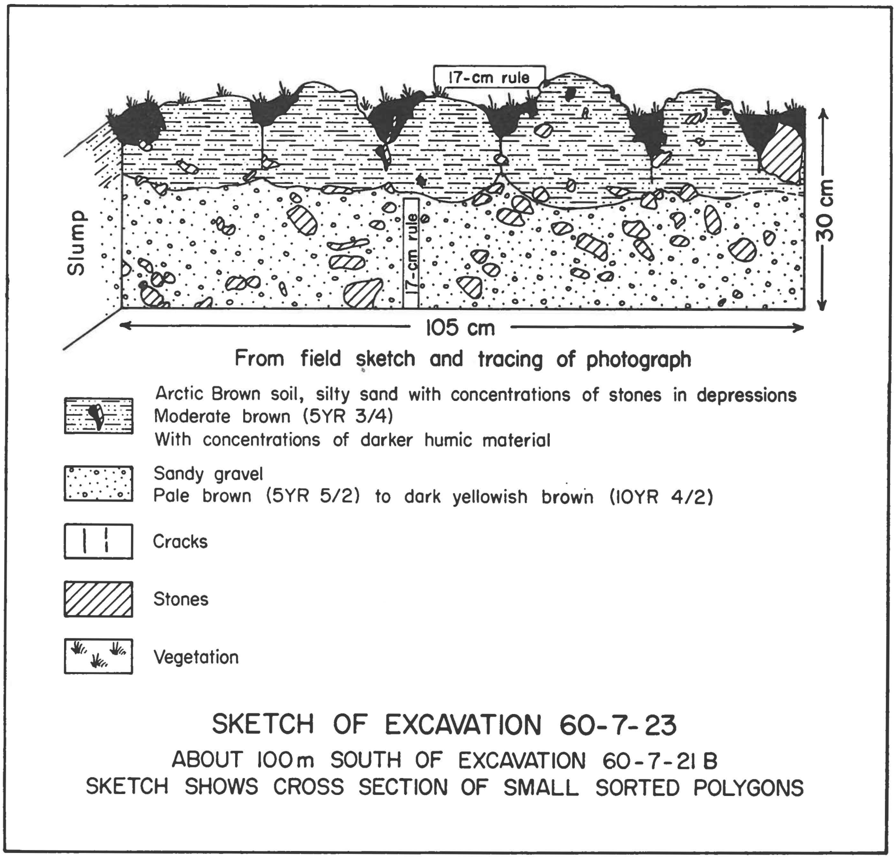

Fig. 22. Sketch of soil profile shown in Fig. 21. 23 July, 1960 (from Washburn, 1969, Fig. 101).

suggesting that they retained moisture throughout the summer. However, they were underlain by coarse gravels, and thus were relatively well drained.

Disturbance of the soil by frost action

No instrumental data on frost heaving were gathered from the small polygons. Consequently the relative intensity of frost action must be inferred from the soil and the structure of the vegetation.

In discussing the formation of the small polygons on the emerged deltas, Washburn concluded that desiccation cracking probably was the principal process involved (1969, p. 136–140). With respect to the sorted forms (Figs. 20, 21, 22) on the 25-m level he expressed the following opinions (1969, p. 161–162): "Present lack of strong frost heaving was suggested by the fact that stones exposed at the surface tended to be lichen covered. Although some sorting was indicated by the concentration of stones in the depressions, the large content of fines (47 per cent) in unit 1 [the silty sand], as contrasted with the very low content (2–4 per cent) in unit 3 [the underlying sandy gravel] and the small total amount of gravel represented by unit 2 [the polygon borders] (despite the high percent within unit 2), make it very unlikely that both units 1 and 2 were derived from unit 3 by sorting. Rather unit 1 is interpreted as an eolian deposit containing isolated stones upfrozen from unit 3, which were frost sorted and washed to the polygon borders to form unit 2."

The prevalence of organic crust on the polygons suggests that whatever heaving now occurs is not enough to destroy it. It is variously broken by small cracks probably caused by needle ice or by simple desiccation. On some of the polygons, particularly those on the 25-m level, there was a nubbin microrelief which may also be related to needle ice activity (WASHBURN, 1969, p. 82–88). Further evidence of relative stability in the crusts is the growth of lichens on them. On the other hand the concentration of the foliose and fruticose species in the cracks argues for less stability on the domes of the polygons. Soil moisture in late summer indicated that heaving was possible at the time of autumn freezeup. Consequently it is probable that a moderate amount of frost action occurs in the polygons, much less than in the centers of the large sorted nets at ES 1, 11-12, but probably considerably more than in the small polygons of ES 9.

Disturbance by nonfrost processes

Disturbance of the polygon soils and their vegetation by nonfrost induced processes has no doubt been intense at times in the past. The underlying gravels were deposited by glacial streams, and the silty sands probably were at least in part eolian (WASHBURN, 1969, l.c.). WASHBURN has suggested that the stones heaved out of the fines were washed out to the margins of the polygons or arrived there by frost sorting. Whether any of these processes are effective now is doubtful. However, it is possible that the present desiccation of the surfaces is comparatively recent, and may have developed within the last 60–75 years (WASHBURN, 1969, p. 139–140; RAUP, 1965 B, p. 96–9). If this is the case, more moisture may have kept the entire system of disturbing processes active until recent years. It is not impossible that some deposition by wind is still going on, for the site is open to strong westerly winds blowing in from the fjord over the annual fine textured deposits at the westerly outlet of Tunnelelv. If this is the case the plants on the delta remnants are subject to a certain amount of abrasion by windblown soil.

The vegetation

Twenty-six species of vascular plants were found on the surfaces of the emerged delta remnants at the 17-m and 25-m levels (Table 5). Two minor habitat variants are noted in the Table: in the broad shallow depressions and on the low rounded knolls previously described. The small polygons with which the present discussion is concerned were largely confined to the general level, and were absent or faintly developed on the knolls and in the depressions. The present analysis will deal only with the 21 species found among the polygons.

Table 5. *Species of vascular plants found on 17-m and 25-m delta remnants near northwest end of Mesters Vig airfield.*

	Among small polygons on 25-m & 17-m terraces	In broad shallow depressions on 25-m & 17-m levels	On low rounded knolls on 25-m & 17-m levels
Equisetum variegatum	+	+	
Lycopodium Selago	+		
Festuca brachyphylla	+		
Poa arctica	+		+
Trisetum spicatum	+	+	
Carex nardina	+		+
Carex glacialis			+
Carex misandra	+	+	
Luzula arctica	+		
Luzula confusa	+	+	+
Salix arctica	+	+	
Oxyria digyna	+	+	
Polygonum viviparum		+	
Cerastium alpinum	+	+	
Minuartia biflora	+		
Silene acaulis	+	+	
Papaver radicatum	+		
Draba glabella	+		
Saxifraga oppositifolia		+	
Saxifraga nivalis			+
Saxifraga cernua	+	+	
Dryas octopetala		+	+
Pyrola grandiflora	+		
Cassiope tetragona	+		
Vaccinium uliginosum ssp.	+		
Pedicularis hirsuta	+		

The soils of the shallow depressions were more moist than those on the general levels, and covered by thin organic crusts with a scattering of vascular plants. On the low knolls, which were seen mainly in the western part of the 25-m terrace, the soils were relatively dry and gravelly at the surface. There were areas of micro-nets having crusted nubbinlike structures of fines separated by pebbly soil. The latter was covered with crustose lichens. The vascular flora was sparse and widely dispersed. This kind of ground is illustrated in WASHBURN, 1969, Fig. 62.

Most of the 21 species found in the polygon areas (86 %) were common to abundant in the Mesters Vig vegetation as a whole. The remaining 14 % were occasional or locally common. The polygons were covered by black organic crust, with a few living mosses in the cracks between them or in depressions among surface nubbins. Most of the vascular flora was rooted in or adjacent to the cracks.

The floras of the 25-m and 17-m terrace levels were essentially the same. Cracks and crevices among the polygons contained most of the lichens, of which *Cladonia pyxidata* and *Cetraria islandica* were most abundant. *Cassiope tetragona* covered patches of varying size up to 6 m or more in diameter. In these patches the *Cassiope* was interrupted by small areas or organic crust. In many places the heath was mixed with mats of *Salix arctica*. Humus accumulated under the *Cassiope* and *Salix* tended to obscure the outlines of the polygons. In polygon areas between the heath patches the vascular plants were sparsely distributed as individuals or small groups. On some parts of the 25-m terrace *Vaccinium uliginosum* occurred here and there in the *Cassiope*, distributed not unlike the *Salix*.

The patches of heath appeared to be rather randomly distributed over the more level parts of the terraces. They appeared to avoid the broad shallow depressions and the low knolls, and they seemed to thrive equally well on the windward fronts of the terraces and on the general level. Snow covered these terraces to depths of a meter or more, and remained all winter. Consequently differences in snow depth and spring exposure times seemed to be unrelated to the occurrence of the heath.

Behavior of vascular plants on gradients of ground coverage, moisture and physical disturbance of the soil

Ten of the 21 species proved to be widely tolerant on all the gradients, leaving 11 that could be used to show differences of behavior.

The coverage gradient (Fig. 44)

Nearly all of the definitive plants showed wide tolerance on this gradient, and none was narrowly tolerant. This was consistent with the wide variation in coverage exhibited by the habitat.

The moisture gradient (Fig. 45)

The plants of the small polygons showed no narrow tolerance on the moisture gradient, and over 50% of wide tolerance. Although the soils were moist when excavated in late summer, their good subsurface drainage, and some surface desiccation, suggest only moderate seasonal variation in the supply available to plants. Therefore the proportion of widely tolerant species seems reasonably consistent with expectations.

The frost disturbance gradient (Fig. 46)

Species widely tolerant of frost disturbance were about 36% of the definitive ones found on the small polygons. These and the somewhat higher proportion of intermediately tolerant plants, with one narrowly tolerant, suggest a fair relationship to the moderate frost heaving that was estimated. The proportions of species tolerances in the small polygons are indicative of more frost heaving than was obvious at the site. They resemble the percentages in the damp sandy soils around the nonsorted circles where heaving was more evident. It can be postulated that the flora reflects a larger moisture supply and more intense heaving that probably occurred within relatively recent years and within the lifetimes of many of the existing plants (see below).

The nonfrost disturbance gradient (Fig. 47)

The general lack of much nonfrost disturbance is reflected in the relatively high percentages of species narrowly tolerant on this gradient. However, the apparent low intensity of this kind of disturbance in the small polygons on the delta remnants would lead one to expect proportions of both narrow and wide tolerance more like those of comparable sites (Fig. 47). But on these polygons more than half the species were widely tolerant, suggesting considerably greater instability than in the other sites.

This discrepancy could be due to faulty ratings of species tolerance, or to incomplete knowledge of the disturbance processes. If deposition and abrasion by wind, postulated in the discussion of site factors, are present even to a limited extent they could account for the relatively high percentage of widely tolerant species. It might also be due in part to historical conditioning of the site and the flora. It is possible that the present flora is more closely adjusted to the wetter conditions that are thought to have obtained in relatively recent years, as was postulated in connection with its adjustment to frost disturbance.

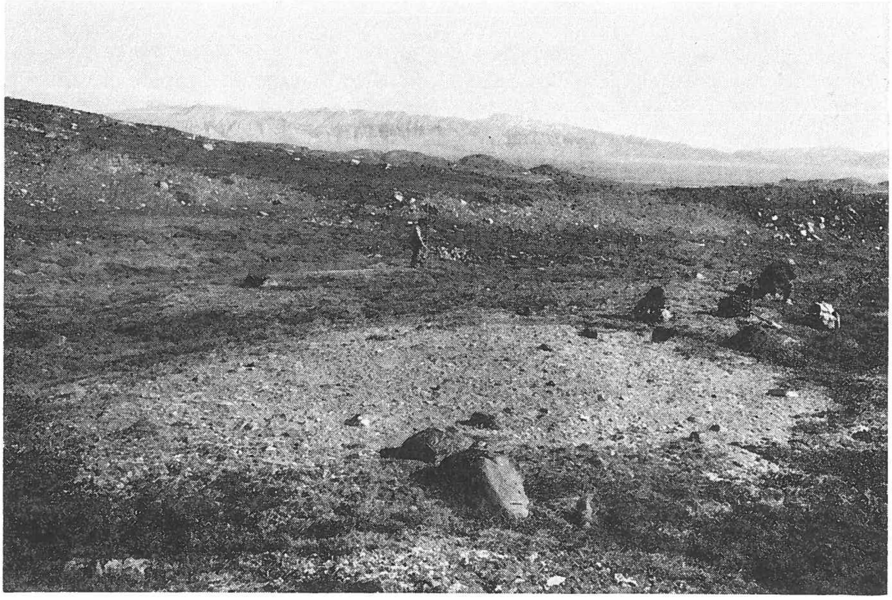

Fig. 23. Large nonsorted polygon on ridge crest just above ES 20. View northeast. Excavation 58–8–10 was through half of this polygon (see Fig. 24). Most barren portion is 6 m in diameter. 10 Aug. 1958 (from WASHBURN, 1969, Fig. 88).

THE VEGETATION OF LARGE NONSORTED POLYGONS

Introduction

Notes on the vegetation of some large nonsorted polygons were made on a low ridge on the lower east slope of Hesteskoen about 0.5 km southwest of "Camp Tahoe", at an altitude of 250 m. Although the locality was visited repeatedly, most of the materials for the present study were gathered on 5 and 9 Aug. 1958. Experimental site 20 was located on one of these polygons. It has been discribed in detail by Dr. WASHBURN, and the origin of the polygons discussed (WASHBURN, 1969, p. 140–149). The following general description of the area is derived from his notes.

Topography and soils

The ridge on which the polygons were found was composed of arkosic bedrock that was strongly disintegrated in the uppermost 1–2 m. It was thinly and patchily covered with glacial till. The polygons were outlined by linear furrows or trenches which gave a clearly polygonal

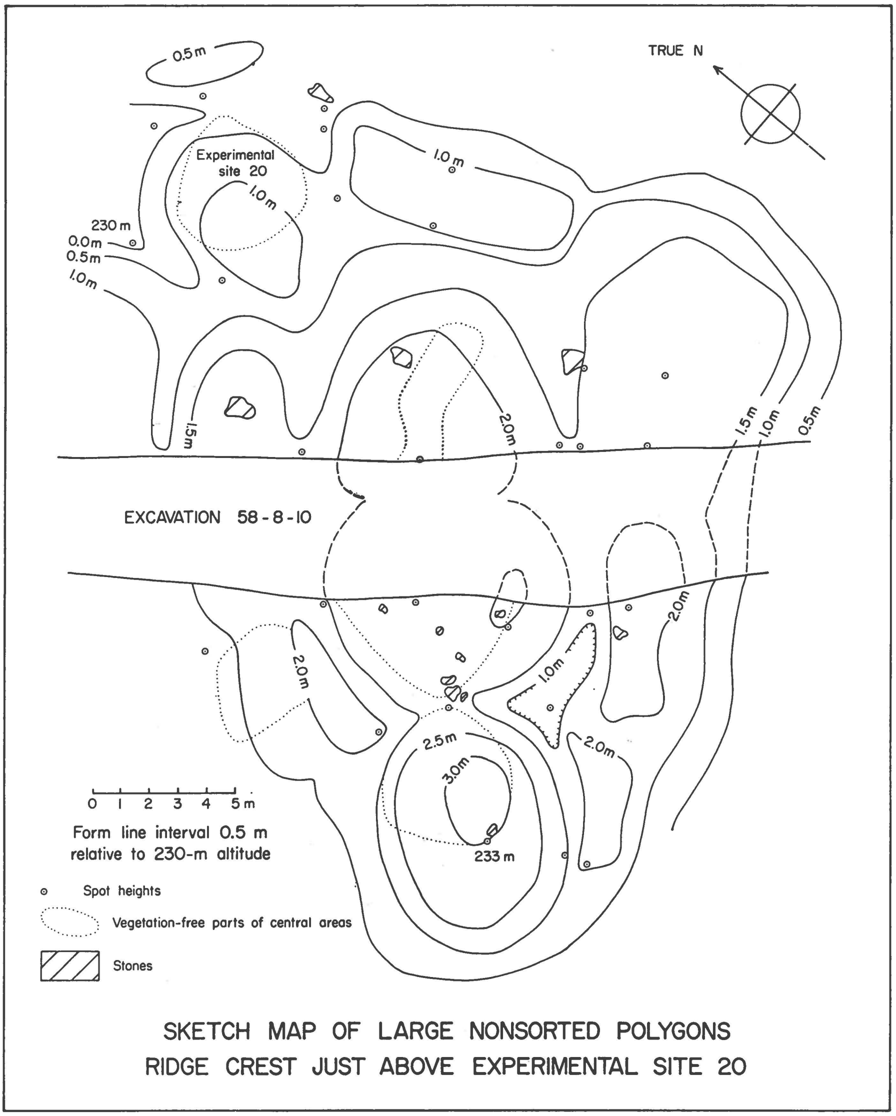

Fig. 24. Sketch map of large nonsorted polygons on ridge crest just above ES 20 (from WASHBURN, 1969, Fig. 87).

form to the general pattern. Most of the polygons were on the crest of the ridge, but a few such as the site of ES 20 were on the flanks forming step-like structures. The polygons ranged in diameter from 5.5 to 10.5 m (measured from the midpoints of the bordering trenches). The nearly or quite barren central areas were roughly circular and were 3 to 6 m in diameter. Some of the central areas were slightly domed while others

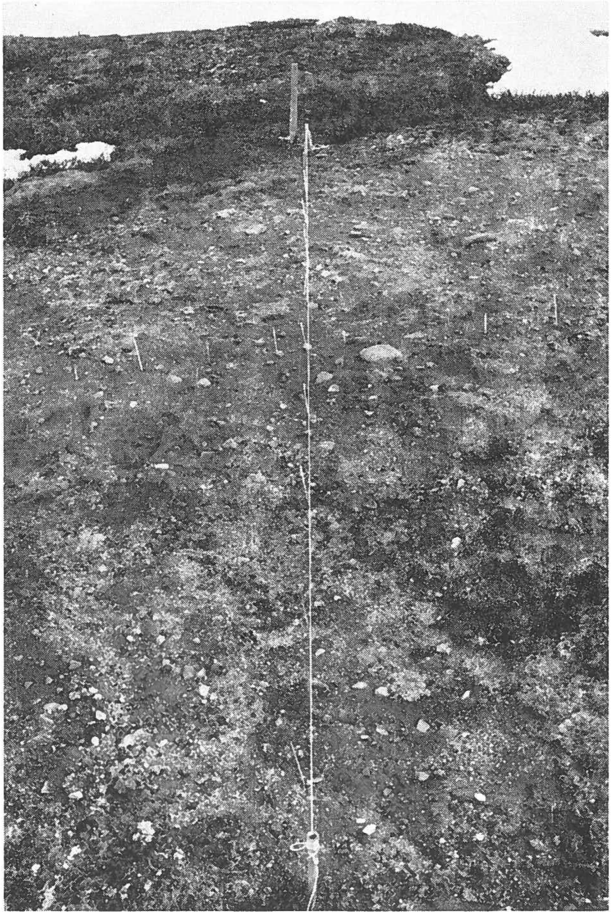

Fig. 25. Experimental site 20. View east along east-west dowel line. 2 July, 1960 (from WASHBURN, 1969, Fig. 55).

were nearly flat. The border trenches had an average depth below the centers of about 50 cm (see Figs. 23–26).

The polygon centers had pale reddish soils of silty-clayey-gravelly sand, with fines (clay and silt) ranging from 9 % to 28 %. The reddish color distinguished these soils from the moderate brown to pale brown soils of the surrounding areas. These bordering soils were diamictons as much as 50 cm thick under the trenches. The underlying weathered bedrock, disintegrated *in situ*, came to the surface in the polygon centers to form the central soils noted above. A deep excavation (2 m), exposing sections of two of the polygons showed their internal structure (Fig. 24, and WASHBURN, 1969, Figs. 89, 90, 91, Pl. 1).

Concerning the origin and development of these features WASHBURN has written as follows (1969, p. 147): "The structures revealed by the

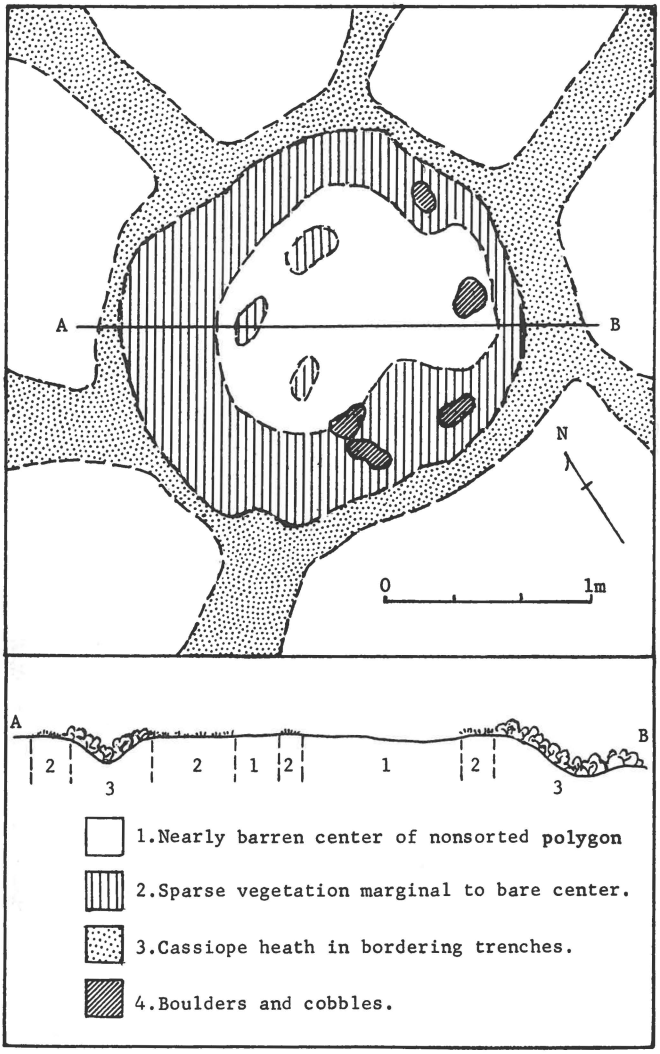

Fig. 26. Map and transect of vegetation at ES 20. 5 Aug. 1958.

excavation are interpreted as resulting from frost cracking, frost wedging, frost heaving, and thawing. Frost cracking of weathered and frozen bedrock is believed to be responsible for the polygonal pattern of the furrows . . . Frost heaving of relatively fine-grained materials beneath the central areas would account for heaving and disruption of bedding and penetration of structureless material between rock fragments. Thawing of differential ice accumulations along the borders would explain the slumping there . . . The dome-shaped structure of the central areas and its maintenance are believed to be due to (1) increase in volume of material because of disintegration of the bedrock and the consequent rearrangement of its constituents, (2) collapse of the borders, and (3) greater frost action in the central areas than borders because the furrows, as depressions, are more favorable locations for insulating vegetation."

When first examined the polygons were thought to be related to deep ice wedges. However the collapse features exposed by the excavation were unlike those associated with the thawing of such wedges. WASHBURN expressed the opinion that "Rather they suggested the melting out of a shallow ice mass that lay at a depth of 1.5 m or so and increased in thickness from the central areas of the polygons toward the borders. An increase in thickness of a massive ice lens toward the furrows would be consistent with frost cracking there without necessarily involving deep ice wedges . . . However, the possibility of deep wedges having been (or still being) present is not eliminated" (WASHBURN, 1969, p. 145–147).

Site factors

Coverage of the ground by vascular plants

Coverage by vascular plants in the polygon area as a whole varied from zero to as much as 80 % (see Figs. 23, 25, 26). The centers of some polygons were quite barren except for small isolated patches of *Stereocaulon.* In others a few scattered vascular plants appeared, forming a cover of less than 1 %. Surrounding these central areas, and lying between them and the border trenches was a somewhat denser cover, usually not over 10 %. Occasional polygons had no barren central area, but were covered by the marginal vegetation just mentioned. Coverage in the trenches was much more dense, ranging from 50 % to about 80 %. It was broken by open spots covered with black organic crust.

Moisture supply

Situated as it was, on a narrow ridge with good drainage on either side, the polygon area had no source of melt-water from lingering snowdrifts. Thus it lost most of its surface moisture early in the summer season, and received only a limited supply from light rain or snow before the autumn freeze-up. Moisture samples collected in the central area of the ES 20 polygon on 2 July, 1960 (following an unusually wet, late spring) yielded only 8 % moisture (w) in the surface soil, 13 % at 5 cm depth, 12 % at 10 cm, and 14 % at 20 cm. It is probable that the areas marginal to the more barren centers, but still on the flat to slightly domed surfaces, retained moisture a little later in the summer, but on most of the occasions when the polygons were seen they were dry all over their upper surfaces.

The soils in the bordering trenches remained somewhat moist throughout the summer and into the autumn. This was due to their protection from insolation and drying winds by their depression below the general level and by their cover of vegetation.

Physical disturbance by frost action

Two lines of dowels were placed in ES 20 on 12 Sept. 1958, and their net heaves measured on 2 July, 1960 (Fig. 25). The lines were approximately at right angles to each other, with the dowels 20 cm apart and inserted alternately to depths of 5 and 10 cm. The 5-cm dowels (20) were heaved, on the average, only 0.08 cm and the average for 20 that were inserted to 10 cm was 0.63 cm. Thus the dowel heaving was relatively insignificant in the uppermost 10 cm of the soil, suggesting that the plants were not much affected by it. No dowels were placed in the trenches, but some heaving would be expected there because of greater autumn moisture. This would be most effective in the more open spots where the ground was covered by organic crusts.

Washburn was of the opinion that: "Although the dowel heaves at ES 20 indicate that surface frost action, at least, is slight, . . . the vegetation-free nature of the best-developed central areas suggests that heaving is still active . . . Seasonal heaving of the central areas would be favored by the higher frost table beneath the furrows than beneath the bare central areas, which would promote centripetal subsurface drainage toward the centers and accumulation of moisture there" (1969, p. 147).

It is quite possible that the frost wedging and heaving in the weathered subsurface rock that are believed to have formed and maintained the polygon centers now go on chiefly at depth. The surface materials, at least to a depth of 10 cm, become so dry that they are now heaved only slightly. Deeper heaving, however, would maintain the forms of the polygons, and would be favored by the centripetal drainage suggested by Washburn in the above quotation. The surface soils, though disturbed by upward pressures, would remain relatively undisturbed by frost action as they were found to be.

Disturbance by nonfrost processes

The surfaces of the barren or thinly vegetated centers were cracked in part by summer desiccation, and in a few places appeared to have been washed and slightly eroded by spring melt-water. If the suggestion made in the preceding paragraph is valid, that the surface soils were being pushed up each year by heaving at depth, this would create a series of nonfrost disturbances in the root zone. It is probable that there has been some lateral displacement of the central soils toward the margins of the polygons. This was accentuated in ES 20 where the lower side of the polygon appeared to have been built up by downslope movement of the material of the center (Fig. 26). Probably of more significance to plants than any of the above factors was deflation by wind and abrasion by windblown sand. Located on the crest and upper slopes of a ridge in the valley of Tunnelelv, the polygon surfaces were subject to strong, dry foehn winds blowing down the valley. These winds desiccated the surface soils and carried away some of the fines. Similar conditions were seen on trap knolls and ridges.

Summary

Variation in coverage by vascular plants was relatively high in the trenches, but somewhat lower in the centers and center margins. Variation in moisture supply was large in the centers and center margins, but medium to low in the trenches. Frost heaving was relatively low in the central portions of the polygons, but medium to relatively intense in the trenches because of autumn moisture. In the denser vegetation of the trenches it probably was fairly low, but in open spots covered by crust it probably was high. Nonfrost disturbance probably was insignificant in the trenches, but may have been of considerable magnitude in the central areas.

The vegetation

Twenty species of vascular plants were found in the study area of large nonsorted polygons (Table 6). Three habitats can be roughly defined, though the first two are so closely related that they are scarcely separable (see Figs. 23, 25, 26).

The first is in the central areas of the polygons where only five species were growing widely scattered as individual plants or small groups. Bare soil predominated, with little or none of the organic crust that is common in the Mesters Vig district. Many of the plants were dead or partially so, indicating a high incidence of mortality.

Surrounding the nearly barren central areas was a marginal vegetation of very low density in which 14 species were found. Here the individual plants were more numerous than in the centers, and the mats or clumps somewhat larger. Cover density was still less than 10 % in most places, and mortality remained high. The marginal space occupied by this vegetation was on the flat or gently domed surfaces of the polygons, and extended only to the upper edges of the trenches between the polygons. *Betula nana* was common on the outer edges of the vegetation marginal to the more open centers. It did not extend into the trenches.

The commonest lichen on the polygons was *Stereocaulon* sp. It occurred in the central areas as small, fragmentary, widely scattered

Table 6. *Flora of large nonsorted circles on ridge crest in the vicinity of ES 20. See Fig. 23.*

	Central areas of polygons	Marginal areas of polygon centers	Trenches between polygons
Equisetum variegatum			+
Poa glauca		+	
Trisetum spicatum	+		
Carex nardina	+	+	
Carex Bigelowii		+	
Carex glacialis	+		
Luzula confusa		+	
Salix arctica		+	
Betula nana		+	
Minuartia rubella	+		
Minuartia biflora			+
Melandrium affine		+	
Draba glabella		+	
Saxifraga nivalis		+	
Saxifraga oppositifolia		+	
Saxifraga cernua			+
Dryas octopetala	+	+	
Cassiope tetragona		+	+
Vaccinium uliginosum ssp.		+	+
Arnica alpina		+	

patches. Stones in the central areas were nearly or quite free of crustose lichens. In the marginal strips the patches of *Stereocaulon* were more numerous and larger, and were mixed with *Cetraria* spp. and *Cladonia pyxidata.* Most of the surface stones here were partially covered with crustose lichens.

The trenches or furrows between the polygons were made conspicuous by *Cassiope* heath which nearly filled them. It was mixed with *Vaccinium uliginosum* in a few places, but for the most part was in pure stands. Its cover was interrupted here and there by openings covered with organic crust. The *Cassiope* was growing on mats of living moss or in organic crust. Only five species of vascular plants were seen in the trenches. It is probable that this vegetation represents the heath tundra which is widespread in the Mesters Vig district. However, the small area involved here and the scattered nature of most of the heath flora, have combined to make the flora of the trenches extremely small and nonrepresentative.

Behavior of the vascular species on gradients of ground coverage, moisture and physical disturbance

For purposes of analysis the floras of the central and marginal portions of the flat or slightly domed polygon surfaces were combined. The sharply contrasted vegetation of the trenches was regarded as not sufficiently representative of heath tundra to be used for comparison.

The central and marginal areas contain 17 species. Eight of these proved to be widely tolerant on all the gradients studied, with no species narrowly tolerant on all gradients. Thus 9 species were considered definitive and used in the following analyses (Figs. 44–47).

The coverage gradient (Fig. 44)

All but one of the species (89 %) were widely tolerant of variation in ground coverage by vascular plants, while the single exception was intermediate. In these proportions the polygon vegetation closely resembled those of the small polygons on the delta remnants.

The moisture gradient (Fig. 45)

The large nonsorted polygons at ES 20, with their sandier soils probably lose less water by evaporation from the surface than the nonsorted circles, and retain more subsurface moisture than the small polygons on the delta remnants. Although they have a higher percentage of widely tolerant plants than the latter, they also have about 22 % of narrowly tolerant species, suggesting that their vegetation reflects the slightly less moisture variation that probably occurs.

The frost disturbance gradient (Fig. 46)

Figure 46 shows sharp contrasts among the compared habitats on this gradient. The high proportions of species especially sensitive to frost disturbance in the large nonsorted polygons and nonsorted circles, together with the absence or relatively low percentage of widely tolerant species, reflects the known minor frost heaving in these sites. Reverse proportions show in the sandy soils among the nonsorted circles and in the small polygons on the delta remnants, where the soils retain more moisture throughout the summer and are subject to autumn heaving.

The nonfrost disturbance gradient (Fig. 47)

Nonfrost disturbing agencies on the polygons were noted above as slight erosion by spring melt-water, heaving at depth that may have been sufficient to disturb the soils of the root zone, and probably most significant, deflation and abrasion by wind. Whatever the cause, the flora of these polygons suggests moderately intense disturbance by nonfrost processes. About 56% of the species were widely tolerant on this gradient, 22% were partially adjusted, and only 22% were narrowly tolerant. These proportions contrast sharply with those in the nonsorted circles and their neighboring soils. In all of the latter sites the preponderance of narrowly tolerant plants reflects the low intensities of this kind of disturbance known to occur in them. An intermediate position, discussed elsewhere in the present paper, was seen in the flora of the small polygons on the delta remnants.

Fig. 27. Debris island at south base of Danevirke hills below trap knob MS 171 m, 25 July, 1958. Scale is 16-cm rule (from WASHBURN, 1969, Fig. 96).

THE VEGETATION OF DEBRIS ISLANDS

Description of the debris island sites

The vegetation of debris islands was noted in two areas: at the southern base of the Danevirke hills below trap knob MS 171 m (alt. ca. 120 m), and at and near the summit of Hesteskoen (alt. 950–1118 m *cf.* WASHBURN, 1969, p. 155–159). Those in the Danevirke area were in the bed of a small drainage basin which was floored with boulders and cobbles. The debris islands were small, more-or-less circular patches of stony mineral soil, up to 50 cm in diameter, scattered here and there in the stony pavement (Fig. 27). On Hesteskoen they were in bouldery rubble consisting in some places of angular fragments of conglomeratic sandstone, and in other places of trap. These islands were commonly 1–2 m in diameter, and contained angular, "fresh" looking debris with much more fine material than could be seen in the surrounding rubble. They were lighter colored, and appeared to have more shaly rock fragments than there were in the rubble (Figs. 28, 29).

Most of the debris islands on Hesteskoen were isolated from each other, but occasionally they were clustered. In a few places they were close enough together to resemble sorted nets. Most were domed on the

Fig. 28. Debris islands on north side of east-west ridge of Hesteskoen, 18 July, 1958. Scale is 16-cm rule (from WASHBURN, 1969, Fig. 99).

Fig. 29. Debris islands on northwest-southeast summit ridge of Hesteskoen. Island at center is about 2 m in diameter. Note step-like structure. 26 June, 1956 (from WASHBURN, 1969, Fig. 97).

surface, and in some places where the islands were adjacent there were furrows between them as much as 50 cm deep containing flat sandstone fragments on edge. Gradients of the general surface in the neighborhood of the islands varied from 17° to 31°, though the slope of the central surfaces was commonly less by as much as 6°, thus producing a step-like appearance (Fig. 29). Some were slightly elongate downslope, while others trended with the contours.

Site factors

Samples from the central areas of the islands were of silty-sandy gravel (with only 9 $^0/_0$ silt), and sandy gravel. The gravel fraction was 63 $^0/_0$ in the first of these, and 78 $^0/_0$ in the second. Coarser fragments up to 15 cm in diameter were embedded in the finer material.

No moisture analyses were made in the debris islands, nor were any specific data gathered on intensity of physical disturbance. Relative values, however, may be inferred from the general situations in which the islands were found, and from the texture of their soils.

The debris islands in the Danevirke area, being in a shallow basin in the hills, were moist when seen on 25 July, 1958. It is probable that their moisture remained through most of the summer, and that there was a considerable amount of frost heaving in the autumn. On Hesteskoen the sandy-gravelly soils of the centers were relatively dry at the surface on 18 July, 1958, suggesting that they did not contain much moisture in late summer. However, situated at relatively high altitudes they received more late summer and early autumn snow than those at lower elevations, and thus probably were subjected to considerable frost heaving at autumn freeze-up. There was only minor evidence of downslope movement of the central fines at the higher altitudes, in the step-like structures.

The vegetation

The vegetation of the debris islands was extremely scanty, though 26 species of vascular plants were found growing on them (Table 7). Usually not more than half a dozen species were on any single island; and all were much scattered, either as individuals or small groups. In the Danevirke area most of the soil surfaces were covered with black organic crusts, with occasional small thin mats of living moss, and a few lichens. On the Hesteskoen debris islands there was very little organic crust or moss. Near the summit of the mountain a thin-bedded shaly sandstone cropped out in a few places, and here the islands contained somewhat more fines and supported a few more plants than did

Table 7. *Vascular flora of debris islands.*

	Danevirke hills	Hesteskoen
Woodsia glabella		+
Poa arctica		+
Poa alpina	+	
Poa glauca		+
Poa abbreviata		+
Carex nardina		+
Carex Lachenalii	+	+
Luzula confusa	+	
Salix arctica	+	
Oxyria digyna	+	
Cerastium alpinum	+	+
Minuartia rubella		+
Ranunculus pygmaeus	+	
Papaver radicatum		+
Draba alpina	+	
Draba lactea		+
Draba subcapitata		+
Saxifraga oppositifolia	+	+
Saxifraga nivalis	+	+
Saxifraga cernua	+	+
Saxifraga caespitosa		+
Epitobium latifolium		+
Cassiope tetragona	+	
Campanula uniflora		+
Taraxacum arcticum		+
Taraxacum phymatocarpum		+

the coarser centers nearby. The surrounding rubble, both in the Danevirke area and on Hesteskoen, was essentially sterile of vascular plants. A few mosses were seen in the deeper crevices, and most of the rocks were covered with crustose lichens.

The vascular flora of the debris islands, like those of other small, highly differentiated sites, was made up largely (73 %) of species common to abundant in the Mesters Vig district. About 19 % were occasional or locally common, and about 8 % were rare or locally occasional.

The behavior of the species on gradients of coverage, moisture and physical disturbance

Of the 26 species listed in Table 7, 13 were found to be widely tolerant on gradients of coverage, moisture, and physical disturbance, leaving an equal number that were regarded as definitive.

The coverage gradient (Fig. 44)

Most of the species in the debris islands show relatively wide tolerance of variation in the coverage of the ground by vascular plants.

The moisture gradient (Fig. 45)

A moderately low proportion of wide tolerance of variation on this gradient, and a relatively high percentage of narrow, suggest a site with a fairly consistent moisture supply throughout the summer season, though not a large one. It is notable that these proportions are not much different from those in the sandy soils among the nonsorted circles and in the large sorted net areas. The fact that both of the latter sites are known to be supplied with moderate moisture through the summer suggests that the debris islands probably also have it.

The frost disturbance gradient (Fig. 46)

No definitive species narrowly tolerant of frost action were found in the debris islands. However, the high percentage of intermediately tolerant plants (about 70 $^0/_0$) relative to the widely tolerant (about 30 $^0/_0$) suggests an intensity of frost heaving somewhat similar to that in the sandy soils around the nonsorted circles. The comparisons in Fig. 46 suggest further that its intensity was considerably less than in the large sorted nets, but much greater than in the nonsorted circles. Finer textured soils in the sorted nets probably held more water than either the debris islands or the sandy soils, thus bringing on more intense heaving in the autumn. The low heave intensity in the sorted circles probably was due to summer desiccation and very little moisture at the time of freeze-up.

The nonfrost disturbance gradient (Fig. 47)

The debris islands showed a preponderance of species narrowly tolerant on the non-frost gradient, indicating for this kind of disturbance a relatively low intensity. However, the proportion of widely tolerant species present suggests a certain amount. There was a little evidence of down slope movement in the debris islands on Hesteskoen, and the bare soils there may also have been affected to some extent by erosion.

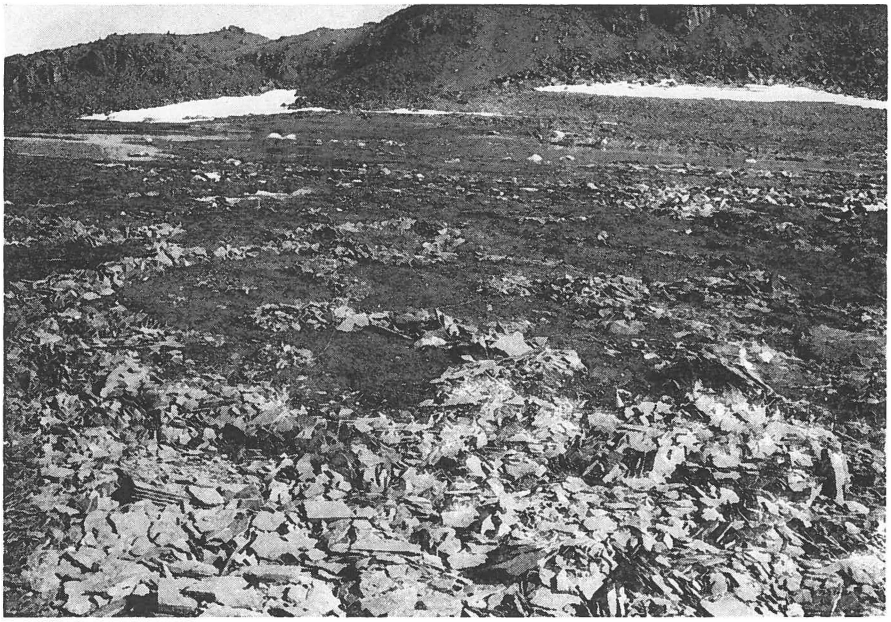

Fig. 30. Large active sorted nets at ES 1, 11–12 and vicinity. View southeast, downslope. 11 July, 1958 (from Washburn, 1969, Fig. 105).

THE VEGETATION OF LARGE SORTED NETS

Introduction

The vegetation of large active sorted nets was observed in many places in the Mesters Vig district, but was studied in detail only in the vicinity of ES 1, 11–12 and near the border of the lake at Myggesø. Most of the following discussion is based on notes from the first of these places.

Topography and soils

The location and general site conditions at ES 1, 11 and 12 have been described in detail by Washburn (1969, p. 164–171). The following description is derived mainly from his notes.

The vicinity of these experimental sites was in a small drainage basin on the Kong Oscar Fjord slope of the Labben peninsula (Fig. 30, see map in Raup, 1965 A, pl. 1). It was in an area of large sorted nets on an average slope of about 2°. Outcrops of slabby sandstone were immediately upslope from the nets, and the stony borders of the nets were composed mainly of flat pebbles, cobbles and boulders of the sandstone. The nets were formed of irregular stone borders separated by finer tex-

Fig. 31. Cracked soil in central area of sorted net near ES 11–12. Note black crust at borders of cracks, and willow roots heaved out of soil.

tured soils. Most of the meshes were elongate downslope, though a few were more or less parallel to the contours. The widths of the meshes varied from less than a meter to as much as 8 m. Stone borders varied from 15 to 100 cm in width, and in height up to 32 cm above the level of the centers.

In places they were discontinuous, so that some of the "centers" resembled, in part, the nonsorted circles of ES 2, 3 and 9 and vicinity. The finer soils were commonly cracked irregularly (Fig. 31). WASHBURN has suggested that some of these cracks result from surface dilation due to heaving. In some meshes the centers were irregularly domed, with relief up to 14 cm. Others showed little or no doming. Occasionally the domed soils were cracked to form small polygons resembling those of ES 9.

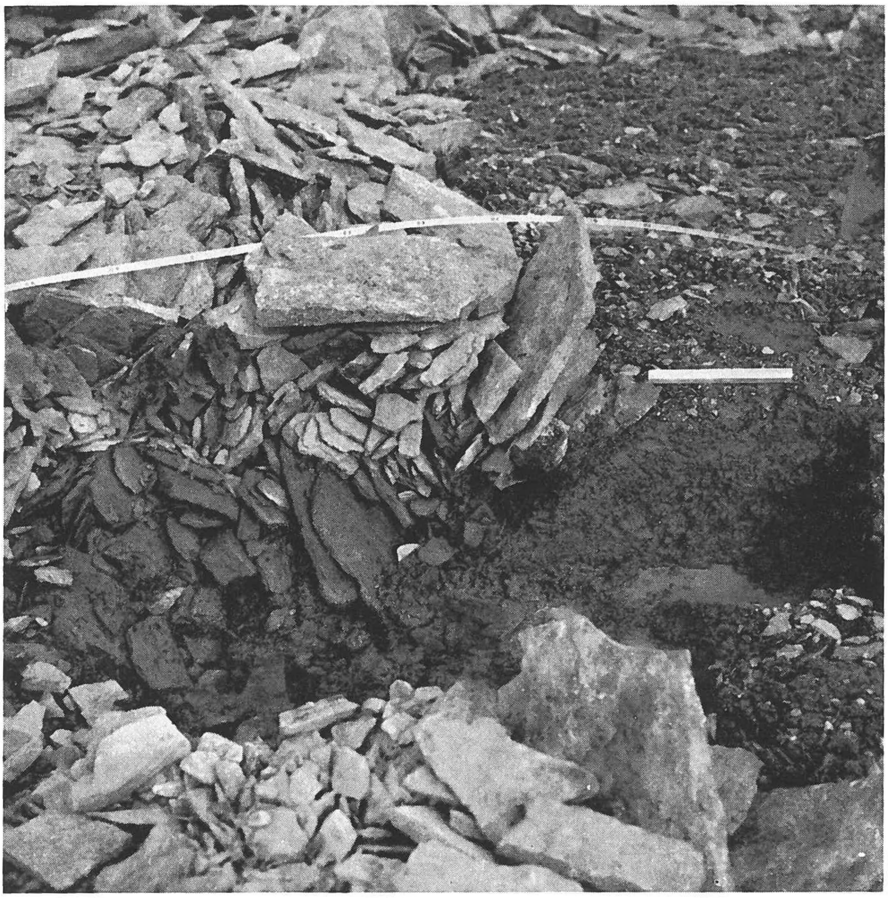

Fig. 32. Excavation through net border, showing contact between stones and fines, decrease of stone size with depth, and turfy material under border stones.

The finer textured soils of the centers ranged from gravelly-sandy silt-clay with 78 % in the silt and clay sizes to clayey-silty-sandy gravel with as little as 30 % fines. About two thirds of the 17 samples analyzed ranged between 40 % and 60 % fines, and the average for all the samples was about 51 %. The stones embedded in the fines were mainly of sandstone, though limestone fragments were found in ES 12. Occasional pieces of trap, granite and quarzite were found throughout, especially in the stone borders.

Experimental site 12 differed from all other meshes seen in the vicinity in having a portion of the center composed of finer textured material. This contained 78 % silt-clay and was olive black in color except at the surface where it was grayish. It was surrounded by dark yellowish brown soil with up to 56 % sandy silt or silty sand. The black

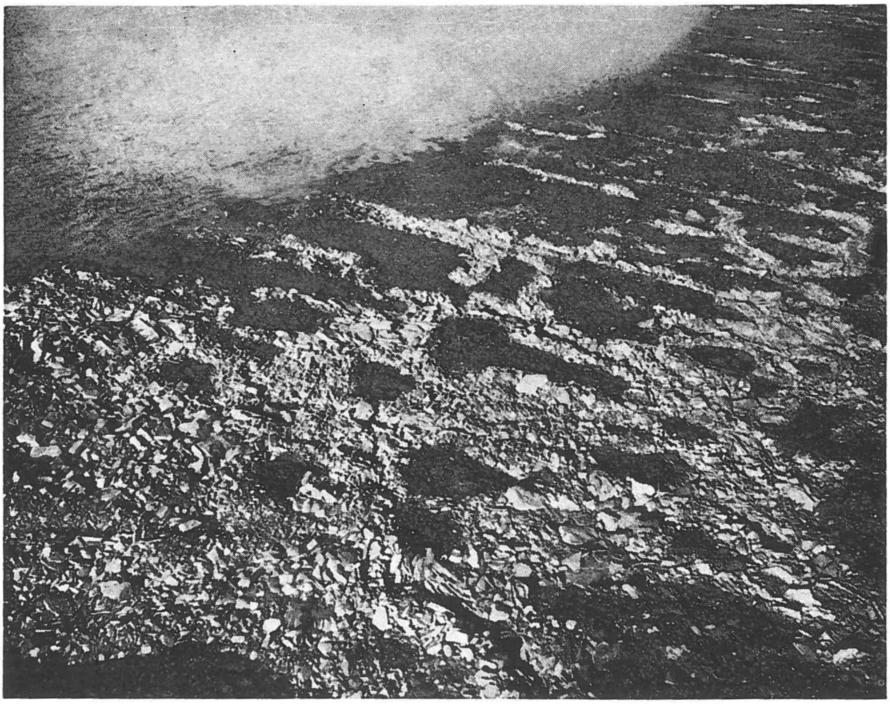

Fig. 33. Large sorted nets at north end of Myggesø. View west from the air. Smallest meshes about 1 m in diameter. 25 Aug. 1955 (from WASHBURN, 1969, Fig. 110).

material was greasy, very compact, highly calcareous, and contained chips of brownish black thin-bedded limestone. WASHBURN has suggested that it came from the weathering of an erratic limestone boulder.

The stones of the borders decreased in size with depth. (Fig. 32). This probably was due to increased frost wedging at depth, and downward movement of smaller pieces wedged from the large stones at or near the surface.

The nets observed at Myggesø (Fig. 33) were on slopes of 3° or less bordering the lake, with some on the adjacent lake bottom in shallow water. On steepening slopes up the nearby mountains the nets merged with stripe patterns. The border stones were mainly of slabby sandstone, though occasional pieces of vein quartz, trap and granite were seen. Their size distribution and attitudes were similar to those found at ES 1, 11–12. The finer textured soils in the meshes were clayey-gravelly-silty sands in the upper 5 cm, with as much as 34 $^0/_0$ fines. They tended to become somewhat coarser with depth.

Site factors

Coverage of the ground by vascular plants

Vascular plant coverage was low throughout most of the net areas (0–10 %). The only places where it was more dense was on the margins of some of the meshes, at or near the contacts between the finer-textured soils and the border stones. Here *Cassiope tetragona*, sometimes mixed with *Salix arctica*, formed coverages up to 80–90 %.

The moisture supply

Active sorted nets were found only where the moisture content of the soils was relatively high, and where most of the soils remained moist throughout the summer. They were always located near late-lying snowdrifts or near sources of moisture from melting ground ice. Many stabilized net areas were seen, mainly on the foot slopes of the mountains, but they were always in places where water was not now prominent (Fig. 43).

At ES 11 the surface moisture (w) was 25 % on 13 July 1958, and on 20 July 1960 it was 33 %. On the latter date there was 31 % at 5 cm depth, and 49 % at 10 cm. On 17 September 1960 ES 11 had 25 % at the surface, 20 % at 5 cm, 24 % at 10 cm, and 27 % at 20 cm. In ES 1 the surface soil had 24 % moisture on 10 July 1958, and 25 % on 13 July. Other samples from ES 1 showed 18 % at the surface on 30 August 1958, and about 19 % at 20 cm. Only one sample came from ES 12, showing surface moisture of 21 % on 13 July 1958. All of these data are from the central areas of the net meshes.

The moisture supply to the ES 1, 11–12 area came from snowdrifts on the slopes immediately above to the northwest, and from drainage out of the nearby sandstone cliffs. Small streams were definable in a few places.

The silt-clay portion of ES 12, partially cracked at the surface into small polygons resembling those in nonsorted circles, probably was somewhat drier in late summer than the silty sands surrounding it. Its grayish surface contrasted with the darker color of the adjacent coarser material, and the polygonal cracking suggested some desiccation. Its fine textured surface should promote rapid evaporation approaching that seen in the nonsorted circles, but the more continuous water supply to the ES 1, 11–12 area as a whole would preclude the extreme desiccation seen in the circles. Nonetheless it is probable that the partial drying may have been, in part, the cause of the relatively low heave intensity noted in the fine soil at ES 12.

Disturbance by frost action

Evidence of intense frost action was conspicuous in the active net areas. In addition to the dowel heaves described below, freshly heaved

Fig. 34. Experimental site 11. View west upslope, 27 Aug. 1956 (from WASHBURN, 1969, Fig. 43).

stones with soil still clinging to their sides and tops were seen here and there. The long slender roots of *Salix arctica* were heaved to the surface in many places, sometimes stretched tight by lateral displacement produced in the heaving process. Organic turfy material was found as much as 15 cm beneath the present surface, indicating burial by overturning or massive lateral movement of the central fines. Mosses at the margins of the central areas were sometimes found covered by recent falling of border stones. Most of the flat pebbles and cobbles in the borders were on edge or at varying angles near the vertical. Pebbles in the central areas were almost completely devoid of lichens, while the larger stones in the borders usually were covered with crustose species. The surfaces of the centers commonly had the wormy or crumb structure resulting from needle ice activity, and needle ice was found there on 1 Sept. 1964.

Small dowels were placed in the central areas of two of the net meshes (ES 11 and 12) on 27 Aug. 1956. They were inserted to 10 cm, and were 10 cm apart in grid patterns 50 cm square. Measurements of dowel heave at ES 11 were made on 12 July, 1 Aug., and 14 Sept. 1958, and at ES 12 on 12 July and 14 Sept. 1958, and on 3 Aug. 1959. The sites were excavated in 1964. See Figs. 34, 35, 36, 37. Experimental site

Fig. 35. Experimental site 11. View west upslope, 20 July, 1960 (from WASHBURN, 1969, Fig. 44).

1 was in another mesh center, and consisted of two thermocouple installations (TCS 1 A & B).

The average net heave of all dowels in ES 11 was greater than in ES 12. On 1 Aug. 1958 at ES 11 it was 5.5 cm, and on 14 Sept. 1958, 6.5 cm. At ES 12 it was only 3 cm on 14 Sept. 1958, while on 3 Aug. 1959, after another year's activity, it was only 4.3 cm.

The heaving in ES 11 was assessed by averaging the net heaves of all dowels that fell within each contour interval, using the measurements made on 1 Aug. and 14 Sept. 1958. The results are in Table 8. This table shows not only that the net heave was relatively great, but also that it was fairly uniform throughout the area sampled (Figs. 34, 35). When examined in 1960 nearly all of the dowels were heaved out of the ground, again with relative uniformity throughout. The soil was clayey-sandy-silty gravel to clayey-silty-sandy gravel. It contained up to 52 % fines.

ES 12 was first analysed for frost heaving in the same way as ES 11, by contour intervals (Table 9). Measurements made on 14 Sept. 1958 and 3 Aug. 1959 show that the heaving was not as uniformly distributed as in ES 11, but tended to decrease toward the upper levels of the domed surface. However, this trend was irregularly defined.

A further analysis was made by averaging the dowel heave measurements for the two dates noted above in two groups based on a photograph

Table 8. *Distribution of average dowel heaves in ES 11, arranged by contour intervals.*

Contour interval (cm)	1 Aug. 1958	No. of dowels	14 Sept. 1958	No. of dowels
6– 7	5.5	3	5.3	2
7– 8	5.5	7	6.5	5
8– 9	5.6	9	6.5	4
9–10	5.7	10	6.2	3
10–11	5.7	9	6.4	6
11–12	5.4	15	6.2	10
12–13	5.4	17	6.7	12
13–14	5.6	9	7.5	5
14–15	4.8	2	6.3	2
15–16	5.0	1		

of the site made on 23 Aug. 1960 (Figs. 36, 37). This photograph shows a group of dowels that were still standing though they were variously heaved. They were surrounded by dowels that were nearly all heaved out like those in ES 11. The 1958 and 1959 heaves were averaged and compared for all standing dowels and for all that were down, as in Table 10. The dowels that were out of the ground in 1960 already had been heaved, on the average, more than twice as much by early August, 1959, as those that were standing in 1960. In September, 1958, they had been heaved three times as much as those still standing in 1960. These data indicate that the heave difference seen in the 1960 photograph was the result of differences in heave intensity that were consistent over a period

Table 9. *Distribution of average dowel heaves in ES 12, arranged by contour intervals.*

Contour interval (cm)	14 Sept. 1958	No. of dowels	3 Aug. 1959	No. of dowels
3– 4	8.0	1		
4– 5	7.5	1	8.0	1
5– 6	6.5	3	7.8	3
6– 7	3.7	10	5.8	10
7– 8	4.0	12	5.6	11
8– 9	3.5	6	3.8	5
9–10	2.7	6	3.5	6
10–11	2.4	7	4.3	7
11–12	1.6	7	1.4	6
12–13	2.3	16	4.3	16
13–14	1.5	13	2.7	13
14–15	1.3	5	2.7	5

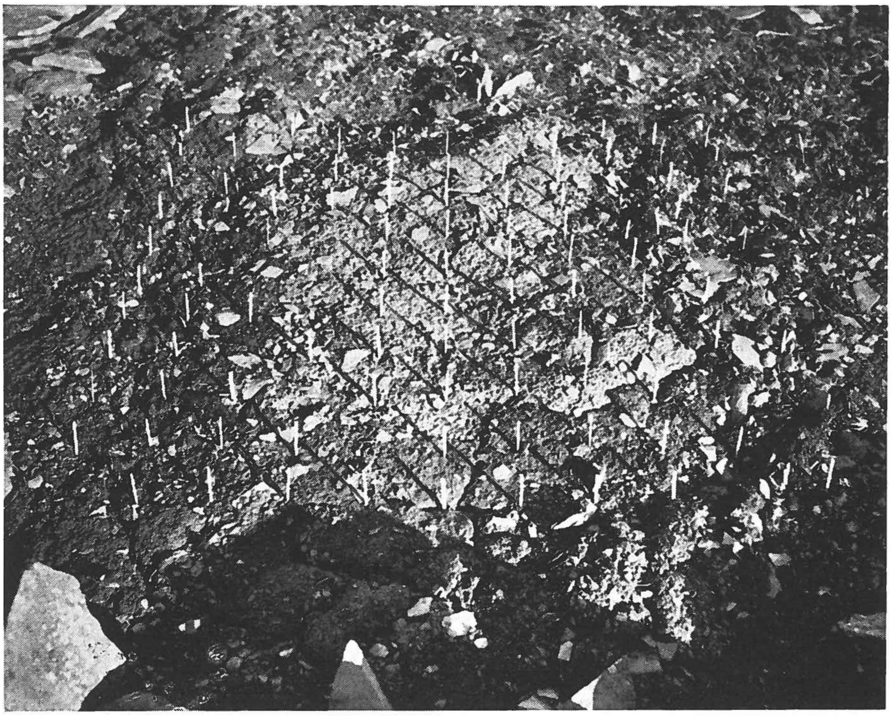

Fig. 36. Experimental site 12. View east downslope, 27 Aug. 1956 (from WASHBURN, 1969, Fig. 45).

Fig. 37. Experimental site 12. View east downslope, 23 Aug. 1960 (from WASHBURN, 1969, Fig. 46).

Fig. 38. Stone border at lower margin of sorted net mesh, vicinity of ES 1, 11–12. Note accumulation of central fines against border (upper left). 27 July, 1957.

Table 10. *Distribution of average dowel heaves in ES 12 on 14 Sept. 1958 and 3 Aug. 1959, arranged in two groups of dowels seen in Fig. 37.*

Photo. 23 Aug. 1960	14 Sept. 1958	No. of dowels	3 Aug. 1959	No. of dowels
Standing dowels..........	1.9 cm	62	3.3 cm	61
Dowels heaved out.......	5.7 cm	21	7.1 cm	24

of four years. The area of greatest heaving was roughly coincident with the lower contours of the site; hence the partial differentiation shown in Table 9, which was based on analysis by contour intervals.

There was a notable difference at ES 12 in soil textures between the areas of standing and heaved-out dowels. This was the difference

Fig. 39. Experimental site 14. View north, 15 July, 1957.

already noted in the discussion of soils. In the former area there was gravelly-sandy silt-clay with 78 % fines, while in the latter the soil was gravelly-clayey-silty sand with about 56 % fines. The content of silt and clay in the latter was about the same as in ES 11 where there was a similar heave intensity.

Disturbance by nonfrost processes

In most of the large active nets there was only minor evidence of mass-wasting or erosional activity. Where gelifluction occurred it was partially masked by the intense heaving. However, many meshes were observed in which the stone borders on the upslope margins stood 10–20 cm higher above the surfaces of the central fines than at the downslope margins (Fig. 38). This was particularly noticeable in meshes having long axes extending up and down slope, and suggested movement of the fines

Fig. 40. Experimental site 14. View north, 11 July, 1960.

toward the lower margins. Whether this was due to gelifluction or frost creep, or both, is unknown.

Where occasional small streams ran through the meshes, keeping the fines saturated during most of the summer, low terraces were formed. Although these were irregular in shape they resembled the small gelifluction lobe studied at ES 15. Experimental site 14 was established on one of these terraces on 15 July, 1957 (Fig. 39). It was bathed over most of its surface at that time by a sheet of gently flowing water, and there was visible water flowing in the stony border trenches. In 1958 there had been very little change in its appearance, but in July, 1960, there was much less water flowing over and around it (Fig. 40) in spite of the fact that the whole net area was much wetter in 1960 than in the preceding years because of a late spring and large late-lying snowdrifts. The small stream that was supplying the site in 1957 and '58 seemed to have been

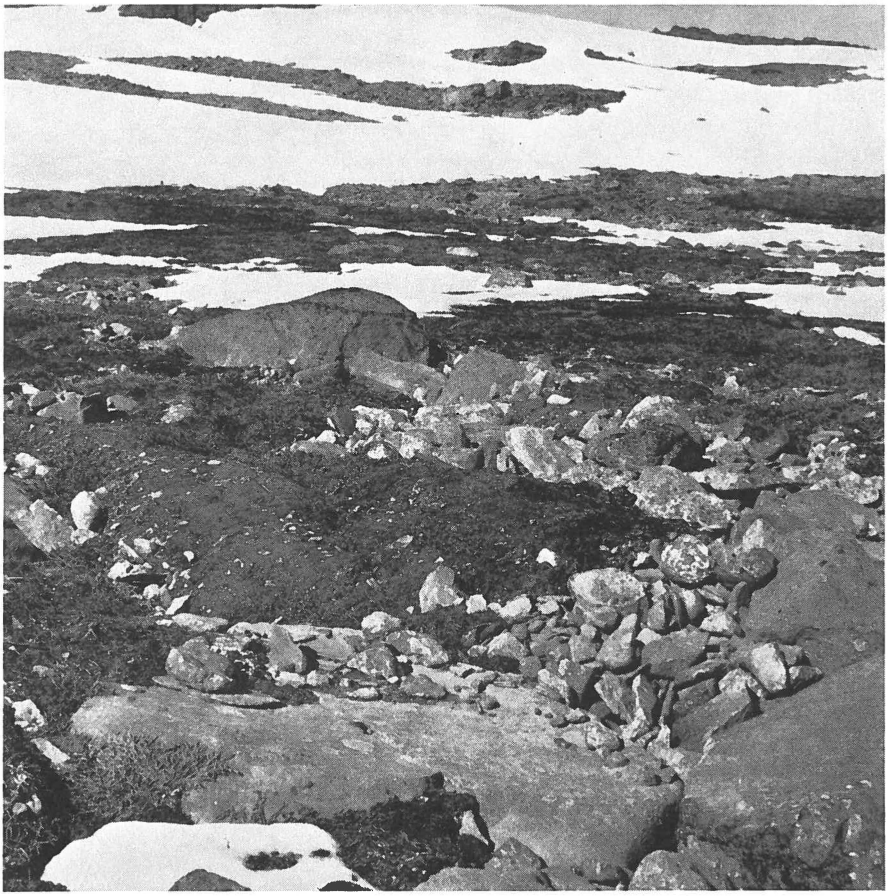

Fig. 41. Terrace-like structure in sorted net area about 6 m north of ES 14, with form similar to the latter but without a large water supply. View northwest, 11 July, 1960.

partially diverted northward greatly reducing the flow to ES 14. Although there was still a thin sheet of water on part of its surface, the stony trenches around it were dry except at depth.

About 6 m northeast of ES 14 was another lobe-like structure closely resembling it in form (Fig. 41). But it had no water flowing over or around it, and its surface, though somewhat domed, was highly irregular with low humps and depressions, and with much bare soil or thin organic crusts. There were several of these structures in the immediate vicinity, some without stones around their lower margins, and others banked up against stony borders to conspicuously higher levels than the surfaces just below them. These structures, and the behavior of the flow at ES 14, suggest that some of the net meshes may be modified in their development by gelifluction movement where small streams saturate the fines of the central areas. They also suggest that the process is intermittent, depending upon the vagaries of the stream channeling. Diversion of the streams may be due to built-up of the lobes themselves, or to alteration of channel systems upslope by the frost heaving in the net system as a whole.

The vegetation

The vascular flora

Twenty-five species of vascular plants were found in the areas of large active sorted nets (Table 11). Nineteen of them ($76\,^0/_0$) were species common to abundant in the Mesters Vig district, and six ($24\,^0/_0$) were occasional and locally common. None was locally occasional or rare. One species was rhizomatous ($4\,^0/_0$), 11 had fibrous roots ($44\,^0/_0$), and 13 had taproots ($52\,^0/_0$). Three of the taprooted species spread by rooting at branch nodes, thus raising the effective proportion in this group to at least 16 ($64\,^0/_0$) (see RAUP, 1969 A, p. 68–69).

Table 11. *Species of vascular plants found in large active sorted net areas.*

	Mesh centers	Stone borders
Equisetum arvense	+	+
Poa alpina	+	
Trisetum spicatum	+	
Carex Lachenalii	+	
Carex misandra	+	
Luzula arctica		+
Luzula confusa	+	+
Salix arctica	+	+
Oxyria digyna	+	+
Polygonum viviparum	+	
Cerastium alpinum	+	+
Minuartia biflora		+
Silene acaulis	+	+
Melandrium apetalum ssp. *arcticum*	+	
Ranunculus pygmaaus	+	
Draba alpina	+	+
Draba lactea	+	+
Saxifraga oppositifolia	+	+
Saxifraga hieracifolia	+	
Saxifraga nivalis	+	
Saxifraga cernua	+	+
Saxifraga caespitosa	+	
Epilobium latifolium	+	
Cassiope tetragona	+	+
Pedicularis hirsuta		+

Vegetation of the principal habitats

Two habitat complexes could be seen although the differences between them were small. One was in the finer textured soils in the central portions of the net meshes, and the other was at and near the stone borders. Table 11 shows that 22 species were found in the former and 14 in the latter. Eleven species (44 $^0/_0$ of the flora) were found in both habitats, leaving 11 to characterize the central areas and 3 that were found only at the borders.

The vascular plants in the central areas were all scattered as individuals or very small clumps, and all were relatively small in stature. Coverage by these plants was not over 10 $^0/_0$ of the ground surface, and in most places was 5 $^0/_0$ or less. The largest plants were in the patches of *Salix arctica*, but these showed a great deal of mortality. Dead *Salix* plants were common, and many living roots had been heaved up and lay exposed on the surface of the soil (Fig. 31). Small plants of *Cassiope tetragona* and other species also showed high mortality.

Much of the soil surface was entirely bare, though here and there were patches of organic crust and a few living moss polsters. In rare instances small turf hummocks had been formed by proliferating mosses, but they appeared to be deteriorating, with willow stems and roots exposed on the tops and around the margins. Most of the living moss was around and in the small clumps of *Salix*. The most barren areas appeared to be the domed portions of the centers, where there were only occasional bits of moss and lichen.

There was much variation among the meshes in the extent of coverage by organic crust and vascular plants. In some the soil was almost completely covered by crust except where small areas of needle ice activity had broken it. The crust usually was formed into small nubbins or wrinkles 1–3 cm high (see WASHBURN, 1969, p. 85–88). The wrinkles had a roughly concentric arrangement in some places (Fig. 42), suggesting flow of the mineral soil or shrinkage due to partial drying. This evidence of minor flow appeared in some meshes having their long axes up and downslope. Here the wrinkled crust was pushed up against stone borders at the lower margins of the central areas.

In more active soil the isolated patches of crust were mainly at or near the margins of major cracks (Fig. 31), where wrinkles in them were commonly oriented parallel to the cracks. Vascular plants were commonest in the more continuous crusts, or in the small patches bordering cracks. The most completely barren area was on the domed mass of fine-textured silt-clay that formed part of ES 12 (Fig. 36, 37).

The stony borders of the meshes were in themselves almost completely devoid of vascular plants. A few mosses could be found deep in

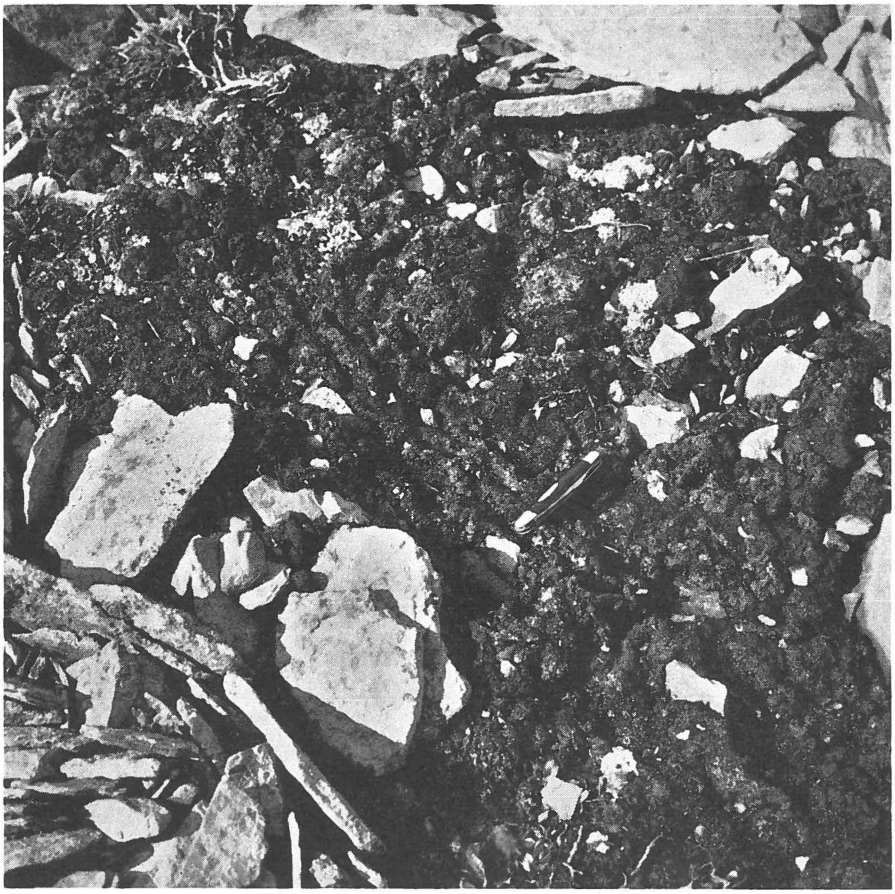

Fig. 42. Nubbins and wrinkled organic crust in sorted net near ES 1, 11–12. 27 July, 1957.

the crevices among the larger stones. In the area of contact between the central mass of fines and the border stones there usually was a small humus accumulation that extended downward a few centimeters into the stone-filled trenches between the meshes (Fig. 32). In many places this turf was expanded and formed the base for most of the scattered plants listed for the border habitat in Table 11. Growth was mostly concentrated at the downslope margins of the meshes where there was evidence of accumulation against the stone borders. It is probable that frost heaving is somewhat lessened in these places due to better drainage of the mineral soil at the upper edges of the trenches, and to insulation by the denser vegetation.

More stabilized nets were found a short distance downslope from ES 11 and 12. Here the centers were covered with a turfy shrub tundra

Fig. 43. Large stabilized sorted nets on lower northeast slope of Hesteskoen, 28 Aug. 1964.

where plants of the active centers and their margins had expanded. The most abundant and conspicuous species was *Cassiope tetragona*, which formed most of the cover. Accompanying it were *Luzula arctica*, *Salix arctica*, *Silene acaulis*, *Draba alpina*, and *Saxifraga oppositifolia*. The turf was formed mainly of mosses, though a few lichens were present (*Stereocaulon* sp., *Cetraria islandica*). Similar vegetation was seen in stabilized nets on the footslopes of Hesteskoen below Camp Tahoe (Fig. 43).

Behavior of the species on gradients of coverage, moisture and physical disturbance

Introduction

The whole flora of the active sorted nets showed relatively wide tolerance on all of the gradients studied. The two poorly defined habitats noted above exhibited insignificant differences in the behavior of their species on the gradients. Variation in the moisture regimes was relatively small throughout the net area; likewise in the disturbance factors with the unique exception of the heavy soil in ES 12. The lack of more species narrowly tolerant on the disturbance gradients in the marginal soils, and the high percentages of widely tolerant species there, suggest that these soils achieve very limited freedom from frost heaving, and that they may be considerably disturbed by lateral movement due in some measure to gelifluction.

Fourteen (56 %) of the 25 species found in the area were rated as widely tolerant of variation on all gradients used (coverage, moisture and physical disturbance), while none was narrowly tolerant on all gradients. Only five species displayed narrow tolerance on any gradient (one on the moisture and four on the nonfrost disturbance gradient). Only 11 species could be regarded as definitive. The proportions of these species on the gradients are shown in Figs. 44–47.

The absence of dry soils other than the exposed stones of the net borders, and the relatively constant moisture supply, suggest that the flora should have relatively low percentages of species widely tolerant of variation on the moisture gradient, and at least some proportion of narrowly tolerant ones. The intensity of frost heaving throughout most of the areas studied suggests that the proportion of widely tolerant species on the frost disturbance gradient should be high, and that of narrowly tolerant species very low. The reverse should be expected on the nonfrost disturbance gradient where the activity of nonfrost processes is small.

The coverage gradient (Fig. 44)

The high percentage of wide tolerance among species in the sorted nets on the coverage gradient reflects the generally large proportion of these species in the whole Mesters Vig flora, particularly among those that were common to abundant.

The moisture gradient (Fig. 45)

Approximately 90 % of the definitive species in the nets were equally divided between wide and intermediate tolerances on the moisture gradient, suggesting that the requirement for wide tolerance of variation in moisture was relatively moderate.

The frost disturbance gradient (Fig. 46)

There were no narrowly tolerant species on the frost disturbance gradient in the nets, so that all of the definitive species were in some degree adjusted to the intense heaving demonstrated by the dowel experiments and by other phenomena. Over half of them were widely tolerant on this gradient. In contrast, in the nonsorted circles fully half of the small flora was narrowly tolerant of frost disturbance (see Fig. 46). The other half was about equally divided between wide and intermediate tolerance, thus reversing the relationship seen at ES 1, 11–12.

Washburn has discussed this situation (1969, p. 170–171), noting that in both places vegetation was extremely sparse, but for different reasons: "The occurrence locally of vegetation in the mineral soil at these localities, and more abundantly in similar soils elsewhere in the Mesters Vig district where the growing season was comparable, shows that desiccation and frost action were the primary deterrents. The ample moisture at ES 1, 11–12 eliminates desiccation, so that the intense frost action in the autumn is the logical explanation for the very sparse vegetation there. At ES 9, on the other hand, near-surface frost action was shown to be very slight and desiccation prominent, so that desiccation rather than frost action probably explains the lack of vegetation."

A problem is presented by the near-absence of vegetation in the silty clay portion of ES 12 where frost heaving was much less intense than in the clayey-silty sand of the bordering portion of at ES 11. Washburn (1969, p. 170) has suggested that the reduced heave was caused by the "'tightness' of the calcareous mineral soil at ES 12 (which was very obvious during digging)". It is not known whether this or the calcareous soil would also preclude the germination and growth of vascular plants, or whether the amount of heaving that still remained in the finer-textured soils was sufficient to produce this result. The average heave for all dowels in this soil was 1.9 cm (see Table 10) while the average for all dowels at ES 9 was about $^1/_3$ as much (0.63 cm). It can also be suggested that summer evaporation from the finer-textured soil at ES 12 produced a certain amount of desiccation which may have hindered successful germination. If this was the case the lack of vegetation may have been due to a combination of partial desiccation and limited frost heaving.

The nonfrost disturbance gradient (Fig. 47)

In the sorted nets the lowest proportion of widely tolerant species (27 $^0/_0$) was on the nonfrost gradient, and the highest proportion of narrowly tolerant (45 $^0/_0$). This suggests that whatever gelifluction, or massive lateral displacement, or subaerial erosion may have occurred had relatively small effect on the selection of species for the net areas. There appears to have been even less in the nonsorted circles, where there were proportionately more narrowly tolerant species and less that were well adjusted to nonfrost disturbance (see Fig. 47).

SUMMARY AND DISCUSSION

Introduction

The distributional behavior of vascular species among the habitats discussed in this paper may be summarized by comparison of the distributions of their tolerance ranges. Seven habitats illustrative of weathering, frost action and patterned ground are used in the comparison. One other, the sandy soils surrounding the nonsorted circles, is incompletely represented by the experimental sites studied here, and will be discussed more fully in a later paper. The tolerance ranges of its species, however, show proportions approaching those that appear when a larger volume of data from the widespread organic crust areas is used.

It is possible, from notes on habitat factors given in the preceding pages, to approximate roughly the position of each habitat on scales of variation in ground coverage density and moisture, and on degrees of intensity of physical disturbance. Field data for these approximations are incomplete and unevenly representative. Coverage figures are available for all of the sites, based on observations made on many occasions. A limited number of moisture analyses have given some comparable figures for the experimental sites (ES 3, 5, 9, 11, 12, 16, 20). In other habitats the moisture has been estimated. Repeated observations throughout the spring, summer and early autumn have made possible estimates of the seasonal moisture regimes. Documentation of frost disturbance is reasonably adequate for the experimental sites noted above, but for others it has been approximated from observations on soil textures and moisture regimes. Nonfrost disturbance has had to be almost entirely estimated from observations of topography, drainage patterns, wind, and soil texture. The only applicable experimental data were on dry creep at ES 16 (Raup, 1969 B).

Figures 44, 45, 46, and 47 compare species tolerance distribution on each of the gradients used. For each gradient the habitats are arranged progressively, in the cases of coverage and moisture, from the highest percentages of species widely tolerant of variation on these gradients, to the lowest. For the frost and nonfrost disturbance gradients the progression is from the vegetation with the highest percentage of species widely tolerant of these disturbances, to that with lowest percentage. In theory there should be parallel progressions in the site conditions from large to small variation in coverage and moisture, and high to low intensities on the disturbance gradients.

It should be kept in mind that the tolerance ratings of the species were based on their capacity to withstand *variation* in the habitat factors. The ratings say nothing, for example, about how much total moisture may be available to a plant, but rather how much variation in the supply, seasonal or annual, it is able to survive.

The graphs in Figs. 44 to 47 have been adjusted to utilize the intermediately tolerant species by adding in each analysis half of them each to the widely and narrowly tolerant. This did not alter the progressive sequences appreciably. It made the curves for wide and narrow tolerances mirror images of one another, and by smoothing made them more usable for the desired comparisons.

Comparison on the coverage gradients

Although as in most of the preceding analyses the species widely tolerant on this gradiant far outnumber the narrowly tolerant, comparison of the seven habitats shows a variation of about 32 %. This suggests that the plants may reflect to some extent differences in density of coverage. Ranges of ground coverage estimates suggest two groups of habitats. In the first the ranges are from zero to 80 (90) %, while in the second they are from zero to about 20 %. The first group contains vegetations in which the prevailingly scattered distribution of plants is interrupted by large or small mats of *Cassiope*, *Salix arctica* or *Dryas*. These are on the small polygons of the emerged delta remnants, among large active sorted nets, and in or near large cracks among compound nonsorted polygons. In the second group the patches of denser cover are absent or present in small sizes and numbers. Here are the small polygons in nonsorted circles, debris islands, rocky hilltops, talus, etc., and large nonsorted polygons.

Figure 44 suggests two similar groups though the order in which the habitats appear in them is not precisely as the percentages indicate. The first has a wide tolerance percentage range from about 95 % to 100 %, while in the second it ranges from about 67 % to 76 %. The groups are of the same habitats as those noted above with the exception of the large nonsorted polygons which are nearer the first group than the second. The suggestion from these figures is that a slightly higher proportion of the species in the first group than in the second are especially well adjusted to wide variation in coverage.

Comparison on the moisture gradient

Variations in moisture availability to plants in the seven habitats can be divided into wide, comparatively narrow, and possibly an intermediate category. The soils in the nonsorted circles and compound non-

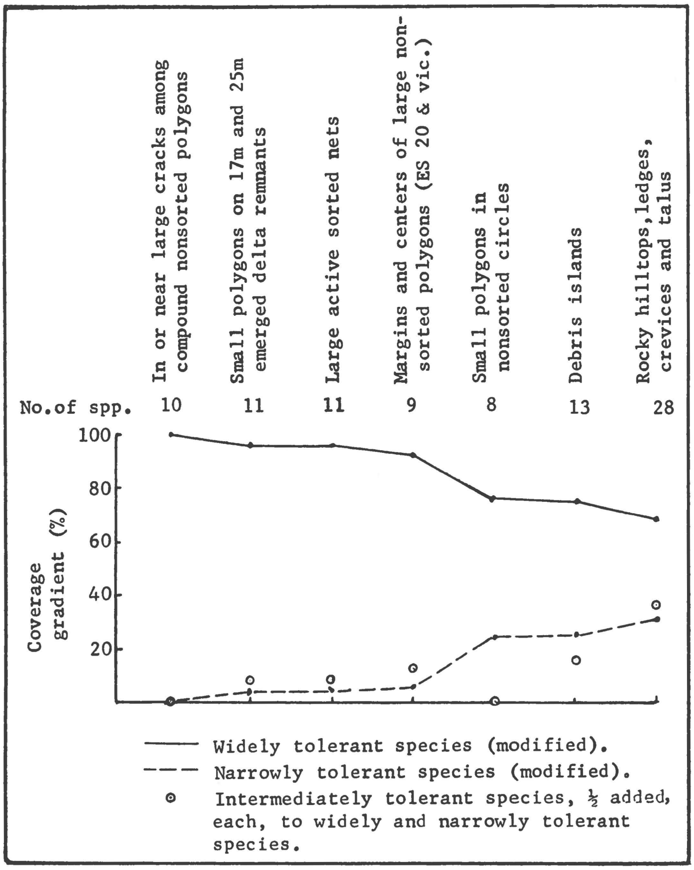

Fig. 44. Comparison of species tolerance distributions on the coverage gradients in seven habitats illustrating weathering, frost action and patterned ground.

sorted polygons probably have the widest range of seasonal change. At snow-melt in spring they are completely saturated and nearly fluid for a short time. They are fine textured, hold a great deal of water, but soon lose it by capillary upward movement and evaporation from the surface.

Sites with comparatively low variation may be very dry or moderately moist throughout the summer. Coarse textured soils that have no other water supply than snow-melt lose their moisture very quickly after the snow is gone, for they have little or no holding capacity. In this they differ from the nonsorted circles and polygons where some moisture remains for a short time, probably long enough for a few plants to germinate. Light rain or snow during the summer season is relatively more effective for plants in the finer textured soils, thus increasing the variability; whereas in the coarse textured soils it is lost so quickly

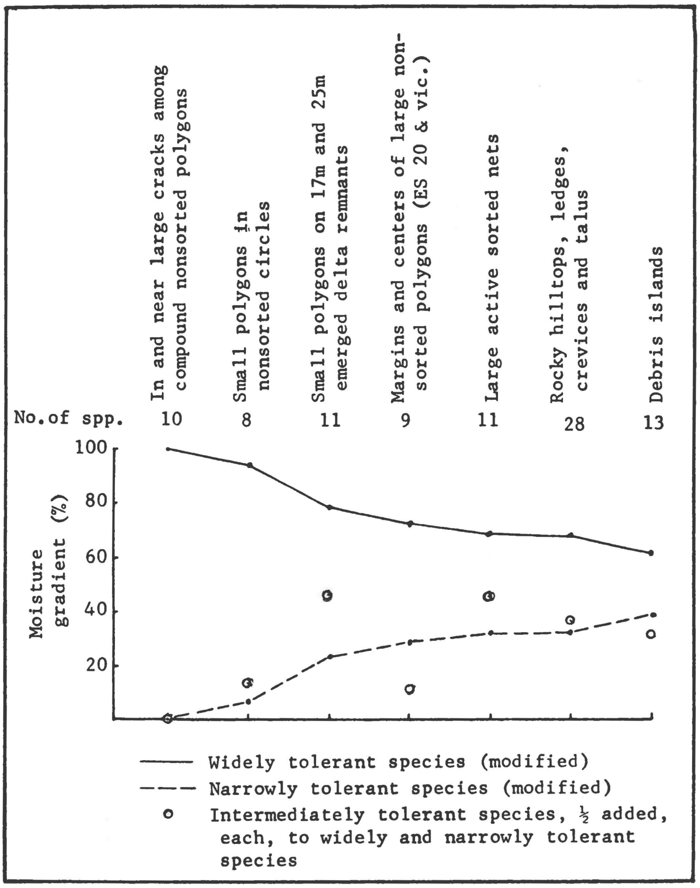

Fig. 45. Comparison of species tolerance distributions on the moisture gradient in seven habitats illustrating weathering, frost action and patterned ground.

that it scarcely affects their uniform summer desiccation. The sandy soils of dry hilltops, ledges, crevices, and talus are in this category.

Sites having more-or-less continuous moisture during the summer and autumn, with relatively small variation, are the large active sorted nets, and probably also the debris islands. The soils of the last, observed at a median altitude near Myggesø, appeared to hold some moisture through the summer. Those on and near the summit of Hesteskoen were rather dry at the surface but moist 2–3 cm below. Further, at their higher altitude (1100 m) the snow-free season is very short, and summer precipitation more frequent and abundant.

The large nonsorted polygons (ES 20 and vic.) may occupy an intermediate position with respect to moisture variation. Their surfaces were drier in summer than those of the debris islands, but not so dry as the nonsorted circles or the hilltop sands. They retained some moisture within a few centimeters of the surface. Another site that may be intermediate is that of the small polygons on the emerged delta remnants near the Mesters Vig airfield. Here the finer textured soils over the delta sands and gravels were somewhat moist whenever they were examined, even late in the summer. However, these areas are subject to very good internal drainage, and in very dry summers, exposed as they are to dry winds, the surface soils may be much more desiccated than our field parties have seen them. If this is the case, the plants would be subject to considerably more moisture variation than is at once apparent.

The tolerance percentages in Fig. 45 show a sequence among the habitats fairly consistent with the three groups just described. The highest percentages of wide tolerance 94–100 %, (and the lowest for narrow tolerance) are in the nonsorted circles and polygons. The lowest percentages of wide tolerance 56–69 % are in the large sorted nets, rocky hilltops, etc., and in debris islands. Intermediate, 72–78 %, are the large nonsorted polygons and the small polygons on the delta remnants.

Comparisons on the frost disturbance gradient

The intensity of frost heaving in the habitats compared here depends mainly upon whether they contain an appreciable amount of moisture at the time of autumn freeze-up. The seven habitats can therefore be divided into two main groups. In the first are the sites that retain moisture through the summer: large active sorted nets, debris islands, and (apparently in most years) the small polygons on the emerged delta remnants. All of these, with the possible exception of the last, are subject to intense heaving. In the second group are the soils that lose most of their moisture early in the summer and undergo much less heaving: the nonsorted circles and polygons, hilltops, talus, etc., and the large nonsorted polygons of the type studied at ES 20. The last appear to be an exception, for in the discussion above they were noted as probably containing some moisture through the summer, and as intermediate in the scale of moisture variation. Dowel heave data show minimal heaving to depths of 5–10 cm, and although moisture in the root zone might actually be "intermediate" during the growing season, the heaving that activates the fines of the polygons may be made possible by moisture at depths below the root zone. If this is the case, the plants would be subject to intermediate moisture variation in the root zone, and to low intensity of heave at autumn freeze-up.

The sequence shown in Fig. 46 separates with fair accuracy the two main groups noted above. Sites that remain moist throughout the summer have from 63 to 87 % of their plants widely tolerant of the more intense frost disturbance that occurs in these habitats, and from 23 to 36 % narrowly tolerant. In habitats having low moisture and frost dis-

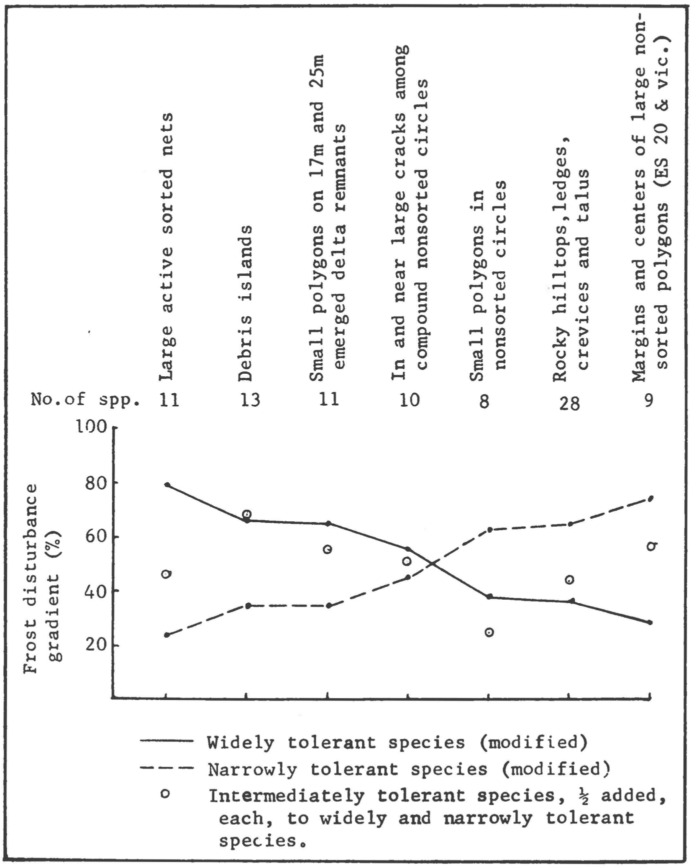

Fig. 46. Comparison of species tolerance distributions of the frost disturbance gradient in seven habitats illustrating weathering, frost action and patterned ground.

turbance the narrowly tolerant plants supercede the widely tolerant, finding the lower intensities of disturbance more permissive for their establishment and growth. With one exception the placement of the habitats within the two groups is about as expected from observations of the site factors involved.

The exception is in the small polygon areas on the emerged delta remnants. No frost heave data from target behavior are available for these areas, and there was very little circumstantial evidence of heaving such as the ejection of stones or needle ice effects. Sorting of stones from fines was evident in some places, but it was not clear that this process was currently active. The behavior of the plants suggests that there is actually more heaving than is apparent, or as suggested above, the present flora still reflects a greater heave intensity that may have occurred in relatively recent years.

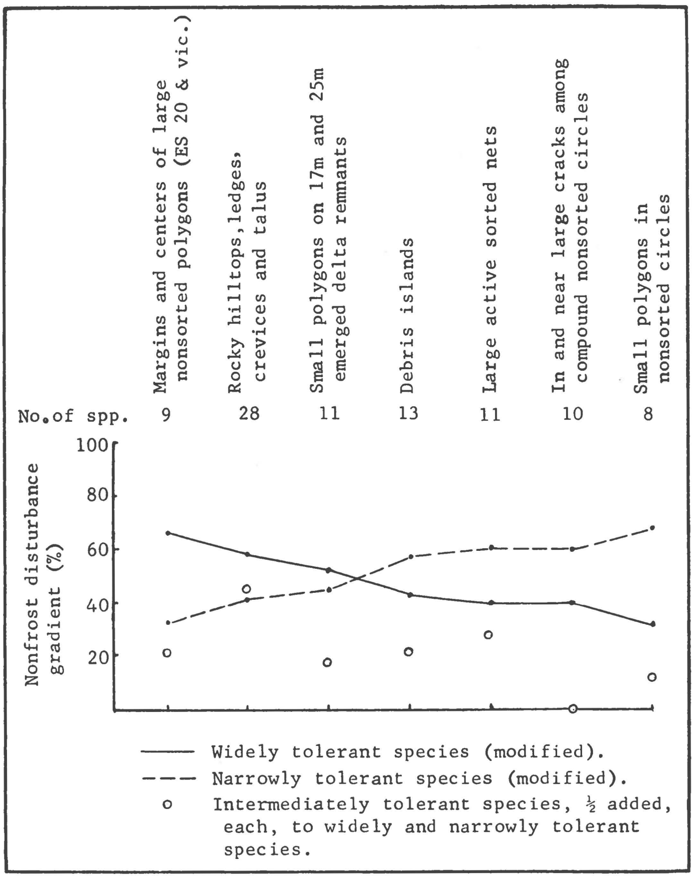

Fig. 47. Comparison of species tolerance distributions on the nonfrost disturbance gradient in seven habitats illustrating weathering, frost action and patterned ground.

Comparisons on the nonfrost disturbance gradient

Physical disturbance in the seven habitats other than that caused by frost action was confined mainly to dry creep of soils on steep slopes, and to deflation or deposition by wind. There was a small amount of gelifluction in some of the nonsorted circles, debris islands and large sorted nets. It may have done some damage to germinating seedlings in fine textured soils while the latter remained saturated in spring, but in general its effects were regarded as minimal. A certain amount of erosion and deposition by spring meltwater was seen in the fine textured soils of the nonsorted circles and compound polygons. It is probable that this was locally limiting to plants, and may have been reflected to some extent in the floras.

For wind action to be effective, the soils must be quite dry at the surface for most of the summer, and located in areas accessible to the wind. Dry creep is limited to equally dry soils located on relatively steep slopes. In both cases the soil is of fine to relatively coarse sand (grus). If it contains much clay or very fine silt, it becomes crusted and does not blow as the surface dries.

Most or all of these conditions were found in two of the habitats; on rocky hilltops, talus, etc., and on the large nonsorted polygons at ES 20 and vicinity. They were not present in large active sorted nets, debris islands, or in nonsorted circles and compound nonsorted polygons. There was no clear evidence of them on the emerged delta remnants near the Mesters Vig airfield. However, the silty sands in the upper horizons there are regarded by WASHBURN as probably eolian. Whether they are still being deposited is uncertain. They are on the floor of the broad valley of the westerly outlet of Tunnelelv (see maps in WASHBURN, 1965, pl. 1, 3, 5). This valley lies between Hesteskoen and the hills back of Nyhavn, and is open to dry northwest winds from the fjord. The valley floor is a gravelly-silty outwash plain upwards of 3 km long and 1.5 km wide. In the latter part of the summer its surface materials become dry and are blown by the wind. Similar plains bound the delta remnants on the east and southeast. Consequently it is highly probable that deposition still occurs, and that strong winds blowing across the old deltas carry abrasive silt and sand. Higher delta remnants 1–2 km away, at the base of Hesteskoen, are presently being greatly modified by the wind.

The two groups of habitats noted above, provided the assessment of conditions on the delta remnants is valid, are clearly defined in Fig. 47. Species well adjusted to nonfrost disturbance are predominant at ES 20 and vic., on rocky hilltops, talus, etc., and in the small polygons, on the emerged delta remnants. The opposite is the case in debris islands, large active sorted nets, and in the fine textured soils of the nonsorted circles and compound polygons.

Analyses presented in this paper, as did those made for the mass-wasting sites, show positive correlations between the local distribution of species tolerance and the local behavior of the site factors of coverage, moisture and physical disturbance. They suggest that the ratings of species tolerance made from general observations are sufficiently valid to be useful as indicators of these site conditions.

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