A. L. Washburn
Seattle, Waschington

PATTERNED GROUND IN THE MESTERS VIG DISTRICT, NORTHEAST GREENLAND

INTRODUCTION

GENERAL

The Mesters Vig district is located on the south side of Kong Oscars Fjord about 50 miles from its entrance (figs. 1—2); the coordinates of the Danish Government weather station at Mesters Vig are lat. 72°14′N, long. 23°55′W.

The present article is a slightly abbreviated excerpt from a discussion of weathering, frost action, and patterned ground in the Mesters Vig district (Washburn, 1968). This is one of series of reports appearing in the *Meddelelser om Grønland* and resulting from a program of cooperative geomorphic and vegetational investigations of the district as described in the *General introduction* to the program (Washburn, 1965).

The general characteristics of the district, including climate, vegetation, topography, and geology are outlined in the *General introduction,* from which the following climatic data are taken.

The mean annual temperature (°C) at the Danish Government station is —9.7°, the mean temperature of the coldest month is —24.3°, of the warmest month 5.9°, and the absolute minimum is —44.2°. Usually only June, July, and August have mean temperatures above freezing, and maximum daily temperatures are above freezing from May through October only, although exceptionally above-zero temperatures have been recorded in other months. Freezing temperatures can occur in any month of the year. In general in the Mesters Vig district, depth to permafrost ranges from about half a meter to somewhat over 2 m, depending on the nature of the mineral soil and the vegetation cover.

The mean annual precipitation is 372.5 mm (measured as water), the minimum being 256.1 mm (1955), the maximum 517.8 mm (1953). Most of it occurs as snow. Because of drifting and the difficulty of accurately measuring precipitation when it falls as snow, the precipitation data are subject to considerable error. Maximum precipitation occurs commonly in autumn and winter, and the minimum in spring. However, there is considerable rain in some summers.

The metric system is used throughout. Colors specified by hue, value, and chroma (in parentheses) are based on the *Rock color chart* distributed by the Geological Society of America in 1951.

Unless otherwise stated, the terminology follows the American Geological Institute *Glossary of geology and related sciences* (Howell, 1960). The nomenclature of sediments follows Washburn, Sanders, and Flint (1963), as a convenient means of characterizing poorly sorted deposits, such as the diamictons (Flint, Sanders, and Rodgers, 1960a, 1960b) in the Mesters Vig district. Based on the Wentworth classification with respect to grain-size limits for gravel, sand, silt, and clay sizes, the nomenclature uses the major component for the principal name, with the lesser components applied as modifiers in order of increasing importance. The actual percentages may be given as subscripts; for instance, $clayey_{10}$-$sandy_{20}$-$gravelly_{30}$ $silt_{40}$. Where percentages fall below 5 percent, the component is omitted in the name. Also, where the principal component is within 5 percent of the next component, it has been found useful to join them; for instance, $clayey_{8}$-$sandy_{16}$ $gravel_{36}$-$silt_{40}$. "Fines" in this article refers to silt and/or clay. The following are some of the abbreviations (singular and/or plural) employed:

ES .... Experimental site(s)
MS .... Map summit(s)
SD .... Specimen depth(s)

Previous publication on patterned ground in the Mesters Vig district comprise a brief note by Enzmann (1960) and detailed discussion of turf hummocks by Raup (1965). A variety of patterned-ground forms are represented but their distribution tends to be local and some forms are rare. The following discussion, primarily descriptive, is intended to provide a survey of the forms occurring in the district and an analysis of some of the factors controlling their origin and distribution. References to related observations elsewhere emphasize those postdating Washburn (1956). Where dimensions of patterned ground are given in the

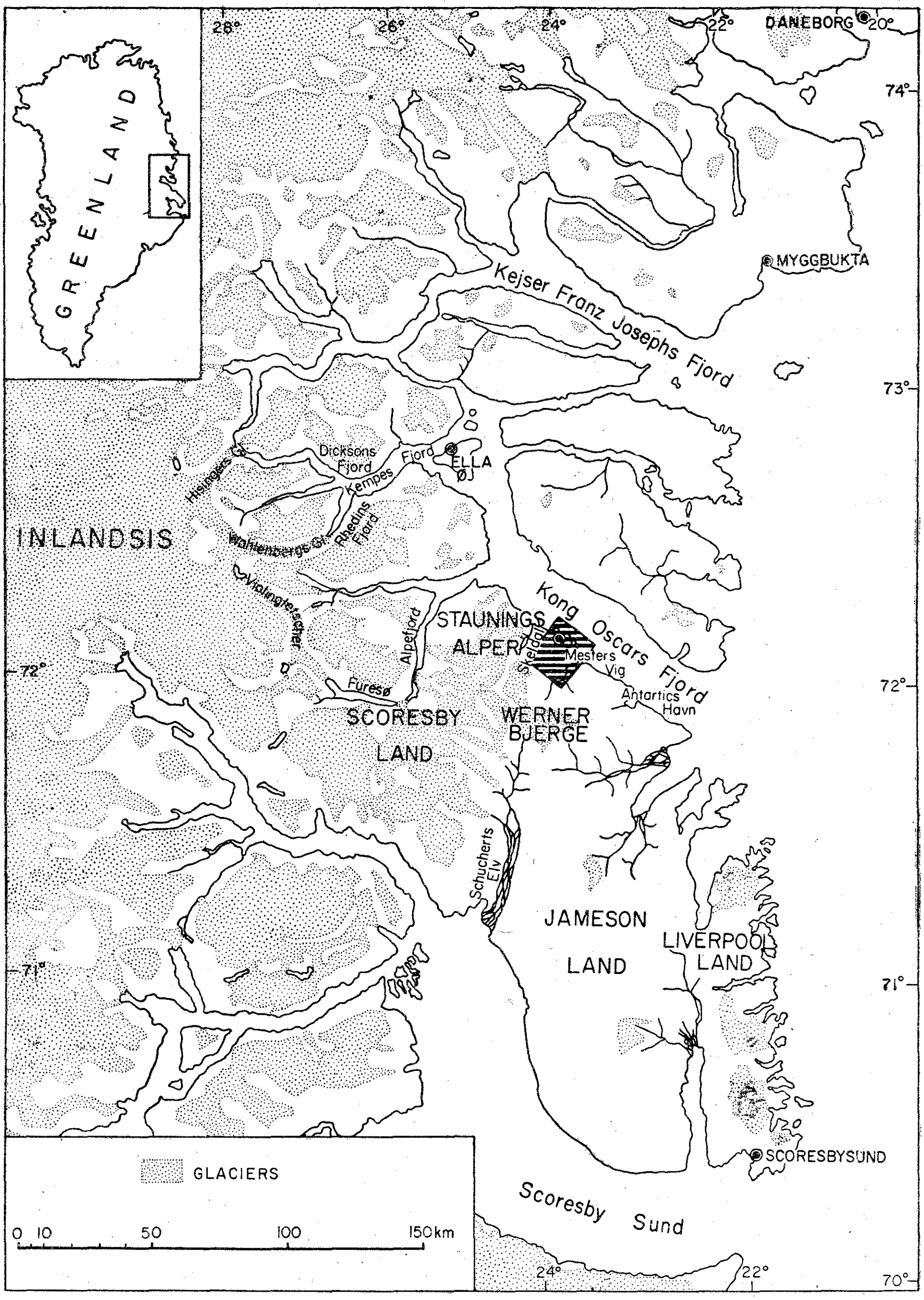


Fig. 1. The fjord region of Northeast Greenland and location of the Mesters Vig **district**

format A × B, they refer to the short and long diameters of individual forms. The various experimental sites cited are described in Washburn (1968, app. A), and their location is shown in figure 3.

ACKNOWLEDGMENTS

A number of people without whose help the Mesters Vig program could not have been undertaken and to whom the writer is deeply grateful are cited in Washburn (1965, 1968). Meriting special mention are the Danish Government authorities who facilitated the program; the reviewers of the report from which this article is taken: Professors R. F. Flint of Yale University, Stephen C. Porter of the University of Washington, and Hugh M. Raup of the John Hopkins University and the writer's colleague in Mesters Vig program; and the writer's family who participated in the field work each year.

TURF HUMMOCKS

The term *turf hummocks* was suggested by Raup (1965, p. 8) to cover both earth hummocks, characterized by a core of mineral soil, and similar features lacking such a core. Both types occur in the Mesters Vig district and are most typically developed in places with abundant moisture throughout the summer. To a considerable degree the origin and distribution of turf hummocks constitute a botanical problem, and Dr. Raup made a special study of it. The abstract of his report is quoted below, and reference should be made to the full report (Raup, 1965) for further data relating to this form of patterned ground.

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

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

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

NONSORTED CIRCLES AND RELATED FORMS

GENERAL

Nonsorted circles and similar but less regular forms were particularly well developed at ES 3, 9, and vicinity on the Nyhavn slope of Labben, where they were studied in some detail. A different type, not recognized elsewhere, occurred near ES 4 on the same slope. Nonsorted circles were also observed at a number of other places.

EXPERIMENTAL SITES 3, 9, AND VICINITY

Surface morphology

At ES 3, 9, and vicinity, nonsorted circles and related forms consisted of bare central areas surrounded by thin tundra (fig. 4). In places the forms were grouped, in other places they were quite scattered. Very few if any were strictly circular but a number were oval, approached a circular shape, and are therefore classed with circular forms of patterned ground. Many forms were very irregular but obviously closely related through forms transitional to ovals, as near ES 3 where a narrow neck joined two ovals (pl. 1).

All the forms tended to be elongate down the slope, which had a gradient of 1° in the vicinity of the experimental sites. Representative diameters of well-developed ovals were 95×120 cm (ES 9), 120×170 cm (ES 3), and 135×180 cm. Where the forms were markedly elongate, short diameters ranged from about 50 to 100 cm, and long diameters from 100 to 250 cm, but dimensions on both sides of these figures were common. Several elongate bare areas had a marked medial crack parallel to the elongation, the crack being represented by abnormally wide fissures between small nonsorted polygons. Thin tundra in the same area also showed a number of up-and-downslope cracks, which were commonly associated with similarly oriented low swells in the tundra, although in some places the tundra had more regular swells and swales without cracks (*cf.* subsequent discussion of excavation 60-8-23). These medial cracks accompanying swells or in bare areas subject to heaving were probably dilation cracks.

The central areas of the nonsorted patterns were commonly somewhat domed, especially the well-developed ovals, in which the maximum microrelief given by the doming was 11—12 cm as at ES 9. Although the high point of some domes was slightly eccentric as at ES 9, doming was commonly symmetric with respect to the central area. However, some bare areas had a central sag up to 8 cm deep. Well-developed but irregular miniature nonsor-

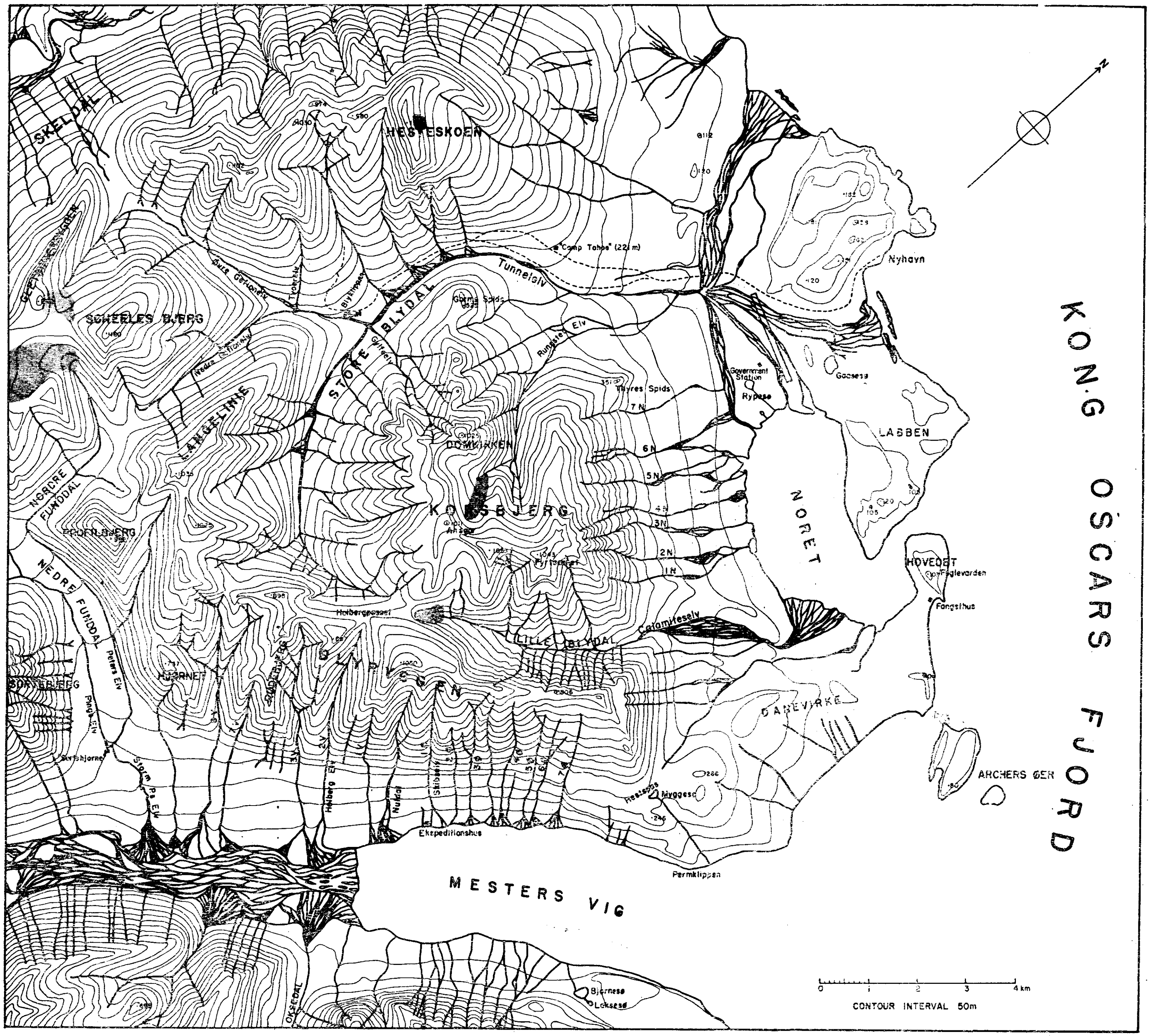


Fig. 2. Topographic map of the Mesters Vig district, Northeast Greenland

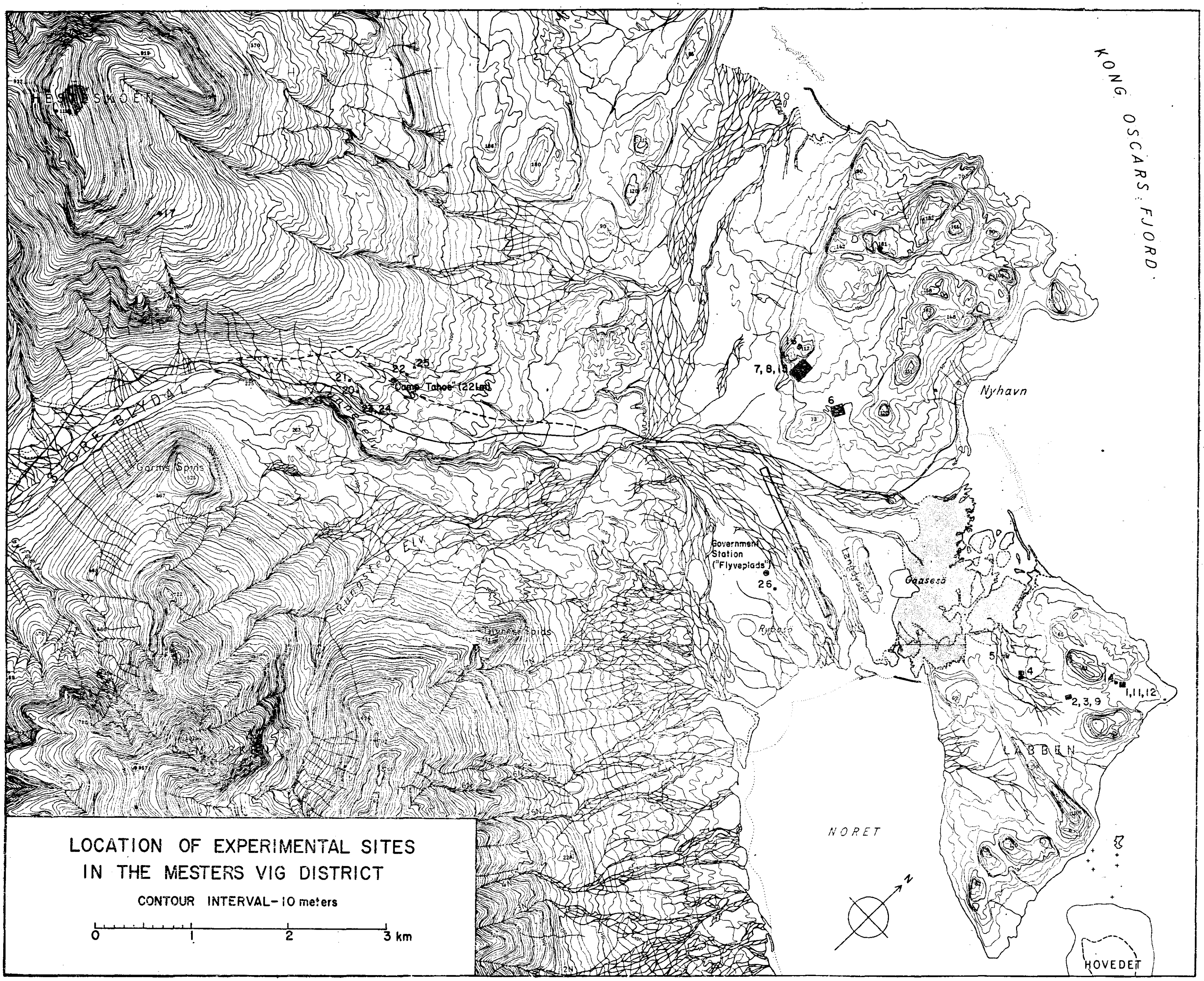


Fig. 3. Location experimental sites in the Mesters Vig district

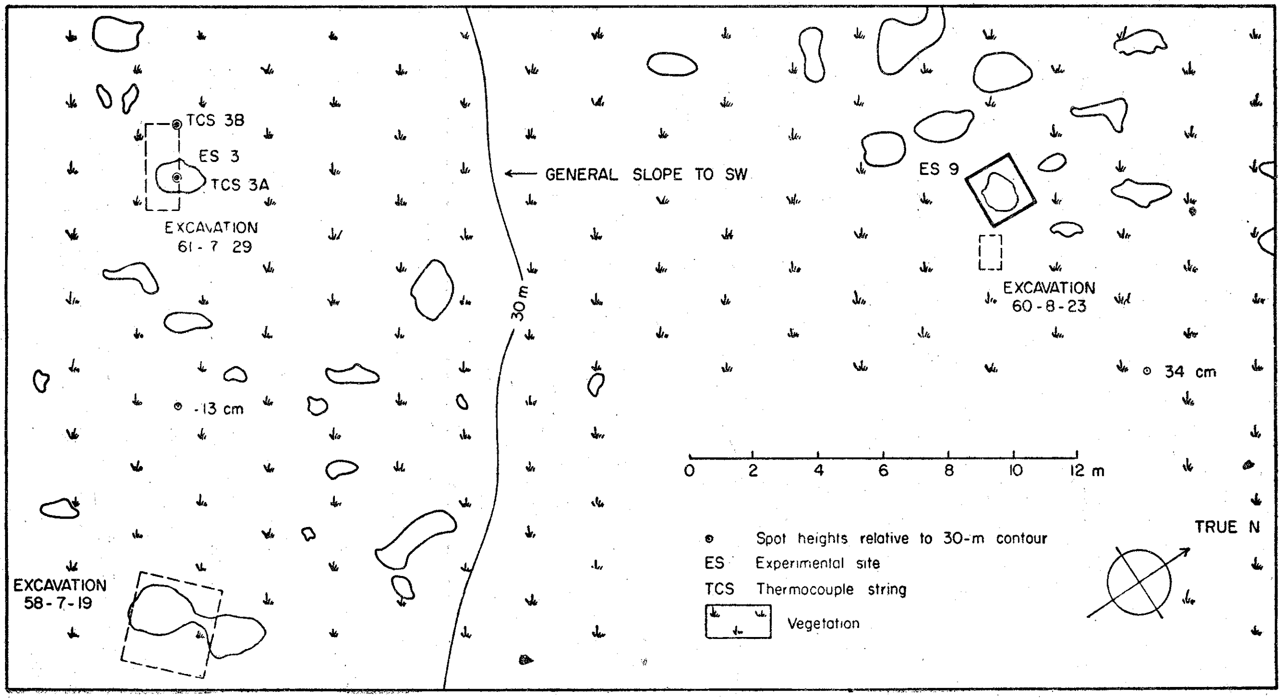


Fig. 4. Experimental sites 3 and 9

ted polygons, described in the section on small nonsorted polygons, were a characteristic feature of central areas.

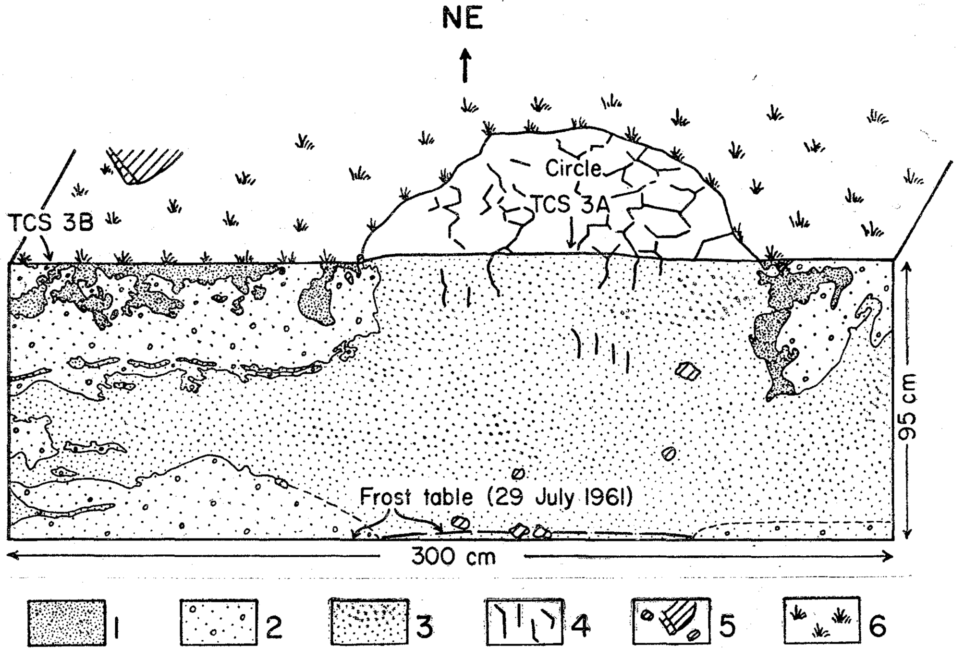
The central areas consisted predominantly of sandy-silty clay with isolated stones. Fines ranged from 74 to 94 percent (SD 1—50 cm) and liquid limits from 28 to 34. The bordering areas were less uniform because of intertonguing and mixing of materials. Near the surface they consisted mainly of nonplastic gravelly sand with less than 10 percent fines but included some finer material; below 30 cm to a depth of 65 cm some of the mineral soil had 69—92 percent fines. In spite of the coarser grain size of the bordering areas near the surface, stony borders, such as characterize sorted types of patterned ground by definition, were absent, and the circles and related forms are therefore regarded as belonging to the nonsorted variety. Both the fine and coarser material carried shells, mostly fragmentary. The moisture content of the bordering material was usually considerably higher than that of the finer central areas to depths of 20 cm. Vegetation was confined almost entirely to the bordering areas, and was composed of a black organic crust thinly populated by vascular plants. Most numerous of these were *Salix arctica*, *Silene acaulis* and *Polygonum viviparum*.

Similar nonsorted forms were widespread on the uppermost parts of the slope and were particularly prominent in and around a tiny shallow lake at the very crest of the low divide just above the experimental sites. The lack of drainage and consequent high-moisture conditions near the lake probably account for the concentration of circles and related forms in the vicinity.

Subsurface morphology

At ES 3 (pl. 2), excavation 61-7-29 revealed the features in figure 5. The frost table at the time (29 July) was at a depth of 97 cm and showed ice veins 1—2 mm wide. It was clear that the fines forming the central area were continuous with fines below the sandy border. Humic material of various shades of brown extended to a depth of 34 cm in the border in places, much of it concentrated in irregular pockets. Although its distribution indicated distortion of the material adjacent to the circle, there was less distortion than in the other excavations described below. In a relatively stable sector of the border there was an incipient soil profile.

Excavation of the central area of the nonsorted circle at ES 9 was started when the frost table was at a depth of 31 cm (20 July 1960), which permitted an examination of the characteristics of frozen ground at shallow depth. From 31 to 35 cm there were



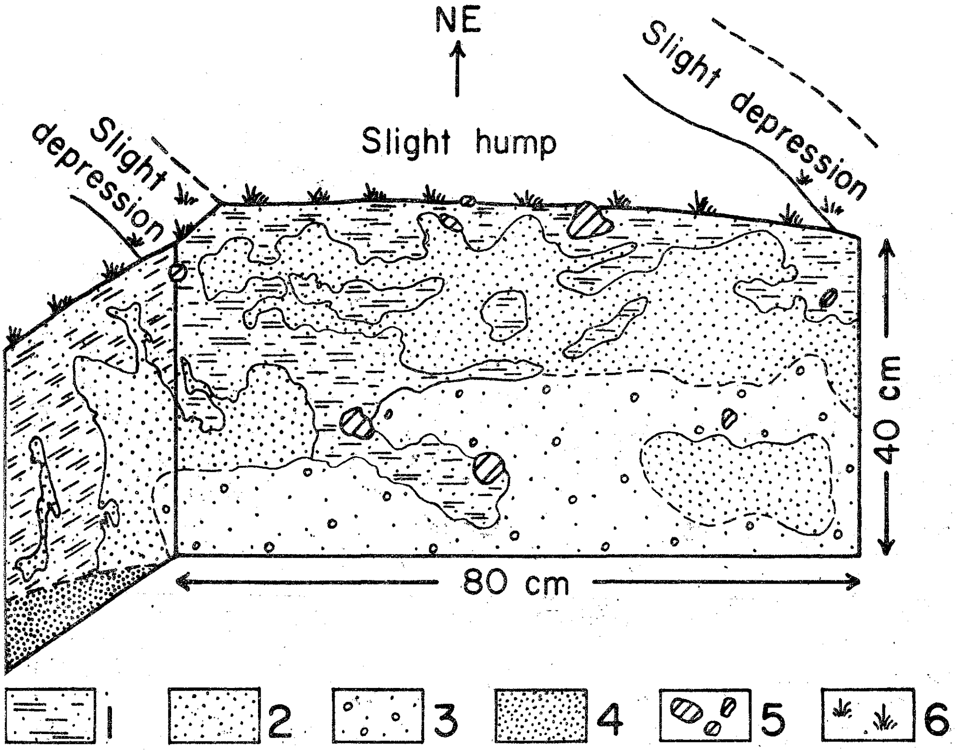
From field sketches by J. Scully and F. Ugolini and from tracing of photograph

Fig. 5. Sketch of excavation 61-7-29, experimental site 3. Sketch shows cross section of a nonsorted circle

1. silty-gravelly sand with humic material. Very dark greyish brown (10YR 3/2) to moderate yellowish brown (10YR 5/4); 2. gravelly sand with shells, brown (10YR 5/3) to light yellowish brown (10YR 6/4); 3. sandy-silty clay with shells, dark gray (10YR 4/1); 4. cracks; 5. stones; 6. vegetation; TCS — thermocouple string

ice veins up to 3 mm wide arranged in an irregular polygonal pattern similar to that of the small nonsorted polygons at the surface. These veins were clearly filling downward extensions of the surface pattern. Tiny discontinuous ice lenses up to 0,5 mm thick but generally thinner than 0,3 mm were scattered throughout the interval from 31 to 40 cm. Up to 4 such lenses were counted in a 2.5-cm thickness of frozen ground, but partings without visible ice and probably originally due to ice lenses suggested that as many as 10 such lenses might occur in a 3-cm thickness. The moisture content (w) of frozen ground above the 40-cm depth was 24 percent.

The small amount of ice and the fact that other excavations showed that the ice content of frozen ground commonly decreased toward the surface correlate well with the observed strong desiccation of the near-surface material during the thaw season. This also sup-



From field sketch and tracing of photograph

Fig. 6. Sketch of excavation 60-8-23, experimental site 9. Northwest corner was 75 cm from southeast edge of the nonsorted circle

1. gravelly-clayey-silty sand with humic material, dusky brown (5YR 2/2); 2. gravelly sand, dark yellowish brown (10YR 4/2); 3. coarse gravelly sand, dusky yellowish brown (10YR 2/2) to dark yellowish brown (10YR 4/2); 4. gravelly-sandy-silty clay with shell fragments, light olive gray (5Y 5/2); 5. stones; 6. vegetation

ports evidence from dowel-heave observations that there was but little frost action in the near-surface material (Washburn, 1968).

Excavation 60-8-23 (fig. 6) was in the bordering sandy area of thin tundra at ES 9, the northwest corner of the excavation being 75 cm from the southeast edge of the central area. The surface here was similar to other areas of thin tundra in the

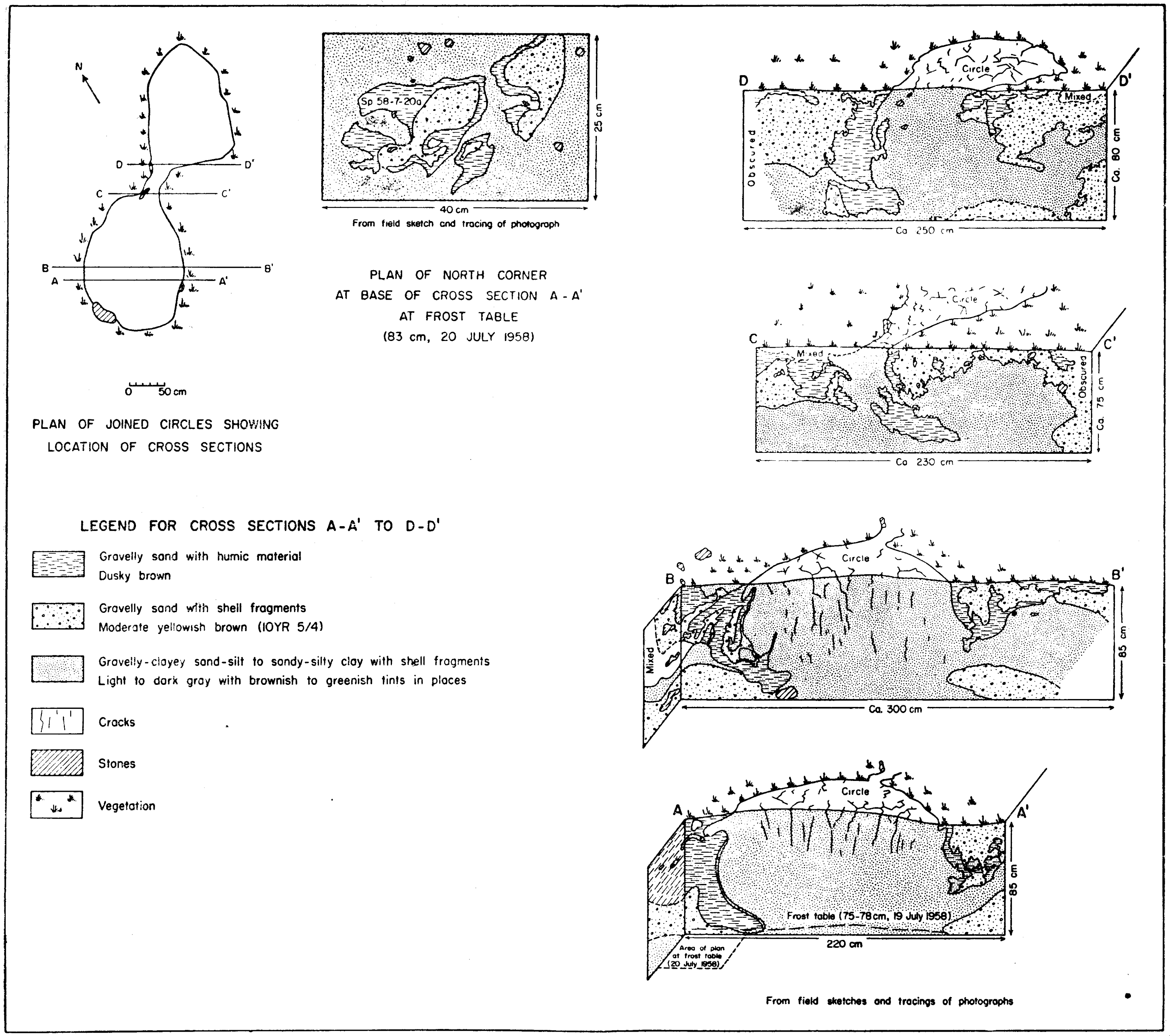


Fig. 7. Sketch of excavation 58-7-19, 12 m east of experimental site 3. Sketch shows parallel cross sections of a nonsorted circle (*Cf.* pl. 1)

vicinity in having slight swells and swales. The diameter of the swells was similar to that of the bare central areas, and the swales formed a netlike pattern. The variations in mineral soil were comparable to those prevailing in border areas. The excavation showed stringers and irregular masses of brown humic material in complicated array within the sand. The humic material was generally thickest beneath the swales but no coincident crack pattern was noted. A domelike mass of fines lay beneath the sand in the face nearest ES 9. Nearby excavations in similar swell-and--swale areas showed fines beneath sand at depths of 50 to 65 cm.

Excavation 58-7-19 (fig. 7) was in the joined circles 12 m east of ES 3 (pl. 1). The surface characteristics here were similar to those elsewhere in the vicinity. The central areas of the circles were domed, the microrelief ranging from 5 cm (downslope circle) to 8 cm (upslope circle). The range of mineral-soil characteristics was similar to that at the other excavations; although this was the only excavation in which a boulder was encountered, a few were present at the surface elsewhere. Shell fragments were common and tended to be broken into smaller pieces in the fines than in the sandy material. The frost table, which was at a depth of 75—78 cm (19 July 1958), showed more segregated ice in fines than in sand. The ice increased with depth, and 10—20 cm below the frost table ice lenses in the fines were up to 14 cm long and 1 cm thick. The lenses were wavy but dominantly horizontal, although some curved upward and were almost vertical in places. The concentration of ice in the ground was estimated to range from 20 to 70 percent, depending on location; an accurate determination was prevented by thawing and slumping. Some of the ice was transparent and had isolated clayey inclusions. Crystal diameters ranged from 0.5 to 2.0 cm, judging from apparent crystal boundaries outlined by melting.

Excavation 58-7-19 provided four parallel cross sections. They revealed that the material bordering the circle was contorted, and that humic material associated with sand extended to a depth of at least 84 cm and intertongued prominently with fines of the central area near this depth. The humic material at the 84-cm depth gave a radiocarbon age of 3970±80 yr B.P. (Y 700), and the nonsorted circles in the area are probably younger. Their maximum age is less than about 7730±210 yr B.P., the radiocarbon age of marine shells at nearby ES 3 (Y 704. Washburn and Stuiver, 1962, table 1, p. 68). Excavation in a nearby circle showed somewhat similar structures at shallower depth. The implications of these structures are discussed under origin.

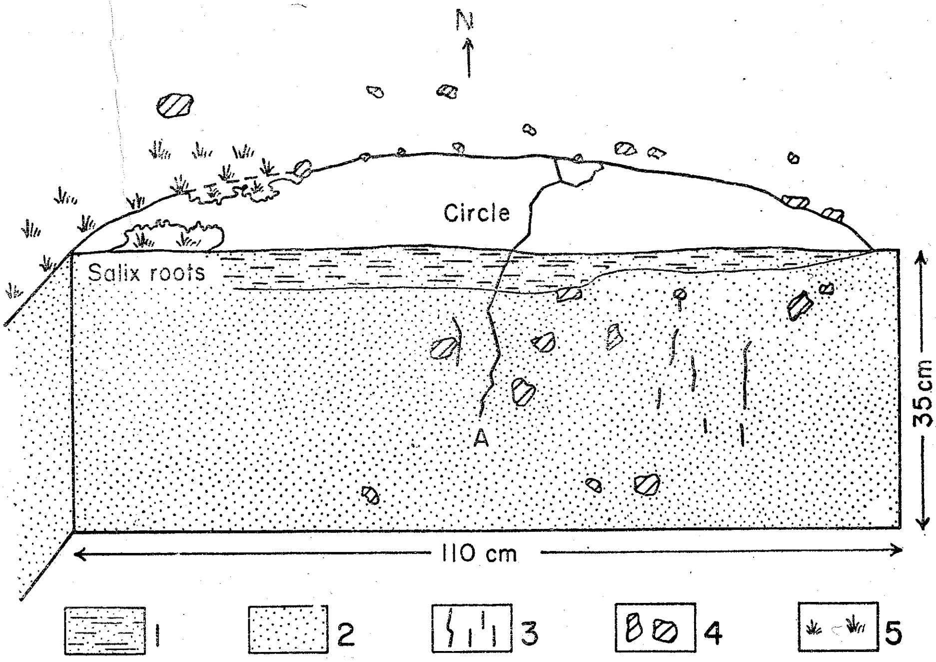
VICINITY OF EXPERIMENTAL SITE 4

Surface morphology

A different type of nonsorted circle was observed 50—100 m upslope from the northwest end of ES 4. The mineral soil of the slope was similar to that of the nonsorted patterns previously described, and was largely bare of vegetation. The slope, which had a gradient of 3°, showed faint channeling and, in places, inundation of isolated plants by fines. These effects were probably primarily due to meltwater in the spring. Some nonsorted patterns were almost perfect circles, 50—100 cm in diameter, others were irregularly elongate downslope (pl. 3). There was no vegetated sandy border as with the forms in the vicinity of ES 3 and 9, and the patterns were apparent only because they had a light gray color that contrasted with the darker gray of the surrounding surface, and because they were largely free of miniature nonsorted polygons that were ubiquitous elsewhere in the area. Some circles were slightly domeshaped and some had isolated edgewise pebbles at the surface. All the nonsorted patterns appeared very fresh.

Subsurface morphology

Excavation 58-8-3 (fig. 8) was typical of the circles. The top 1.5—5.5 cm consisted of mineral soil approximating sandy$_{10}$-silty$_{32}$ clay$_{56}$, judging from analysis of identically appearing material in a nearby circle. Vesiclelike holes 2—3 mm in diameter made the upper 2—3 cm quite porous. They were too regular to have been the site of granular ice masses and were probably due to air bubbles whose paths were preseved as the mineral soil dried (*cf.* Gradwell, 1957, p. 797—798; Springer, 1958, p. 65—66). Tricart (1954, p. 260), Jerry Brown (1966, p. 11—12), and Ugolini (1966, p. 15—16) reported similar voids associated with freezing and thawing but did not exclude development during the thawing and drying phase. The fines had delicate horizontal laminae, some only a fraction of a millimeter thick, very few of which were distorted. In general this layer thinned toward the borders of the circles. It was underlain by more compact, darker



From field sketch and tracing of photograph

Fig. 8. Sketch of excavation 58-8-3, some 100 m upslope from experimental site 3. Sketch shows cross section of a nonsorted circle
1. laminated silt, light gray; 2. fines, gray; 3. cracks, light gray silt to base at A; 4. stones; 5. vegetation

gray and somewhat stonier mineral soil that was also laminated in places, the contact being obscure in spots. A few cracks extended from the surface into this underlying material and some were filled with the upper fines. In a few places the upper layer buried an older crack pattern. Of the 8 excavations made, some of which cut back the major part of a circle in stages, not one revealed evidence of a feeder pipe for the upper fines.

ORIGIN

Sedimentation

It was at first thought that the forms upslope from ES 4 might represent point eruptions of fluid silt that had overflowed the surface slightly, as suggested by the isolated distribution of the forms and the lamination of the silt. However, the excavations showed no indications of an upward flow or of significant distortion of the laminations. It is much more probable that the forms originated as the result of meltwater, 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 beneath the snow. The faint channeling of the ground, in places directly upslope of the nonsorted circles, the inundation of some plants by silt, and the lack of evidence for upward movement of the fines strongly support this origin. The occurrences demonstrate how misleading the surface appearance of patterned ground can be.

Mass displacement

The nonsorted circles and related forms at ES 3, 9, and vicinity were structurally quite different from those near ES 4 in (1) being isolated masses of dominantly fine mineral soil laterally surrounded by sandy soil at the surface and, in part, at depth, and in (2) showing prominent marginal disturbance. These relations indicate mass displacement of the underlying finer material into the overlying coarser.

The downward and laterally penetrating tongues of humic material at considerable depth in the borders pose a problem. Penetration along desiccation cracks (Ellis and Shafer, 1928) or frost cracks (*cf.* Washburn, 1956, p. 848—852) is probable where these cracks exist but no such bordering crack patterns were observed. Moreover the laterally penetrating tongues would be enexplained, since their strong irregularity, lack of lateral continuity at depth, and, in places, their attitude would argue against gelifluction as an explanation as favored for some occurrences in northern Canada (Mackay, 1958; Mackay, Mathews, and MacNeish, 1961, p. 43—46). The increasing amount of humic material toward, and eventual continuity with, the surface argue against its origin as a subsurface-developed pedogenic horizon (Tedrow, 1965) and is more consistent with the concept of burial of surface vegetation by mineral soil from depth (Douglas and Tedrow, 1961, p. 296, 298), via upward and outward spreading of nonsorted circles (Jerry Brown, 1966, p. 11), as suggested for occurrences in arctic Alaska. More specifically, the relations at ES 3, 9, and vicinity suggest a general downward movement along the borders of the circles concurrently with an upward displacement of mineral soil in the central areas. This would bring surface horizons to depth; even the lateral tongues might then be consequent on such displacement, or they might be due to thrusting during annual freezing. In several respects the subsurface structures were similar to those illustrated from Spitsbergen by Gripp (1927, fig. 6, p. 13), who concluded they were due to upward moving material in the central areas. Müller (1954, fig. 57c, p. 134; p. 205) recorded a similar cross section and regarded a number of nonsorted circles and sorted circles that he studied in Greenland as probably due to density differences in the sense of Sørensen (1935, p. 32—53).

Displacement of the kind described, the concentration of circles in a high-moisture environment, and the generally low liquid limits of the mineral soil in the central areas, would be consistent with either the cryostatic hypothesis for the origin of patterned ground, or with the hypothesis based on moisture-controlled changes in intergranular pressure. Conceivably both apply, but the latter has the advantage over the cryostatic concept in that intrusion is into unfrozen material. This and other reasons for favoring the hypothesis based on changes in intergranular pressure are discussed elsewhere (Washburn, 1968).

Other hypotheses are less promising for these particular circles. Elsewhere in the Mesters Vig district certain netlike circular forms, bounded by polygonal depressions and discussed with large non-sorted polygons, were probably initiated by frost cracking. However, the explanation is inapplicable to the circles at ES 3, 9, and vicinity because of the isolated rather than netlike occurrence of the forms and the general absence of bounding frost cracks. True convection hypotheses are discredited (*cf.* Washburn, 1956, p. 852—855). Frödin (1918, p. 21—27) argued that features similar to nonsorted circles, although more nearly approaching steps, developed by local differential heaving (*cf.* Taber, 1943, p. 1458—1459) during freeze-up, followed by water absorption, swelling, and flow of material during thawing. Steche (1933, p. 231—239) for cold-climate forms, and Hallsworth, Robertson, and Gibbons (1955, p. 21—30) for gilgaies in Australia (some of which closely resemble nonsorted cold-climate forms; Bremer, 1965; Costin, 1955) also emphasized swelling by absorption of water as a basic factor. Yet Frödin's observations did not prove extrusion by swelling, nor is it clear that swelling of the necessary magnitude would prevail in the Arctic (Washburn, 1956, p. 846—847). Local differential heaving may well explain some nonsorted circles and related forms lacking extensive upward displacement of material from depth (*cf.* P. J. Williams, 1959; 1961, p. 345—346).

However, for forms with marked upward displacement of material any hypothesis based simply on differential heaving and/or swelling and flow from swelling, encounters the fundamental difficulty that it does not explain the continued addition of material from depth. Without such addition, reduction of volume by thawing of ice in the active layer and subsequent drying would tend to restore the original situation annually and inhibit permanent upward displacement of material. The Hallsworth, Robertson, and Gibbons explanation, which ascribes the upward movement in gilgaies to compression between deep desiccation fissures as they fill in and close during wet intervals, gets around this difficulty but involves conditions quite different from those in the Mesters Vig district, including climate and clay mineralogy. Whereas highly expandable minerals are required for the gilgai mechanism, they are absent at ES 9, where poorly crystallized illite, and chlorite and/or kaolinite were the dominant clay minerals at depths of 10 and 50 cm, according to X-ray analyses by Professor R. A. Berner of Yale University to whom the writer is indebted for the work; similar clay mineralogy was also found elsewhere in the district (Washburn, 1967, p. 102). The volume increase due to sorting, reported by Corte (1961, p. 9—17) from laboratory freeze-thaw experiments, would help to explain addition of material as long as sorting continued, and it would also help to explain maintenance of the microrelief where there has been local differential heaving and sorting. However, sorting of this kind does not appear to be involved at ES 3, 9, and vicinity, since the fines clearly arise from a layer at depth rather than from any *in-situ* sorting. On the basis of observations near Thule, Greenland, Schmertmann and Taylor (1965, p. 66—71) suggested that progressively greater ice segregation at the base of an active layer leads to a decrease in thickness of the layer by delaying thawing. Production of fines by frost wedging at the base of the active layer would aid by promoting increased development of ice lenses. Such a decrease in thickness of the active layer is dependent on expansion of the mineral soil by ice and, if confirmed and found to be differential with respect to microrelief, it would also help to explain maintenance of this relief. However, to account for material in the central areas rising at least 85 cm in places (fig. 7) implies an equal difference in thickness of the active layer at such places, whereas the excavations clearly showed that the difference if any between central areas and borders did not exceed a few centimeters.

Perhaps the upward movement of fines in front of an upward--moving freezing plane (Corte, 1962a, 1963a, 1963b) is a significant factor in some forms of patterned ground, but it can hardly explain the movement of fines all the way to the surface. Although a freezing front probably moves up from the permafrost table in the Mesters Vig district and in most other places where continuous permafrost exists (*cf.* Washburn, 1967, p. 138—139), downward freezing from the surface probably affects a greater thickness of the active layer. Therefore any fines moving up in front of an upward-moving freezing plane should never reach the surface from depth; rather during downward freezing of the upper part of the active layer they should move down relative to coarser material, as described by Corte (1961, p. 2—8, 17—20) from both the field and laboratory. Mechanical sorting in the sense of Corte (1962c, p. 8—9, 19; 1962d, p. 54, 65), would have the same effect.

Structures suggestive of a dynamic, upward mass displacement of mineral soil in patterned ground have been repeatedly described, especially in sorted circles where structures, such as "plugs" of finer material within coarser, would be most likely to be clearly revealed (*cf.* Corte, 1962b, p. 14—18; Mackay, 1953, p. 34—37; Washburn, 1950, p. 35—37; 1956, p. 844). It seems doubtful that horizontal and vertical sorting alone, in the sense of Corte (1961, 1962a, 1962b, 1962c, 1962d, 1963a, 1963b), can produce such structures. Although various processes may be involved, movement due to saturation-controlled density differences is the preferred, but by no means demonstrated, origin of the nonsorted circles and related features at ES 3, 9, and vicinity.

SMALL NONSORTED POLYGONS

GENERAL

By small nonsorted polygons is meant those whose diameter is less than about 1 m. This size grouping is convenient for discussion, since most small nonsorted polygons in the Mesters Vig district probably differ from larger ones in origin. They were most commonly observed in the extensive vegetation free areas of diamicton characterized by abundant fines, but were not confined to such areas. Locations to be discussed include the vicinity of ES 1, 11, and 12; 3 and 9; 5, 8, and emerged delta remnants.

VICINITY OF EXPERIMENTAL SITES 1, 11—12

The small nonsorted polygons in the vicinity of ES 1, 11—12 were in the bare central areas of sorted nets. These areas showed a considerable range in mineral soil, both within an area and from area to area, the content of fines ranging from 30 to 78 percent (SD 0—45 cm).

The best developed polygons were much like those associated with the circles at ES 3, 9, and vicinity as described later. A quite different crack pattern was provided by cracks that tended to be radial and concentric with respect to the roughly circular sorted mesh in which they occurred. The resulting nonsorted polygons (pl. 4) had estimated sizes ranging from 15×20 cm to 20×45 cm. Nearby an elongate central area had two prominent cracks oriented parallel to the long axis and one transverse to it. These crack patterns were clearly related to the shape of the central areas in which they occurred. There was much evidence of heaving in the vicinity, and the cracks were probably dilation phenomena associated with the heaving. In this respect the origin of the nonsorted polygons outlined by the cracks is probably different from that of most small nonsorted polygons in the Mesters Vig district.

VICINITY OF EXPERIMENTAL SITES 1, 11—12

At ES 3, 9, and vicinity small nonsorted polygons were much more common and better developed than those near ES 1, 11—12. The polygons (pl. 1) were confined to the bare central areas of the nonsorted circles and related forms. The associated mineral soil, judging from ES 9, was sandy-silty clay to clayey-sandy silt, the fines ranging from 74 to 94 percent (SD 1—50 cm). The individual polygons tended to be pentagonal and convex up. Sizes ranged from 7 × 11 cm to 18 × 20 cm, most of the polygons being distinctly smaller than those of the radial and concentric crack pattern near ES 1, 11—12. Although the borders of the nonsorted circles tended to influence the trend of adjacent cracks, no basic radial and concentric pattern was observed.

Crack width at the surface ranged from 0.1 to 2.0 cm. Most of the cracks had a surface width of about 0.5 cm, and the widest were probably erosional. Some could be probed with a wire to depths as great as 15 cm, and excavations showed several knife-thin cracks to depths of 30 cm. However, tiny roots that grew preferentially in cracks extended to depths of 40—50 cm, and some cracks were probably this deep. The crack pattern was an enduring feature. Although the nonsorted polygons were soft when first subject to thawing in the spring, they became strongly desiccated and hard during the summer, and they were resistant to erosion. They were observed emerging from beneath snow and basal ice in the spring with very little change from the previous year, and at one locality were well preserved in spite of submergence beneath trickling water that had thawed a hole in the snow and basal ice. That there was very little change by frost action or other activity is demonstrated by the dowel observations at ES 9 as previously discussed, and by the fact that individual polygons can be clearly identified on photographs taken 4 years apart.

VICINITY OF EXPERIMENTAL SITE 5

Surface morphology

Nonsorted polygons that were clearly due to desiccation cracking were observed in fines in the bed of the streamlet and a tributary adjacent to ES 5. Sharp-edged fresh cracks outlined polygons with a size range of 10 × 12 cm to 21 × 32 cm which was comparable to that of polygons on the adjacent beyond the channel. The cracks were up to 0.5 cm wide at the top and were open to a depth of at least 3 cm. The ground was still somewhat moist. Parts of the fresh pattern coincided with an underlying pattern that had been thinly blanketed by alluvium; other parts cut across the older pattern. The fresh polygon were flat but some of the older were slightly domed. It was obvious that the fresh polygons had formed in new alluvium deposited during the spring thaw and that they were therefore due to desiccation rather than to either frost cracking, thawing (*cf.* Washburn, 1956, p. 852), or partial wetting ("wetting cracks") (Corte and Higashi, 1964, p. 68, 70—71; *cf.* Högbom, 1914, footnote 1, p. 298).

Small nonsorted polygons were prominently developed on the general surface beyond the channel. The slope consisted of shell--bearing sandy-silty clay to sandy-clayey silt, the fines ranging from 78 to 93 percent (SD 1—20 cm), and was largely bare of vegetation except in interpolygon depressions, especially at crack intersections, where there were a few grasses, *Salix*, *Draba*, and some moss. The area was characteristically very dry during the summer. Polygon sizes ranged from 6 × 8 cm to 20 × 20 cm, diameters of 10—15 cm being common. The polygons were thus similar to those at ES 3 and 9 but they differed in being grouped into a still-larger pattern whose meshes ranged from 40 to 100 cm in diameter (pl. 5). This major pattern was outlined by depressions and by more prominent cracks than those responsible for the minor pattern; also the major pattern was less distinctly polygonal, although some of the larger cracks were straight and joined in threes at an angle of 120°. Cracks associated with the minor pattern were 0.1—1.0 cm wide at the top. Many associated with the major pattern did not exceed 1.0 cm but some were up to 4 cm wide. A number of cracks were open to a depth of at least 15 cm; a few contained a little gravel. The depressions constituting the major borders were up to 15 cm deep at intersections and showed collapse features in places, as where an area measuring 10 × 30 cm had dropped down 3.5 cm in a block. The orientation of the major borders and that of the abutting small polygons were obviously related, but there was no indication of shape control in the sense that the larger forms controlled the basic orientation of all the smaller as described for some of the nonsorted polygons in the vicinity of ES 1, 11—12. Both minor and major polygons tended to be domed, some of the latter markedly so. Excavation of compound patterns in places where snow had recently retreated, showed ice veins coincident with the cracks at the depth of thaw, which was 10—15 cm at the time (11 July 1960). The veins associated with the minor crack pattern were up to 0.5 cm wide, those allied to the major pattern were up to 5 cm wide.

Subsurface morphology

Slumping along a small stream revealed a section that showed the general nature of the material and the subsurface structure of the polygons. To a depth of 45 cm the material was silty with some sandy zones; pebbles were numerous in the top 15—25 cm.

The material was increasingly clayey below 45 cm with isolated thin sandy streaks down to 65 cm. Stones, including a few small boulders, occurred sparingly in the section, but many more, including larger boulders, lay in the stream bed and had been obviously derived from similar material. Scattered shell fragments occurred throughout the section. The frost table was at a depth of about 90 cm (20 July 1957) as indicated by ice lenses in plastic fines, and from 100 cm to the bottom of the section at 140 cm there was clear ice with vertical bubble zones and thin clayey layers. The polygons at the top of the bank were similar to those described above except that he doming and compound aspect were much less marked. Their bounding cracks, narrowing downward, were responsible for a well-developed columnar structure to depths of 30—35 cm. A few cracks, slightly curving, could be traced from the surface to as deep as 55 cm, and cracks delimiting the same polygon varied in depth by as much as 15 cm. The deepest *Salix* roots observed were at 45 cm. Vertical cracks that were not continuous with the surface extended to the top of the clear ice and contained ice fillings below the frost table. Horizontal partings, probably left by small ice lenses, were spaced some 0.1—0.3 cm apart in the upper half of the section with the spacing increasing to 1.0 cm in the lower half. Pronounced drying had already affected the polygons to a depth of 15 cm as indicated by the light gray color of the dry material, which contrasted with the darker gray of the moist.

VICINITY OF EXPERIMENTAL SITE 8

Small nonsorted polygons similar to those near ES 5 were observed at the top of the small trap bluff just southeast of ES 8. They occurred on gradients of to 5°. The material was similar to the diamicton at ES 8, which had 32 to 61 percent fines (SD 10—20 cm). Much of the surface was free of vegetation except along major mesh boundaries, which were vegetated with *Salix*, *Dryas*, and moss. The minor pattern consisted of polygons ranging in size from about 6×10 cm to 25×36 cm, outlined by cracks that were 0.2 to 1.5 cm wide at the top and contained granules in places. When examined in the early spring the cracks were filled with ice that was continuous with basal ice, formed of meltwater refrozen beneath the snow. Subsequent excavation showed cracks extending to a depth of 5 cm where some cracks branched into two, each of which diverged toward the polygon centers. Entire polygon centers could be peeled off along a parting at a depth of 6—7 cm, but is was not established that the branch cracks formed this parting. Possibly differences in cohesion related to degree of drying at this depth was responsible. A color change from light gray at the surface to a darker gray at a depth of 2 cm was clearly due to desiccation, and the clods that were lifted off were firmer that the underlying material. There was no apparent difference in grain size at the parting depth.

The major pattern had meshes consisting of assemblages of minor polygons and ranging in size from 55×55 cm to 90×120 cm; long axes if present were commonly oriented downslope, the gradient being 3° in the area examined. The borders were depressions, up to 20 cm deep at intersections but commonly about 5 cm deep, that were coincident with cracks whose depths exceeded 20 cm. The meshes were strongly domed in places. The major pattern was not obviously polygonal (and could thus be considered a nonsorted net), but the original pattern was probably polygonal as discussed later. Some meshes in the area were alined parallel to linear depressions, up to 50 cm deep, that extended across the knob and sloped down on either side. Commonly one side of the depression was higher than the other, producing a steplike effect.

EMERGED DELTA REMNANTS AND VICINITY

Surface morphology

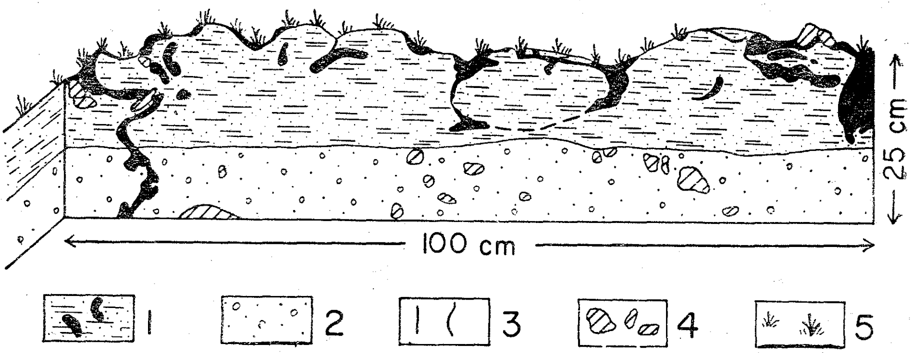
Nonsorted polygons obviously related to heaving and dilation were noted near an active channel of the northwest distributary of Tunnelelv. The most striking occurrence was provided by an elongate heaved area, measuring 2.5×8 m, whose surface was cracked into numerous polygons, most of which were elongate parallel to the length of the heaved area (pl. 6). The polygons were in damp sand and had sizes ranging from 9×27 cm to 18×36 cm; a few were equidimensional. Dividing cracks were up to 2 cm wide and very fresh appearing. The fact that polygons were absent in the adjacent unheaved surfaces, which were underlain by similar materials, and that the polygonal pattern was so clearly dependent on the shape of the heaved area, warrants the conclusion that these polygons were consequent on dilation of the surface during the heaving.

Nonsorted polygons clearly due to desiccation cracking occurred on the shore of the central of three small lakes abutting the upslope side of emerged delta remnants on the east side of Tunnelelv. The east shore where these polygons were best developed consisted of $silty_6$-$gravelly_9$ $sand_{83}$ (SD 0—15 cm). The polygons were outlined by a generally rectangular crack system in which the longest cracks were at right angles to the edge of the lake. The system began near, but not at, the shoreline, and transverse cracks were increasingly common away from the lake. Although some cracks curved and the rectangular pattern was somewhat irregular, the spacing between the long cracks commonly ranged from 20 to 50 cm. The depth of cracks was at least 15 cm in places. The polygons within a few meters of the edge of the water had developed on a stretch of shore that had been exposed by a drop in lake level since an earlier visit the same summer. At the time of the earlier visit the lake was already ice free and the shore had thawed to appreciable depth. No subaqueous crack pattern was noted during either visit, and it seemed obvious that the cracks were due to progressively greater desiccation of the recently exposed shore as the lake receded.

Most polygons do not occur on steep slopes but small nonsorted polygons on a 27° gradient were noted on a cut bank of the emerged delta remnants fronting Tunnelelv. They occurred in silty sand containing isolated stones, and had an average diameter of about 15 cm. The downslope cracks were the best developed, and the pattern tended to be slightly elongate in this direction. Similar occurrences have been observed elsewhere in Greenland and constitute an exception to the view that polygons generally occur on gradienst of less than 8°. (*cf.* Washburn, 1956, p. 833; footnote 13, p. 836—837. Some large nonsorted polygons, especially in the Antarctic, represent another exception.)

In places on the upper surfaces of these emerged delta remnants, nonsorted polygons with a diameter of about 50 cm occurred in moss-*Cassiope* turf.

Well-developed small nonsorted polygons were observed on many low-level delta remnants in the Tunnelelv distributary complex. Most of the benches were covered with thin tundra and were underlain by fines, at least in part of eolian origin, overlying gravelly sand and marine silt. A number of polygons were excavated on benches at altitudes of 15—25 m near the northwest end of the airfield. These excavations are described below.



From field sketch and tracing of photograph

Fig. 9. Sketch of excavation 60-7-21A, bench tread (alt. ca. 17 m) just beyond northwest end of airfield. Sketch shows cross section of small nonsorted polygons

1. Arctic Brown soil, silty sand, moderate brown (5YR 3/4) with concentrations of darker humic material; 2. gravelly sand, light brown (5YR 5/6); 3. cracks; 4. stones; 5. vegetation

Subsurface morphology

Excavation 60-7-21A (fig. 9) was in the almost horizontal tread of a low bench at an altitude of about 17 m just beyond the northwest end of the airfield. The vegetation included *Carex scirpoides*, *Dryas*, and black organic crust. The soil consisted of two units:

Top	*Thickness (cm)*
1. Moderate brown (5YR 3/4) sand with isolated stones and stringers of humic material	14—18
2. Light brown (5YR 5/6) gravelly sand	>5

The polygons had diameters of 10—18 cm, were outlined by cracks up to 12 cm deep, and were dome shaped with a microrelief of 5—8 cm. The humic material was concentrated along the cracks, and the cracks appeared to curve under the polygons.

Excavation 60-7-21B (fig. 10) was nearby in a similar tread at an altitude of about 25 m. Lichens (*Cetraria*), moss, and black organic crust were prominent. The soil consisted of 3 units:

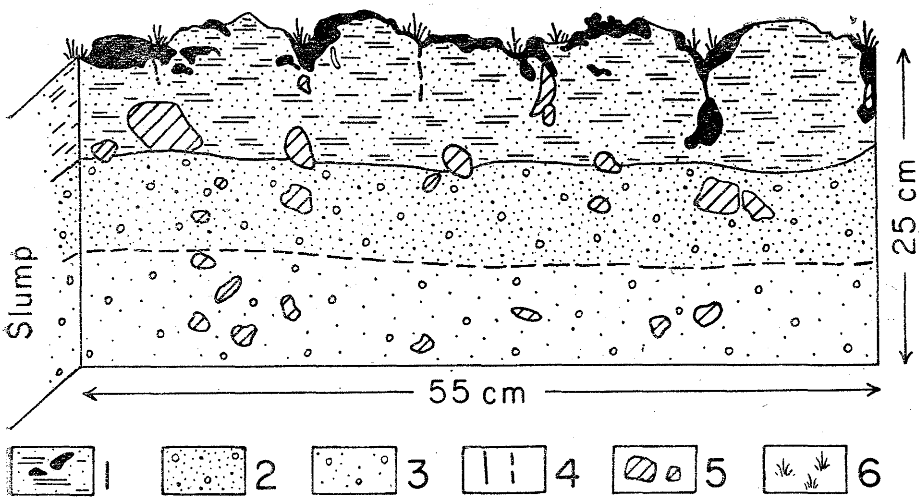


Fig. 10. Sketch of excavation 60-7-21B, bench tread (alt. ca. 25 m) just beyond northwest end of arifield. Sketch shows cross section of small nonsorted polygons

1. Arctic Brown soil, silty sand, moderate brown (5YR 3/4) with concentrations of darker humic material; 2. silty sandy gravel with rootlets, dark yellowish brown (10YR 4/2); 3. gravelly sand, light brown (5YR 5/6); 4. cracks; 5. stones; 6. vegetation

Top	*Thickness (cm)*
1. Moderate brown (5YR 3/4) $silty_{29}$ $sand_{66}$ with very few stones, numerous rootlets, and humic material	10—13
2. Dark yellowish brown (10YR 4/2) $silty_{7}$-$sandy_{39}$ $gravel_{53}$ with few rootlets, transitional to	7—8
3. Light brown (5YR 5/6) $gravelly_{22}$ $sand_{77}$ with rootlets	>20

The specific gravity of the mineral soil increased with depth from 2.61 in unit 1 to 2.64 in unit 2, to 2.69 in unit 3. The significance of this increase is not clear, but the same trend was also noted in some small sorted polygons in the same area as described later. There was no HCl reaction. The pH ranged from 5.2 near the surface to 6.6 at a depth of 42 cm. The polygons had diameters of 5—10 cm, were outlined by cracks 3—7 cm deep, and were dome shaped with a microrelief of up to 4 cm.

Comparison of the two excavations showed that (1) the polygons were confined to the relatively fine-grained sand, (2) the bordering cracks tended to extend through the entire thickness of this sand, and there was thus a direct correlation between crack depth and sand thickness, (3) there was also a direct correlation between mean polygon size and crack depth, and therefore also with thickness of the relatively fine sand.

That the size of desiccation polygons is a function of the thickness of the layer in which they occur was observed by Segerstrom (1950, p. 115) in the field and by Corte and Higashi (1964, p. 7—9, 27) in the laboratory.

ORIGIN

Dilation cracking

Dilation of the ground surface during frost heaving as a factor in the origin of small nonsorted polygons has not been extensively discussed in the literature. Poser (1931, p. 224—225) cited dilation as the cause of radial cracks in some nonsorted circles, and Hopkins and Sigafoos (1951, p. 82—83) and Schenk (1955a, p. 60) cited it for nonsorted polygons associated with doming, although Schenk also included contraction processes.

The irregular polygons with radial and concentric pattern near ES 1, 11—12, and the polygons confined to the elongate heaved area in the Tunnelelv northwest distributary complex, are ascribed to dilation and support it as one possible mode of origin for nonsorted polygons. In the former case it is reasonable to conclude that dilation caused the concentric as well as the radial cracks, although Poser (1931, p. 225) described patterned ground with concentric cracks that he believed were contraction phenomena.

Dilation is probably not a common cause of most small nonsorted polygons, even in a district with as much frost heaving as Mesters Vig. If dilation were a common cause, (1) patterns of radial, and probably concentric, cracks should be widespread in dome-shaped central areas of patterned ground, (2) in places with other shapes, crack trends should likewise reflect orientation by heaving, and (3) nonsorted polygons in general should be where frost heaving is particularly intense. However, most small nonsorted polygons do not show such oriented patterns, the individual polygons tend to be more regular and equidimensional than those ascribed to dilation, and they occur where evidence of desiccation tends to be more prominent than evidence of heaving. These differences argue for a distinct origin. As discussed below desiccation cracking is believed to be the primary cause of most small nonsorted polygons; however, this conclusion does not deny that a contraction pattern can be influenced by its boundaries or emphasized by heaving.

Desiccation cracking

Abundant evidence indicates that true polygons, as distinct from nets and other patterned-ground forms that are sometimes referred to as polygons, are primarily contraction phenomena. As reviewed elsewhere (Washburn, 1956, p. 848—852), frequently cited causes of contraction in contraction hypotheses for the origin of patterned ground include thawing, drying, and lowering of temperature.

Thawing as a cause of polygons lacks convincing evidence but has not been sufficiently investigated. Other possibilities that should also be investigated are the roles, if any, that synaeresis cracks (Jüngst, 1934), and cracks developed by partial wetting, may have on polygon formation.

"Synaeresis cracks are fissures that develop in a suspension where waters are expelled from the clay-water system by internal forces; they may resemble mud cracks in the sediments" (White, 1961, p. 561).

They form subaqueously in a saline environment where clays are flocculated, and they are apparently due to adjustments accompanying realinement of clay particles under the influence of electrochemical forces between the particles (White, 1961, p. 569). Cracks formed by partial wetting in laboratory experiments were reported by Corte and Higashi (1964, p. 68, 70—71), who suggested surface tension as a possible explanation. They were apparently also observed by Högbom (1914, footnote 1, p. 289), who mentioned contraction of fine sand upon wetting. These subjects remain to be investigated but to the extent that such cracks persist they probably determine the location of later desiccation cracks, and pending further data including field observations they are here regarded as probably unimportant as a cause of polygons in the absence of subsequent desiccation.

Desiccation may be due not only to drainage and evaporation but also to withdrawal of moisture to loci of ice formation, a process that Taber (1929, p. 457—458) demonstrated could produce tiny polygonal fissures in laboratory specimens. Subsequently Taber (1943, p. 1522—1527) suggested that the same process could produce ice-wedge and sorted polygons, and Schenk (1955a, p. 64—68, 75—76; 1955b, p. 177—178) argued that it was important in a wide variety of polygonal forms, including small ones. This and other aspects of desiccation as a cause of polygons have been reviewed elsewhere (Washburn, 1956, p. 848—850). Subsequent laboratory experiments by Pissart (1964a) show that the process described by Taber can produce small nonsorted polygons up to about 10 cm in diameter, but the polygons were subsurface rather than surface phenomena and were very irregular. Although subsurface desiccation of this kind, aided perhaps by smaller scale moisture transfer during freezing (Hamilton, 1966), may influence a surface crack pattern, there is no proof that it is actually responsible for this pattern. To the extent that desiccation is involved, the fact that polygonal cracks confined to the active layer are best developed at the surface and become rapidly less prominent with depth argues strongly for the predominant effect of subaerial desiccation; in fact Büdel (1960, p. 42) regarded such evidence as conclusive for forms he studied. Pissart's preliminary report clearly supports the desirability of further work and experimental data relating to Taber's hypothesis, particularly as applied to small polygons. Without further evidence, however, thermal cracking and/or subaerial desiccation cracking would seem to be the most probable basic processes responsible for well-defined polygonally patterned ground.

A major problem in places is to distinguish between thermal cracking and desiccation, whatever the latter's origin. Where cracks bordering polygons can be traced into similar cracks in permafrost, thermal contraction can be assumed to be the principal cause. However, frost-crack polygons, which by definition are not necessarily related to permafrost, have been described from Alaska (Black, 1952, p. 131—132; Hopkins and others, 1955, p. 137—139) and elsewhere (Pataleev, 1955; Washburn, Smith, and Goddard, 1963). Although their occurrence in Alaska has been challenged (Church, Péwé, and Andresen, 1965, p. 38), they may be common in some places. Yet, in a permafrost environment like Mesters Vig confinement of bordering cracks to shallow depth and the active layer strongly suggests that the polygons were formed by desiccation rather than frost cracking.

The maintenance of permafrost without a talik intervening between it and the active layer requires deep penetration of frost, and therefore it can be logically assumed that frost cracking would affect the permafrost and not be confined to the active layer or, as in places, to just the upper part of it. Desiccation cracks in a permafrost environment, on the contrary, are necessarily confined to the active layer.

Size is another criterion. The factors controlling depth and spacing of cracks in nonsorted polygons are complex but have been quantitatively considered by Lachenbruch (1961, 1962, 1966) and, for desiccation polygons investigated in the laboratory, by Corte and Higashi (1964). According to Lachenbruch (1966, p. 68): „The use of temperatures measured in Alaskan permafrost, a "power-law model" to calculate thermal stress, and an estimated value of G_c [critical rate of strain energy release necessary for fast fracture] to calculate crack depth, lead to computed stress relief compatible with observed polygonal dimensions."

These dimensions, in terms of the diameter, vary "...from a few meters to more than 100 meters..." (Lachenbruch, 1966, p. 63). According to Péwé (1966, p. 77), ice-wedge polygons are 2 (or 3) to 30 m or more in diameter. Although Black (1952, p. 130) indicated that ice-wedge polygons may be less than 1 m in diameter, he referred to polygons 1—3 m in diameter as resulting from subdivision of larger ice-wedge polygons. In general it would seem that ice-wedge polygons have diameters exceeding 1 m. As for frost-crack polygons, they tend to be larger than ice-wedge polygons occurring in the same area according to Hopkins and others (1955, p. 139). Small nonsorted polygons in West Greenland (Boyé, 1950, p. 134) and the arid environment of North Greenland (Davies, 1961a, fig. 2, p. 49; p. 50), have been ascribed to desiccation as have small polygons to arctic Canada (Smith, 1961, p. 74), Spitsbergen (Büdel, 1961, p. 347, 353; Elton, 1927, p. 176—180, 190—191) and elsewhere in the Arctic, and they are demonstrably due to drying in many environments (Longwell, 1928; Segerstrom, 1950, p. 115; Shrock, 1948, p. 188—209; and many others). The conclusion seems warranted that in general well-developed and regular nonsorted polygons less than 1 m in diameter are probably due to desiccation cracking, a conclusion also cited by Tricart (1963, p. 88). (That desiccation may produce large polygons as well does not affect the argument.)

Most small nonsorted polygons in the Mesters Vig district are believed to be due to desiccation cracking because they (1) are more regular than those ascribed to dilation, (2) were confined to the active layer wherever excavated, (3) occur characteristically in areas subject to pronounced drying, and (4) have dimensions typical of desiccation polygons in other environments but incompatible with dimensions of polygons known to be due to frost cracking.

The oriented polygons on the shore of the lake abutting the upslope side of the emerged delta remnants on the east side of Tunnelelv differ from most of those described in their rectangular and oriented pattern. However for reasons cited in their description they are also regarded as desiccation phenomena. Their pattern is believed to be the result of slope control and differential desiccation, a subject discussed under the origin of small nonsorted stripes.

The origin of the compound aspect of the small nonsorted polygons in the vicinity of ES 5 and 8 is uncertain. Perhaps the smaller pattern reflects subdivision of the larger as the result of some normal aging process. On the other hand, according to Lachenbruch (1961, p. 4287) a superimposed crack system may reflect prolonged desiccation that caused selective deepening of widely spaced cracks, since a deep crack could relieve tension over greater horizontal distances than a shallow crack. He therefore suggested that deeper and more widely spaced cracks might represent longer intervals of drying than shallower and more closely spaced cracks, and in places might be related to a secular climatic trend toward aridity as suggested by Willden and Mabey (1961) for some very large nonsorted polygons in Nevada. A possible relationship between the compound patterns in the vicinity of ES 5 and 8 and a climatic trend toward desiccation is intriguing, because there is botanical evidence of desiccation as the result of increasing warmth and reduction of lingering snowdrifts on slopes such as those where the compound patterns were noted (Raup, 1965, p. 77, 96—98). The origin of the pronounced doming, associated with the compound pattern in places, is not clear. A probable factor is compression accompanying the growth of seasonal ice veins in the cracks, alternating with some infilling of the cracks during the thaw season. As described earlier, such ice veins were observed. Infilling would answer Elton's (1927, p. 178) objection to this factor. In addition, a possible factor to be investigated is salt content, which appreciably influences volume changes associated with wetting and drying, as discussed long ago by Wollny (1897, p. 20—21, 31—32, 51). Sodium chloride, for instance, appears to affect development and doming of desiccation polygons (Dow, 1964; Elton, 1927, p. 179; Kindle, 1917, p. 140—144), it is involved in synaeresis cracking (White 1961) as previously described, and is known of affect frost heaving (Beskow, 1935, p. 100—101, 232; 1947, p. 57—58). Also the wide variety of patterned ground in warm deserts, where salt is an important variable in forms related to desiccation as well as in some other forms (Hunt and Washburn, 1966), suggests the desirability of investigating the role of chemical variations in the mineral soil of patterned ground.

LARGE NONSORTED POLYGONS

VICINITY OF EXPERIMENTAL SITE 20

Surface morphology

Several large nonsorted polygons were strikingly developed on the ridge crest just above ES 20. The ridge, consisting of arkosic bedrock that was strongly disintegrated in the top 1—2 m, was thinly and patchily veneered with till. Although tha patterns were concentrated at the crest, some were on the flanks near it in step-like fashion. The patterns were outlined by a clearly polygonal system of vegetated, linear furrows; the relatively bare central areas of some of the meshes, however, were dominantly circular (fig. 11, pl. 7). The forms are classed as polygons rather than circles because the basic pattern is polygonal and the circular aspect is believed to be secondary.

Polygon diameters between midpoints of furrows ranged from about 5.5 to 10.5 m, and the circular areas were 3 to 6 m across. Some of the central areas were somewhat dome shaped, others were almost flat except for a convex-up appearance produced by the marginal furrows. These furrows averaged about 0.5 m deep measured from the crest of adjacent central areas. Vegetation was concentrated in the furrows over widths of 0.5—2.0 m and consisted mainly of *Cassiope*. Some central areas had nearly continuous vegetation, others were bare except for isolated plants of *Carex* and *Dryas* in the inner part, with *Betula* and *Vaccinium* coming in toward the margin. There wery few lichens on stones at the surface of the least vegetated parts but many more on stones where vegetation was more continuous.

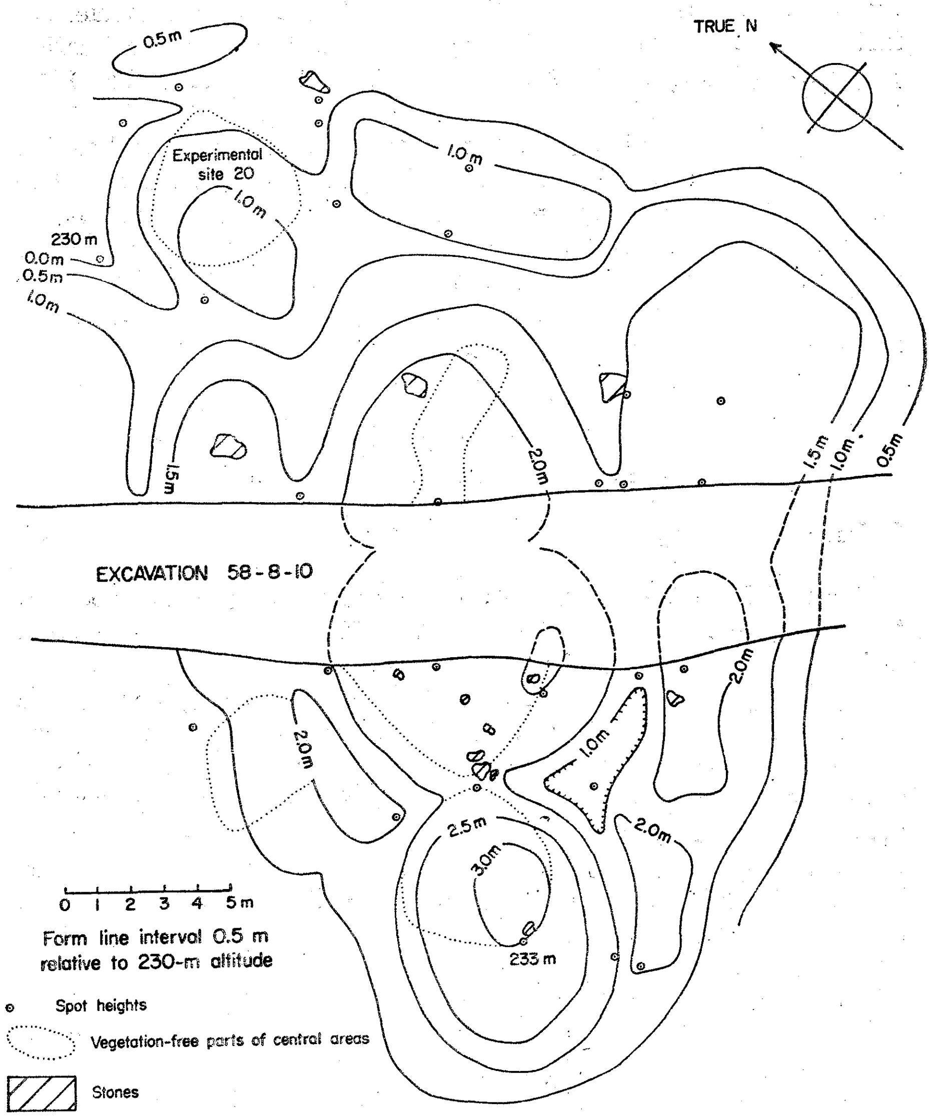


Fig. 11. Sketch map of large nonsorted polygons, ridge crest just above experimental site 20

Subsurface morphology

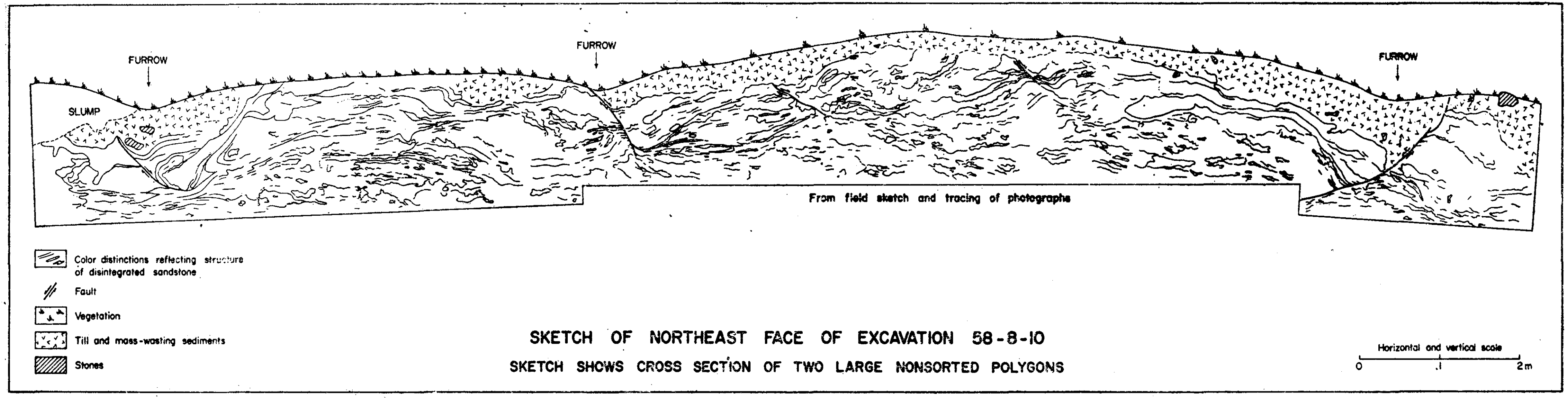
Excavation 58-8-10 was bulldozed between two of the best-developed polygons, cutting each in half to a maximum depth of 2 m. The excavation was nortwest-southeast parallel to the dividing furrow and it transected at right angles furrows on either side of the polygons (fig. 11). The polygon (pl. 7) on the southwest side of the excavation was almost completely bare of vegetation near the center of the mesh and was one of the two most active-appearing forms in the vicinity; the polygon on the northeast side was more vegetated but otherwise similar. The depth of the frost table at the time (10 Aug. 1958) ranged from about 135 to 200 cm, being deepest under the central areas and shallowest under the well-vegetated furrows, probably because of the difference in insulation by vegetation. The excavation provided excellent cross sections of the polygons and some surprises regarding their material and structure.

In the central bare area of the southwest polygon, there was pale red (5R 6/2) silty$_{8}$-clayey$_{10}$-gravelly$_{26}$ sand$_{56}$ (SD 0—5 cm). Other bare central areas were similar, an example being clayey-silty sand to silty-gravelly sand, with fines ranging from 9 to 28 percent (SD 1—50 cm). The pale red color contrasted with the moderate brown (5YR 4/4) to pale brown (5YR 5/2) of the surrounding mineral soil, which was a diamicton up to 50 cm thick in the furrows and 90 cm thick in one other place. It contained striated trap stones and was a fragmentary till cover. The underlying material, which reached the surface in the central bare areas, was unconsolidated to the depth of the excavation except for sandstone slabs near the base. This unconsolidated material was weathered bedrock, disintegrated *in situ*. Its constituents, obviously disturbed by frost action, were those characteristic of nearby conglomeratic and arkosic sandstone. It was varicolored, including grayish red (10R 4/2), grayish red purple (5RP 4/2), moderate brown (5YR 4/4), pale brown (5YR 5/2), dark yellowish brown (10YR 4/2), moderate yellowish brown (10YR 5/4), and dark yellowish orange (10YR 6/6). Locally the colors produced a mottled effect but in some instances corresponded to bedding and, together with differences of grain size, helped to reveal the structure of the polygons.

In general the structure was slightly dome shaped beneath the central areas with the dip increasing toward the furrows (figs. 12—13, pl. 8). The bedding was much disrupted, and structureless mixed material transgressed it locally and enclosed fragments of the disrupted rock. In one place displacement of small and angular, ghostlike fragments, which were rotated with respect to each other and separated by several centimeters of structureless matrix, illustrated on a small scale the disruption that was apparent on a large scale. Several apophysislike projections of fine-grained material suggested minor injections. No deeply penetrating wedge structures were observed beneath the furrows but faults and the increasing dip toward the furrows indicated slumping. The availabe evidence suggests that the slumping was restricted to the top 1.0—1.5 m or so. The faults tended to be curved in cross section, and their dip and direction of curvature on each face of the excavation were toward the center of the largest polygon cut by the face. The movement along the fault as shown by offset beds was in the same direction, and the whole effect was that of a hingelike collapse with the direction of rotation being toward the center of the two polygons.

The collapse features were unlike the V-shaped faulting and infilling commonly associated with thawing of a deep-seated ice wedge. Rather they suggested the melting out of a shallow ice mass that lay at the 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 lense toward the furrows would be consistent with frost cracking there without necessarily involving deep ice wedges. The slumping might have smeared subsurface traces of any cracks that were not coincident with the faults. However, the possibility of deep wedges having been (or still being) present is not eliminated. Accumulation of water in the excavation and other circumstances prevented deep enough examination to settle the question.

The structures revealed by the 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 for reasons elaborated later under origin. Frost heaving of relatively fine-grained material 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 as outlined in the preceding paragraph. 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 lacations for insulating vegetation.



FURROW
FURROW
FURROW
SLUMP
From field sketch and tracing of photographs
Color distinctions reflecting structure of disintegrated sandstone
Fault
Vegetation
Till and mass-wasting sediments
Stones
SKETCH OF NORTHEAST FACE OF EXCAVATION 58-8-10
SKETCH SHOWS CROSS SECTION OF TWO LARGE NONSORTED POLYGONS
Horizontal and vertical scale
0
1
2m

Fig. 12.

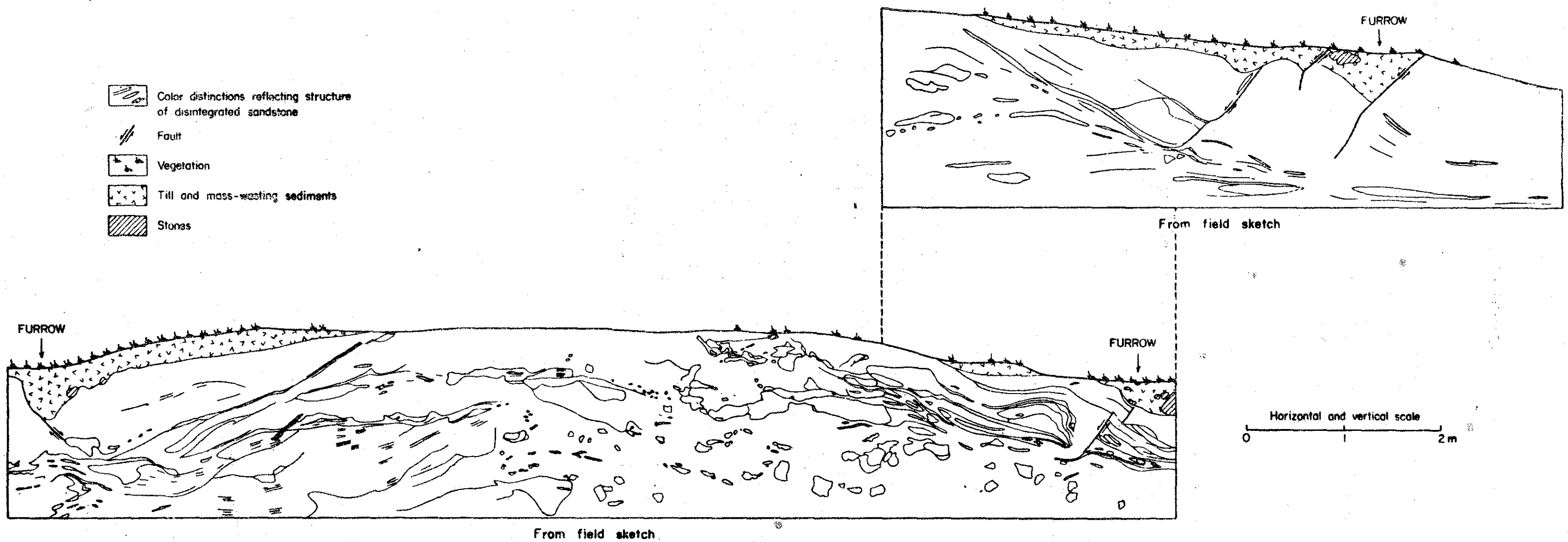


Fig. 13. Sketch of southwest face of excavation 58-8-10. Sketch shows cross section of one large nonsorted polygon

Upper profile is parallel to, and 0.5—1 m back, of, lower profile. Dashed lines indicate overlapping parts of profiles

Although dowel-heave observations at ES 20 indicate that surface frost action, at least, is slight (Washburn, 1968), and although relative dryness may help to explain some of the difference in vegetation cover, the vegetation-free nature of the best-developed central areas suggests that heaving is still active. Such heaving and the fact that the greatest concentration of insulating vegetation is at furrow intersections probably explain the dominantly circular aspect of these central areas. 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.

DANEVIRKE HILLS

Large nonsorted polygons were well developed in a saddle between trap knobs MS 105 m and MS 85 m in the Danevirke hills. They were on a very gentle slope, in pebble-veneered gravelly sand associated with some emerged strands. The polygons ranged from irregular froms, some of which were pentagonal, to almost perfectly hexagonal forms with a diameter of about 3 m (pl. 9). The patterns were outlined by dark vegetation and, in places, faint cracks that surrounded bare central areas. The vegetation was in very faint depressions except where deflation had lowered some central areas and left the vegetation-protected borders standing slightly in relief.

VICINITY OF GEFIONELV AND MYGGESØ

Large nonsorted polygons, which differed from those previously described by occurring in till, were noted on the crest of the spur at the junction of Gefionelv and Tunnelelv, and at the crest of a low gentle rise about 0.7 km northeast of Myggesø. The Gefionelv polygons were in rubbly till on gradients up to 18°. They were outlined by depressions up to 30 cm deep in which *Cassiope* was concentrated; no open cracks were observed. The central areas were more sparsely vegetated. Representative polygon size were 5×9 m and 6.5×11 m. The Myggesø forms were in stony but somewhat less rubbly till, and in some places where the gradient steepened they merged into poorly defined stripes. In general appearance they were similar to the Gefionelv polygons.

ORIGIN

The large nonsorted polygons of the Mesters Vig district were developed in disintegrated bedrock, in gravelly sand, and in till. The definitely polygonal character of the patterns probably indicates a contraction process. As previously discussed in connection with the origin of small nonsorted polygons, desiccation cracking in the Mesters Vig environment is believed to be characteristic of these small forms rather than of large ones. Frost cracks containing sand wedges such as those described from the Antarctic (Péwé, 1959) were not observed in the Mesters Vig district. Neither is the presence or absence of ice wedges demonstrated, for no exposures of frost cracks revealed undoubted permafrost. However, the interpolygon furrows transected by excavation 58 8-10 above ES 20 (figs. 12—13, pl. 9) suggest melting of underlying ice masses. That the weathered bedrock at excavation 58-8-10 should be subject to frost cracking and formation of ice masses in it is not surprising. Polygons in bedrock that is much less weathered have been reported from other places in the Arctic (Washburn, 1950, p. 47—49), including Greenland (Davies, 1961b), although jointing as well as frost heaving were involved in these instances. The bedrock at excavation 58-8-10, however, was so disintegrated as to be essentially unconsolidated when thawed, and jointing may not have been a factor in the polygonal pattern here. Although at first glance the dominantly circular pattern of the bare central areas of the polygons in the vicinity of ES 20 appears inconsistent with the frost-crack hypothesis, the inconsistency can be explained by the bare areas being of secondary origin as discussed earlier. The contrary point of view that the central areas are primary and the polygonal borders secondary as the result of mutual impingement of circles, as suggested long ago by Högbom (1914, p. 315, 319) for sorted forms, and favored by some subsequent investigators, including Dżułyński (1963) on the basis of experimental data, is countered by (1) the blocklike collapse rather than crumbling of the border areas, and (2) the fact that the furrows are so sharply polygonal and similar to others associated with proved contractional cracking that any other origin calls for special pleading.

Thus, the available evidence supports the hypothesis that the large nonsorted polygons in the Mesters Vig district originated by frost cracking and that some are ice-wedge polygons, although perhaps inactive at the present time. The polygons at the Danevirke hills locality, which were in gravelly sand where a thick active layer is expectable, may have formed without ice wedges and therefore be frost-crack polygons similar to those described from Alaska by Hopkins and others (1955, p. 138—139).

SMALL NONSORTED STRIPES

GENERAL

By small nonsorted stripes is meant those whose width between center lines of linear elements is less than 1 m. Their size is thus consistent with the diameter of small nonsorted polygons. Such stripes were observed in the Danevirke hills, in the Nyhavn hills, and among the emerged delta remnants immediately west of Tunnelelv.

DANEVIRKE HILLS

Especially well-developed small nonsorted stripes occurred at the base of a cliff in the Danevirke hills. They were on a 3° gradient in mineral soil characterized by abundant fines. The vegetation cover was mainly black organic crust but included moss. The stripe pattern was outlined by cracks extending in the direction of the gradient and was notable for its regularity (pl. 10). The inter-crack areas were 15—20 cm wide. Some poorly formed transverse cracks were also present, and at the very base of the cliff, where there was a more irregular and slightly steeper slope, the stripes merged into poorly developed small nonsorted polygons.

Probable reasons for the stripes being on a gentler slope than the polygons, the reverse of the common situation, are that (1) the slope with the stripes is the more regular so that the pattern is less broken by irregularities, and (2) the mineral soil of the stripes is probably finer and has a higher silt content, so that it would drain less readily and be more subject to gelifluction and the closing of transverse cracks than the material at the very base of the cliffs. In general where the writer has seen small nonsorted polygons on an appreciable gradient, they have been associated with coarse silty to sandy material or with commonly dry slopes where gelifluction was minor.

NYHAVN HILLS

Small nonsorted stripes near the base of a trap knob in the Nyhavn hills were on a 15° gradient in stony loam that was sparsely vegetated. They were about 15 cm wide and were bordered by cracks, 0.1—1.0 cm wide at the surface and at least 3—4 cm deep, in which plants were preferentially rooted. Although very similar in size to the stripes at the Danevirke hills locality, they differed particularly in occurring on a considerably steeper slope and in much coarser mineral soil, and in being much less developed.

EMERGED DELTA REMNANTS

An uncommon variety of nonsorted stripes was noted on a sandy slope of emerged delta remnants. The pattern was on a 19° gradient and was delineated by stripes of clean sand alternating with stripes characterized by black organic crust on slightly "dirtier" sand (pl. 11). Although the pattern gave a sorted appearance, stones were completely lacking and the sorted aspect was primarily due to the contrast between the light-colored sand and the black organic crust. Where clearly defined the stripes of clean sand were 1—5 cm wide, and the sand lay in depressions about 1 cm deep, which formed an anastomosing pattern. The stripes of black organic crust averaged slightly wider and in places had the appearance of nubbins (*cf.* Washburn, 1968).

ORIGIN

Rillwork

The pattern of the stripes at the emerged delta locality is quite inconsistent with contraction as an explanation for them, and no cracks were seen in association with the stripes. The scale and anastomosing character of the stripes of clean sand, and the fact that the sand filled shallow depressions and appeared washed, whereas the underlying and adjacent sand was slightly "dirty", strongly suggests that these stripes were primarily due to rillwork. The nubbinlike aspect of some of the black organic crust indicates that frost action may have been a contributory factor, perhaps in several ways but especially by causing microheaving of the nubbinlike areas and thus helping to concentrate rills. However, the cause-

-and-effect relationship here is not clear, for the rills may have also helped to determine the location of the nubbinlike areas.

Desiccation cracking

The downslope orientation of the stripes at the Danevirke hills locality was too regular and unbranching to be the product of rills. It is clear that they formed essentially *in situ* and were not merely gelifluctional modifications of the polygons higher up the slope, for they were much better developed than the polygons. The cracks of such polygons are believed to be due to drying, as discussed earlier in connection with the origin of small nonsorted polygons, and the cracks associated with the stripes were so similar that they were probably of the same origin. The stripes are therefore interpreted as desiccation features. Their orientation is believed to reflect a gradient control of the initial crack pattern, with drainage emphasizing downslope cracks and gelifluction closing transverse ones.

Kindle (1917, p. 137—139) found that desiccation of a clay mixture in a tilted pan produced parallel cracks mainly in the direction of tilt, a result he attributed to differential drying. Furrer (1954, p. 237—239, 242), using mineral soil from sorted stripes on experimental inclinations of 10° and 20°, also found that desiccation cracks were oriented mainly parallel to the inclination, but he did not explain why. He thought that cracks on natural slopes were influenced by gravity and solifluction, and he implied that solifluction might reorient cracks. The cracks of some ice--wedge polygons are also slope controlled in being parallel and normal to a slope, and suggested causes include stress differences due to gravity and to zonal differences in soil properties (Black, 1952, p. 130), and thermal gradient (Lachenbruch 1960, p. B408; 1962, p. 46—48). Such stress differences might also cause orientation of drying patterns. Neal (1966, p. 1327—1328) cited a personal communication from Lachenbruch suggesting "...that mud cracks might display oriented polygons where a desiccation gradient exists, such as might be produced by a sloping water table".

The small nonsorted stripes at the Nyhavn hills locality, although in stonier material and much less well developed, are otherwise so similar to the stripes at the Danevirke hills locality that it is concluded they, too, are desiccation phenomena.

LARGE NONSORTED STRIPES

Large nonsorted stripes were noted on the slopes of a low gentle rise about 0.7 km northeast of Myggesø. They occurred in till and were delineated by pronounced vegetated furrows that extended downslope from large nonsorted polygons at the crest of the rise. The stripes were observed mainly from the air and details are lacking. Their origin is believed to involve frost cracking and probably gelifluction.

DEBRIS ISLANDS

DANEVIRKE HILLS

Well-developed debris islands were observed at the south base of the Danevirke hills. They were in the bed of a spillway, and consisted of circular areas of stony mineral soil, some 50 cm in diameter, surrounded by cobbles and boulders of the spillway. Vegetation was very sparse. This occurrence demonstrates that debris islands in the Mesters Vig district are not confined to high altitudes, although many more were seen in the summit area of Hesteskoen than elsewhere.

HESTESKOEN

Debris islands on the upper slopes of Hesteskoen (1118 m) were well developed in a number of places. On the northeast side of the northwest-southeast summit ridge they consisted of commonly isolated but occasionally bunched, dominantly circular patches of angular rock debris that was lighter colored, fresher looking, and characterized by more fine material than the surrounding bouldery conglomeratic sandstone rubble. No statistical analyses were made but the circular patches seemed to have a higher proportion of shaly, more easily weathered rock types than the surrounding rubble. The diameter of the most regular debris islands was about 2 m, but some forms were elongate, not only at an angle to the contour but also parallel to it. Most forms had a dome shape, and where adjacent to other debris islands were separated from them by depressions up to 50 cm deep containing edgewise slabs of sandstone. Some forms were marginal to linear furrows suggestive of underlying ice wedges, and a few of the bunched islands approached being sorted nets and polygons.

On the west side of the northwest-southeast ridge at an altitude of about 1050 m, debris islands were on a gradient of 31°. A representative example (pl. 12), which ranged in diameter from 1.2 to 1.5 m, was elongate downslope and had a surface inclination of 25° in the same direction so that the form was faintly steplike. The near-surface material of the central area, which was distinctly finer than the surrounding slabby rubble but contained fragments up to 15 cm across, was $silty_9$-$sandy_{27}$ $gravel_{63}$, consisting of sandstone and shaly debris. The existence of debris islands on appreciable gradients was reported long ago by Meinardus (1912a, p. 251; 1912b, p. 5), but the present instance demonstrates that their surfaces are not necessarily approximately horizontal as usually depicted.

Debris islands on the north side of the east-west ridge, at an altitude of about 950 m where it joins the northwest-southeast ridge, occurred on a gradient of 17° in steplike fashion, with treads inclined 11° downslope. Near the surface they consisted of light colored $sandy_{20}$ $gravel_{78}$ that was breaking through much coarser, dark trap debris from a dike a few meters upslope. In one place doming of trap debris next to a fully developed island suggested another in process of forming (pl. 13).

ORIGIN

Several hypotheses have been advocated for the origin of debris islands, including *in-situ* weathering (for example, Meinardus, 1912a, p. 254—255; 1912b, p. 12—13, 32), mass heaving (Hamberg, 1915, p. 596, 603—604), and "convection" due to moisture--controlled density differences (for example, Mortensen 1932, p. 421—422) and its amended version of mass displacement due to moisture-controlled changes in intergranular pressure (Washburn, 1956, p. 854—855). Mass heaving is open to serious objections (*cf.* Washburn, 1956, p. 840—841), but local differential heaving (Taber, 1943, p. 1458—1459) may be an important factor. With the probable exception of mass heaving, all these hypotheses emphasize processes that may combine in different degrees in different situations to produce debris islands, without any one process being the sole explanation in all instances.

The importance of surfaceward movement of material from depth is proved by the debris islands on the north side of the east-west ridge of Hesteskoen. Arguing from (1) such movement, (2) the size disparity between the material of the debris islands and of the surrounding rubble, and (3) the fact that both the dry and wet densities of coarse rock material are generally greater than of relatively fine material (*cf.* Washburn, 1968), it seems that density differences may play a significant role. The relation of some debris islands on the northwest-southeast ridge of Hesteskoen to ice-wedgelike furrows is similar to that described for some nonsorted circles near ES 3 and 9, and the explanation preferred in connection with the circles — that the relation may be due to differential accumulation of moisture — appears equally applicable to the debris islands.

SMALL SORTED NETS AND POLYGONS

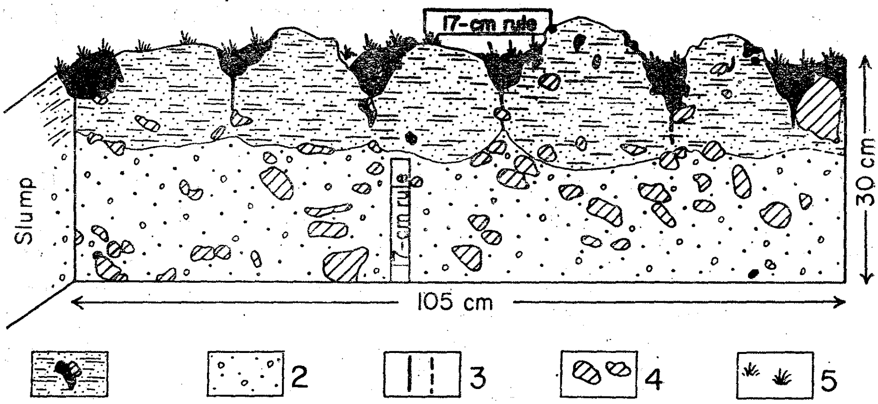
GENERAL

The distinction between nets and polygons is geometrical in that nets are intermediate forms that are neither dominantly polygonal (straight borders between angular bends) nor dominantly circular. The distinction can be important in places, since the origin of polygons and circles may be very different (*cf.* Washburn, 1956, p. 830). Well-developed small sorted nets and polygons were observed in only a few places in the Mesters Vig district.

EMERGED DELTA REMNANTS

Small sorted polygons and polygons transitional to sorted forms were associated with nonsorted polygons on the low-level emerged delta remnants near the northwest end of the airfield. Excavation 60-7-23 (fig. 14, pl. 14) was on a bench tread similar to the one with the nonsorted polygons described in connection with excavations 60-7-21A and 60-7-21B, the latter being about 100 m north of excavation 60-7-23.

The vegetation included mainly moss, black organic crust, and *Silene acaulis*. The soil consisted of 3 units:



From field sketch and tracing of photograph

Fig. 14. Sketch of excavation 60-7-23, about 100 m south of excavation 60-7-21B. Sketch shows cross section of small sorted polygons

1. Arctic Brown soil, silty sand with concentrations of stones in depressions, moderate brown (5YR 3/4), with concentrations of darker humic material; 2. sandy gravel, pale brown (5YR 5/2) to dark yellowish brown (10YR 4/2); 3. cracks; 4. stones; 5. vegetation

Top	*Thickness (cm)*
1. In central areas, moderate brown (5Yr 3/4) silty$_{42}$ sand$_{53}$, coarser toward borders	15—20
2. In polygon borders, black peaty humus with sandy$_{11}$ gravel$_{84}$	5
3. Pale brown (5YR 5/2) to dark yellowish brown (10YR 4/2) sandy$_{33-35}$ gravel$_{62-66}$	>3p

As at excavation 67-7-21B, described under Small Nonsorted Polygons, the specific gravity increased with depth. In unit 1 it was 2.65; in unit 3 it was 2.69 in the upper part, 2.70 in the lower part. The polygons (pl. 15) ranged in size from 8×12 cm to 24×30 cm; pentagonal forms predominated but square forms were also present. The bordering depressions, some 5 cm wide and deep, were well vegetated. This vegetation masked a number of stones, so that the polygons were really sorted or transitional to sorted polygons in spite of their nonsorted surface aspect. Humic material was concentrated beneath the depressions and in places hair--thin vertical cracks extended through it to depths of at least 7—12 cm and seemed to reach the top of unit 3, whose highest points were characteristically beneath the depressions (fig. 14, pl. 14). The cracks probably facilitated penetration of roots (*cf.* N i e l a n d, 1930, p. 348; Poser, 1931, p. 210) and development of the humus concentrations (Ugolini, 1965, p. 50). The polygons were dome shaped as at the other excavations in the vicinity, the microrelief being up to 5 cm, but unlike the other polygons there was an additional microrelief provided by lichen-covered nubbins, 1—3 cm across. 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 percent) in unit 1, as contrasted with the very low content (2—4 percent) in unit 3 and the small total amount of gravel represented by unit 2 (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.

KORSBJERG

Small sorted polygons, transitional to nets in places, were noted in the summit area of the Korsbjerg massif south of Ansgar (1011 m). They were in the central areas of larger sorted nets on a 1—2° gradient and were commonly about 20 cm in diameter (pl. 16). The mineral soil of the central areas appeared similar to the fine facies of the larger nets, which was gravelly$_5$-sandy$_{22}$-clayey$_{25}$ silt$_{48}$ (SD 0—10 cm); the borders of the small forms were characterized by edgewise gravel. The sorted polygons were associated with nearby nonsorted polygons, which were also located in the central areas of the larger sorted nets but in places where there were fewer stones at the surface.

STORE BLYDAL

Excellently developed small sorted nets occurred in a shallow kettlelike depresion near Rungsted Elv. Their borders were characterized by cobbles and small boulders, many black with microscopic plants as also noted in other places where depressions had contained standing water and then dried out. The central areas of the meshes consisted of silty$_9$-gravelly$_{19}$ sand$_{69}$ (SD 0—15 cm). The dimensions of the meshes varied considerably, ranging from some 15 to 150 cm. In places several meshes had merged to form elongate forms as large as 2.0×5.5 m and there was a tendency for mesh size to increase toward the bottom of the depression. However, most forms were 1 m or less im diameter (pl. 17). Many central areas were characterized by nonsorted polygons 15—30 cm in diameter.

ORIGIN

Except for their sorting, which was mainly apparent upon excavation, the small polygons of the emerged delta remnants were very like the nearby nonsorted forms, some of which had a few stones in the borders and appeared to be transitional to sorted polygons.

Similarly the association of the Korsbjerg small sorted polygons with nearby nonsorted polygons of similar size strongly suggests that both polygons types are of comparable origin. In the Korsbjerg forms, especially, the essential difference was whether or not the polygons happened to be where stones were abundant. Since the writer believes that such nonsorted polygons are due to desiccation, he also regards the sorted polygons as being primarily of this origin. Small sorted polygons elsewhere in Northeast Greenland were similarly interpreted by Poser (1932, p. 50—51). The bordering stones probably accumulated in the cracks by mass-wasting and washing (*cf.* Chambers, 1967, p. 11; Corte and Higashi, 1964, p. 60—64; Lliboutry, 1965, p. 980, 989; Washburn, 1956, p. 848—849) and frost sorting (*cf.* Gradwell, 1957, p. 796—806).

The origin of the Store Blydal sorted nets is much less apparent than that of the Korsbjerg forms. Although the Store Blydal forms were in a place particularly subject to wetting and drying, their appearance is quite different from the pattern commonly associated with contraction and more like that of bunched debris islands. This similarity suggests that mass displacement, perhaps by moisture-controlled changes in intergranular pressure, may be responsible for the Store Blydal forms.

LARGE SORTED NETS AND POLYGONS

GENERAL

Except for small nonsorted polygons, large sorted nets are the predominant variety of patterned ground in the Mesters Vig district. In contrast to the nonsorted polygons, the best-developed and most-active appearing sorted nets were invariably in localities that tended to have a high moisture content throughout the thaw season. These localities included ES 1, 11—12, and vicinity on the Kong Oscars Fjord slope of Labben, a similar area 1 km to the south, some slopes on Hesteskoen and the Korsbjerg massif, and slopes at Myggesø. Numerous other localites had forms that were less well developed.

EXPERIMENTAL SITES 1, 11—12, AND VICINITY

Surface morphology

Large sorted nets were particularly well developed at ES 1, 11—12, and vicinity (fig. 15, pl. 18). They were on an average gradient of 2°, on a slope that received abundant seepage from higher-lying steeper slopes where snowdrifts tended to linger during the thaw season. Slabby sandstone appeared immediately upslope from the patterns in places and probably underlies them at shallow depth near the outcrops. Fragments from disintegrating bedrock littered the slope just above the patterns and decreased in abundance downslope.

The patterns were formed of prominent and very irregular stony borders surrounding areas of finer material. Shapes and dimensions of the meshes are given in figure 15. The meshes were commonly elongate downslope, although several had long diameters parallel to the contour. Diameters varied greatly, ranging from a few tens of centimeters to about 8 m; a few of the forms approached being sorted circles (pl. 4). Measured widths of borders ranged from 15 to 100 cm. In general the stony borders rose appreciably above the central areas, the relief of some being up to 32 cm. Slabby stones in the borders were characteristically on edge but a few at the surface were flat lying. Vegetation, including *Salix, Saxifraga,* lichen, and moss, was commonly concentrated adjacent to the borders, leaving the more central parts of the meshes completely bare or bare except for isolated plants; a few central areas were somewhat better vegetated.

A number of central areas were irregularly dome shaped, the local relief being up to 14 cm at ES 11—12. A few central areas that were only partly enclosed by stone borders were somewhat similar to the nonsorted circles at ES 3, 9, and vicinity. Isolated

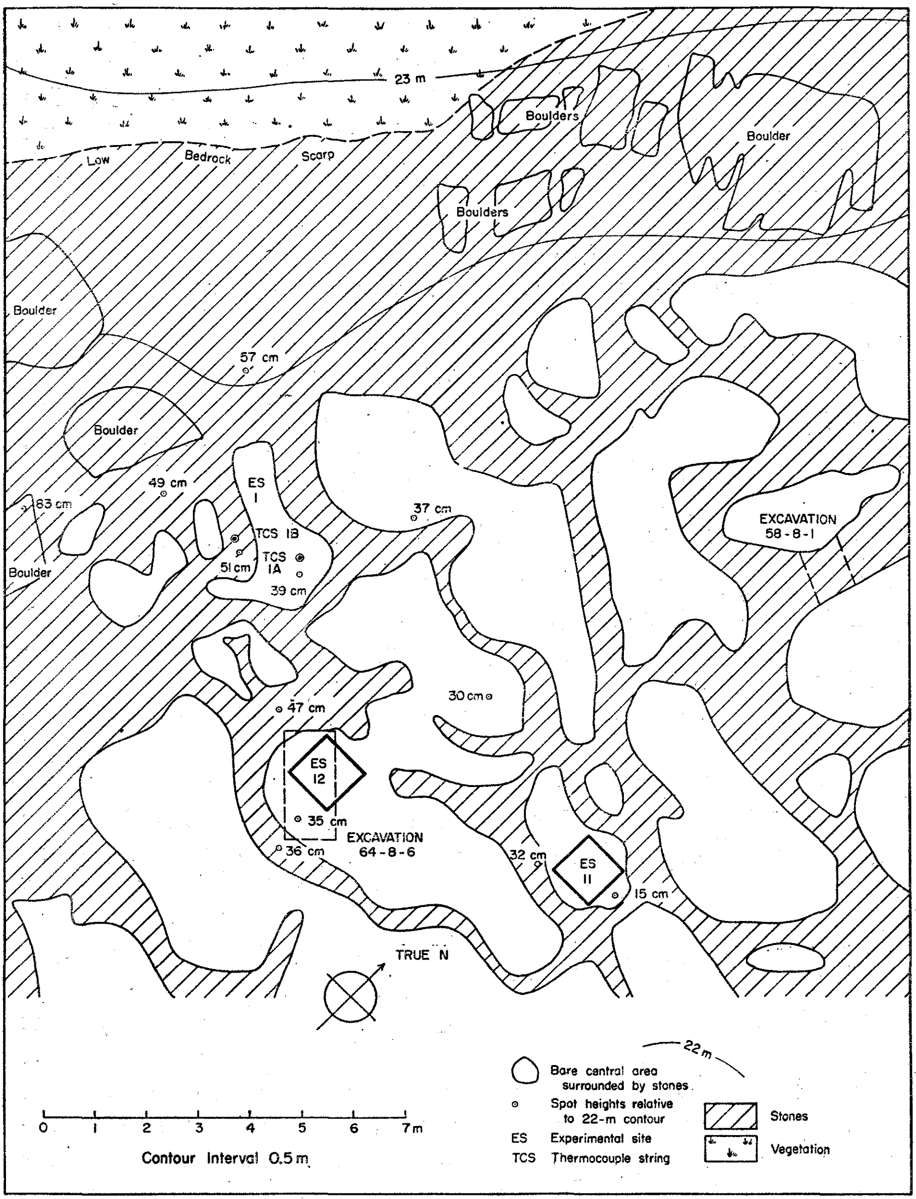


Fig. 15. Experimental sites 1, 11—12

cracks occurred in some central areas, especially in parts that appeared freshest and most active. Some cracks in elongate areas were medial like those previously described from the vicinity of ES 3 and 9, and similarly the heaved aspect of many central areas near ES 11—12 strongly suggested that the cracks resulted from dilation of the surface by heaving. Medial cracks in sorted patterns have also been reported from the Thule district, but were thought to be possibly due to frost cracking (H o l m e s and C o l t o n, 1960, p. 8). In addition to this evidence of disturbance at depth, there were indications of intense near-surface frost action in the central areas. Wormy or crumblike spots due to the work of needle ice were common. Very few stones had lichens, and in one central area at least 10 stones had been recently heaved as shown by fresh appearing loam on their sides or tops. Tightly stretched *Salix* roots were noted in several places. Striking proof of intense frost action was provided by dowel-heave observations at ES 11—12 (W a s h b u r n, 1968).

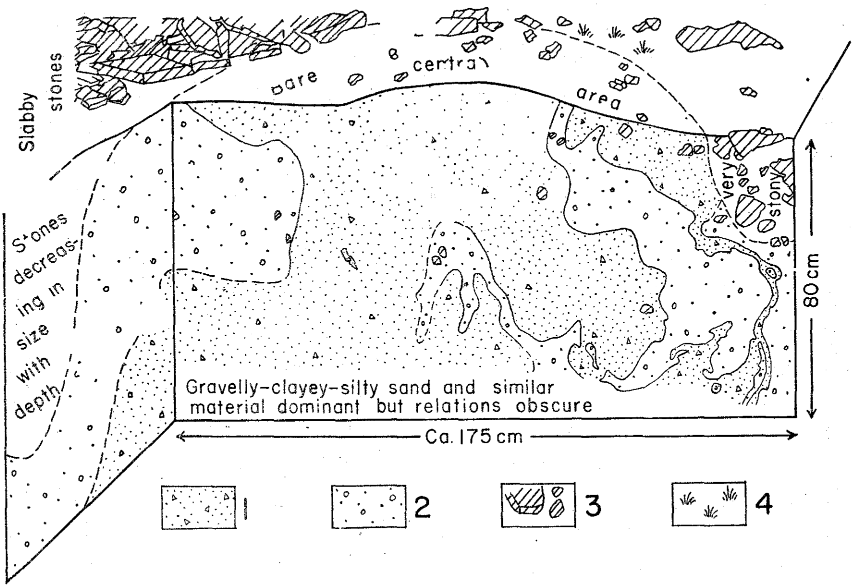
The mineral soil of the central areas ranged from gravelly--sandy silt-clay with 78 percent fines to clayey-silty-sandy gravel with 30 percent fines (SD 0—45 cm). The contained stones included a few cobbles but were mainly pebble-size chips of fine-grained sandstone; and, at ES 12, also of limestone. The borders consisted principally of slabby fine-grained sandstone fragments ranging in size from pebbles to boulders, cobbles and small boulders being common at the surface and pebbles increasing with depth. The color of the sandstone fragments was dominantly light olive gray (5Y 6/1), but the weathered surfaces of the border stones had a tan tinge that was lacking on the stones of the central areas, a difference probably due to longer exposure of the border stones. Stones of granite, quartzite, and trap, some of which were probably derived from conglomeratic phases of the sandstone bedrock, were also present, especially in the borders.

Subsurface morphology

Excavation 59-8-1 (pl. 19) transected the stony border between two meshes 7 m north of ES 11 (fig. 15). Although limited by the water table, which lay at a depth of 30 cm at the time (1 Aug. 1958), the excavation revealed that the border was wedge shaped in cross section. Most slabby stones were on edge but a few at the surface were flat lying; in general the stones decreased in size with depth. Humic material lay 15 cm below the surface adjacent to one of the central areas, and moss in the upper part of the border had been buried by a stone.

Excavation 64-8-6 (fig. 16) transected ES 12 (fig. 15) to a depth of 90 cm, which coincide with the frost table (6 Aug. 1964). Deeper excavation was prevented by water seeping in when the stony border was cut.

Aside from the stony borders, the mineral soil had two main phases: (1) gravelly-sandy-silty clay with up to 78 percent fines (SD 0—35 cm), which was olive black (5Y 2/1) except at the very surface where it was grayish, and (2) gravelly-clayey-silty sand to



From field sketch and tracing of photograph

Fig. 16. Sketch of excavation 64-8-6, experimental site 12. Sketch shows partial cross section of sorted mesh

1. gravelly-sandy-silty clay, olive black (5Y 2/1); 2. gravelly-clayey-silty sand and similar material, dark yellowish brown (10YR 4/2); 3. stones; 4. vegetation

clayey-gravelly-sandy silt with up to 56 percent fines (SD 0—35 cm), which was dominantly dark yellowish brown (10YR 4/2). The black phase was *greasy*, and had a well-developed lamellar structure that became increasingly prominent with depth and probably reflected the location of former ice lenses. Reaction with HCl was vigorous. No shell fragments were found. This black phase, which was unlike any other clayey soil observed at Labben, contained chips of brownish black (5YR 2/1) thin-bedded limestone with black laminae that were isotropic in thin section and presumably of organic origin. Weathering of limestone, perhaps an erratic block, probably gave rise to the black phase. The yellowish brown phase had more voids, a less prominent lamellar structure, and reacted much less vigorously to HCl than the black clayey material. It occurred as irregular masses in the black phase and was predominant at the base of the excavation, where it contained downslope-trending streaks of the black phase and underlay the transected stony border. Stones in the border were mainly on edge, but stones in the other phases had no obvious orientation.

The general structure revealed by the excavation was consistent with an upward movement of silty clay and, as suggested by silty clay over sand at the north corner, a lateral spreading of it at the surface. Although the relations and boundaries were less distinct in places than implied by figure 16, no source for the silty clay at greater depth than the excavation was apparent. The subsurface extent of the olive black silty clay beyond ES 12 was not determined; it did not appear at the surface of nearby patterns.

An attempt to excavate ES 11 was unsuccessful because of seepage. The mineral soil of the central area was gravelly-clayey sand-silt to clayey-silty-sandy gravel with fines ranging from 30 to 52 percent (SD 0—20 cm), and was much more permeable than the clay at ES 12. Specimens of frozen ground collected earlier from the central area of a sorted mesh next to ES 11 were of similar material. The excavation was too shallow to show major structure but revealed numerous discontinous ice lenses, ranging in thickness from 0.03 to 1.25 cm, within 15 cm of the surface. As many as 20 lenses, 0.03 to 0.2 cm thick, were counted in a specimen 3 cm thick from immediately beneath the frost table, which was at a depth of 7 cm at the time (20 July 1960).

HESTESKOEN AND KORSBJERG

Large sorted nets with bouldery borders were observed at the northeast base of Hesteskoen in a broad saddle between trap knob MS 180 m and trap knobs MS 112 m and 120 m. Some of the borders had boulders over a meter in diameter. The area included considerable vegetation, and the forms did not appear active.

Large sorted nets with bouldery borders were also noted in several places on the east slope of Hesteskoen below the steep upper part. They were best developed where it was characteristically wet; vegetation here was largely lacking, and the forms appeared active. The nets merged into stripes where there was a steepening of gradient. The area is discussed in connection with the stripes, which were more strikingly developed than the nets.

Well-developed sorted nets occurred in the summit area of the Korsbjerg massif on the east side of MS 910 m, south of Ansgar. Despite being on gradients as low as 1—2°, most meshes were elongate downslope; in other respects the patterns were quite irregular (pl. 20). Many meshes were 50—150 cm in diameter and had stony borders 5—20 cm wide. Most central areas were characterized by small sorted and/or nonsorted polygons (pl. 16). A channel sample of the top 10 cm of a central area that was free of small sorted forms was gravelly$_5$-sandy$_{22}$-clayey$_{25}$ silt$_{48}$. The border stones were mainly pebbles and cobbles of rusty-weathering quartzose calcarenite, which formed shallow concentrations some 7 cm deep in several places that were examined. All the material of the central areas and borders appeared to be derived from disintegration of the local bedrock.

In general sorted patterns were quite common in the Korsbjerg summit area in places where moisture was abundant and gradients were not too steep. A less common occurrence was noted on the southwest slope of the Korsbjerg massif, opposite Gefionelv, on the bench at map altitude 469 m. The bench was vegetation free and consisted of purplish conglomeratic sandstone that was so disintegrated near the surface as to be like mineral soil. The bench was well drained and appeared to be a characteristically dry site, yet rudimentary large sorted polygons were developed in the disintegrating bedrock. However, sorted nets in nearby wetter areas were better developed.

MYGGESØ

Large sorted nets were particularly common and well developed along the toe of the slopes next to Myggesø (pl. 21). In general they were where the ground was wettest, many of the most active-appearing patterns being on the Blyryggen side where snowdrifts lingered. Some patterns were beneath the shallow water at the lake's edge. The nets were commonly on gradients of 3° and less, and merged into sorted stripes where the gradient was steeper. The meshes were irregularly elongate downslope and had very variable dimensions. A representative mesh measured 80×180 cm and had a stony border 40—50 cm wide in most places. Both smaller and larger forms were present. Some borders were 10—20 cm higher than the central areas, some 10—20 cm lower.

The mineral soil of central areas seemed identical to that of the fine facies of the sorted stripes farther up the slope. In the top 5 cm this facies was clayey-gravelly-silty sand with up to 34 percent fines; at depth it was somewhat coarser. The border stones were mainly slabby sandstone fragments but included vein quartz, trap, and a sprinkling of granitic types. Most stones were angular and, as indicated by matching fragments, many had been frost wedged *in situ*. The size range was from pebbles to boulders, with cobble sizes being predominant at the surface and smaller stones increasing in number with depth. Slabby stones were commonly on edge.

Vegetation was completely lacking in some central areas, and sparsely to moderately well represented in others. Where present it tended to decrease toward the mid-points. Black organic crust, commonly wrinkled, and in places disrupted by needle-ice activity, characterized a number of central areas. Moss was present in some, especially near the shore. Lichens grew on some border stones. The lack of vegetation, presence of needle-ice effects, and stones apparently in process of heaving indicated that a number of central areas were active.

Excavation of a mesh showed that the depth of the frost table was 28 cm beneath the central area and half a centimer less beneath the border (28 Aug. 1958). Since the height of the border above the central area was up to 8 cm, the rise of the frost table beneath the border was quite clear. Water occurred at a depth of 19 cm in the border, and stones there extended to a depth of 22 cm. The size of stones decreased with depth as was also observed in excavation 58-8-1 near ES 11.

This size decrease may be due to the combined effect of: (1) Increased effectiveness of frost wedging accompanying increasing persistence of moisture at depth as argued, for instance, by Elton (1927, p. 184—188) and Poser (1931, p. 205—206, 225—226) for forms in Spitsbergen, (2) downward movement by gravity of smaller frost-wedged fragments between larger as the result of various processes including mechanical sorting in the sense of

Corte (1962c, p. 8—9, 19; 1962d, p. 54, 65), and (3) horizontal sorting (Corte, 1962c, 1962d; Pissart, 1966). Because of the lack of fine particles in stony borders, vertical sorting (Corte, 1961, 1962a, 1963a) is probably relatively unimportant, except as it may have contributed to the development of a widespread rubble cover that was subsequently redistributed during mesh formation.

ORIGIN

Frost cracking

The large sorted forms in the disintegrating bedrock of the bench (map alt. 469 m) on the southwest slope of the Korsbjerg massif differed from the other forms described in having a clearly defined polygonal pattern. Except for the sorting, less prominent microtopography, and lack of vegetation, they were much like the large nonsorted polygons in the vicinity of ES 20, which were also developed in disintegrating bedrock. The difference with respect to sorting is attributed to a relatively high proportion of stones in the conglomeratic bedrock of the Korsbjerg locality. In view of this, their well-defined polygonal character, and the arguments presented in discussing the origin of the large nonsorted polygons, these Korsbjerg forms, like the nonsorted forms, are believed to have originated by frost cracking. In stone-rich mineral soil, movement of stones into bordering fissures would be the logical consequence of various sorting processes (*cf.* Washburn, 1956, p. 851, 859).

Mass displacement

The large sorted nets at ES 1, 11—12 and vicinity, and at Myggesø were notable for the prominence of the near-surface frost action that characterized their central areas. Edgewise position of stones, needle-ice effects, and absence of vegetation in some central areas all attested to this activity. However, near-surface frost action is also prominent in many places lacking patterned ground, and related sorting effects cannot explain the juxtaposition of broad accumulations of rubble adjacent to the relatively small central areas that were noted in places. It is concluded that near-surface frost action is a contributory rather than primary cause of the sorted nets described.

A number of lines of evidence suggest an upward movement of material from depth in the central areas of the sorted nets in the Mesters Vig district: (1) Heaving, involving an upward push from depth, is indicated by the dome shape of some central areas and by their crack pattern, as discussed in connection with ES 1, 11—12, and vicinity. (2) The occurrence of nonsorted circles and similar spots in some of the meshes in the vicinity of ES 1, 11—12. There is clear evidence of upward transport of material, as distinct from upfreezing of stones, in some of these forms elsewhere in the Mesters Vig district. (3) Some sorted meshes approach being sorted circles, and debris islands, which constitute a variety of sorted circles, demonstrably involve an upward movement of material as described for forms on Hesteskoen. (4) The general aspect of the stony borders suggests that they are accumulations between domelike upward displacement of finer material into an overlying rubble cover. The trenching of the border at Myggesø showed the border to be shallow and without underlying crack, and in general the irregulary curving trend and variable width of borders argue against their being localized by cracks. The decrease in size of bordering stones with depth has already been mentioned and may be a secondary feature unrelated to the origin of the meshes.

The active-appearing sorted nets have in common abundant moisture and evidence of upward mass displacement of fine material. Of the various explanations that were considered for the origin of other patterned ground forms with these characteristics (debris islands, and nonsorted circles and related forms), the hypothesis based on changes in intergranular pressure consequent on freezing and thawing appears to be the most promising for reasons discussed in connection with these forms. It seems equally applicable to the sorted nets observed in the Mesters Vig district. It is, nevertheless, largely speculative. Upfreezing of stones and horizontal and vertical sorting are probably very important locally but the writer knows of no proof that they are necessary to the origin of large sorted circles or nets. Gelifluction satisfactorily accounts for the downslope extension and wavy pattern of sorted nets.

SMALL SORTED STRIPES

GENERAL

By small sorted stripes is meant those whose width between center lines of linear elements is less than 1 m and is thus consistent with the diameter of small sorted nets and polygons. Such stripes were uncommon. They were particularly noted near the base of Hesteskoen and on the Korsbjerg massif.

HESTESKOEN AND KORSBJERG

Small sorted stripes near the top of trap knob MS 180 m, on the northeast basal slope of Hesteskoen, consisted of alternating stripes of coarse grus and fine grus derived from the disintegration of the local bedrock. The stripes were a few centimeters wide and several tens of centimeters long. Stones on this slope tended to have a concentration of coarse grus around them, and in places the coarse grus stripes were particularly prominent downslope from stones.

Among other places, small sorted stripes were observed on the north slope of the Korsbjerg massif just west of Thyres Spids. Where they occurred the slope consisted mainly of grus, was bare of vegetation, and had gradient of 17°. The pattern was formed of downslope-trending linear concentrations of stones, separated by stripes of relatively stone-free grus. Although including a few cobbles, the stones were mainly pebble-size angular trap fragments. The stony stripes were a few centimeters to some 25 cm wide and were spaced roughly 25 to 100 cm apart. They were but a shallow veneer on underlying grus, and there was a marked tendency for them to join downslope like tributaries.

ORIGIN

The absence of cracks in the sorted stripes described above eliminates the possibility hat the stripes originated by accumulation of stones in pre-existing cracks as held, for instance, by Chambers (1967, p. 5—7, 11), Furrer (1954, p. 235—239, 241—243, 252), Gradwell (1957, p. 795, 799—806), and Klatka (1961, p. 311—319) for occurrences elsewhere. Differential mass-wasting, discussed later in connection with large sorted stripes, does not seem applicable, especially for the Korsbjerg forms with their dendritic pattern.

A number of workers have stressed rillwork, operating alone or in conjunction with contraction cracking or frost heaving, as the origin of sorted stripes, especially small ones (*cf.* Washburn, 1956, p. 857—858; Czeppe, 1965, p. 144—146; fig. 6, p. 147). Rillwork with stones washing into rills and/or finer material becoming eluviated and leaving a lag concentrate, would seem to be an adequate explanation for both the Hesteskoen and the Korsbjerg forms. Lliboutry (1961, p. 216—219; 1965, p. 994) in particular has stressed the importance of eluviation. At the Hesteskoen locality, although the concentrations of coarse grus around some stones may be due to granular disintegration of the stones, there were places where differences in lithology eliminated this possibility and where eluviation of finer material is a logical alternative. The downslope extension of coarse grus from these and other places where threads of water are likely to be concentrated very probably reflects the joint effect of rillwork and mass-wasting on the slope. At the Korsbjerg locality, the dendritic nature of the stony stripes strongly suggests the prodominating influence of rillwork in their origin.

Meltwater from snow is probably the main moisture source for rillwork in both localities. However, thaw furrows in snow, which may constitute a critical factor in establishing rill patterns beneath the snow and thereby initiate sorted stripes in some nonpermafrost environments (Flohr, 1935; Lliboutry, 1955; 1961, p. 217), are unlikely to be significant in the origin of the Mesters Vig stripes. Thaw furrows were not observed in the spring and only once in the autumn, and because of permafrost any meltwater within the snow commonly refreezes upon contact with the ground beneath as shown by the widespread development of basal ice in the spring. Except where lines of drainage originate in bare patches upslope, this protective effect of snow cover is general in the Mesters Vig district. It has also been reported elsewhere in Northeast Greenland (Poser, 1932, p. 22—24), although a case where ground 0.4 m back from the edge of snow had thawed to a depth of 6 cm has been recorded (Müller, 1954, fig. 55, p. 131).

LARGE SORTED STRIPES

HESTESKOEN

Large sorted stripes were particularly prominent on the north side of the east-west ridge of Hesteskoen where this ridge curves to join the northwest-southeast summit ridge. The stripes headed just below the crest of the east-west ridge and extended some 120 m downslope on a gradient of 20—22°. The slope was largely bare of vegetation.

The pattern comprised stripes of light-colored conglomeratic sandstone debris separated by stripes of dark trap debris (pl. 22). The sandstone debris was from the local bedrock, and formed sandy_{19} gravel_{80}. The trap fragments were from a disintegrating dike at the ridge crest and formed angular gravel consisting mainly of pebbles and cobbles. The stripes were thus sorted according to lithology as well as grain size. The lithologic sorting was impressive but not complete, for sandstone pebbles and cobbles were mixed in with the trap debris. Both the trap debris and sandstone debris decreased in grain size with depth and distance downslope.

Near the top of the slope the trap stripes commonly merged into trap rubble derived from a disintegrating trap dike at the ridge crest; in one place where the gradient decreased from 20° to 17°, they merged into some of the debris islands discussed previously. Where the trap stripes became clearly developed their width was about 1 m and that of the sandstone stripes was but a few centimeters. From here the trap stripes gradually narrowed downslope and the sandstone stripes broadened as the amount of trap debris became less, until the sandstone stripes merged into a general cover of sandstone debris. Traced downslope the trap stripes tended to become tributary to each other at very acute angles, some stripes running for 50 m or so between junctions and being traceable for the entire 120-m extent of the striped area; other stripes could be traced for a few meters only. Some trap stripes terminated downslope in small lobate fronts up to about 10 cm high, indicating that the rate of movement of the trap stripes here was greater than that of the sandstone debris in that more trap fragments reached this point than could be carried away from it by the mass-wasting of the sandstone debris cover. Sandy material was prominent some 10 cm beneath the surface of the lobes.

Large sorted stripes were also noted in several places on the east side of Hesteskoen below the break in slope at about 750 m, above which the steep upper slope begins. Seepage from coarse rubble on the upper slope and from lingering snowdrifts associated with benches kept much of the sector below the break in slope saturated until late in the thaw season. The stripes, which in general were much less regular and continuous than those in the east—west ridge locality, were in this relatively low-gradient sector; in the gentlest parts they merged into sorted nets. The pattern comprised stony stripes, characterized by cobbles and boulders, alternating with stripes of till-like gelifluction debris. The width of the stony stripes was estimated to range from 0.3 to 1.0 m, and that of the till-like stripes from 1—3 m. Commonly some vegetation was present on the till-like debris but a few places were completely bare. The stony stripes served as channels and carried considerable drainage, as indicated by melting snow being colored by silt at the lower end of some stripes, by water accumulating downslope from others, and by the sound of trickling water beneath the stones.

MYGGESØ

Surface morphology

Sorted stripes occurred in profusion on the west side and at the north end of Myggesø (pl. 23) where they were associated with the sorted nets previously described. The stripes were concentrated where lingering snowdrifts provided abundant moisture, and in general were confined to gradients of 3° and steeper. Many stripes were at the Myggesø shore and headed in sorted nets on a gentler gradient farther up the slope, but many others occurred independently. The stony stripes were characterized by cobbles and boulders. The accompanying stripes of finer material showed, in the top 5 cm, clayey-gravelly-silty sand with 21—34 percent fines; a sample of the fine facies from a depth of about 50 cm showed gravelly sand with 19 percent fines. The materials were in all respects like those the sorted nets, and vegetation conditions were similar. There was considerable variation in length. Where the patterns were best developed, the width of the stony stripes was 25—100 cm and that of the finer stripes, 50—500 cm. The surfaces of some stony stripes were lower, and of others higher, than those of the adjacent finer stripes. The stripes were thus much less regular than the stripes on the east-west ridge of Hesteskoen and, in both appearance and materials, more like those on the east side of Hesteskoen.

Subsurface morphology

Excavation 58-8-28 (pl. 24) revealed that the attitude of slabby stones and their decrease in size with depth paralleled the situation in the borders of the sorted nets in the same area. The frost table was at a depth of 24 cm (28 Aug. 1958), and the stripe had almost pinched out at a depth of 33 cm, the maximum depth of the excavation. No water was encountered in the excavation, but dead *Salix* leaves at the frost table had probably been washed in by drainage along the stripe. The frost table in the adjacent $silty_{15}$-$gravelly_{32}$ $sand_{48}$ was at a depth of 53 cm. The surface of the stony stripe was lower than that of the finer stripe but by no more than 15 cm. Since the frost table in the stony stripe was at 24 cm, it was not only higher with respect to the thickness of overlying material but also with respect to the level of the frost table in the finer stripe.

In two parallel trenches across a stony stripe some 50 m away, there was water at a depth of 12 cm and the stripe pinched out at a depth of 20 cm. The frost table in the stony stripe was 0.5 cm shallower than in the adjacent finer stripe, where its depth was 28 cm. The date of excavation was the same as for excavation 58—8—28, the debris was similar, and the shallower depth to the frost table was probably due to later exposure from snow. The surface of the stony stripe was at the same level as that of the finer stripe, and in places slightly higher, so that the frost table beneath the stony stripe was again at a higher level than in the finer stripe. This difference in level late in the thaw season corresponds to the situation in the stony borders of nets in the same area and in the vicinity of ES 1, 11—12.

NYHAVN HILLS

Large sorted stripes were also studied at the south edge of the Nyhavn hills. The gradient in the striped area ranged from 5° to 14°. The pattern comprised stony stripes, characterized by sandstone rubble but containing a few erratics, alternating with less stony areas. The latter were vegetated in most places but occasional bare spots with edgewise stones attested to effective frost action, particularly downslope from a lingering snowdrift near the top of the slope. The sandstone rubble, much of it carrying lichens, was slabby to blocky; cobble-to-boulder sizes predominated and individual blocks were up to 1 m in diameter. Lithologically it was similar to the bedrock underlying the trap. The stony stripes ranged from less than one up to about 5 m wide, and the inter-stripe areas were commonly several times wider than the adjacent stony stripes. Some stony stripes were up to 90 m long. In places their surface was somewhat above the adjacent surface, in others somewhat below, the difference in relief being up to 50 cm. Along one prominent stony stripe, where this variation was particularly noted, the low surface was in the upslope sector, and the high surface in the downslope sector, of the stripe.

Near the top of the slope, sandstone bedrock, exposed below a low trap cliff, showed several sets of joints including a nearly vertical set with a strike ranging from 150° to 178°. The trend of the stripes was about 170°. This coincidence in trend, and the fact that some stony stripes terminated abruptly next to where another stripe began, strongly suggest that the stony stripes were controlled by jointing in the underlying bedrock.

ORIGIN

Frost wedging along bedrock joints

Frost wedging and heaving along nearly vertical bedrock joints probably explains the stony stripes of the large sorted pattern in the Nyhavn hills locality. This explanation is supported by (1) coincidence in trend of joints and stripes, (2) offsetting of stripes, (3) blocky nature of the material and the fact that some blocks showed joints parallel to the stripes, (4) unusually massive and irregular appearance of the stripes compared to most in the Mesters Vig district. The role of joints in relation to stripes was stressed by Kunský and Louček (1956, p. 345—347) who argued for accumulation of stones in weathered joints. Frost wedging and heaving of blocks along joints has produced polygons (Davies, 1961b; Washburn, 1950, p. 47—49) or has been associated with polygons (Müller, 1954, p. 109—110) elsewhere, and would seem to be capable of producing stripes as well. Meltwater from the snowdrift that accumulated upslope from the Nyhavn hills stripes would promote frost wedging and heaving by seeping into the joints. Possibly the eluviation of fines from along the upslope stretch of a stony stripe and their accumulation farther downslope where they would favor further heaving would help to explain the relief difference in these places that was noted in the stony stripes.

Mass displacement and gelifluction

Several investigators, including Poser (1933, p. 117) have argued that some sorted stripes form by a simple stretching out of sorted nets by solifluction where the gradient steepens. Others, including Sørensen (1935, p. 19, 31), have countered that mass--wasting would destroy pre-existing sorted patterns unless a sorting process continued to operate on the steeper gradient.

Although some sorted stripes on the east slope of Hesteskoen and at Myggesø are clearly transitional to nets, many at Myggesø showed no such relationship to higher-lying nets, and these stripes must be due to a sorting process on the slope. Because of this and their similarity to the nets in all respect save pattern, these stripes almost certainly originated by the same process as the nets but with the addition of gelifluction as an essential genetic factor responsible for the striped pattern. It follows that the stripes downslope from sorted nets probably also originated in the same way. As previously discussed the nets appear to have originated by an upward mass displacement of finer material into coarser, perhaps as a result of moisture-controlled changes in intergranular pressure. There is no apparent reason why upward mass displacements should not occur on slopes as well as on very low-angle gradients, whatever the origin of the displacements.

Differential mass-wasting

The sorted stripes of the east-west ridge of Hesteskoen differed from those discussed above in being remarkably straight and continuous and in having some litholigic sorting accompanying the size sorting. Sorting by frost action as the basic origin of the stripes is discounted because the trap fragments of the coarse stripes were derived from disintegrating bedrock upslope rather than from adjacent material. Rillwork (*cf.* discussion under Small Sorted Stripes) is eliminated by this general absence of trap fragments in

GENETIC GROUPING OF PATTERNED GROUND IN THE MESTERS VIG DISTRICT

	Desiccation cracking (combined with sorting process(es) for sorted forms)	Frost cracking (combined with sorting process(es) for sorted forms)	Dilatation cracking	Sedimentation	Mass displacement (combined with gelifluction for stripes)	Rillwork	Differential mass-wasting	Frost wedging along bedrock joints
Experimental sites 1, 11—12, and vicinity	Small nonsorted		Small nonsorted polygons		Large sported nets			
Experimental sites 3, 9, and vicinity	Small nonsorted polygons			Nonsorted circles and related forms	Nonsorted circles and related forms			
Experimental site 4 vicinity	Small nonsorted polygons							
Experimental site 5 vicinity	Small nonsorted polygons				Turf hummocks			
Experimental site 6					Turf hummocks (in part. cf. R a u p, 1964)			
Experimental site 8 vicinity	Small nonsorted polygons (below ES 8)							
Experimental site 20 and vicinity		Large nonsorted polygons						
Danevirke hills	Small nonsorted stripes (base trap knob MS 105 m)	Large nonsorted polygons			Debris islands (base trap knob MS 171 m)			
Emerged delta remnants	Small nonsorted polygons		Small nonsorted polygons (Tunnelv NW distributary)			Small nonsorted stripes (W of Tunnelv)		
Gefionelv vicinity		Large nonsorted polygons						
Hesteskoen					Debris islands (summit ridges) large sorted nets and stripes (E slope)	Small sorted stripes near trap knob MS 180 m)	Large sorted stripes (E—W ridge)	
Korsbjerg massif	Small nonsorted polygons and small sported nets and polygons (MS 910 m)	Large sorted polygons (bench at alt. 469 m)				Small sorted stripes (near Thyres Spids)		
Myggesø and vicinity		Large nonsorted polygons and stripes (0.7 km NE of Myggesø)			Large sorted nets and stripes			
Nyhavn hills	Small nonsorted stripes (basal trap knob MS 181 m)							Large sorted (basal slope trap knob MS 78 m)
Store Blydal	Small nonsorted polygons near (near Rungsted Elv)				Small and large sorted nets (near Rungsted Elv)			

the sandstone debris, since under these conditions eluviation of fine material along rills could not leave a lag concentrate that was sorted with respect to lithology as well as size. Moreover, some of the coarse stripes were unbranched for distances up to 50 m. Fluvial transport of the coarse fragments is eliminated by this unbranched character of the stripes and by the lack of adequate channels. The only alternative mode of downslope transport is mass-wasting, which is clearly active as shown by the unvegetated and generally loose nature of the surface material.

Downslope stringing out by mass-wasting of the debris islands at the head of the slope does not explain the stripes, for the stripes also headed where debris islands were lacking. However, a downslope stringing out of the trap mantle at the base of the disintegrating trap bedrock would produce the observed result if the material of the coarse stripes moved faster than the sandstone debris between them. As previously noted the slightly lobate character of the lower end of the coarse stripes suggests a faster movement of the coarse material than of the adjacent finer material. Several processes could contribute to such differential mass--wasting: (1) Some portions of the disintegrating trap dike are probably weathering faster than others and producing more debris, which would tend to string out below such places. However, a coincidence between trap stripes and such debris production was not actually established. (2) Drainage would tend to become concentrated in an initial stripelike accumulation of coarse debris, and by disturbing underlying finer material would tend to hasten the downslope movement of the coarse debris. Such piecemeal transport would be more closely akin to mass-wasting than rillwork. (3) The greater weight and size of any coarse surface debris that was disturbed by mass-wasting of any kind, or by freezing and thawing of adjacent and underlying finer material, would favor differential movement downslope, since the coarse debris would be less likely to be stopped by small unevennesses of the surface. Furthermore, any sorting effects of frost action in the stripes, for instance by the work of needle ice (Gradwell, 1957; Hay, 1936) and by differential heaving (Caine, 1963), would help to preserve and emphasize the sorting of the coarse stripes.

More rapid movement of coarse than fine material was noted in some small stony stripes on Mt. Washington, New Hampshire, by Antevs (1932), who suggested expansion and contraction of adjacent clay stripes as the cause. Although clay was lacking at the surface of the Hesteskoen locality, freezing and thawing of other material may have a similar effect as just mentioned. The faster creep of small stone streams than of adjacent finer material has been reported (Washburn, 1947, p. 87—88) as has that of boulders characterized by furrows on their upslope, and ridges on their downslope, sides (Högbom, 1914, p. 350—351; 1926, p. 260; J. Lundqvist, 1962, p. 51; Pissart, 1964b, p. 306—308; and others). Similar occurrences were noted in the Mesters Vig district. Taber, (1943, p. 1460) argued that in creep coarse debris can move faster than fine debris, not only because of overturning or rolling of stones but also because coarse material would be less impeded, since cohesion increases with surface area and the finer the particles the greater their total surface area. Moisture content would be critical, and seasonal desiccation of fines might well lead to a reversal in movement rate as between coarse stripes and intervening finer debris (Lliboutry, 1965, p. 993—994). In many places in the Mesters Vig district the predominance of saturated flow is obvious and clearly involves a more rapid movement of silty than coarser material. Where coarse material is moving faster than fine, creep may be the predominant process.

In summary, the sorted stripes of the east-west ridge of Hesteskoen are interpretated as mass-wasting phenomena. The sorting of material according to size and lithology is believed to be mainly due to the surface material of the coarse stripes moving faster than the intervening sandstone debris, probably largely by creep. A sorting process such as that involved in the origin of the sorted stripes on the east slope of Hesteskoen and at Myggesø is not ruled out; there, however, gelifluction rather than creep appeared dominant and it was the finer material rather than the stony stripes that seemed to be subject to the fastest movement. The writer recognizes the danger of interpreting similar phenomena in different ways, but the danger of interpreting dissimilar phenomena in the same way is equally great, and the stripes of the east-west ridge of Hesteskoen showed some marked differences from those of the other localities.

THE POLYGENETIC ORIGIN OF PATTERNED GROUND

Patterned ground as a whole includes many dissimilar forms and is obviously of polygenetic origin. Even the origin of many similar forms is still too speculative to discard a purely descriptive approach such as the one in this report. However, as a result of this approach it is possible to suggest a genetic grouping of the forms observed in the Mesters Vig district. This has been done in table I which is arranged according to the essential originating process and, for ease of reference, according to location of the forms. No attempt has been made to list contributory processes for a given occurrence, despite the fact they may be essential elsewhere and/or include such widespread and important processes as, for instance, *in-situ* weathering, eluviation of fines from stony accumulations, heaving and horizontal and vertical sorting (in Corte's sense).

The grouping summarizes the writer's conclusions regarding the origin of the Mesters Vig forms he observed and shows that in his opinion the basic processes are (1) desiccation cracking for most small nonsorted polygons, some small nonsorted stripes, and, in combination with one or more sorting processes, for the small sorted polygons; (2) frost cracking for the large nonsorted polygons, the large nonsorted stripes, and, in combination with one or more sorting processes, for the large sorted polygons; (3) dilation cracking for some small nonsorted polygons; (4) sedimentation for some nonsorted circles and related forms; (5) mass displacement (perhaps due to moisture-controlled changes in intergranular pressure) for most nonsorted circles and related forms, the debris islands, the large sorted nets, some turf hummocks (in part), and, in combination with gelifluction, for most large sorted stripes; (6) rillwork for some small nonsorted stripes and the small sorted stripes; (7) differential mass-wasting for some large sorted stripes; (3) frost wedging (and frost heaving) for some other large sorted stripes.

Further research may well modify some of the conclusions, but the Mesters Vig observations strongly support the polygenetic origin of many similar, as well as dissimilar, forms of patterned ground.

References cited

Antevs, Ernest, 1932 — Alpine zone of Mt. Washington Range. Auburn, Maine, Merrill & Webber Company; 118 p.

Beskow, Gunnar, 1935 — Tjälbildningen och Tjällyftningen (Soil freezing and frost heaving). *Sveriges Geol. Undersökning,* Årsbok 26 (1932), no. 3 (Avh. och uppsatser, ser. C, no. 375); 242 p.

Beskow, Gunnar, 1947 — Soil freezing and frost heaving with special application to roads and railroads (Translated by J. O. Osterberg). Northwestern Univ., Technol. Inst.; 145 p.

Black, R. F., 1952 — Polygonal patterns and ground conditions from aerial photographs. *Photogrammetrical Eng.*, v. 18; p. 123—134.

Boyé, Marc, 1950 — Glaciaire et périglaciaire de l'Ata Sund nord-oriental, Groenland. *Expéditions Polaires Françaises* 1: Paris, Hermann & Cie, Actualites Scientifiques et Industrielles 1111; 176 p.

Bremer, Hanna, 1965 — Musterböden in tropisch-subtropischen Gebieten und Frostmusterböden. *Zeitschr. f. Geomorphologie*, N. F., Bd. 9; p. 222—236.

Brown, Jerry, 1966 — Soils of the Okpilak River region, Alaska. *U. S. Army Cold Regions Research and Engineering Laboratory Research Rept.* 188; 49 p.

Büdel, Julius, 1960 — Die Frostschutt-Zone Südost Spitzbergens. *Colloqium Geographicum*, v. 6; 105 p.

Büdel, Julius, 1961 — Die Abtragungsvorgänge auf Spitzbergen im Umkreis der Barentsinsel. *Deutscher Geographentag Köln, Tagungsbericht und wissenschaftliche Abhandlungen;* Wiesbaden, Franz Steiner Verlag GMBH; p. 337—375.

Caine, T. N., 1963 — The origin of sorted stripes in The Lake District, northern England. *Geog. Annaler*, v. 45; p. 172—179.

Chambers, M. J. G., 1967 — Investigations of patterned ground at Signy Island, South Orkney Islands: III. Miniature patterns, frost heaving and general conclusions. *British Antarctic Survey, Bull.* 12; p. 1—22.

Church, R. E., Péwé, T. L., and Andresen, J. J., 1965 — Origin and environmental significance of large-scale patterned ground, Donelly Dome area, Alaska. *U. S. Army Cold Regions Research and Engineering Laboratory Research Rept.* 159; 71 p.

Corte, A. E., 1961 — The frost behavior of soils: laboratory and field data for a new concept, part I: Vertical sorting. *U. S. Army Cold Regions Research and Engineering Laboratory Research Rept.* 85, pt. 1; 22 p.

Corte, A. E., 1962a — Vertical migration of particles in front of a moving freezing plane. *Jour. Geophys. Research*, v. 67, no. 3; p. 1085—1090.

Corte, A. E., 1962b — Relationship between four ground patterns, structure of the active layer, and type and distribution of ice in the permafrost. *U. S. Army Cold Regions Research and Engineering Laboratory Research Rept.* 88; 79 p.

Corte, A. E., 1962c — The frost behavior of soils: laboratory and field data for a new concept, part II: Horizontal sorting. *U. S. Army Cold Regions Research and Engineering Laboratory Research Rept.* 85, pt. 2; 20 p.

Corte, A. E., 1962d — The frost behavior of soils, part II: Horizontal sorting. *Natl. Acad. Sci.-Natl. Research Council Highway Research Board Bull.* 331; p. 46—66.

Corte, A. E., 1963a — Vertical migration of particles in front of a moving freezing plane. *U. S. Army Cold Regions Research and Engineering Laboratory Research Rept.* 105; 8 p.

Corte, A. E., 1963b — Particle sorting by repeated freezing and thawing. *Science*, v. 142; p. 499—501.

Corte, A. E., and Higashi, Akira, 1964 — Experimental research on desiccation cracks in soil. *U. S. Army Cold Regions Research and Engineering Laboratory Research Rept.* 66; 72 p.

Costin, A. B., 1955 — A note on gilgaies and frost soils. *Jour. Soil Sci.*, v. 6; p. 32—34.

Czeppe, Zdzisław, 1965 — Activity of running water in south-western Spitsbergen. *Geographia Polonica*, v. 6; p. 141—150.

Davies, W. E., 1961a — Surface features of permafrost in arid areas. *Folia Geog. Danica*, v. 9; p. 48—56. (19th Internat. Geog. Cong., Norden 1960, Symposium SD 2; Physical geography of Greenland).

Davies, W. E., 1961b — Polygonal features on bedrock, North Greenland. *U. S. Geol. Survey Prof. Paper* 424-D, art. 336; p. D-218-D-219.

Douglas, L. A., and Tedrow, J. C. F., 1961 — Tundra soils of northern Alaska. *Internat. Cong. Soil Science (Comm. V), 7th, Madison. Wisc. 1960, Trans.*, v. 4; p. 291—304.

Dow, W. G., 1964 — The effect of salinity on the formation of mud-cracks. *The Compass of Sigma Gamma Epsilon*, v. 41; p. 162—166.

Dżułyński, S., 1963 — Polygonal structures in experiments and their bearing upon some periglacial phenomena. *Bull. Acad. polonaise sci.*, Sér. sci. géol. et géog., v. 11, no. 3; p. 145—150.

Ellis, J. H., and Shafer, Wm., 1928 — The nitrogen content of Red River Valley soils. *Sci. Agriculture*, v. 9; p. 231—248.

Elton, C. S., 1927 — The nature and origin of soil-polygons in Spitsbergen. *Geol. Soc. London, Quart. Jour.*, v. 83; p. 163—194.

Enzmann, R. D., 1960 — Morphology of frost polygons as related to ground slope in eastern Greenland. *Iowa Acad. Sci. Proc.*, v. 67; p. 357—361.

Flint, R. F., Sanders, J. E., and Rodgers, John, 1960a — Symmictite: a name for nonsorted terrigenous sedimentary rocks that contain a wide range of particle sizes. *Geol. Soc. America Bull.*, v. 71; p. 507—509.

Flint, R. F., Sanders, J. E., and Rodgers, John, 1960b, — Diamictite, a substitute term for symmictite. *Geol. Soc. America Bull.*, v. 71; p. 1809.

Flohr, E. F., 1935 — Beobachtungen über die Bahnen der Schneeschmelzwässer im Riesengebirge. Ein Beitrag zum Problem der Blockrinnen ("Steinstreifen"). *Gesell. Erdkunde Berlin Zeitschr.*, 1935; p. 353—369.

Frödin, John., 1918 — Über das Verhältnis zwischen Vegetation und Erdfliessen in den alpinen Regionen des schwedischen Lappland. *Lunds Univ. Arssk.*, N. F. Avd. 2, v. 14, no. 24; 30 p.

Furrer, Gerhard, 1954 — Solifluktionsformen im schweizerischen Nationalpark. *Schweizer. naturf. Gesell. Ergebnisse der wissenschaftlichen*

Untersuchungen des schweizerischen Nationalparks, v. 4 (Neue Folge), no. 29; p. 201—275.

Grandwell, M. W., 1957 — Patterned ground at a high-country station. *New Zealand Jour. Sci. and Technology*, v. 38, sec. B; p. 793—806.

Gripp, Karl, 1927 — Beiträge zur Geologie von Spitzbergen. *Naturw. Ver. Hamburg Abh.*, v. 21, no. 3—4; p. 1—38.

Hallsworth, E. G., Robertson, G. K., and Gibbons, R. F., 1955 — Studies in pedogenesis in New South Wales. VII. The "gilgai" soils. *Jour. Soil. Sci.*, v. 6; p. 1—31.

Hamilton, A. B., 1966 — Freezing shrinkage in compacted clays. *Canadian Geotechnical Jour.*, v. 3; p. 1—17.

Hay, Thomas, 1936 — Stone stripes. *Geog. Jour.*, v. 87; p. 47—50.

Högbom, Bertil, 1914 — Über die geologische Bedeutung des Frostes. *Uppsala Univ., Geol. Inst. Bull.*, v. 12 (1913—14); p. 257—389.

Högbom, Bertil, 1926 — Beobachtungen aus Nordschweden über den Frost als geologischer Faktor. *Uppsala Univ., Geol. Inst. Bull.*, v. 20 (1925—1927); p. 243—280.

Holmes, C. D., and Colten, R. B., 1960 — Patterned ground near Dundas (Thule Air Force Base), Greenland. *Medd. om Grønland*, v. 158, no. 6; 14 p.

Hopkins, D. M., and Sigafoos, R. S., 1951 — Frost action and vegetation patterns on Seward Peninsula, Alaska. *U. S. Geol. Survey Bull.* 974-C; p. 51—100.

Hopkins, D. M., and others, 1955 — Permafrost and ground water in Alaska. *U. S. Geol. Survey Prof. Paper* 264-F; p. 113—146.

Howell, J. V., chm., 1960 — Glossary of geology and related sciences. 2d ed., Washington, D. C., Am. Geol. Inst.; 325 p. (with supplement).

Hunt, C. B., and Washburn, A. L., 1966 — Patterned ground, p. B104—B133, *in*: Hunt, C. B., and others: Hydrologic basin, Death Valley, California. *U. S. Geol. Survey Prof. Paper* 494-B; 138 p.

Jüngst, H., 1934 — Zur geologischen Bedeutung der Synärese. *Geol. Rundschau*, v. 25; p. 312—325.

Kindle, E. M., 1917 — Some factors affecting the development of mud-cracks. *Jour. Geology*, v. 25; p. 135—144.

Klatka, Tadeusz, 1961 — Problèmes des sols striés de la partie septentrionale de la presqu'île de Sörkapp (Spitzbergen). *Biuletyn Peryglacjalny*, no. 10; p. 291—320.

Kunský, J., and Louček, D., 1956 — Stone stripes and thufurs in the Krkonoše. *Biuletyn Peryglacjalny*, no. 4; p. 345—349.

Lachenbruch, A. H., 1960 — Contraction-crack polygons. *U. S. Geol. Survey Prof. Paper* 400-B; p. B403—B409.

Lachenbruch, A. H., 1961 — Depth and spacing of tension cracks. *Jour. Geophys. Research*, v. 66, no. 12; p. 4273—4292.

Lachenbruch, A. H., 1962 — Mechanics of thermal contraction cracks and ice-wedge polygons in permafrost. *Geol. Soc. America Spec. Papers*, no. 70; 69 p.

Lachenbruch, A. H., 1966 — Contraction theory of ice wedge polygons: A qualitative discussion, p. 63—71, *in*: Permafrost International Conference (Lafayette, Ind., 11—15 Nov. 1963) proceedings. *Natl. Acad. Sci.-Natl. Research Council pub.* 1287 (1966); 563 p.

Lliboutry, Louis, 1955 — L'origine des sols striés et polygonaux des Andes de Santiago (Chili). *Acad. sci. (Paris), Comptes rendus*, v. 240; p. 1793—1794.

Lliboutry, Louis, 1961 — Phénomènes cryonivaux dans les Andes de Santiago (Chili): *Biuletyn Peryglacjalny*, no. 10; p. 209—224 (Polish summary, p. 371—372; Russian summary, p. 425—426).

Lliboutry, Louis, 1965 — Traité de glaciologie, v. 2 (Glaciers — variations du climat — sols gelés). Paris, Masson & Cie.; 612 p. (p. 429—1040).

Longwell, C. R., 1928 — Three common types of desert mud-cracks. *Am. Jour. Sci.*, 5th ser., v. 15; p. 136—145.

Lundqvist, Jan, 1962 — Patterned ground and related frost phenomena in Sweden. *Sveriges Geol. Undersökning Årsbok* 55 (1961), no. 7 (Avh. och uppsatser, ser. 6, no. 583); 101 p.

Mackay, J. R., 1953 — Fissures and mud circles on Cornwallis Island, N.W.T. *The Canadian Geographer*, no. 3; p. 31—37.

Mackay, J. R., 1958 — A subsurface organic layer associated with permafrost in the Western Arctic. *Canada Dept. Mines and Tech. Surveys, Geog. Br. Bull.*, no. 18; 21 p.

Mackay, J. R., Mathews, W. H., and MacNeish, R. S., 1961 — Geology of the Engigstciak archeological site, Yukon Territory. *Arctic*, v. 14; p. 25—53.

Meinardus, Wilh., 1912a — Beobachtungen über Detritussortierung und Strukturboden auf Spitzbergen. *Gesell. Erdkunde Berlin, Zeitschr.*, 1912; p. 250—259.

Meinardus, Wilh., 1912b — Über einige charakteristische Bodenformen auf Spitzbergen. *Naturh. Ver. preussischen Rheinlande u. Westfalens, Medizinisch-naturw. Gesell. Münster Sitzungsber.*, Sitzung 26 Feb. 1912; p. 1—42.

Mortensen, Hans, 1932 — Über die physikalische Möglichkeit der "Brodel"-Hypothese. *Centralbl. Mineralog.*, v. 1932, Abt. B; p. 417—422.

Müller, Fritz, 1954 — Frostbodenerscheinungen in NE- und N-Groenland. Zürich Univ., Philos. Fakultät II, Diplomarbeit für das Höhere Lehramt in Geographie; 221 p. (thesis).

Neal, J. T., 1966 — Polygonal sandstone features in Boundary Butte anticline area, San Juan County, Utah. Discussion. *Geol. Soc. America Bull.*, v. 77; p. 1327—1329.

N i e l a n d, Hans, 1930 — Über Erscheinungen des Bodenfrostes und Auftaubodens in Westgrönland. *Zeitschr. Gletscherkunde*, v. 18; p. 346—351.

P a t a l e e v, A. V., 1955 — Morozoboinye treshchiny v gruntakh (Frost fissures in grounds). *Priroda*, v. 44, no. 12; p. 84—85.

P é w é, T. L., 1959 — Sand-wedge polygons (Tesselations) in the McMurdo Sound Region, Antarctica — A progress report. *Am. Jour. Sci.*, v. 257; p. 545—552.

P é w é, T. L., 1966 — Ice-wedges in Alaska — classification, distribution, and climatic significance, p. 76—81, *in*: *Permafrost International Conference* (Lafayette, Ind., 11—15 Nov., 1963) *proceedings*. Natl. Acad. Sci., Natl. Research Council pub. 1287, 1966; 563 p.

P i s s a r t, A., 1964a — Contribution expérimentale à la genèse des sols polygonaux. *Soc. géol. Belgique, Annales*, v. 87 (1963—1964), Bull. 7; p. B214—B223.

P i s s a r t, A., 1964b — Vitesses des mouvements du sol au Chambeyron (Basses Alpes). *Biuletyn Peryglacjalny*, no. 14; p. 303—309.

P i s s a r t, A., 1966 — Expériences et observations à propos de la genèse des sols polygonaux triés. *Rev. Belge Géogr.*, v. 90, pt. 1; p. 55—73.

P o s e r, Hans, 1931 — Beiträge zur Kenntnis der arktischen Bodenformen. *Geol. Rundschau*, v. 22; p. 200—231.

P o s e r, Hans, 1932 — Einige Untersuchungen zur Morphologie Ostgrönlands. *Medd. om Grønland*, v. 94, no. 5; 55 p.

P o s e r, Hans, 1933 — Das Problem des Strukturbodens. *Geol. Rundschau*, v. 24; p. 105—121.

R a u p, H. M., 1965 — The structure and development of turf hummocks in the Mesters Vig district, Northeast Greenland. *Medd. om Grønland*, v. 166, no. 3; 112 p.

S c h e n k, Erwin, 1955a — Die Mechanik der periglazialen Strukturböden. *Hessischen Landesamtes für Bodenforschung Abh.* 13; 92 p.

S c h e n k, Erwin, 1955b — Die periglazialen Strukturbodenbildungen als Folgen der Hydratationsvorgänge im Boden. *Eiszeitalter u. Gegenwart*, v. 6; p. 170—184.

S c h m e r t m a n n, J. H., and T a y l o r, R. S., 1965 — Quantitative data from a patterned ground site over permafrost. *U. S. Army Cold Regions Research and Engineering Laboratory Research Rept.* 96; 76 p.

S e g e r s t r o m, Kenneth, 1950 — Erosion studies at Parícutin, State of Michoacán, Mexico. *U. S. Geol. Survey Bull.* 965-A; p. 1—151.

S h r o c k, R. R., 1948 — Sequence in layered rocks. New York, McGraw-Hill Book Company, Inc.; 507 p.

S m i t h, D. I., 1961 — Operation Hazen — The geomorphology of the Lake Hazen region, N.W.T. *McGill Univ., Geog. Dept. Misc. Papers*, 2; 100 p.

S ø r e n s e n, Thorvald, 1935 — Bodenformen und Planzendecke in Nordostgrönland. *Medd. om Grønland*, v. 93, no. 4; 69 p.

S p r i n g e r, M. E., 1958 — Desert pavement and vesicular layer of some soils of the desert of the Lahontan Basin, Nevada. *Soil., Sci. Soc. America Proc.*, v. 22; p. 63—66.

Steche, Hans, 1933 — Beiträge zur Frage des Strukturböden. *Sächsischen Akad. Wiss. Leipzig, Math.-phys. Kl., Ber.*, v. 85; p. 193—272.

Taber, Stephen, 1929 — Frost heaving. *Jour. Geology*, v. 37; p. 428—461.

Taber, Stephen, 1943 — Perennially frozen ground in Alaska: its origin and history. *Geol. Soc. America Bull.*, v. 54; p. 1433—1458.

Tedrow, J. C. F., 1965 — Concerning genesis of the buried organic matter in tundra soil. *Soil. Sci. Soc. America Proc.*, v. 29, no. 1; p. 89—90.

Tricart, Jean, 1954 — Premiers résultats d'expériences de solifluxion périglaciaire. *Acad. sci.* (Paris), *Comptes rendus*, v. 238; p. 259—261.

Tricart, Jean, 1963 — Géomorphologie des régions froides. Paris, Presses Universitaires de France; 289 p.

Ugolini, F. C., 1965 — The recognition of Arctic Brown Soils in Northeast Greenland. *Arctic*, v. 18; p. 49—51.

Ugolini, F. C., 1966 — Soils of the Mesters Vig district, Northeast Greenland. 2. Exclusive of Arctic Brown and Podzol-like soils. *Medd. om Grønland*, v. 176, no. 2; 25 p.

Washburn, A. L., 1947 — Reconnaissance geology of portions of Victoria Island and adjacent regions, Arctic Canada. *Geol. Soc. America Mem.* 22; 142 p.

Washburn, A. L., 1950 — Patterned ground. *Rev. Canadienne Géographie*, v. 4, no. 3—4; p. 5—59.

Washburn, A. L., 1956 — Classification of patterned ground and review of suggested origins. *Geol. Soc. America Bull.*, v. 67; p. 823—865.

Washburn, A. L., 1965 — Geomorphic and vegetational studies in the Mesters Vig district, Northeast Greenland — General introduction. *Medd. om Grønland*, v. 166, no. 1; 60 p.

Washburn, A. L., 1967 — Instrumental observations of mass-wasting in the Mesters Vig district, Northeast Greenland. *Medd. om Grønland*, v. 166, no. 4; 296 p.

Washburn, A. L., 1968 — Weathering, frost action, and patterned ground in the Mesters Vig district, Northeast Greenland. *Medd. om Grønland*, v. 176; no. 4 (in press).

Washburn, A. L., and Stuiver, Minzi, 1962 — Radiocarbon-dated postglacial delevelling in Northeast Greenland and its implications. *Arctic*, v. 15; p. 66—73.

Washburn, A. L., Sanders, J. E., and Flint, R. F., 1963 — A convenient nomenclature for poorly sorted sediments. *Jour. Sed. Petrology*, v. 33; p. 478—480.

Washburn, A. L., Smith, D. D., and Goddard, R. H., 1963 — Frost cracking in a middle-latitude climate. *Biuletyn Peryglacjalny*, no. 12; p. 175—189.

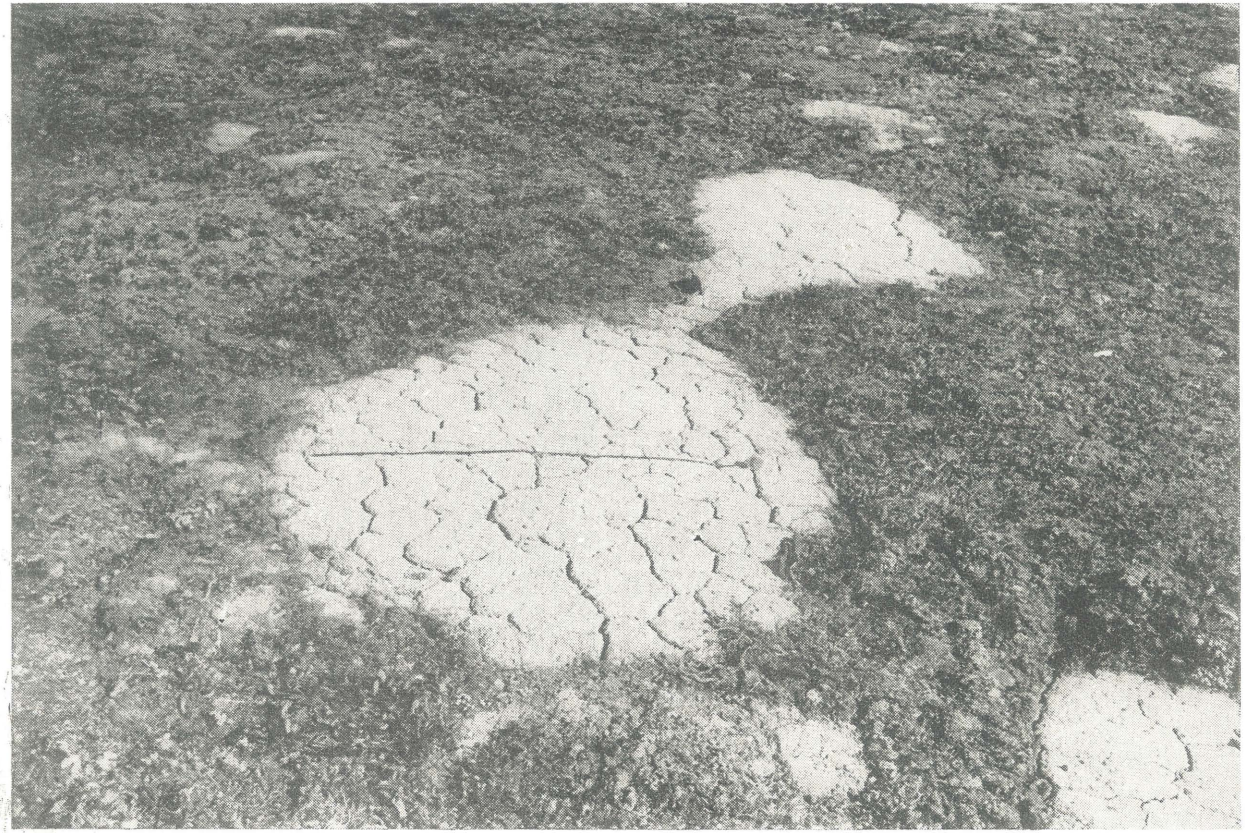
White, W. A., 1961 — Colloid phenomena in sedimentation of argillaceous rocks. *Jour. Sed. Petrology*, v. 31; p. 560—570.

Willden, Ronald, and Mabey, D. R., 1961 — Giant desiccation fissures on the Black Rock and Smoke Creek deserts, Nevada. *Science*, v. 133; p. 1359—1360.

Williams, P. J., 1959 — The development and significance of stony earth circles. *Norske Vidensk.-Akad. Oslo, I.* Mat.-naturv. Kl. 1959, no. 3; 14 p.

Williams, P. J., 1961 — Climatic factors controlling the distribution of certain frozen ground phenomena. *Geografiska Annaler*, v. 43; p. 339—347.

Wollny, E., 1897 — Untersuchungen über die Volumveränderung der Bodenarten. *Forschungen auf dem Gebiete der Agrikultur-Physik*, v. 20 (1897—98); p. 1—52.

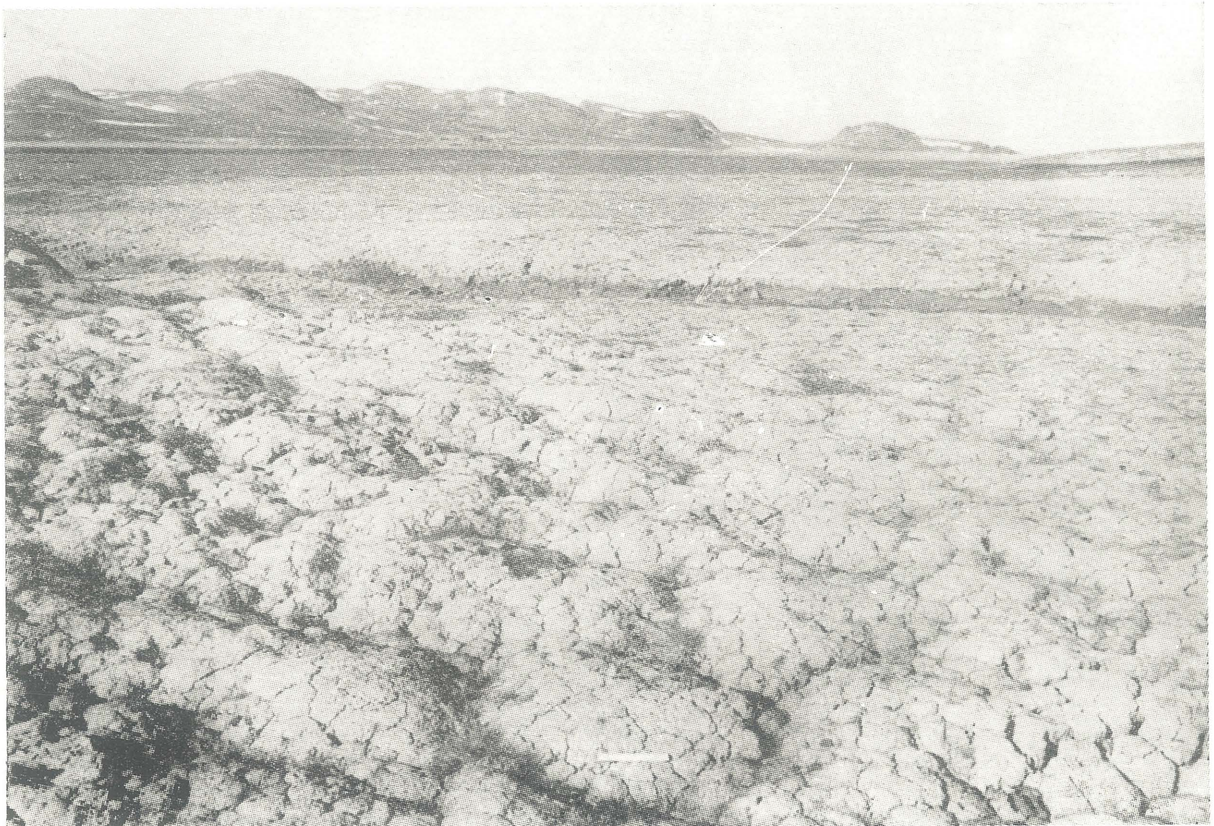


Pl. 1. Nonsorted circles joined by narrow neck. Area of excavation 58-7-19, 12 m east of experimental site 3. View northeast upslope. Scale given by 1-m tape. (19 July 1958)

Pl. 2. Experimental site 3. View southeast. (23 Aug. 1956)

Pl. 3. Nonsorted circles, some 100 m upslope from experimental site 4. View downslope. Scale given by figure. (1 Aug. 1958)

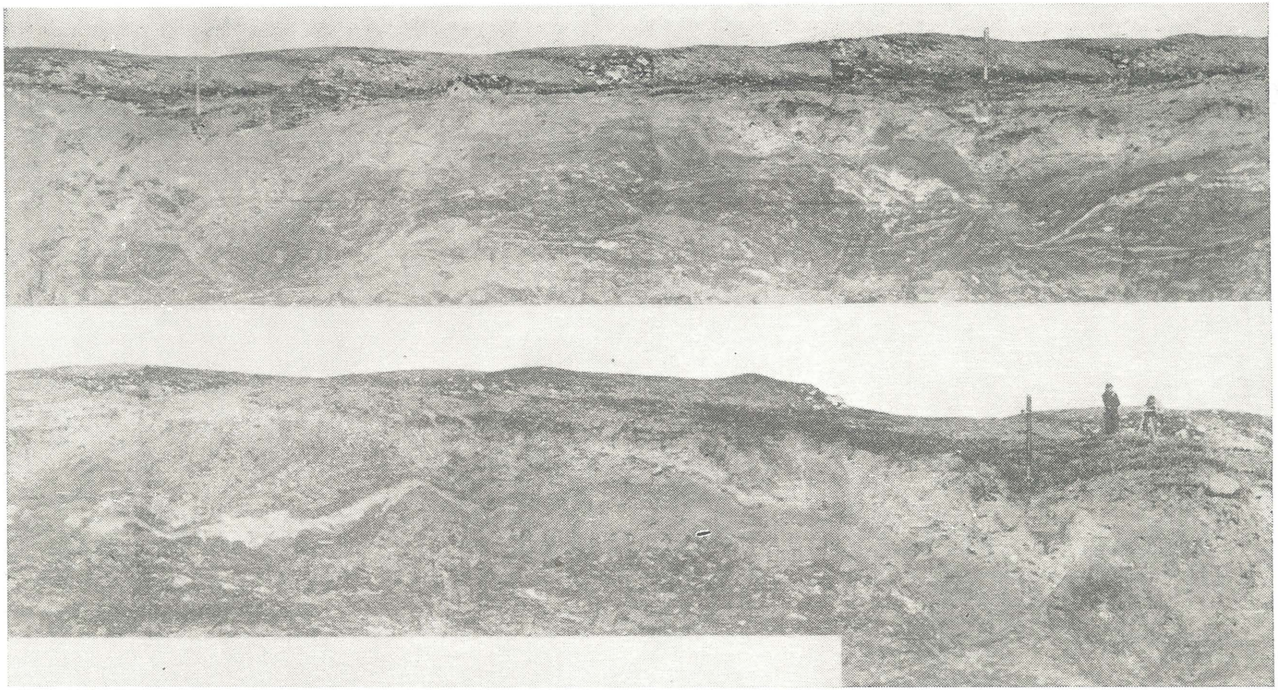
Pl. 4. Small nonsorted polygons outline by radial and concentric cracks in central part of sorted mesh. Vicinity experimental sites 1, 11—12. View downslope. Scale given by 16-cm rule. (1 Aug. 1958)



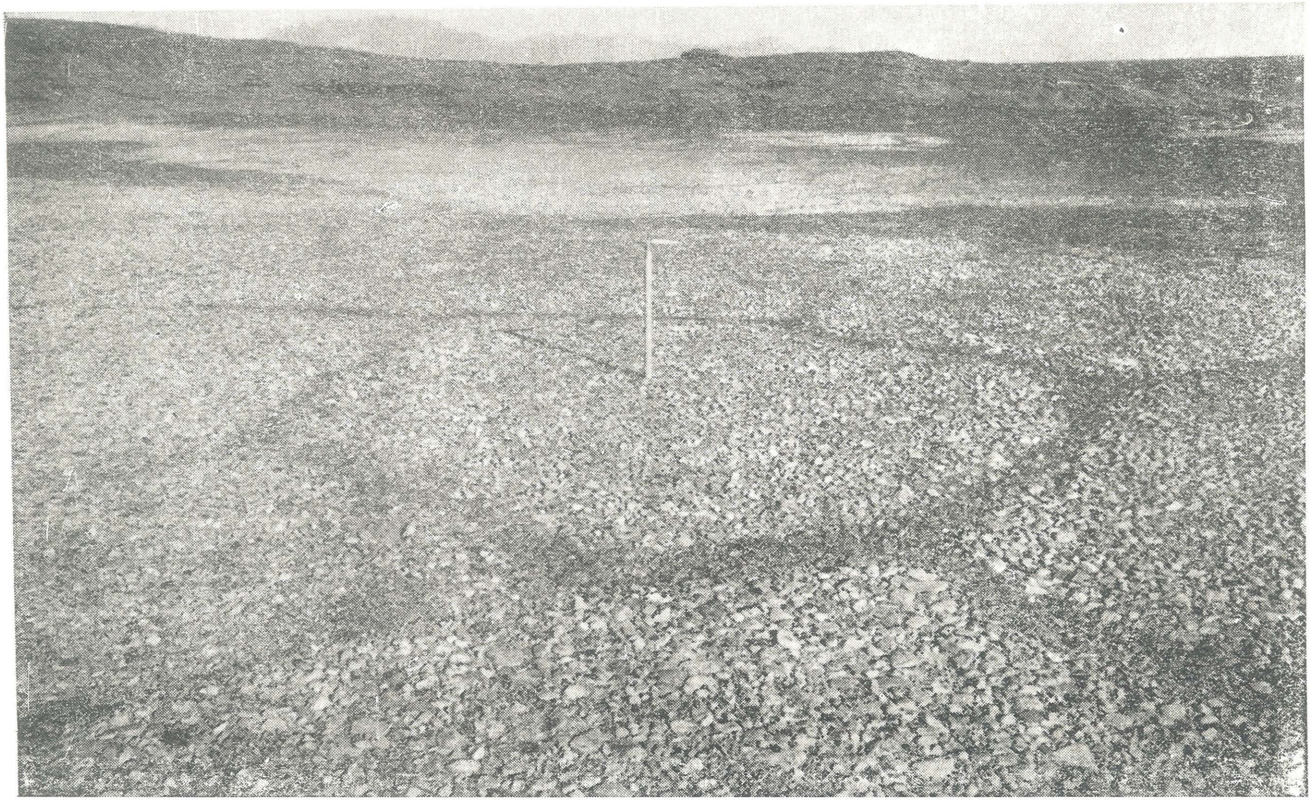
Pl. 5. Compound nonsorted pattern of small polygons within larger. Vicinity experimental site 5. Edge of large boulder in middle ground at extreme left. Scale given by 17-cm rule in center fereground. (30 Aug. 1960)

Pl. 6. Small nonsorted polygons associated with elongate heaved area. Northwest distributary complex of Tunnelelv. View north. Scale given by 17-cm rule. (15 Aug. 1960)

Pl. 7. Large nonsorted polygon, ridge crest just above experimental site 20. View northeast. Excavation 58-8-10 was across northeast half of polygon. Bare area is 6 m in diameter. (10 Aug. 1958)



Pl. 8. Excavation 58-8-10. Panorama of northeast face (slight overlap between sections). Scale given by trench shovels marking interpolygon furrows. (10 Aug. 1958)



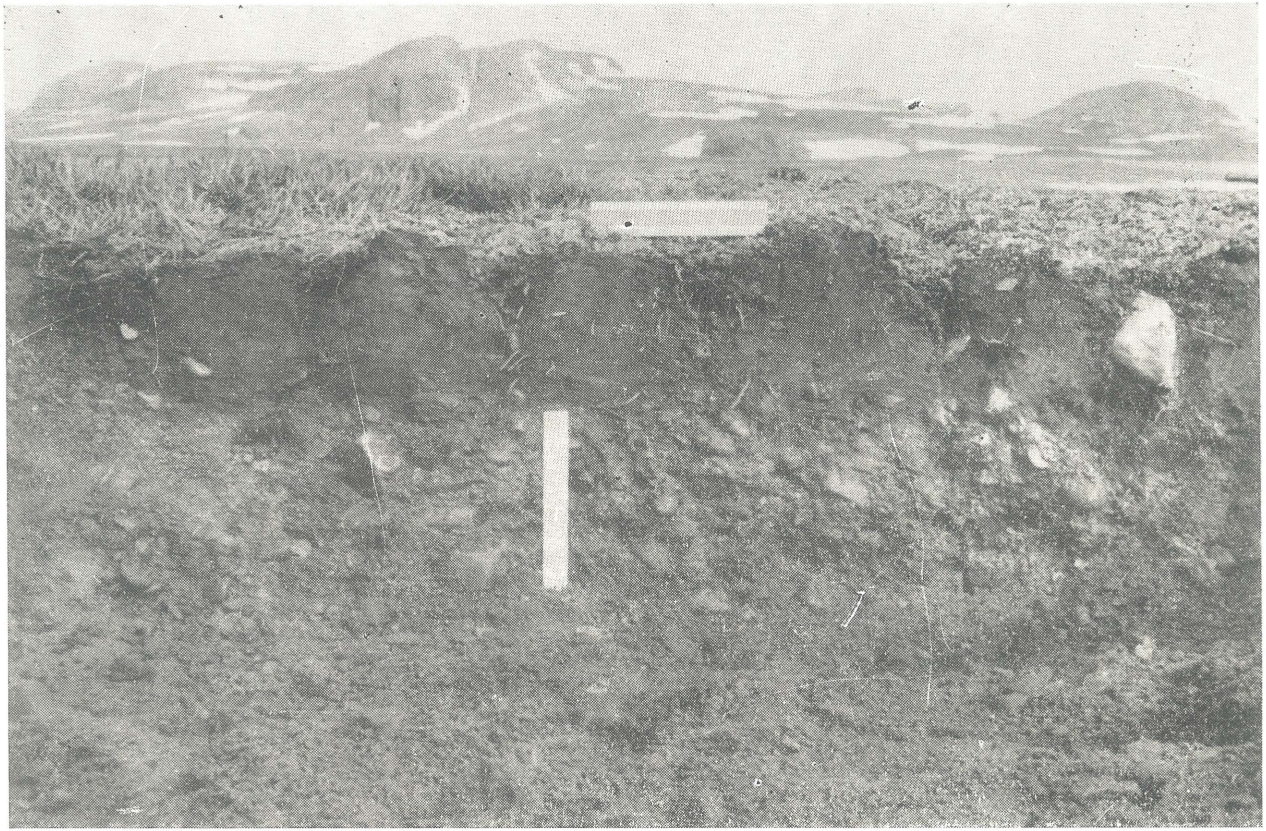
Pl. 9. Large nonsorted polygons in saddle between trap knobs MS 105 m and MS 85 m, Danervirke hills. Polygon marked by ice axe is 3 m in diameter. (20 Aug. 1958)

Pl. 10. Small nonsorted stripes on northwest side of trap knob MS 105 m, Danevirke hills. View upslope. Scale given by 16-cm rule at center. (20 Aug. 1958)

Pl. 11. Small nonsorted stripes on sandy slope of emerged delta remnants immediately west of Tunnelelv. View upslope. Scale given by 17-cm rule. (4 Aug. 1960)

Pl. 12. Debris island on 31° gradient. West side of northwest-southeast summit ridge of Hesteskoen. Scale given by hammer at center. (18 July 1958)

Pl. 13. Debris island with another apparently forming at upper right. North side of east-west ridge of Hesteskoen. Scale given by 16-cm rule in foreground. (18 July 1958)



Pl. 14. Excavation 60-7-23, about 100 m south of excavation 60-7-21B. Scale given by 17-cm rules. (23 July 1960)

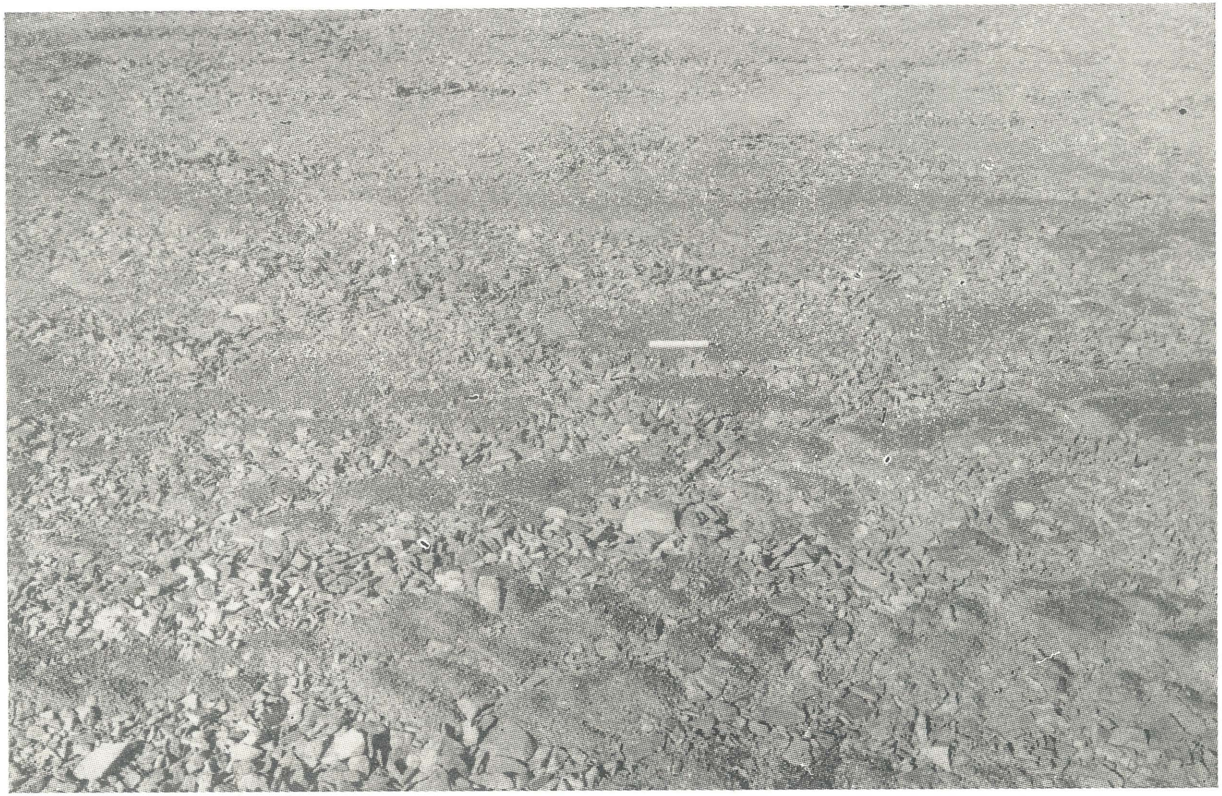
Pl. 15. Polygons adjoining excavation 60-7-23. Vertical view with excavation, 120 cm long, in foreground. (23 July 1960)

Pl. 16. Small sorted polygons in the central area of large sorted mesh. East side of MS 910 m, Korsbjerg massif, 1 km south of Ansgar. Scale given by 16-cm rule. (7 Aug. 1964)

Pl. 17. Small sorted nets in kettlelike depression. Store Blydal between 130- and 140-m contours 100 m east of Rungsted Elv. Scale given by 16-cm rule. (23 Aug. 1964)

Pl. 18. Large sorted nets at experimental sites 1, 11—12, and vicinity. View southeast downslope. Experimental site 1 is next to largest boulder at extreme right. Scale given by fig. 15. (11 July 1958)

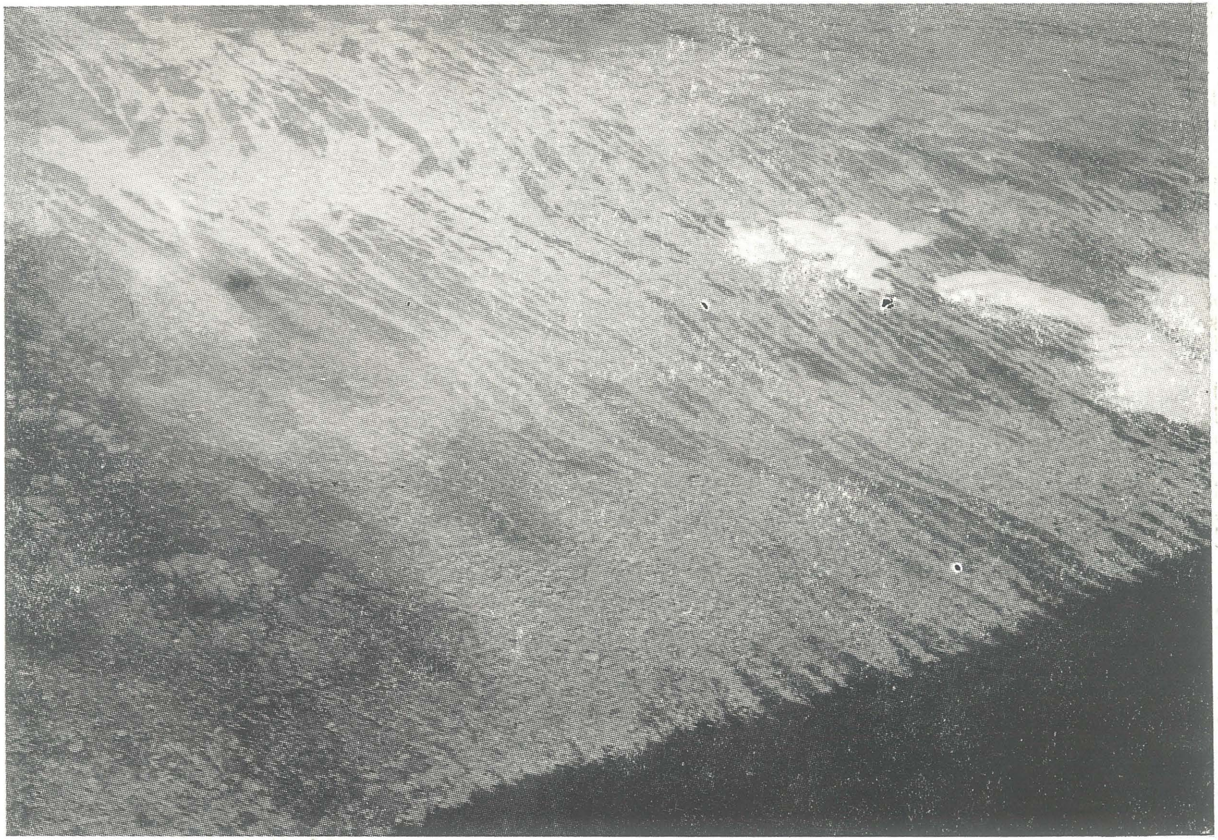
Pl. 19. Excavation 58-8-1 across stony border between two sorted meshes. 7 m north of experimental site 11. Scale given by 16-cm rule at right. (1 Aug. 1958)



Pl. 20. Large sorted nets on east side of MS 910 m, Korsbjerg massif, 1 km south of Ansgar. View north parallel to contour. Scale given by 16-cm rule at center. (7 Aug. 1964)

Pl. 21. Large sorted nets at north end of Myggesø. View west from air. Smallest meshes are about 1 m in diameter. (25 Aug. 1955)

Pl. 22. Large sorted stripes on north side of east-west ridge of Hesteskoen. View downslope. Dark stripes are about 50 cm wide. (16 July 1958)



Pl. 23. Large sorted stripes on west side of Myggesø. View west from air. The best defined stony stripes are about 1 m wide. (25 Aug. 1955)

Pl. 24. Excavation 58-8-28 across large sorted stripe on west side of Myggesø. View upslope. Scale given by 16-cm rule. (28 Aug. 1958)

Pl. 25. Large sorted stripes on south slope of trap knob MS 78 m, Nyhavn hills. View upslope. Scale given by figure. (14 July 1957)