Quantitative Data from a Patterned Ground Site over Permafrost

by

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and
R. Spence Taylor

U.S. ARMY MATERIEL COMMAND
COLD REGIONS RESEARCH & ENGINEERING LABORATORY
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PREFACE

This paper is based on data obtained under U. S. Army Snow, Ice, and Permafrost Research Establishment (USA SIFRE) contract DA-11-190-ENG-13 with the University of Minnesota. Dr. R. S. Taylor was the principal investigator and author of the contract report entitled Studies on patterned ground, October, 1956. Mr. Schmertmann, acting as a consultant to USA SIFRE, reviewed the contract report and prepared this report.
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SUMMARY

Techniques were established by which quantitative data can be obtained from patterned ground features. The field work was carried out during the summers of 1954 and 1955 near Camp Tuto, Greenland. The investigation site is described, and extensive data are presented. The soil materials composing the patterned ground features were found to be of common mineralogy, grain size distribution, and plasticity. The chemical nature of the soils does not contribute to feature formation; it is the mechanical processes acting on these materials that are important. A sharp rise in the soil water content in the form of ice was consistently noted when passing through the base of the active layer into the present permafrost. A net heave occurred at both feature center and border locations. The magnitude of the heave is about 0.05 ft for the centers and 0.03 ft for the borders. Feature age was estimated to be about 150 yr. Vertical sorting occurs over the entire depth of the active layer but radial sorting is confined to the upper 2 ft. Groundwater flow occurs mostly through the feature borders, and incoming radiation has an important effect on the progression of the frost line. The progression of thaw is very rapid and, by the end of summer, the thaw penetration is greatest under the feature centers.
QUANTITATIVE DATA FROM A PATTERNED GROUND SITE OVER PERMAFROST

by

John H. Schmertmann and R. Spence Taylor

INTRODUCTION

Patterned ground is most commonly associated with arctic, subarctic, and high mountain regions. In gross appearance, patterned ground consists of areas of soil marked by regular arrangements of stones, by vegetation, or by intersecting or nearly parallel depressions or ridges. Some of the more striking types are sorted circles or nets that have centers of sandy material and borders of cobbles or boulders.

The many types of patterned ground may be caused by a complex of processes initiated and maintained by frost action. Although there are many hypotheses concerning the processes of formation (Washburn, 1956, p. 838-859), there are few reports based upon precise measurements of the features themselves or their mechanical and thermal environments.

The general purpose of this investigation was to establish techniques by which quantitative data could be obtained from patterned ground features, and to present and evaluate data thus obtained. The study follows in part the approach outlined by Kersten (1954).

The field work was carried out during the summers of 1954 and 1955 near the First Engineer Arctic Task Force's Camp Tuto in northwest Greenland (Fig. 1). The field party generally consisted of two or three men, including R. S. Taylor who was the principal investigator. Temporary additional manpower was supplied when needed by either the 1st EATF or by USA SIPRE.* Laboratory work and compilation of data were done at the University of Minnesota. (For final contract report to USA SIPRE, see Taylor, 1956a).

SITE OF INVESTIGATION

An area between the Moltke and Petowik Glaciers, 3 to 5 miles wide from the edge of the ice cap and about 12 miles long, was investigated for a possible site. Approximately 60% of the ground surface is covered with patterned ground (Taylor, personal communication, 26 August 1957). The following patterned ground types, as classified by Washburn (1956), were noted in the area.

<table>
<thead>
<tr>
<th>Type</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circles and nets†—sorted Depressed center**</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Raised center**</td>
</tr>
<tr>
<td>Polygons—nonsorted (frost crack)</td>
<td>30</td>
</tr>
<tr>
<td>Stripes—sorted and nonsorted</td>
<td>25</td>
</tr>
</tbody>
</table>

*Now redesignated U. S. Army Cold Regions Research and Engineering Laboratory.
†The distinction between circles, nets, and polygons is not clearly defined. It appears that these forms are transitional and grade into one another.
**Features with the average elevation of their central areas less than that of their borders are termed "depressed center." Conversely, those features with their average central area elevations greater than the average elevations of their borders are termed "raised center."
Observations related to sorted circles, nets, and stripes will be presented here, since they are most closely related to the features studied in detail in the study area. Details of observations on other features are reported by Taylor (1956a, 1956b). The following is quoted from Taylor (1956a, p. 9-10):

"Sorted circles and nets, 2 to 30 ft across the mesh* centers, are common throughout the area. In general, they are found on the higher, better-drained ground, and are not common along present water-courses or in areas of older outwash deposits that are relatively free of fines. Generally the centers are a stony sand and the borders are cobbles and boulders. The centers stand higher, lower, or at the same general elevation as the borders. A very few examples of small sorted circles with pebble centers and cobble borders were seen. These occur in the bottom of the lateral drainage channels on the slope west of Tuto.

"Sorted circles in the area generally occur on surfaces with slopes less than 2°. On steeper slopes the circles are elongate and merge into sorted nets. These slope limitations do not hold true, however, in the angular debris in an old lateral drainage channel of the Moltke Glacier, perched about 500 ft up on the south wall of Wolstenholme Fjord, where a complete transitional sequence was found. Sorted circles with diameters of 12 to 16 ft occur on a 5 to 6° slope; where the slope is 9 to 10°, the mesh of the net is twice as long as wide; where the slope breaks abruptly from about 12° to 23°, sorted stripes appear.

*The unit component of patterned ground (excepting steps and stripes)—a circle, polygon, or intermediate form—is here termed the mesh" (Washburn, 1956, p. 825).
"Sorted stripes, transitional from sorted circles and nets, occur in quantity on the west slope of "B" Mountain, the south slope of South Mountain, and in lesser numbers in most of the areas in which sorted circles and nets are found. The amount of slope required to produce sorted stripes from the circles and nets varies with location and materials. Slope values assigned to the zone of demarcation between stripes and circles or nets vary also with the observer's discrimination and powers of observation. For those zones the writer has seen, 2 to 7° appears to cover the range of values encountered, except for the Wolstenholme Fjord occurrence. The angular nature of these latter materials may directly influence the slope transition factor."

Selection of the study area

The study effort was concentrated on sorted circles, which are common in the Thule area and have been observed in many areas throughout the world (Washburn, 1956). The site contained both raised and depressed center phases of this type and the individual mesh was large enough to permit instrumenting the feature without unduly disturbing its natural structure.

A site which met scientific and practical requirements was selected about 1000 yd north of Tuto. This site is illustrated in Figures 1, 2, and 3. The site was approximately 600 by 500 ft. The patterned ground features within this area were sorted-circle types with both depressed and raised centers (Washburn, 1956).

Eleven individual features, or small areas encompassing several features, were studied and quantitative data were obtained. These features and areas are shown in Figures 2 and 3.

General information about site and vicinity

Climate. The ice-free coastal areas of Greenland have a polar tundra climate. The mean monthly temperatures in Thule, based on a 6-yr observation period, are shown in Figure 4 (Hogue, 1956).

The extreme temperatures for this period are +64 and -43°F. The average annual freezing index is about 8100°F degree-days. The average precipitation for the 8 years is 2.95 in./yr, with extremes of 2.20 and 4.80 in. About one-half of the annual precipitation is in the form of rain during the months of June, August, and September. The elevation of the meteorological station in Thule is 57 m above MSL.

Long-time meteorological observations are not available for the Tuto area. However, pertinent information reported by Schytt (1955) for the summer of 1954 has been summarized in Table I.

Table I shows that the average monthly summer temperatures at Tuto were 1.8 and 2.6°F lower than those at Thule in 1954. The higher elevation and the proximity of Tuto to the edge of the ice cap make the Tuto climate generally colder and windier and make precipitation in the form of rain a rare occurrence.

Bedrock and surface materials. The following brief outline of bedrock structure and lithology is taken mainly from Koch (1928, 1929) and Munck (1941), as abstracted by Taylor (1956a, p. 5-6).

"The Thule district has a gently basinal structure with the axis of the basin trending northwest-southeast. The highest dips reported are about 15°. The Archean complex, an extension of the Canadian Shield composed of northeast-striking metamorphics and intrusive rocks, is exposed east of Uvdlé in the north and west of Narssarsuaq in the south. Hornblende schist and dark biotite gneiss are common.

"The Archean rocks are overlain by varicolored conglomeratic, cross-bedded, ripple-marked, locally siliceous sandstones with a thickness of about 300 m in the north. These are overlain by interbedded dolomite, siltstone, black shale, and limestone. The sedimentary rocks have a total thickness of about 800 m; they were named the Thule formation (of
late Algonkian era) by Koch. The sequence is unfossiliferous, except possibly for Cryptozoon (?). The nature of the uppermost of these rocks is uncertain. No younger strata have been recognized in the district.

"Sills and dikes of diabase 5 to 50 or more meters thick intrude the Thule formation. Their age is unknown."

Figure 2a. Low-angle oblique airphoto looking NNE across the study area. The study area is in the center of the photo. The dark centered features with light-colored borders are depressed center features whose central dark color is caused in part by discontinuous thin black crusts of lichen. The stippled appearance in the lower left corner and left center is caused by raised center features. The edge of the ice cap is at the right, with Lake Tuto in the foreground. The ragged stony shoreline projections into Lake Tuto are the borders of depressed center features. Piktufik Lobe is in the upper left. The irregular division between light and dark ground surface, particularly evident on the far wall of the small canyon, is the trim line. The shear-plane moraine in the upper right is 250 to 300 ft above the toe of the ice cap.
Figure 2b. Medium-angle oblique airphoto looking SE across the study area. The study area is in the far center of the photo. Raised center features occupy the foreground, and also the background near the proglacial lake. The light colored band across the center of the photo slopes about 5° toward the background, and bounds a relatively flat area of depressed center features. The trim line is at the upper edge of this slope. The borders of many of the raised center features appear darker than their centers because of lichen on the stones. The reason for the difference in the color of the centers between adjacent areas of raised center features in the right and left foreground was not determined; it may lie in the amounts of vegetation on the centers of the different areas.

Figure 2c. High-angle oblique airphoto looking WSW down into the study area. Raised center features are along the upper right edge and most of the left edge of the photo; depressed center features are in the middle. The two main members of the portable drill-rig platform on the core-sampled feature (upper center) are 6 in. x 22 ft; scale may be estimated from these.
Figure 3. Plane table map of study area.
Table I. Summer weather at Tuto and vicinity.

<table>
<thead>
<tr>
<th>Month recorded</th>
<th>Thule (57 m)</th>
<th>Tuto (480 m)</th>
<th>Ramp Station* (569 m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Avg temp (F)</td>
<td>Avg temp (F)</td>
<td>Avg wind velocity (mph)</td>
</tr>
<tr>
<td>July 1954</td>
<td>40.9</td>
<td>39.1</td>
<td>13</td>
</tr>
<tr>
<td>Aug 1954</td>
<td>41.7</td>
<td>39.1</td>
<td>8</td>
</tr>
</tbody>
</table>

*Meteorological station located on the ice cap, about 1 mile east of Tuto.

Glacial drift derived from the Archean complex and the Thule formation accounts for most of the surface soil* found in the Thule area. The soil cover is thin and discontinuous in places. Bedrock is generally exposed only on the steeper slopes adjacent to streams near the coast, or where the more resistant intrusions occur. A recognizable morainic deposit occurs in the valley between North Mountain (Fig. 1) and the next ridge to the north.

The entire area is underlain by permafrost of unknown thickness. The present thickness of the active layer varies between \( \frac{1}{2} \) and 6 ft in the entire Thule area, and from 2 to 4 ft in the study area.

Geomorphology and glacial geology. The Thule area may be described as a dissected plateau of rolling relief, ranging from 0 to 2900 ft elevation, with an average elevation of about 1300 ft. The higher areas are composed of, or underlain by, gneiss, resistant sandstone, or intrusions.

*"Soil" is used in the engineering sense to mean all the unconsolidated materials of the mantle.
QUANTITATIVE DATA FROM A PATTERNED GROUND

At present, the principal agent of erosion in the area is solifluction.* The presence of permafrost may accelerate solifluction by preventing the downward drainage of excess water in the soil. Water erosion appears negligible now, although streams have cut deep V-shaped valleys near the coast. The down-cutting may have resulted from a rise in the land following recession of the glaciers from the now ice-free areas. Nichols (1953, p. 269) found no evidence at Thule of marine beaches above about 130 ft, but solifluction may have destroyed evidence of higher beaches. Koch (1928, p. 499, Fig. 4, and 1929, p. 297-299) attributed the abrupt rise of the area from the sea—more than 1000 ft in places—to movement along faults bounding the coast. He believed the faulting to be Cretaceous or older. The start of the cutting of the coastal valleys may date from the time of faulting.

Wind erosion appears negligible here, although in northern Greenland it is reported to be of considerable importance (Troelsen, 1949; Fristrup, 1953). Wind-blown snow and small mineral particles have polished the sides of the rocks facing the prevailing easterly wind as far as a mile from the edge of the ice cap. The polished sides look fresh while the lee sides of the rocks are commonly black with lichen.

Little is known of the sequence of glacial action in the Thule area. Wright (1939, p. 28-30) interpreted the lighter-colored, lichen-free areas along the margin of the ice cap (Fig. 2) as caused by the recent removal of the ice cover. In this paper the border between the lichen-covered and the lichen-free areas is referred to as the "trim line." The trim line, from Piktufik Lobe southwestward, lies an average of 200 to 300 yd west of the present ice front. No evidence was found to indicate that the edge of the ice cap recently extended beyond the trim line.

Frost-crack polygons and sorted circles with raised centers may be traced into and seen under the present edge of the ice cap. Thus, the features at the study site, which is within the trim line, may have been formed prior to the last advance of ice into the area.

A much earlier ice recession is recorded by a number of old lateral drainage channels and kame terraces between elevations of 1550 and 800 ft in the area between Piktufik Lobe, the east fork of the South River, and the upper valley of the South River at the foot of "A" Mountain (Fig. 1). The major slope of this ice was up to the northeast or north, and as it wasted away to its southeast margin it receded downslope from the present position of Tuto.

ACCUMULATION AND INITIAL EVALUATION OF DATA

Each of the features or feature areas is discussed separately. Their locations within or near the study area may be noted on the contour map of the site (Fig. 3).

The eleven features and the studies made on them are as follows:

Feature 1. Preliminary study (raised center feature)
Feature 2. Bench mark excavation—preliminary soils study (depressed center feature)
Feature 3. Cobble orientation study
Feature 4. Precise movement survey
Feature 5. Radial comparison studies
Feature 6. Moisture content survey
Feature 7. Temperature and heat flow study (depressed center feature)
Feature 8. Temperature and heat flow study (raised center feature)
Feature 9. Ground-water table studies
Feature 10. Permafrost table survey (depressed center features)
Feature 11. Permafrost table survey (raised center features)

*The downslope movement of soil as a result of freeze-thaw cycles.
The contour map of the site and immediate vicinity (Fig. 3) is based on a plane table survey of over 100 points, all taken on the finer-grained centers of the patterned ground features. The survey bench mark, which will be discussed more fully later, was assigned an elevation of 1560 ft from a map of the area having a 50-ft contour interval. Thus, the error in contour elevations may be as much as 25 ft, but the accuracy of the survey warrants the 1-ft contour interval shown.

**Feature 1 — preliminary study (raised center feature)**

Feature 1 is a sorted circle of the raised center type, 22 ft long downslope and 14 ft across slope, located about 250 ft northwest of the study area (Fig. 5). This feature was trenched by hand shovel in the active layer and by air compressor and paving breaker in the frozen ground.

Soil samples were obtained at 1-ft increments down the vertical face of the trench at seven locations, as shown in Figure 5. Because of the limited volume of the soil samples obtained, all cobbles and some pebbles were eliminated from the sieve analysis; therefore, the grain size distribution data presented for this and other features are the distributions for the approximate < 3-in. fraction. Water contents in all features were generally determined from the < no. 4 sieve fraction in thawed soil and from the entire sample in frozen soil. Thus, the presented grain size distributions indicate a finer grained soil than if the > 3-in fraction were also considered, and the presented water content values of thawed soil are greater than if the > no. 4 sieve fraction were included.

The grain size distributions (Fig. 6a) were obtained in the Soil Mechanics Laboratory of the University of Minnesota, using the Unified Soil Classification System. The samples were first oven dried to obtain water content values, and then screened on the no. 4 and 10 sieves. A hydrometer test was run on the material passing the no. 10 sieve, with sodium silicate as the deflocculating agent. After completion of the hydrometer test, the sample was again dried and another sieve analysis was run with the no. 20, 40, 60,
Figure 6. Data from Feature 1 excavation. (a) Grain size distribution, (b) Water content distribution (numbers denote water content in percent, by dry weight).
Figure 7. Soil fines — water content relationship in Feature 1.

100, 200, and 270 sieves. Essentially the same procedure was used for all grain-distribution tests reported in this paper. The hydrometer test permitted a determination of the percentage of soil < 5µ in grain size. In only 4 of the 22 samples tested from this feature did the < 5µ fraction exceed 1%; these are numbers 2(4-5 ft) = 4.5%, 4(4-5 ft) = 4.0%, 7 (top) = 1.5%, and 7 (bottom) = 1.7%. These four samples are all in the immediate vicinity of the frost table, which at the time of sampling was close to the permafrost table*.

Figure 6b presents the water-content data obtained from Feature 1. Frozen samples were collected in polyethylene bags† and thawed samples in tarred gil cups. The wet weights of the samples were determined to the nearest 0.01 lb in the field, using a 35 lb capacity Fairbanks Morse counter scale. The dry weights were determined later at the University of Minnesota.

Figure 7 indicates a potentially important relationship between the water content of frozen samples just below the frost table and the percentage of very fine material in the soil—the < 5µ fraction in this case. Even though the percentages are very small, they appear to be significant and consistent with the standard criterion used for determining the frost susceptibility of a soil (Corps of Engineers, 1962). It therefore appears that frost susceptibility of the freezing soil may be important to the distribution of segregated ground ice.

*The term "frost table" is used to denote the boundary between frozen and not-frozen soil at any time in the freezing-thawing cycle. The term "permafrost table" is used to denote the base of the present active layer. The term "frost zone" will refer to the boundary between frozen and not-frozen soil at any time when this boundary is not sufficiently fixed to be termed a "line."

†Use of polyethylene bags is not recommended for storing wet samples, as the samples dried out even in sealed bags.
Comments on Feature 1.

1. There is a general trend towards increasing soil fineness with increasing depth to, and just below, the frost table. The samples in line 4, Figure 6a, present the only exception.

2. The water contents generally tend to increase with depth to the frost table, with an average of 7.4% for the surface samples and 16.5% for those immediately above the frost table (Fig. 6b).

3. There is a great accumulation of water, in the form of ice, below the frost table. The average water content here is 72%.

4. Ice below the frost table concentrates under the center of the feature. The frozen samples for lines 2, 3, and 4 have an average water content of 11.5%, while those for lines 6, 1, 5, and 7 have an average of 40.5% (Fig. 6b).

Feature 2 — bench mark excavation — preliminary soils study (depressed center feature)

It was necessary to have a fixed bench mark within the study area for the surveys made as part of this overall study (Fig. 3). In August 1954 a shaft was excavated to a 15-ft depth with the aid of paving breakers and dynamite. The "permanent" bench mark installed (Fig. 8a) is a type used by the contractors at Thule in unconsolidated materials within this permafrost area. The 15-ft depth was assumed to be sufficient to insure that the inner pipe would be securely frozen and held in position. That part of the pipe subject to the action of the 3 to 4 ft deep active layer was protected by a 6-ft length of larger diameter pipe, with grease in between the pipes. Four thermocouples were placed along the pipe to determine when the bench mark could be considered sufficiently frozen-in to be used. The temperature data indicated that the bench mark was securely frozen-in on 1 September 1954.

The excavation was accomplished within a 6-by 6-ft crib used to retain the active layer. The area within this crib was bisected by the border of a small sorted circle of the depressed center type. Detailed soil sampling was conducted during excavation at about 1-ft intervals both under and outside the border and under the center of the dissected feature. Care was taken to select samples that had not been moved from position by the explosive work.

Figure 8b shows the grain size distribution of the samples from outside the border and in the center of the dissected sorted circle. Four samples (indicated by asterisks) were tested for plasticity, using the standard Atterberg liquid and plastic limit tests on the < no. 40 sieve fraction. The finest of these samples had only 10% by weight of fines < 5µ grain diameter. All tests indicated the samples to be non-plastic (Taylor, 1955).

All stones larger than \( \frac{1}{8} \) in. diam, from those samples obtained under the border in the bench mark excavation, were subjected to mineralogical investigation. A total of 235 stones were examined, the largest being 4 in. long. Each was broken open and the lithology and mineralogy determined with a binocular microscope, and, in some cases, with the aid of a petrographic microscope. Data from this analysis are presented in Figure 8c, summarized for depth increments of 0 to 7 ft and 7 to 14 ft. The material below a depth of 8 ft was stratified outwash. Above 8 ft the materials were not stratified; they were slightly oxidized with varying degrees of discoloration, giving the appearance of being frost-stirred.

Two samples from the 2 to 3-ft depth were fractionated to their < 1µ grain size fraction and then subjected to X-ray mineralogical analysis. Unfiltered iron radiation with a camera radius of 57.3 mm was used. The predominant minerals in this fraction were quartz and potash feldspar, in that order. The mineral geothite (hydrated iron oxide) was present in very small amounts.

Wet densities of frozen samples from the bench mark shaft were determined by weighing the samples and then using an oil displacement method to determine their volume. The dry weights were later determined at the University of Minnesota, thus permitting estimates of water content and dry density.
Assumed Elevation 1560.0 Ft. A. S. L.

4" I.D. Pipe, capped

Standard Oil No. 6004 cup grease between pipes

Approx. Frost Line

1 1/2" I.D. Pipe, capped at top and centerpunched. Filled with dry -4 fine sand

1/8" by 8" steel disc welded to pipe

Outside of Border

Center

Center

52% GRANITIC GNEISS, Fine to medium foliation.
27% DIORITIC GNEISS, Fine foliation.
10% SANDSTONE
2% QUARTZ SCHIST
1% GARNET GNEISS and SCHIST
8% OTHER

50% DIORITIC GNEISS, Fine foliation.
19% GRANITIC GNEISS, Fine to medium foliation.
12% QUARTZ SCHIST
5% SANDSTONE
7% GARNET GNEISS and SCHIST
7% OTHER

88 STONES

147 STONES

(a) BENCH MARK INSTALLATION

(b) GRAIN SIZE DISTRIBUTION

(c) LITHOLOGY and GROSS MINERALOGY of STONES ≥ 3/8"

* Samples tested for Plasticity

Figure 8. Bench mark excavation - soil.
Figure 9. Bench mark excavation - moisture.

Figure 10. Soil fines — water content relationship in Feature 2, bench mark excavation.
Figure 9 presents the water content profiles for the samples taken both outside the border and under the center of the feature. Water contents below the frost line are for frozen samples which were thawed and placed in an oven to determine weight loss upon drying.

The observations and measurements appear to indicate that the 8 to 10-ft depth represents the limit of some type of frost behavior—perhaps the maximum depth of the active layer in postglacial times. There also appears to be a relationship between the percentage of fines in the frozen soil and its moisture content (Fig. 10).

Comments on Feature 2.

1. Figure 8b shows a pronounced change in the texture of the soil at a depth of 9 to 10 ft. From soil with 30-50% fines there is a drop to less than 10% fines. This change may indicate a past limit of frost weathering such as an older level of the permafrost table. This hypothesis is supported by evidence of oxidation and frost-stirring to a depth of 8 ft.

2. There is a greater percentage of the fine fraction between 2 and 5 ft. Five feet is the approximate depth of the present frost table.

3. The change in lithology with depth is marked. The stones in the 0 to 7-ft depth were considerably more silicic than those in the 7 to 14-ft depth increment.

4. Water content values are much larger below the frost line. These large values are pronounced to a depth of 9 to 10 ft.

Feature 3 — cobble orientation study

Feature 3 is an elongate depressed center of fines approximately 16 by 12 ft, with its long axis parallel to the general line of slope of the area, which averages about 1.2%. A detailed contour map of the center of the feature, and showing the locations of soil-sampling holes, is presented in Figure 11. The 0.1-ft contours are based on levels taken on a 3-ft grid, with a precision of 0.01 ft.

Upon completion of the survey, Feature 3 was subjected to an extensive soil investigation. Selected cobbles in the 0 to 6 in. layer were studied with respect to their number and the orientation of their major axes, and samples were obtained for density, grain size distribution, and moisture content determinations at 17 symmetrically located sites within the feature. The sampling pattern (Fig. 11) was made up of a center hole (no. 3), an inner ring of eight holes (no. 2, 4, 7, 8, 10, 13, 15, and 16), and an outer ring of eight holes (no. 1, 5, 6, 9, 11, 12, 14, and 17). After completion of the orientation study, the feature, with its top 6 in. removed, was covered with canvas for 3 weeks until the fall freeze-up was well under way. At that time sampling was continued at the previously established 17 locations, and samples for grain size and water content determination were obtained. At 9 of the 17 sampling holes, samples were obtained in 6-in. depth increments to a depth of 66 in. The remaining eight holes were sampled to a depth of 36 in. Dynamite was used to clear frozen soil from the center of the feature, above the 3-ft depth, after sampling was completed to that depth. The sampling holes were about 6-in. diam and quartering was generally used to reduce the size of the samples. Figure 12 shows the feature during the final stage of excavation.

Grain size distribution. Figure 13 presents grain size distribution profiles through the center of Feature 3, one parallel to and the other across the 1.2% slope of the local area. Only 9 of the 17 sampling locations are included in these profiles. Figure 13 shows no obvious changes in the grain size distribution of the soils as one moves parallel to or across the center of Feature 3. Figure 14 presents the average percent, at each sample depth, of < 5 µm fines, < no. 200 sieve fines, and > no. 4 gravel for the inner and outer ring samples.

To see if the general slope of the area influenced grain size properties in the feature, upslope and downslope sampling locations were compared over the 0 to 36-in. depth range (Table II).
Figure 11. Plan and surface contours of Feature 3 (cobble orientation study). Numbers indicate sample position. Contours based on elevations at 3-ft grid intersections and on sketch of surface features.
Figure 12. Excavation below permafrost table in Feature 3.

Figure 13. Feature 3 grain size distribution profiles.
Figure 14. Comparison of selected soil fractions for inner and outer rings, Feature 3.
QUANTITATIVE DATA FROM A PATTERNED GROUND

Table II. Soil fraction averages for upslope and downslope locations, 0 to 36-in. depth, Feature 3.
(Area slope = 1.2%)

<table>
<thead>
<tr>
<th>Location and hole no.</th>
<th>&gt; 4 (gravel)</th>
<th>&lt; 200 (fines)</th>
<th>&lt; 5µ fines</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upslope, holes 1, 6, 12</td>
<td>23%</td>
<td>22%</td>
<td>3%</td>
</tr>
<tr>
<td>Downslope, holes 5, 11, 17</td>
<td>27%</td>
<td>20%</td>
<td>4%</td>
</tr>
<tr>
<td>Upslope, holes 2, 7, 13</td>
<td>18%</td>
<td>22%</td>
<td>3%</td>
</tr>
<tr>
<td>Downslope, holes 4, 10, 16</td>
<td>17%</td>
<td>25%</td>
<td>3%</td>
</tr>
</tbody>
</table>

Notes:
1. All percentages are dry weight.
2. The < 5µ fines were determined by hydrometer analysis using sodium silicate as the deflocculating agent.
3. Depth limit of 36 in. used because two of the three holes in each group were only 36 in. deep.

Water and ice content. Water contents were also obtained for all samples used for grain size analyses. Figure 15 presents the water content profiles and dry densities for the same sections first shown in Figure 13. In this case only the samples from the upper 6 in. were unfrozen at the time of sampling.

The locations of the major ice segregations were also noted and their elevations carefully determined by level readings to 0.01 ft (Fig. 15). The uppermost ice layer appeared to be continuous.

The water contents for the inner and outer rings (eight sampling locations each) were averaged. The resulting profiles, one for each ring, are plotted in Figure 16. The possible influence of the slope in the vicinity of Feature 3 on the water contents may be evaluated from the data from the 0 to 30-in depth increment presented in Table III.

Table III. Average water contents, 0 to 30-in depth, Feature 3.

<table>
<thead>
<tr>
<th>Location and hole no.</th>
<th>Water content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upslope, holes 1, 6, 12</td>
<td>11</td>
</tr>
<tr>
<td>Downslope, holes 5, 11, 17</td>
<td>9</td>
</tr>
<tr>
<td>Upslope, holes 2, 7, 13</td>
<td>11</td>
</tr>
<tr>
<td>Downslope, holes 4, 10, 16</td>
<td>10</td>
</tr>
</tbody>
</table>

Figure 17 indicates the relationship between ice content and the percent of < 5µ fines in the frozen soil. Three 6-in. depth intervals were chosen for study — two at the peak water content depths shown in Figure 16, and the other (30-36 in.) at or near the base of the present active layer beneath this feature. There is a general trend toward higher ice content with increasing soil fines. Also, conditions conducive to ice accumulation were materially different at the present base of the active layer than they were at the time the deeper ice was accumulating.
Figure 15. Feature 3 water content profiles, observed ice layers, and surface dry densities. Water content given in % of dry weight.
Figure 16. Average water contents, Feature 3 (after freeze-up).

Figure 17. Soil fines-water content relationship in Feature 3.
(a) Cobble with major axis y-x, centered at O. (Azimuth angle = u0h, dip angle = h0x.)

(b) Distribution and size of cobbles. Numerator gives number of ≥ 3-in. cobbles in each segment, denominator shows average length in inches. Fractions shown on upper half of major axis give total cobbles and average lengths for middle, central and outer rings.

Figure 18. Cobble orientation study, 0 to 6 in. depth, cobbles with 3 in. or longer major axis.
Cobble orientation. To obtain information on the mechanical processes active in the formation of sorted circles, a special study was made of the coarse particles in the 0 to 6-in. layer of Feature 3. The location, size, and orientation and dip of the major axis of all cobbles with a major axis equal to or greater than 3 in. was measured. Over 645 cobbles which did not intersect the surface were measured in the central area of the feature.

A 6 ft square, stretched-wire grid, with one axis oriented upslope, was established over the feature and leveled to 0.01 ft. It served as the datum plane for determination of elevations and also provided the coordinates for cobble orientation in the horizontal plane. The finer soil surrounding each cobble was carefully excavated until the cobble was exposed enough to permit measurement of azimuth and dip. The latter were measured with 10-in. protractors having 12-in. swing arms. The accuracy of measurement was determined to be ±5°.

Figure 18 shows the cobble orientation data from Feature 3. Each cobble is imagined to be at the center, 0 of a one-half spherical shell (Fig. 18a). The major axis of the cobble is then projected until it intersects the shell at point x. The projection of point x on the horizontal plane gives point h. The angle h0x measures the dip of the major axis. The upslope direction is here represented by line 0u. The angle u0h then measures the azimuth of the major axis.
Figure 18b shows the fine-grained center of this feature divided into center, middle, and outer rings of equal area. The total number of cobbles and the average length of the major axes is indicated for each ring and for each 30° segment. Figure 18c graphically indicates the azimuth distribution of the cobbles found in each of the 36 smaller areas. The number of cobbles whose azimuth falls within each 45° azimuth interval is indicated by the length of the line plotted in the center of each 45° interval. In all cases one of the azimuth intervals directly faces the indicated center of the feature. Those cobbles having dip angles of 0 and 90° could not be included because the azimuth is not defined; therefore, the total number of cobbles included in Figure 18c is 566 instead of 645.

To determine if there is a preferred azimuth orientation, probability diagrams were prepared for the inner, middle, and outer rings (Fig. 19). The area under the curve is equal to 1.0—there is a probability of 1.0 that the horizontal angle between cobbles and line to center ranges from 0 to 180°. Figure 19d compares the probability curves from the three rings.

Another study was made of the distribution of dip angles for the 645 cobbles measured. Since there appeared to be no significant differences between the results from the three rings treated individually, a single probability curve was prepared (Fig. 20). Again the area under the curve equals 1.0—there is a probability of 1.0 that the dip angle ranges from 0 to 90°.

Comments on Feature 3.

1. The surface 6 in. is the coarsest portion of the active layer. The least gravel is found in the 24 to 36-in. depth range.

2. The percentage of < 200 fines remains about constant (10 to 20%) until the 24-in. depth. Past this depth the percentage increases sharply, reaching a maximum of 50 to 60% at a depth of about 42 in.

3. The percentage of < 5 μ fins slowly increases from 0 at the surface to about 2% at 21 in., followed by an abrupt increase to about 9% at a depth of 27 in. and a gradual reduction to 5% at 63 in.

4. In general there are only minor differences between the grain size distributions for the inner and outer rings of eight holes each. The main difference is over the 0 to 21-in. depth where the inner ring has a greater percentage of < 200 fines and a lower percentage of gravel.

5. Table II indicates no consistent differences between grain size distributions for the upper and lower slope positions.

6. Perhaps the most striking feature of the water content data is the great increase in soil water content below about 30-in. depth. From a low average value of 9% at about 25-in. depth, the water content jumps to an average value of 115% at the 45-in. depth. It then decreases with further depth.

7. There is no apparent significant difference between the water content profiles of the inner and outer sampling rings (Fig. 16).

8. Slope position has no apparent significant influence on the water content distribution in the active layer.

9. The 0 to 6-in. dry density data indicate the soil to be in a compact condition with little, if any, frost fluffing. The 140 lb/ft^3 values probably indicate an error in the volume determinations of these samples.

10. Figure 16 shows a zone of water depletion between, roughly, the 20- and 30-in. depths. This zone was reported by Taylor (personal communication, 6 February 1958) to be partially frozen, but yielding no visible water. It would yield in a stiff, mushy fashion and excavate much more easily than the solidly frozen soil above and below.

11. There is a distinct increase with distance from the center of the feature in the number of cobbles in the 0 to 6-in. layer; 130 cobbles were found in the center
Figure 19. Probability curves for horizontal angle between major axis of cobble and line to center of Feature 3 (0 to 6-in. depth).
Figure 20. Probability diagram for dip of major axis of cobble.

Figure 21. Feature 4 (precise movement survey) looking downslope.
ring and 292 in the outer. Since the area of the feature center is about 155 ft² and the area of each ring about 52 ft², the density of 3-in. or larger cobbles averages about 5/ft³ for the center and 12/ft³ for the outer ring over the first 6 in. of depth.

12. The average size of the cobbles increases from 3.8 in. in the center ring to 4.2 in. in the outer ring.

13. There is a definite tendency for the major axes of cobbles to point toward the center of the feature. The probability curves (Fig. 19) indicate a probability of about 0.40 that the cobbles will form a horizontal angle of 45° or less with the line from the cobbles to the feature center—vs 0.25 if any direction were equally probable. There appears to be no significant difference between the orientation in the center, middle, and outer rings.

14. Figure 20 shows that the preferred dip angles are toward the horizontal rather than the vertical. There is about 0.50 probability that the dip will be 20° or less. This probability would be 0.26 if the dip angle distribution were random.

Feature 4—precise movement survey

One large and one small sorted circle of the depressed center type were used to measure the horizontal and vertical movement of surface stones. The smaller circle (6 ft diam) was directly upslope from the larger one (14 ft diam) (Fig. 21).

Forty stones, which were part of the natural surface of the feature area, and seven artificial disks were used for this study. A point was marked on each stone—a paint spot, a hacksaw cross cut, or a mark on a lead plug poured into a ½-by 1-in. hole drilled into the stone. The movements of these points were then determined by precise survey methods.

A closed base line traverse (Fig. 3) was established from the bench mark. Between each of the five point-surveys performed, the traverse was surveyed by a four-man party using a 200-ft steel tape calibrated by the Bureau of Standards and a 1-sec theodolite. The computed orders of precision for the base line traverse were 1/33, 930; 1/27, 260; 1/53, 800; and 1/33, 900 for surveys 2 through 5. The base line traverse was also surveyed for elevation, using a precise level and rod to read elevations to 0.001 ft. The maximum vertical error of closure was 0.010 ft.

Horizontal movement. An X and Y grid coordinate system, with the bench mark as the origin, was established over the area of the 40 survey points. The 1-sec theodolite was set over base line traverse points SB and CB, and single or double sets of direct and reverse angles were read for each survey point. Using these two angles and the known length of the side SB-CB, the X and Y coordinate of each point was calculated. Five surveys were made. The results of the first survey were discarded because the survey was made with a 10-sec Gurley transit before the bench mark was established.

Since the movements obtained from comparisons of surveys are small, it was desirable to estimate the absolute accuracy of the point locations, as determined by these survey methods. For this purpose the positions of a number of points about 100 ft upslope of Feature 4 were determined independently from two base lines, SB-CB and CB-NB. The calculated positions were then compared and the distance between the points was taken as a measure of the absolute accuracy of the point surveys (Table IV). All theodolite sight distances were less than 200 ft. It may be concluded that an error of between 0.001 and 0.065 ft may be expected in the locations of the survey points. The average error expected would be something like 0.020 ft.

The detailed point-movement data are not presented in this report; for that information the reader is referred to Taylor (1956a, p. 213, 224, 252). Taylor believed surveys no. 2 and 5 to be the most accurate. Since those surveys were made a little over a year apart, any yearly movement of the stones on which the points were placed should be indicated. Movement between surveys 2 and 5, based on surveys of 40 points, shows: least movement = 0.000 ft, greatest movement = 0.046 ft, average movement = 0.016 ft.

Vertical movement. The Z (vertical) coordinate was also determined for each of the survey points. Precise survey methods were used and elevations were read to 0.001 ft.
Table IV. Point triangulation survey, absolute accuracy check. Distances in 0.001 ft.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>43</td>
<td>-</td>
<td>-</td>
<td>27</td>
<td>-</td>
</tr>
<tr>
<td>44</td>
<td>-</td>
<td>61</td>
<td>31</td>
<td>26</td>
</tr>
<tr>
<td>45</td>
<td>6</td>
<td>65</td>
<td>13</td>
<td>26</td>
</tr>
<tr>
<td>46</td>
<td>6</td>
<td>32</td>
<td>1</td>
<td>22</td>
</tr>
<tr>
<td>47</td>
<td>-</td>
<td>46</td>
<td>9</td>
<td>14</td>
</tr>
<tr>
<td>48</td>
<td>-</td>
<td>52</td>
<td>42</td>
<td>1</td>
</tr>
<tr>
<td>Avg</td>
<td>6</td>
<td>51</td>
<td>21</td>
<td>18</td>
</tr>
</tbody>
</table>

Table V. Summary of vertical movement data, Feature 4. Elevation changes between surveys (in 0.001 ft).

<table>
<thead>
<tr>
<th>Location</th>
<th>No. of points</th>
<th>2-3 (avg)</th>
<th>3-4 (avg)</th>
<th>4-5 (avg)</th>
<th>Surveys 2-5 avg</th>
<th>range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upslope half border of large circle stones</td>
<td>12</td>
<td>+74</td>
<td>-28</td>
<td>+89</td>
<td>+135</td>
<td>+106</td>
</tr>
<tr>
<td>Downslope half border of large circle stones</td>
<td>14</td>
<td>+71</td>
<td>-28</td>
<td>+86</td>
<td>+129</td>
<td>+106</td>
</tr>
<tr>
<td>Border of small circle stones</td>
<td>6</td>
<td>+70</td>
<td>-34</td>
<td>+106</td>
<td>+142</td>
<td>+132</td>
</tr>
<tr>
<td>Center of large feature stones</td>
<td>4</td>
<td>+74</td>
<td>-59</td>
<td>+121</td>
<td>+136</td>
<td>+127</td>
</tr>
<tr>
<td>large feature disks</td>
<td>6</td>
<td>+74</td>
<td>-56</td>
<td>+128</td>
<td>+146</td>
<td>+134</td>
</tr>
<tr>
<td>Center of small feature disk</td>
<td>1</td>
<td>+64</td>
<td>-26</td>
<td>+209</td>
<td>+247</td>
<td></td>
</tr>
</tbody>
</table>

Note: Survey no. Dates
2 5 Sept ’54
3 29 June ’55
4 19 Aug-3 Sept ’55
5 24 Sept ’55

The rod used was a special lightweight one designed by Taylor to reduce the likelihood of disturbing the stone on which the survey point was located. The maximum vertical error of closure for the base line traverse surveys was 0.010 ft. The vertical errors of closure in Feature 4 for surveys 3 through 5, each of which started and finished at the bench mark, ranged from +0.008 to -0.004 ft (Taylor, personal communication, 27 August 1957). Since the vertical movements obtained are greatly in excess of 0.01 ft, it is believed that the results obtained are meaningful.

Table V summarizes the vertical movements of the stones and disks.

Comments on Feature 4.

1. The yearly movement determined by precise survey methods falls within the limits of accuracy for determining point locations. The average movement is less than the expected absolute accuracy. Thus, precise survey methods, using calibrated...
QUANTITATIVE DATA FROM A PATTERNED GROUND

Tapes and 1-sec theodolites, are not suitable for determining individual stone movements for time intervals of 1 year. It is of interest to note that Williams (1957, p. 57) indicates that photographic methods, from the ground, may be a successful means of determining surface movements.

2. The precise surveys indicated that the horizontal movements of the surface stones are on the order of 0 to 0.5 in./yr. The movements give a preliminary indication of being radially outward from the center of the sorted circles.

3. The position of the border stones, whether upslope or downslope, makes no difference in the average vertical movements of the stones (Table V).

4. The vertical movements are about the same for the centers and borders.

5. The vertical movements are about the same in both the 6- and 14-ft circles.

Feature 5—radial comparison studies

Feature 5 is approximately circular, with a diameter of about 25 ft (Fig. 22). The width of the surrounding stone border varies from 2 to 6 ft. The general slope of the fine-grained centers around the area of Feature 5 is approximately 1.1%.

Grain size distribution. Soil samples were taken from 12 locations (Fig. 23) throughout one-half of this almost circular feature. Ten locations were within the center and two were in the stone border. These soil samples represent the first detailed soil study attempted in this research.

At the time of sampling, the thawed layer was 27 to 30 in. deep. Samples were obtained from the active layer by driving a 6 in. diam open pipe in 6-in. increments and removing the soil trapped within the pipe after each increment. The disadvantage of this sampling method is that it compacts the soil below the sampling pipe and creates lateral compaction within the sample and outside the pipe. The former was particularly apparent when a large cobble was encountered and was either pushed down by the edge of the pipe or became wedged inside the pipe. Vertical compactions of 6 in. or more were sometimes experienced when sampling the top 18 in. Because of this method of sampling, the grain size distribution values are somewhat suspect since the exact depth for which each sample is representative cannot be stated with certainty. Individual 6-in. water-content and density values determined in conjunction with the soil sampling of the thawed layer were considered unreliable and are not reported here.

Core samples of the frozen soil below 30 in. were obtained by drilling with a 2-11/16 in. ID tube surrounded by a core barrel which increased the diameter of the drilled hole to 42 in. Power was supplied by a 3-hp motor used in conjunction with a portable vertical-tripod drill. The vertical coring increment was generally 15 in., but rarely was more than half of this length of core recovered. Thus, the soil data obtained from each increment may not be the same as if the entire core length had been recovered.

Figure 24 presents results of the grain size analyses. Gaps in the data resulted from the mildewing of cloth labels on sample containers, rendering their contents unidentifiable for testing.

The vertical distribution of selected grain size fractions is compared in Figure 25 to show the influence of radial distance from the center. The average curves were estimated by the writer from the scattered data from the centrally located sample holes 2, 3, 4, and 7 and the outer holes 1, 5, 6, 8, 9, and 10, which are located near the edge of the fine-grained center of the feature (see Fig. 23). The individual points are from holes 11 and 12, located within the stone border.

Water content, soil density, and ice distribution. Water contents were also determined from the samples obtained for the grain size distribution tests. The water-content samples from the thawed layer were taken in tarred 2-oz tins and weighed on a 0.01-g balance. Compaction during sampling makes the values for the 6-in. increments unreliable, and only the average values for the surface 0 to 30 in. are presented (Fig. 26a). If in error, these average values should be on the low side. Water contents of the frozen soil were determined directly from the cores. However, heat developed during the core drilling operations may have melted some ice and it is possible that the frozen-soil water contents reported here are too low.
Figure 22. Feature 5 (radial comparison studies) looking NE across its slope.

Figure 23. Soil sample and heave plate location, Feature 5. Dashed line outlines the fine-textured center. Feature is encircled by a stone border 2 to 6 ft wide. No. 1-12 are core-sampled positions; No. 1-18 are heave plates emplaced in 1954; No. 1A, 2A, 4A, 7A-9A, 15A, 16A are heave plates emplaced in 1955.
Figure 24. Grain size distribution profiles, Feature 5.
Figure 25. Comparison of selected soil fractions from Feature 5.
QUANTITATIVE DATA FROM A PATTERNED GROUND

(a) Individual water content profiles.

(b) Average water content profile.

Figure 26. Water content profiles, Feature 5.
Dry density determinations were also made (Fig. 26a). Since the sampling for each 6-in. increment is unreliable, only the average of the 0- to 30-in. thawed layer is presented. The computed degree of saturation for the 0- to 30-in. thawed layer is also given. Volume determination for the frozen samples depended on the measurement of irregular and often partially crushed cores, making these density values too questionable for inclusion.

Figure 26b presents the average water content profile, based on all data from the 12 sampling holes. A great deal of scatter was observed in this data and the average curve shown is therefore fairly subjective. As far as we could evaluate, there appears to be no significant difference between the data from the center, edge, and border hole locations. Again, only an average value of water content is shown for the upper 30 in.

During sampling by hand from the surface, before core sampling was started, partly frozen soil was first encountered at depths of 27 to 30 in. in a zone 2 to 2.5 in. thick, and immediately above the solidly frozen soil. The frost table did not exist as a sharply defined surface between thawed and frozen soil, but as a transitional zone of discrete ice crystals in a wet soil mass of increasing stiffness from top to bottom. Similar conditions were observed elsewhere in the study area.

In general, the ice observed in the cores was hard, clear, and colorless. It was also noted that three pebbles, in different cores, had 0.25- to 0.5-in. lenses of ice under them. The latter was a common observation in frozen soil. Taylor also observed pebbles with ice lenses over them—but this was apparently less common. In one instance, an elongate and near-vertical pebble had ice lenses both above and below it.

Additional soil testing. The acid-soluble content of 12 samples from the 12- to 30-in depth was determined in order to discover if leaching and chemical weathering could be significant agents in the study area. The < no. 10 sieve fraction (<2 mm) was digested for 24 hr at about 70°F by 6N hydrochloric acid. After drying, the weight loss was determined and the percent lost of the dry weight of the total sample was calculated.

The acid-soluble material ranged from 2.5 to 10.9% for these 12 samples, with an average of 6.1%. There appeared to be no significant difference in the values with depth, nor with radial distance from the center of the feature.

Seven similar determinations on samples from the 12- to 44-in. depth range in Feature 1 yielded a solubility of 3.9 to 9.6% by weight with an average of 6.4%.

In connection with the acid solubility determinations, it is desirable to know the pH values for the water in the features. While Tuto soil water was not tested for pH, the pH was determined at a number of points in lakes and streams in the Tuto and Thule area (Taylor, 1956a, Tables 16, 17). The values determined in the field, using pHhydrion paper, ranged from 4.5 to 5.5. Values determined later in the laboratory ranged from 5.8 to 7.4. The latter were part of the results obtained from chemical analysis of 10 water samples collected from the general Thule area (Taylor, 1956a, Table 16).

The mineralogy of the colloidal soil fraction, here taken as less than 1μ, was determined for the following boring locations and sampling depths chosen for their highest content of fines: 1. 12 to 18 in.; 2. 18 to 24 in.; 7. 18 to 24 in.; and 12. 24 to 30 in. Determination was made by X-ray analysis, using unfiltered iron radiation and a camera radius of 57.3 mm.

The percent of the total weight of the sample which is less than 1μ in grain size was tested, using a pipette method with sodium oxalate as the peptizer. The < 1μ fraction was as high as 4%. The results of the mineral analysis showed the following colloidal minerals, in order of predominance: quartz, potash, feldspar, chlorite, and possibly vermiculite and kaolinite.

The specific gravity of the soil solids was determined by a volume displacement method for six < no. 10 sieve samples from 0 to 72-in. depths. Duplicate tests were performed on each of the samples. The results from the 12 tests ranged from 2.64 to 2.73, with an average value of 2.68.
Heave plate measurements. After the soil sampling was completed in Feature 5, the 12 excavated holes (Fig. 23) were used for installation of specially designed heave plates. A single heave plate was placed in each hole, at a depth of 1, 2, 3, 4, or 5 ft. Before placing the plate, the hole was filled to the proper level with soil excavated from the hole, and the whole installation was allowed to freeze to the existing frost table before any heave measurements were taken. Six additional heave plates (no. 13 to 18) were installed in late August 1954, and eight more plates (no. 1A, 2A, 4A, 7A, 8A, 9A, 15A, and 16A) in August 1955. Holes not made during the soil sampling were drilled with a 4\(\frac{1}{4}\) in. auger.

The general design of the heave plate is shown in Figure 27. A 4-in. diam iron plate was attached to a \(\frac{1}{4}\)-in. ID vertical pipe above the surface of the feature (Fig. 22). Three-quarter-in. diam rubber tubing surrounded the vertical pipe to protect it against adfreezing to the surrounding soil. The tubing was clamped to the bottom of the pipe and to the top of the dowel to prevent moisture from getting between the rubber and the pipe.

The heave plate design may not have been successful since the rubber tubing used deteriorated before freeze-up, and moisture penetrated the breaks in the tubing, possibly permitting vertical movement of the pipe by tangential adfreezing. Considering this fact, the heave plate measurements could be in error. Another possible source of error is preferential conduction of heat along the metal shaft and plate, resulting in local ice lens formation under the plate itself. This might have caused a heave of the plate that was mistakenly assumed to be a heave of the underlying soil. Study of the data indicates that such lens formation was likely under plates 10 and 1A. Minor sources of error would be moisture swelling and shrinkage of the wood dowel, leveling errors, and changes in length of the pipe with temperature.

Heave-plate levels were read nine times during the 1954 and 1955 summer seasons. Levels were read to 0.001 ft, suggesting an estimated maximum error of \(\pm 0.005\) ft, although this was not determined. Figure 28 shows the average heave vs time at each of the five heave-plate levels for the center, inner ring, outer ring, and border hole positions. Heave occurring within each 1-ft thickness of soil is plotted at the top of the 1-ft thickness. Note that the heave scale is exaggerated. Time is also plotted to scale, with a gap between the 1954 and 1955 data.

No surface measurements of heave were made at this feature, and the heave for the 0- to 1-ft soil layer cannot be determined. The lowest heave plate (for example: inner ring, hole 4, with plate at 5-ft depth) measured the total heave occurring below the level of the plate. Only two heave plates were placed in the border holes, and both were at a 3-ft depth.

At the time of the soil sampling in Feature 5 (1-10 Aug 1954) the frost table was at a depth of approximately 2.5 ft. Thus, it appears reasonable to suppose that the heave plates at 5-ft depth were below the permafrost table. Assuming that there is no movement of the soil below the permafrost table, then the heave of the soil below 5 ft should be zero. The heaves indicated for the soil below the lowest heave plate are probably an indication of tangential adfreezing and leveling errors. A further estimate of these errors must await additional vertical heave data from other features with which these data can be compared.
Figure 28. Average heave for 1-ft depth increments in Feature 5.
Figure 26b indicates that the average water content of the frozen soil is about the same for the 30- to 40-in. and 60- to 70-in. depth increments. Figure 29 shows that the ice content increases with an increasing percentage of fines in the soil and that the variation is similar for samples from the chosen depth increments. Conditions during the freezing of the soil may have been similar for these soil layers, indicating that the active layer may have been at the 65-in. depth in the past.

Comments on Feature 5.

1. Obtaining samples from the thawed layer by driving an open pipe is not recommended because of the serious compaction which may occur.

2. Figure 24 indicates that for the surface 6 to 12 in. there is a radial increase in the > no. 4 fraction across the slope. A less pronounced increase may also be noted downslope from hole 1. Below about 12 in. there is no apparent upslope or across-slope trends in the grain size distribution profiles.

3. The < no. 200 fraction increases abruptly over the 15- to 27-in. depth range. The center and edge holes show very similar distribution curves. It is especially interesting to note that the distribution of the < no. 200 fraction below the 27-in. depth is the same under the border as under the center of the feature.

4. The depth at which the rapid increase in the < no. 200 fraction stops corresponds to the 27- to 30-in. depth reported as the location of the frost table in the central area of the feature at the time of sampling.

5. The > no. 4 gravel fraction decreases rapidly from the surface to 27 in., below which the changes are gradual. The average center and edge profiles have a similar shape, with the edge having a higher percentage of gravel in the surface 40 in. The > no. 4 data from the border holes are too erratic to evaluate.

6. The data from under the border show that the < 5µ fraction has essentially the same vertical distribution as under the center of the feature.

7. The data indicate that slope or radial position in the feature does not significantly affect the soil water-content distribution. However, too much reliance should not be placed on these data since when part of a core was lost it is considered likely that the greater part of this loss would be ice.

8. The average water content profile (Fig. 26b) shows a sharp increase from 14% in the thawed zone to about 64% at 35-in. depth. The sharp increase occurred at the approximate position of the depth of thaw at the time of sampling (1-10 August 1954).

9. The average dry densities of the thawed layer vary from 110 to 118 lb/ft³. These are low to medium density values for this type of soil, and perhaps indicate that not all soil entered the sampling pipe during sampling. However, the computed degrees of saturation vary between the very reasonable values of 75 and 86%, and show that the average density values are not likely to be more than 5 lb/ft³ too low.

10. The frost table at the Feature 5 location was not a sharply defined line, but was a transitional zone of about 2- to 2.5-in. thickness.

11. Under certain, perhaps common, circumstances, ice segregations will form under individual pebbles.

12. About 6% of the < no. 10 sieve fraction of the soil composing the Tuto patterned ground features is soluble in strong hydrochloric acid. Tests show the ground water to
be slightly acid. Thus, there exists the possibility of some chemical leaching and weathering by ground water flow.

13. The mineral content of the colloidal soil fraction consists primarily of quartz and feldspar, both of which are most likely the product of mechanical rather than chemical weathering. Small percentages of the clay minerals chlorite, vermiculite, and kaolinite may also be present. The < 1μ fraction is in all cases less than 4.7% of the total dry weight of the soil.

14. The average specific gravity of the < no. 10 sieve soil solids is 2.68. This is a typical value for cohesionless soils.

15. The heave of the 3- to 4-ft and 4- to 5-ft soil layers is within the probable error of this determination and is most likely zero. Thus, the vertical movement of the ground surface is due to movement within the active layer and/or movement below 5 ft (Fig. 28).

16. The largest heave, up to 0.15 ft, or 1.8 in., occurred in the 2- to 3-ft soil layer.

17. The heave of the 1- to 2-ft soil layer reached a maximum value of about 0.03 ft. The expected time pattern of settlement with thaw and heave with freezing is not evident in the 1- to 2-ft layer, as it is in the 2- to 3-ft layer.

18. Since the data span a period of over 1 yr, they indicate the plates at the 1- and 2-ft levels have a net heave of from 0.10 to 0.20 ft per year. Thus, there is either a net increase in the soil elevations or, more likely, the heave plates are not settling as much as they are rising.

Feature 6—moisture content survey

Feature 6 is a sorted circle, about 16 by 24 ft across and downslope, respectively, in an area with a general slope of about 1.0% (Fig. 3). The surface moisture content changes were measured in 1954, and the surface heave was studied in 1955.

Grid surveys. A 4-ft grid was established over the feature, using wire stretched between stakes driven into the ground outside the area to be mapped. One axis of the grid was oriented parallel to the general slope of the surrounding area. Orange-painted stakes were placed on the extensions of the grid axes, so that the survey grid could be recovered in later surveys. Although some movement of these stakes due to ground movement between surveys was to be expected, it was assumed that negligible error would occur in the recovery of the grid intersections owing to the length of the grid lines compared to the small amount of movement anticipated.

Level determinations were made on a 2-ft grid interval with the positions between the 4-ft wire grid being determined by eye. Level readings were taken to 0.01 ft with an estimated maximum instrument error of ±0.02 ft.

Surveys were made on 6 July, 18 August, and 18 September 1955. The results of these surveys, as taken from Taylor (1956a, p. 148-153), are presented in Figure 30. Figure 30a shows a plan of this feature, based on the 6 July survey, with 0.05-ft contours for the center of the feature and point elevations for the border. The elevations shown are in feet above an assumed datum of 1559.54 ft, as determined from the bench mark. The border was not contoured because of the irregularity of its stony relief.

Figures 30b-d present contours of the difference in surface elevations between the surveys. The irregularity of border surfaces discouraged determination of the movements of individual stones—i.e., the exact survey point on a stone with a sloping surface could not be determined. Instead, border elevations were averaged.

The average vertical movement for all border and center points for the interval between the different surveys was computed by Taylor and is tabulated in Table VI.
(a) Elevation contours, survey of 6 July 1955. Positions of elevations in the border are indicated by the decimal points. No. 1-6 are the moisture-sampling positions.

(b) Change in surface elevation, 6 July to 18 Aug 1955.

Figure 30. Grid surveys of Feature 6.
Figure 30 (Cont'd). Grid surveys of Feature 6.

(c) Change in surface elevation, 18 Aug to 18 Sept 1955.

(d) Change in surface elevation, 6 July to 18 Sept 1955.
QUANTITATIVE DATA FROM A PATTERNED GROUND

Table VI. Average vertical movement of surface of Feature 6.

<table>
<thead>
<tr>
<th>Survey interval</th>
<th>Movement in ft</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 July-18 Aug</td>
<td>Center</td>
</tr>
<tr>
<td>(43 days)</td>
<td>-0.05</td>
</tr>
<tr>
<td>18 Aug-18 Sept</td>
<td>+0.13</td>
</tr>
<tr>
<td>(31 days)</td>
<td></td>
</tr>
<tr>
<td>6 July-18 Sept</td>
<td>+0.08</td>
</tr>
<tr>
<td>(74 days)</td>
<td></td>
</tr>
</tbody>
</table>

Surface moisture content. Soil water-content samples were collected weekly during an 8-wk period in the summer of 1954. Samples were taken from the surface 2 to 3 in. of soil at six locations (Fig. 30a). Only the soil fraction passing the no. 4 sieve was used.

Figure 31 shows the average water content at all six sampling locations and the individual value for the center-of-feature position, no. 4, and the edge-of-center position, no. 1. Moisture in the upper 2- to 3-in. of soil is most likely derived either from precipitation (including blowing snow) or through upward capillary movement of water from a source below. The source of the supply below can be visualized as either melt water directly below the frost table, or drainage from the surrounding border. Since precipitation was negligible during the summer months of this field study, it can be said that the primary source of surface water is upward flow due to capillarity.

After the initial spring thaw, water is removed from the surface soil by evaporation into the atmosphere. The accumulation or depletion of surface water is then determined by the net rate of surface supply through capillary flow less the rate of loss by evaporation. The rate of upward flow depends on the distance between the surface and the source of the water supply and the quantity of water available at the source. When the ground surface just begins to thaw after the winter snow cover has melted, the surface soil may be saturated with water. As the summer thaw progresses, the distance to the source, assumed to be the water table, increases and thus would contribute to reduction of water at the soil surface. With the onset of freeze-up thaw ceases and the water supply at the frost table is no longer replenished. As the water supply is reduced, the rate of upward capillary flow of water is also reduced. This would contribute to reducing surface water contents until this water is locked by freezing at the surface.

Comments on Feature 6.

1. The slope of the fine-grained center of this feature is reversed, opposing the general slope of the surrounding area. The contour plan shows the maximum difference in elevation across the center of the feature to be 3 to 4 in.

2. The net changes in elevation of the center of the feature between surveys during the 74-day period exceeded the range of -0.05 to +0.10 ft, with an average value of +0.08 ft.
3. No definite pattern of heave or subsidence of the center of the feature is apparent. The over-all impression is one of more or less uniform heave and subsidence.

Feature 7—temperature and heat flow study (depressed center feature).

Feature 7 is a sorted circle of the depressed center type, about 19 by 23 ft across and downslope respectively, in an area with a general slope of about 1.0% (Fig. 3). The narrow and shallow border between this feature and the elongate one immediately to the northeast of it makes the two appear as one feature (Fig. 32). The surface heave of this feature was studied in 1955, and the soil temperatures in and below the feature were measured from the 1954 season through the 1955 field season. An attempt was also made to measure the pore-water pressures developed during the 1955 freeze-up.

Grid surveys. The grid surveys to determine vertical movement of the surface were made in exactly the same manner, using the same personnel and equipment, as the grid surveys of Feature 6. The three surveys were made on 9 July, 18 August, and 18 September 1955. The results of these surveys, as taken from Taylor (1956a, p. 154-159), are presented in Figure 33.

The average vertical movement for all border and center points was computed by Taylor (1956a, p. 43) and is presented in Table VII.

Table VII. Average vertical movement of surface of Feature 7.

<table>
<thead>
<tr>
<th>Survey interval</th>
<th>Movement in ft</th>
</tr>
</thead>
<tbody>
<tr>
<td>9 July-18 Aug (40 days)</td>
<td>Center: -0.05, Border: -0.02</td>
</tr>
<tr>
<td>18 Aug-18 Sept (31 days)</td>
<td>Center: +0.14, no data</td>
</tr>
<tr>
<td>9 July-18 Sept (71 days)</td>
<td>Center: +0.09, no data</td>
</tr>
</tbody>
</table>
(a) Elevation contours, survey of 9 July 1955. Open circles indicate thermocouple strings; solid circles indicate disk positions; triangles show positions of pressure gages.

(b) Change in surface elevation 9 July to 18 Aug 1955.

Figure 33. Grid surveys, Feature 7 (depressed center thermocouple feature).
(c) Change in surface elevation 18 Aug to 18 Sept 1955.

(d) Change in surface elevation 9 July to 18 Sept 1955.

Figure 33 (Cont'd). Grid surveys, Feature 7 (depressed center thermocouple feature).
It may be seen that the magnitude of average vertical movements in Feature 7 is very similar to that in Feature 6 (Table VI). As with Feature 6, the contours of elevation difference between surveys present no apparent pattern of movement.

Thermocouple installation. Five vertical strings of thermocouples were placed in this feature in 1954 to determine the time variation of the thermal conditions within the feature. A total of 76 thermocouples were installed and the maximum depth was 12 ft. The plan locations of these thermocouple strings are shown in Figure 33a. Four were within the fine-grained center and one below the coarse border. Figure 32 shows where the thermocouple strings emerge from the surface of the feature and clearly shows how the strings were placed on a line across the slope of the area.

The individual thermocouples were composed of Brown Instrument Co. 24-gage copper-constantan wire enclosed in Carlon 1/4-in. OD, 1/8-in. ID polyethylene tubing, with the couple heat-sealed in the plastic. Each vertical string was placed in a 5-in. diam hole drilled with an earth auger, with the slumping active layer held back by casing to the permafrost table. All drilling was done from a portable platform to minimize surface disturbance of the feature during the drilling operations. The plastic tubing enclosing each thermocouple was fastened to the next longer one with two turns of masking tape. The longest thermocouple was fastened immediately behind a shield at the end of a steel rod. The rod was used to position the deeper thermocouples, four at a time. When the proper depth was reached with the rod and attached thermocouples, the hole was back-filled for several feet with soil. While the plastic tubes were securely held at the surface, the rod was twisted free of the deepest couple and withdrawn.

The medium depth thermocouples were placed in the above fashion either in groups of four or individually. The shallow thermocouples were placed individually by hand around the perimeter of the hole after the casing was removed. Every effort was made to separate the plastic tubing of the different thermocouples and minimize preferential vertical conduction down the thermocouple hole. The maximum positioning error, with one exception, is estimated to be 1 in.

Forty-eight of the couples were led into four Leeds and Northrup 12-position 2-pole selector switches. Twenty-four were connected to a thermopanel made by Thermo Electric Co., Inc. The bottom four thermocouples of string no. 4 were read individually, as were the four on the bench mark.

Readings were made using a Rubicon potentiometer (S/N 68686) with an ice bath as a reference point. The thermocouple circuit was checked against the standard cell after each two readings, and, if necessary, readings were retaken until the circuit was balanced. The instrument was calibrated in degrees Centigrade and readings were made to 0.1 degrees by visual interpolation. It was also determined by SIPRE personnel that the longest thermocouple used (20 ft) did not appreciably affect the sensitivity of the galvanometer used.

Weather permitting, the thermocouples were read every other day during the summer of 1954, daily in 1955, and ten times during the winter of 1954-55.

Study of heat flow at the frost table. If one dimensional, vertical heat flow is assumed to occur at the frost table, then the amount of heat available at the frost table for freeze-thaw may be evaluated from the thermocouple data. The heat of fusion, $Q$, represents the difference between the heat entering and the heat leaving the frost table. Figure 34 and the derivations under (a) show how $Q$ can be calculated if the thermal conductivity and the temperature gradients are known in both the unfrozen soil above and the frozen soil below the frost table. Because of the difference in the thermal conductivity of frozen and not-frozen soil and the release of the heat of fusion during thaw, the temperature gradients in frozen and unfrozen soil are likely to be markedly different during thaw. The intersection of the temperature gradient lines permits a convenient means for determining the position of the frost table. This method does not involve assuming the frost table to be at a given temperature and circumvents constant instrument errors.

If the movement of the frost table is thus measured and studied in conjunction with data on the heat available for fusion, it is possible to compute the amount of water in the soil. This is shown by equation 4 in Figure 34b. Comparing the computed water contents
A study of the type outlined above was performed using the 1954 thermocouple data from string no. 1 in Feature 7. For convenience when presenting the temperature profiles and computations, the 15 July to 8 September study period was divided into eight intervals of 7 days each. The number of thermocouple readings during an interval varied from three to five. The temperatures at each thermocouple position were averaged and it was assumed that this average represented the average temperature condition over the 7-day period. The eight temperature profiles obtained from these data are presented in Figure 35.
Table VIII lists the temperature gradients at the frost table and the positions of the frost table as they were determined graphically from Figure 35. Using assumed values for thermal conductivity, $q_u$ and $q_f$ were calculated and $Q$ was determined.

Using this $Q$ in conjunction with the penetration of the frost table, equation 4 was then used to calculate the soil water content over each increment of frost table penetration. A degree of saturation of 100% was assumed since free water is likely to be standing at the frost table. The computed average $Q$ and water content are also presented in Table VIII.

The values assumed for the thermal conductivity of the unfrozen and frozen soil are very important in the above computations. The values used, and indicated below Table VIII, were taken from tables (Aldrich, 1956) based on the work reported by Kersten (1949). Study of Figures 6b, 9, 16, and 26 and Table III indicated that water content values of 11 and 65% would be representative of the unfrozen and frozen soil, respectively, several feet on either side of the permafrost table. An estimate of 115 lb/ft$^3$ was made for the average dry density of the soil above the permafrost table, based on data presented in Figures 15 and 26. An estimate of $K_u$ was made on the basis of these dry density and water content values. $K_f$ was estimated on the basis of the percentage of volume

Figure 35. Weekly average thermocouple temperature profiles, summer 1954. Feature 7, string no. 1.
Table VIII. Calculation of average heat flow and soil water content at frost table,
Feature no. 7, thermocouple string no. 1.

<table>
<thead>
<tr>
<th>Symbol (Fig. 35)</th>
<th>Time interval (1954)</th>
<th>Avg thermal gradient at FT (°C/cm)</th>
<th>Avg conduction heat flow at FT (cal/day/cm²)*</th>
<th>Avg Q (cal/day/cm²)</th>
<th>Avg y (ft)</th>
<th>Δy</th>
<th>Δt (days)</th>
<th>Avg Q over Δt</th>
<th>w = water content</th>
</tr>
</thead>
<tbody>
<tr>
<td>●</td>
<td>15-21 July</td>
<td>70.8x10⁻²</td>
<td>43.3x10⁻²</td>
<td>27.8</td>
<td>19.7</td>
<td>8.1</td>
<td>2.44</td>
<td>0.06</td>
<td>1.8</td>
</tr>
<tr>
<td>X</td>
<td>22-28 July</td>
<td>71.5</td>
<td>40.6</td>
<td>28.1</td>
<td>18.4</td>
<td>9.7</td>
<td>2.50</td>
<td>0.07</td>
<td>2.1</td>
</tr>
<tr>
<td>Φ</td>
<td>29-4 Aug</td>
<td>87.2</td>
<td>40.0</td>
<td>34.3</td>
<td>18.2</td>
<td>16.1</td>
<td>2.57</td>
<td>0.19</td>
<td>5.8</td>
</tr>
<tr>
<td>Δ</td>
<td>5-11 Aug</td>
<td>71.5</td>
<td>42.6</td>
<td>28.1</td>
<td>19.4</td>
<td>8.7</td>
<td>N. D.</td>
<td>0.19</td>
<td>5.8</td>
</tr>
<tr>
<td>■</td>
<td>12-18 Aug</td>
<td>79.3</td>
<td>41.3</td>
<td>31.2</td>
<td>18.8</td>
<td>12.4</td>
<td>2.76</td>
<td>0.21</td>
<td>6.4</td>
</tr>
<tr>
<td>○</td>
<td>19-25 Aug</td>
<td>54.4</td>
<td>36.0</td>
<td>21.4</td>
<td>16.4</td>
<td>5.0</td>
<td>2.97</td>
<td>0.21</td>
<td>6.4</td>
</tr>
<tr>
<td>▼</td>
<td>26-1 Sept</td>
<td>41.3</td>
<td>34.1</td>
<td>16.2</td>
<td>15.5</td>
<td>0.7</td>
<td>N. D.</td>
<td>0.03</td>
<td>0.9</td>
</tr>
<tr>
<td>□</td>
<td>2-8 Sept</td>
<td>24.3</td>
<td>28.2</td>
<td>9.6</td>
<td>12.8</td>
<td>-3.2</td>
<td>3.00</td>
<td>0.03</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Total interval 18 July-5 Sept 0.56 16.8 49 7.9 15.7%

*Assuming:

\[ K_u = 1.1 \text{ BTU/hr-ft-°F} = 393 \text{ cal/day-cm-°C} \]
\[ K_f = 1.27 \text{ BTU/hr-ft-°F} = 454 \text{ cal/day-cm-°C} \]

N. D. = not defined.
occupied by ice and soil solids and the approximate $K$-values of each. The $K$-values thus determined may be subject to errors as large as $\pm 50\%$. However, they were estimated as carefully as available data would permit—before the heat flow computations were started.

Table VIII shows an average water content of 15.7% for the 6 in. of soil immediately above the level of maximum thaw penetration during 1954. When compared with measured water contents, the computations indicate good agreement and tend to support the accuracy of the heat flow computations at the frost table. The indicated variation of water content of from 5 to 50% also appears reasonable for the increments of depth within the 6 in.

Heat flow at frost table and total incoming radiation. Schytt (1955, p. 9) recorded daily incoming radiation data obtained at the Thule ramp station about 2 miles from the patterned ground study area. His measurements demonstrate that the incoming radiation energy on a clear day in the middle of July was about 700 cal/cm$^2$/day. Yet, heat flow studies similar to those presented in Table VIII indicate that the maximum energy available for thaw at the frost table was about 25 cal/cm$^2$/day or less than 4% of the incoming energy. Fluctuations in the amount of incoming radiant energy should significantly affect freeze-thaw behavior at the frost table.

In order to determine if the above might be true, thermocouple string no. 1 was chosen for study between 18 July and 26 August 1954. Study of the radiation data indicated that this time interval could be divided into five increments, each representing a time of comparatively uniform incoming radiation values. Frost table heat flow studies, similar to those previously discussed, were made for these five time intervals. A lag of 1 day was used as an estimate of the time required for changes in incoming radiation values to be felt at the frost table.

![Figure 36. Average thermocouple temperature profiles used in radiation study, summer 1954. Feature 7, string no. 1.](image-url)
Figure 36 presents the average thermocouple temperature profile for each of the five time periods considered. Table IX lists the calculations for the average $Q$ values during each increment. The same assumptions were used for thermal conductivities as in the calculations for Table VIII. Table IX also presents the average measured incoming radiation at the Thule ramp station. The incoming radiation at the site of Feature 7 can be taken as a percentage, about 90%, of that at the ramp where multiple reflection from the snow surface is greater.

The graph in Figure 37, based on the data from Table IX, indicates the relationship between heat of fusion at the frost table, string no. 1, and the value of incoming radiation at the Thule ramp station. Four of the five data points plot on a smooth curve. The fifth point is significantly different for unknown reasons. The curve shown should be regarded as indicating a general trend rather than an exact relationship, because the nature of the data and calculations on which it is based are only approximate. However, an interesting prediction can be made using Figure 37.

The intersection of the indicated curve with the line of zero heat of fusion is at a ramp station radiation value of 390. This would indicate that this is the minimum value required to maintain the frost table when it is about 2.4 to 3.1 ft deep. The latest date at which this minimum value is available is about 23 August, as indicated on Figure 38. Thus, this represents the latest date possible for the start of freeze-up at Feature 7 and at similar features in the study area. Figure 28 shows that the 1955 heave associated with the fall freeze-up in Feature 5 started between 19 and 26 August.

Before continuing, a brief summary of the heat flow study development may be helpful. A conduction heat flow study at the frost table was made and a successful comparison of computed and expected water contents at the frost table gave a general substantiation to the analysis. A similar analysis was then used to correlate heat flow at the frost table with values of incoming radiation. A relationship was found that could be used to predict successfully the time of onset of the fall freeze-up. Thus, there appears to be a relationship between the heat of fusion available at the frost table and the total incoming radiation. This relationship is not surprising and is discussed in more detail in Appendix A.

Variations in the position of the frost table. During the summer months the general progression of the frost table is downward, and during the time of freeze-up it is upward. However, in any particular time interval, it has been demonstrated that the amount of incoming radiation can determine whether thaw or freeze occurs at the frost table. Incoming radiation is quite variable with amount of cloud cover, as the data presented by Schytt (1955) demonstrate. For example: during the 54-day interval between 1 July and 23 August 1954 there were 15 days during which the incoming radiation at the Thule ramp station was less than the 390 cal/cm$^2$/day estimated to be required for continued thaw at a frost table depth of about 3 ft. Thus, the progression of the frost table may be variable, with many oscillations in the general trend.

Figure 39 presents the results of attempts to determine the position of the frost table, by the graphical method of the intersection of gradient lines, at 2-day intervals. Although the positioning of the frost table by this method is subject to variable error, it is thought that the frost table movements are great enough to show that the frost table does oscillate in its general downward progression. The variation in the position of the frost table, if it is assumed at the 0.0C depth, is also shown on this figure. With this basis, the frost table shows an even greater oscillation. If daily temperature readings had been taken, the oscillations would probably have been more numerous. It appears that the soil in the active layer, particularly near the frost table, is subject to many cycles of freeze-thaw during the summer season.

Temperature variation with depth across Feature 7. One purpose of placing a line of five thermocouple strings across Feature 7 (Fig. 33) was to study the time variation of the temperature contours across the section defined by this plane of thermocouples. Dr. Taylor prepared such sections (1956a, p. 171-175). Some of these are presented here as Figures 40a to r.
QUANTITATIVE DATA FROM A PATTERNED GROUND

Table IX. Heat of fusion at frost table, Feature 7, string no. 1 and incoming radiation at Thule ramp station.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Time Interval 1954</th>
<th>Number of Days</th>
<th>Average Temperature Gradient (°C/cm)</th>
<th>Conduction Heat Flow at Frost Table (Cal/cm²/day)</th>
<th>Q=(q_uq_f)</th>
<th>Measured Average Daily Incoming Radiation at Thule Ramp Station</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Unfrozen</td>
<td>Frozen</td>
<td></td>
<td>Date Interval</td>
</tr>
<tr>
<td>O</td>
<td>18-23 JULY</td>
<td>6</td>
<td>$41 \times 10^{-3}$</td>
<td>$45 \times 10^{-3}$</td>
<td>16.1</td>
<td>20.4</td>
</tr>
<tr>
<td>X</td>
<td>24-31 JULY</td>
<td>8</td>
<td>88</td>
<td>45</td>
<td>34.6</td>
<td>20.4</td>
</tr>
<tr>
<td>Δ</td>
<td>1-9 AUG</td>
<td>9</td>
<td>83</td>
<td>42</td>
<td>32.6</td>
<td>19.1</td>
</tr>
<tr>
<td>□</td>
<td>10-19 AUG</td>
<td>10</td>
<td>74</td>
<td>40</td>
<td>29.0</td>
<td>18.2</td>
</tr>
<tr>
<td>*</td>
<td>20-26 AUG</td>
<td>7</td>
<td>49</td>
<td>36</td>
<td>19.2</td>
<td>16.4</td>
</tr>
</tbody>
</table>

Figure 37. Influence of magnitude of incoming radiation on heat of fusion available at Feature 7 frost table.

Figure 38. Prediction of latest date for start of freeze-up, based on heat flow and incoming radiation studies.
Figures 40a-c show the final stages of the progression of freeze-up in 1954. Remembering that the depth of the permafrost table was about 3 ft, it can be seen that the progression of the 0°C isotherm is predominantly from the ground surface downward. Since the thermal gradients are approximately the same both downward and upward, this is an indication that the upward movement of the freezing surface is being delayed by the formation of ice lenses at the vicinity of the permafrost table. Figure 40b, as well as Figure 40q taken at about the same date in 1955, demonstrates that during the time of freeze-up the center of the feature either gives up its stored heat more slowly than the border or it has more heat to give up, or both. Figures 40h, i, and j also demonstrate this during the spring warm up—it either takes more heat to warm up the center of the feature or not as much is penetrating under the center as under the border, or both.

It may easily be shown by calculation that the finer-grained center of a feature, with its higher water content (at least in comparison with the upper levels in the coarse border), has a greater heat content than the comparatively dry coarse border. Thus, with an equal amount of energy absorbed over the entire area of the feature, and equal conductivities, the thaw would proceed most rapidly under the border. However, neither equal energy absorption nor equal conductivities are likely to be the case, so more rapid initial thaw under the borders is not certain. Since the borders also provide the best drainage paths for the melt water, it is likely that this water will seek these paths and thereby accelerate the thaw of the borders in comparison to the feature centers. Unfortunately, the thermocouple data did not include the period of initial thaw.

Reference to the 0°C isotherm on Figures 40f, m, n, and o, spanning dates from 30 June to 15 August 1955, shows that during most of the summer the frost table is at a greater depth under the center than under the border of Feature 7. Frost table penetration must have been more rapid under the center after the initial more rapid penetration under the border.

To summarize the above: early in the thaw period the frost table may penetrate more rapidly under the border, and later in the thaw period the frost table penetrates more rapidly under the center—an interesting switch, if this is the case. It may be that the flow of water through the borders, with the water near 0°C, retards the progression of the frost table under the border in the later stages of thaw. The possibility of a more rapid initial border thaw will be further amplified in the discussion of Feature 8.

An important observation to be made from Figures 40j and k is the rapid onset of thaw sometime between 18 May and 17 June 1955. Unfortunately, no readings were taken between these two dates so the actual onset of ground thaw can only be guessed at—perhaps about 1 June. Figure 41 helps illustrate the difference in conditions between the onset of thaw and the onset of freeze-up. The figure shows the computed clear-day incoming radiation data for the Tuto latitude and elevation as given by Gerdel et al. (1954). Ground thaw starts when the daily incoming radiation energy is about 700 cal/cm²/day and ceases when it diminishes to about 300. The difference between this 300 and the previous value of 390 is due to multiple reflection at the ramp, different sources of data, and the errors in obtaining both values. It probably takes until about 1 June for the sun to melt the accumulated ground cover of snow.
Figure 40. Temperature profiles, Feature 7.
Figure 40 (Cont'd). Temperature profiles, Feature 7.
Once the snow cover has been removed, the soil surface is suddenly subjected to the intense June solar radiation. The high position of the frost table in combination with this high incoming radiation causes high thermal gradients in the active layer and rapid penetration of the frost table. The June ground thaw is a phenomenon that occurs rapidly.

Pore water pressure measurements. An attempt was made in Feature 7 to determine if freezing induced positive pore-water pressure (compression), also called cryostatic pressure, to develop during the final freeze-up. Five gages were installed at different levels around thermocouple string no. 1. Two gages recorded pressure—up to about 15 psi—but the unproved design of the gages makes the readings questionable and a detailed discussion will not be presented here. More details may be found in Taylor (1956a, p. 28, 65, 66, 154, 176).

Comments on Feature 7.

1. In general the thermocouple installations were successful and permitted accurate evaluation of the temperatures within the feature. The heat available for fusion at the frost table could be computed from the thermocouple data.

2. Only a small percentage of the total incoming solar energy is used for fusion at the frost table. Thus, the large fluctuations possible in day to day incoming radiation can have an important effect on the progression of the frost table and cause fluctuations in its general downward progression.

3. Small differences in the albedo of the ground surface can have a significant effect on freeze-thaw behavior under that portion of the ground surface. The borders reflect more than the centers.
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4. The first thaw in the feature was rapid, probably because it was late May or early June before the snow cover melted. Thaw is considered likely to start under the border of the feature—although the data were not taken early enough in the thaw period to demonstrate this.

5. During July and August the frost table is at a greater depth under the center of the feature than under the border. Thus, the later stages of frost table degradation must be more rapid under the center than under the border.

Feature 8—temperature and heat flow study (raised center feature)

Feature 8 is a sorted circle of the raised center type, located along the southern edge of the study area in an area with about a 1.1% slope (Fig. 42). The upslope and across-slope dimensions of this feature center are about 13 x 16 ft respectively.

The study of this feature was similar to that of Feature 7. Surface heave was measured in 1955, three strings of thermocouples were placed and read in 1955, and an attempt was made to measure pore-water pressure during the 1955 freeze-up.

Grid surveys. The three grid surveys made to determine the vertical movement of the surface of this feature were made in the same manner and with the same personnel as Feature 6. The same difficulties were experienced when trying to determine the vertical movement of the border stones. The results of these surveys, as taken from Taylor (1956a, p. 182-187), are presented in Figure 43.

The average vertical movement for all border and center points between the different surveys was computed by Taylor (1956a, p. 70). The results are presented in Table X.

<table>
<thead>
<tr>
<th>Survey interval</th>
<th>Movement in ft</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Center</td>
</tr>
<tr>
<td>6 July-18 Aug</td>
<td>-0.02</td>
</tr>
<tr>
<td>(43 days)</td>
<td></td>
</tr>
<tr>
<td>18 Aug-18 Sept</td>
<td>+0.04</td>
</tr>
<tr>
<td>(31 days)</td>
<td></td>
</tr>
<tr>
<td>6 July-18 Sept</td>
<td>+0.02</td>
</tr>
<tr>
<td>(74 days)</td>
<td></td>
</tr>
</tbody>
</table>

Table X. Average vertical movement of surface of Feature 8.

Figure 42. Feature 8 (raised center feature).
(a) Surface elevation contours, 6 July 1955.

(b) Change of surface elevation, 6 July to 18 August 1955.

Figure 43. Grid surveys of Feature 8. Circles indicate thermocouple strings; triangles show position of pressure gages.
(c) Change of surface elevation, 18 Aug to 18 Sept 1955.

(d) Change of surface elevation, 6 July to 18 Sept 1955. Circles indicate thermocouple strings; triangles show position of pressure gages.

Figure 43 (Cont'd). Grid surveys of Feature 8.
Thermocouple data. Three vertical strings of thermocouples were placed in Feature 8 in 1955 to a maximum depth of 6 ft. The strings were placed on a line across the feature, with two (no. 6 and 7) in the central area and one (no. 8) in the border. The locations of these strings may be seen in Figures 42 and 43a.

The type of thermocouple used, the method of drilling the holes and positioning the thermocouples, and the instruments and techniques used to read the thermocouples were all similar to those described for the thermocouples placed in Feature 7. Daily readings were started 28 July 1955. Taylor reported that large quantities of clear ice were broken out at depths of 40 to 70 in. during drilling of the hole for thermocouple string no. 8 under the border.

The thermocouple data from center string no. 6 and border string no. 8 were used to study the differences in thermal properties between the center and border of this feature. Of particular interest were comparative average thermal conductivity and specific heat values.

Comparison of thermal conductivity. Figure 44 presents the thermal profiles obtained from thermocouple strings 6 and 8, read within 15 min of each other on 28 July 1955. From the note in the caption it can be seen that 28 July was during a sustained period of warming. The figure shows the frost table under the center to be about 1 ft deeper than under the border, and the temperature gradient in the active layer to be about 6.1 x 10^{-2}°C/cm under the center and 16.4 x 10^{-2}°C/cm under the border of the feature. The gradients were computed to be the average values on the active layer side of the frost table. Temperatures in the surface 9 in. of the active layer were not considered because of their rapid fluctuations.

If border and center thermal conductivities were equal, then the heat flow to the frost table would be about 2.7 times as great under the border. If one assumes equal water contents for the border and center soils (equal values of specific heat at equal depths), the difference in the levels of the frost table indicates that less total heat flows downward through the border. Furthermore, the suspected greater albedo of the border would also indicate that less heat flow should be expected. Thus, less heat is flowing, but under a greater thermal gradient. This is clear evidence that the thermal conductivity of the border active layer, at the time of these data when the border was dry, was much less than that of the center of the feature. The ratio of center/border thermal conductivity is at least 3 when the border is dry.

Comparison of specific heat values. If, after a period of uniform conditions, the value of incoming radiation is suddenly changed, then the temperature of the active layer will change with time. The depth profile of such a temperature change, after a given time interval, depends primarily on the conductivity and specific heat of the active layer. The greater the conductivity the more the heat transfer; the less the specific heat the greater the temperature changes.

In the absence of incoming radiation data, changes in the average daily air temperature at the study area will be taken as the measure of changes in level of incoming energy.

The upper table accompanying Figure 45 shows that there was a sudden cooling between 9 and 10 August 1955—following a period of comparatively uniform air temperature. Over approximately a 26-hr period the thermocouple temperatures dropped as shown. Between 4 and 5 August 1955, there was a sudden warming following a time of comparatively uniform air temperatures.

The area between the 0°C temperature-difference line and each curve in Figure 45 represents a quantity of heat gained or lost in the active layer during 1 day. The ratio of the area between the border curve and the 0°C line to the same area for the center curve is 3.3 for warming and 2.8 for cooling. If the amount of heat gained or lost is the same at the center and border, then the specific heat of the center is about three times that of the border. However, the heat gained or lost may not be the same because of different thermal conductivity. From mathematical analysis (Fishenden and Saunders, 1932) it can be shown that if the border and center cooling or warming temperature-difference curves were identical, the specific heats would be in the inverse ratio of the thermal conductivities. Thus, for identical temperature-difference curves, the specific
Figure 44. Comparison of center and border thermocouple temperature profiles, Feature 8.
Note: Average air temperature in study area:
26 July 1955 = 2.2°C
27 July 1955 = 5.6
28 July 1955 = 6.7

Figure 45. Comparison of the rate of temperature change under center and border of Feature 8.
Therefore, when the borders are dry, the specific heat of the active layer at the center of the feature appears to be at least three times that of the border. It should be noted that from specific heat estimates based on the known specific heats of water and ordinary rocks it is difficult to account for a ratio of center/border specific heats greater than about 3.

Temperature variation with depth across Feature 8. As was done for Feature 7, the three strings of thermocouples across Feature 8 were used to draw contours of isotherms at selected dates. Some of Taylor's drawings (1956a, p. 189, 190) are presented here as Figure 46a to e.

Figure 46a indicates the pronounced dishing of the frost table after freeze-up has already started—at least under the border. Figure 46b through e illustrates the reservoir of heat under the center of the feature which, despite the higher conductivity of the center of the feature, requires more time to reduce temperature.

Pore water pressure measurements. As shown in Figure 43a, five pore-water-pressure gages were installed around center thermocouple string no. 6. The gage design was the same as those used in Feature 7. Again, because of unproved design, no further discussion will be presented herein. More details may be found in Taylor (1956a, p. 66, 176).

Comments on Feature 8.

1. Figure 42 shows the border of this feature to be well developed and very coarse. Figure 43a shows that the center of the feature has a dome shape, being approximately 0.6 ft higher in the center than at the edges.

2. Except for strong vertical movements along one side of the center, there is no obvious pattern to the vertical movements between surveys. Figure 43d as well as Table X indicates that there was only small net vertical movement between the 6 July and 18 September surveys.

3. The average thermal conductivity of the essentially dry gravel, cobbles and boulders constituting the border of this feature is on the order of one-third that of the finer and wetter active layer at the center of the feature.

4. The average specific heat of the dry border, to a depth of approximately 2 ft, is about one-third the average specific heat of the first 2 ft of the active layer under the center of the feature.

5. Figures 45 and 46 clearly demonstrate that during the months of August and September the border of the feature responds much more rapidly than the center to changes in the values of incoming solar energy. It seems likely from this that when the feature surface is first hit with the intense solar radiation of late May to early June, the borders will thaw more rapidly.

Feature 9—ground water table studies.

Feature 9 is a sorted circle in an area with a general slope of about 2% (Fig. 3). A contour map of the central area of this feature and a photograph, looking across slope, are presented in Figure 47a and b. This figure shows the locations of thermocouple string no. 9 and the 17 ground-water boxes used to study ground-water levels, ground-water movement, and heave.

Thermocouple data. A single string, no. 9, of 12 thermocouples was placed in the center of Feature 9 to study the movement of the frost table in detail. The thermocouples were placed in 2-in. depth increments from 26 to 48 in. inclusive. Readings were made daily, when possible, starting 2 August 1955.

Figure 48 presents some of the thermal profiles obtained from string no. 9 which best illustrate certain behavior. Figure 48a shows two good examples of a phenomenon observed in most of the temperature profiles obtained from thermocouple string no. 9. It appears that thawing is occurring over a depth zone, 42 to 46 in. on 2 August and 40
Figure 46. Selected temperature profiles, Feature 8. Dots are thermocouple positions. Dashed lines are extrapolated from strings 7 and 8.
(a) Open circle indicates thermocouple string. Solid circles indicate ground-water boxes.

(b) Looking across slope to NE.

Figure 47. Feature 9 (ground water feature).
to 46 in. on 7 August, rather than at any single frost table. This zone will be called the frost zone. The temperature profiles for 27 and 28 August, shown in Figure 48b, also illustrated the existence of a frost zone rather than a frost table. Note that between 27 and 28 August the frost zone moved upward about 1 in. It is possible that recognizing the existence of a frost zone will make otherwise confusing thermal profiles easier to interpret.

Figure 48a also illustrates the depression of the freezing point in the frost zone. As is well known (for example, see Jackson and Chalmers, 1956), some water in fine-grained soils freezes at a considerably lower temperature than 0°C. Air temperatures on 2 to 4 August were about +1°C (34°F), followed by temperatures of +7°C (44°F) from the 5th to 7th. The cold air temperatures, probably indicating a reduction in incoming solar radiation, meant some upfreezing of the frost zone and a drop in the temperature of freezing in the frost zone. On the 8th the temperature of the frost zone again rose to about -0.4°C (31.3°F).

As with all the groups of thermal profiles studied in the different features, some of them are difficult to interpret—suggesting either faulty data or insufficient understanding of the phenomena being measured.

**Ground water hydrology.** As shown in Figure 47, 17 ground-water boxes were placed in the center and border of Feature 9. Thirteen were in the central area; positioned in 5-in. auger holes drilled from a platform. The four in the border were placed in small pits dug to below the frost table, and then backfilled. The purpose of these boxes was to observe the elevation and changes in elevation of the ground-water table. The ground-water boxes were 36 to 48 in. long and 3.5 to 5 in. wide. They were constructed of wood with an open bottom and open corners to permit the free flow of ground water. A mark of known elevation was placed on each box to permit the rapid determination of the daily elevation of the ground-water table at the box. The boxes were kept cleaned out down to the frost table.

Daily contour maps of the ground-water table (Taylor, 1956a, p. 167-170) indicate that, within the mesh, in general, the ground-water flow was downslope.

To estimate the volume of water flowing daily through the center of feature no. 9, a section was taken through the center of the feature approximately parallel to the direction of ground-water movement, and ground-water level along this section was then plotted (Fig. 49). This figure shows the highest ground-water table during the 1 to 21 August period of observation, which occurred on 16 August, the lowest ground-water table,
Figure 49. Ground water flow through center of Feature 9.

which occurred on 21 August prior to freezeup, and the ground-water table on 1 August, the beginning of the observations.

If a two dimensional case is assumed and the water-permeability of the soil between the ground-water table and top of the frost zone is estimated, then calculation from Darcy's law (eq 5, Fig. 49) permits an estimate of water flow through Feature 9. The permeability estimate can introduce the largest error. Permeability of a soil varies most significantly with its grain size distribution. If the grain size distribution is similar to that illustrated in Figures 6, 8, 13, and 24 then the soil is a well graded, gravelly, silty sand with about 20 to 40% passing the no. 200 sieve. According to Hough (1957, p. 69) the permeability can be expected to be about $3 \times 10^{-1}$ ft/day.

As shown by the calculations accompanying Figure 49, the volume of water flowing through the center of Feature 9 is of the order of $1/200$ ft$^3$/day/ft in third dimension. Even if the above calculations are in error by a factor of 10, it can be seen that the quantity of water flowing through the center of Feature 9 is small indeed—less than 1 ft$^3$/day for a feature 20 ft across.

The ground-water table contour maps show that the hydraulic gradient along the feature border can be taken as roughly the same as that through the center of the feature. Since the material in the coarse border trench may be 1000, or more, times as permeable as the soil in the center of the feature, it is clear that most of the ground-water flow during August passes through the borders of the feature and that the water level in the border generally controls the ground-water table in the center of the feature. This would be so provided the coarse border trench is of sufficient depth, about 1.5 to 2.0 ft, to intersect the ground-water table.

Heave of the ground-water boxes. The marks placed on the ground-water boxes were surveyed on 6 July and on 24 September 1955. Heave ranged from 0.07 to 0.13 ft for the 13 boxes in the center (avg 0.10 ft) and from -0.01 to 0.10 ft (avg 0.04 ft) for the four
boxes on the border. Since it did not appear that the individual boxes were heaving out of the soil surface, the heave recorded is attributed to the heave of the entire feature. In plan, the heave values indicate no significant pattern.

Comments on Feature 9.
1. Feature 9 thermocouple data clearly indicate that freeze-thaw may occur over a depth range, herein called the frost zone, rather than at a single level called the frost table.
2. A freezing point depression during the continued freezing of the frost zone is indicated by the data.
3. The volume of water moving through the center of Feature 9 in August 1955 was probably less than 1 ft³/day.
4. It is very probable that the great percentage of ground-water flow occurs through the borders of features similar to Feature 9, and that these borders govern the general ground-water table of the feature.

Features 10 and 11—permafrost table survey (depressed and raised center features)
These features, or rather feature areas, are located on the site map (Fig. 3). In each of these areas a ground surface and frost table survey was made before and after removal of the active layer, in order to study the configuration of the permafrost table and active layer over an area encompassing several center and border areas. Feature 10 was an area of depressed center features. Feature 11 was an area of raised center features.

The feature areas surveyed were about 40 x 40 ft in plan. A stretched-wire grid was established over each area and the elevations of 2-ft grid intersection points were measured on 12 July 1955. The active layer was then bulldozed away, the grids re-established, and the new frost table elevations were determined at 2-ft grid intersections. The results of the permafrost table survey may be found in Taylor (1956a, p. 210-212 and 221-223). The results indicated that in the middle of July the permafrost table in both areas was about 0.5 to 1 ft higher under the boulder borders than under the fine-grained centers of the individual features in each area. The active layer was correspondingly of greater thickness under the feature centers. In addition, the active layer was markedly thicker in the area of raised center features, compared to the area of depressed center features.

COMBINED ANALYSIS OF DATA
A great amount of data obtained by Taylor has been presented in the previous section of this report. However, the discussion of the data was generally confined to that obtained from each individual feature. This section includes further analyses which consider the data obtained from all features.

Sharp rise in water content at frost table
One of the most prominent observations made in this study was the sharp increase in water content, in the form of ice, when passing downward into the soil below the active layer. This observation is shown in Table XI. Thus the overall average comparison is 12% water content for the active layer and 68% for the soil below the permafrost table. Furthermore, the sharp difference was noted in every feature in which water contents were measured both above and below the permafrost table. The phenomenon is apparently more than chance and requires an explanation.

If it is assumed that the initial water content was about equal throughout the depth range studied, then the present condition can be explained by either of two possibilities:
1. The soil was deposited at a high ice content and the low water content of the active layer is due to depletion resulting from thawing and run-off.
2. The soil was deposited at a low water content, and the high water contents below the active layer are due to an accumulation of water, in the form of ice, resulting from ice segregation at the bottom of the active layer during freeze-up.
Table XI. Comparison of average water contents above and below frost table.

<table>
<thead>
<tr>
<th>Feature no.</th>
<th>D or R*</th>
<th>Size (ft)</th>
<th>General slope</th>
<th>Avg water content</th>
<th>Void ratio below permafrost table (G = 2.70, S = 100%, G1 = 0.90)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D or R*</td>
<td>Down-</td>
<td>Across-</td>
<td>Active layer</td>
<td>Below permafrost</td>
<td>Depth below included</td>
</tr>
<tr>
<td></td>
<td>slope</td>
<td>slope</td>
<td>layer</td>
<td>table</td>
<td>included</td>
</tr>
<tr>
<td>1</td>
<td>R</td>
<td>22</td>
<td>14</td>
<td>0.5%</td>
<td>12% 72%</td>
</tr>
<tr>
<td>2</td>
<td>D</td>
<td>small</td>
<td>10</td>
<td>75</td>
<td>6.5 ft 2.3</td>
</tr>
<tr>
<td>3</td>
<td>D</td>
<td>16</td>
<td>12</td>
<td>1.2%</td>
<td>11 70</td>
</tr>
<tr>
<td>5</td>
<td>D</td>
<td>25</td>
<td>25</td>
<td>1.1%</td>
<td>14 55</td>
</tr>
<tr>
<td>Avg.</td>
<td></td>
<td></td>
<td></td>
<td>12% 68%</td>
<td></td>
</tr>
</tbody>
</table>

*D = Depressed center type  
R = Raised center type

If no. 1 were true, then the soil was merely dumped in place as a mixture of soil and ice, and a relationship between grain size distribution and ice content would not be expected. On the other hand, if case no. 2 is correct, then the ice would segregate most in the soil that is most susceptible to ice lens formation. Since it has been well established that frost susceptibility is directly dependent on the percentage of fines in the soil at least until clay sizes are reached (Corps of Engineers, E. M. 1110-1-306, p. 5), case no. 2 should show a relationship between ice content and percentage of fines. It appears that a definite relationship exists in the soils below the permafrost table between ice content and the < 5µ soil fraction (Fig. 7, 10, 17, 29). A relationship also was observed between ice content and the percent < 5µ, but use of the < 5µ fraction generally gave better results. Some scatter of data points is to be expected since ice content varies not only with the fine soil fraction, but also with availability of water to form ice and sufficient time to build up large concentrations of ice. It is remarkable, in view of these interrelationships and possible errors in the determination of the < 5µ fraction, that the relationship is as clearly defined as these figures show.

A photograph taken during the permafrost excavation under Feature 3 (Fig. 50) clearly shows that the ice accumulation is in essentially horizontal layers.

In view of what has been presented, there can be little doubt that no. 2 is the correct postulation for the study area investigated. The ice has accumulated since deposition and progressively heaved the ground surface. How can this heave be estimated?

Estimate of heave since deposition

From Table XI the average void ratio of the frozen soil is about 2.0. The average dry density of the 0- to 6-in. layer of Feature 3 was about 125 lb/ft³. In Feature 5, the average dry density of the active layer is about 115 to 120 lb/ft³. Assuming a dry density of 120 lb/ft³ and a specific gravity of 2.70 (average of 28 tests of 14 samples in Features 1 and 5), then the void ratio of the present active layer is about 0.4. Then, an estimate of the average void ratio increase due to ice accumulation would be 1.6.

The excavation in Feature 2 showed a sudden increase in coarseness at the 9- to 10-ft depth (Fig. 8) accompanied by a decrease in water content (Fig. 9). Taylor observed that the soil below 8 ft was stratified outwash, while that above 8 ft was frost-stirred. From this, the writer estimates that the past maximum depth of the active layer was about 9 ft. Since the present active layer averages about 3 ft thick, there is a 6-ft zone of soil with marked ice accumulation.

If this 6-ft zone originally had a void ratio of 0.4, then it must have been only 2.8 ft thick. Thus, an estimate of the net ground surface rise to the time of this study, due to the accumulation of ice at the base of a rising frost table, is 6.0 - 2.8 = 3.2 ft. Whether the present ground surface was the ground surface throughout this period of ice accumulation cannot be determined with the present data.
The above would indicate that there is a history of net ground surface heave in the study area. It is now of interest to investigate the heave data obtained to ascertain if a net heave was measured during the time of this study.

Study of heave measurements

Figure 51 presents data points representing the average vertical movement of the six feature centers measured. The legend indicates the data symbol associated with each feature and the manner in which the vertical movement was measured. The heavy solid line represents an estimate of the composite average for all features where the curve is bracketed by the observed data. The data from Features 6, 7, 8, and 9 are plotted to best conform to the pattern of heave indicated by the data for Features 4 and 5.

As shown in Figure 40j and k, the approximate start of ground thaw is 1 June. Thus, an unknown amount of settlement occurred between the start of thaw and the first 1955 data points at the end of June. However, we do know from the heave plate data presented in Figure 28 that most of the freeze-up heave is concentrated in the 1-ft layer above the permafrost table. It is presumed that most of the settlement would also be concentrated in this zone. Since the frost table takes part of June to reach this depth, it appears unlikely that a large settlement occurs during this time. Figure 51 shows, by means of dashed lines, two of the possible interpolations of ground surface movement between September 1954 and June 1955. It seems reasonable to conclude that, over the time interval studied, a net annual heave did actually occur at the feature centers, estimated at about 0.05 ft. It should be mentioned that the summer of 1954 was markedly warmer than that of 1955 (ratio, at Tuto, of degree days of thaw for the period 2 July to 19 August was 379/253).
Figure 51. Composite average ground surface movement of feature centers.

Figure 52. Composite average ground surface movement of feature borders. Legend same as Fig. 51, except Feature 4: 32 border stones, Feature 9: 4 border ground water boxes.
The above estimate of net heave assumes the fixity of the bench mark placed in the study area. If the bench mark did move, it would be heaved. Thus, any conceivable bench mark movement would tend to increase the above net heave.

Figure 52 presents the average vertical movement in each of the five features in which such movement was measured in the borders of the feature. The data are not as complete as for the feature centers. However, it is sufficient to indicate that the heave-time pattern is similar to that for the feature centers. The settlement during the summer is not as great, nor is the heave during freeze-up. This is consistent with what is expected in an area where the vertical energy transfer is not as great as under the feature centers. That this energy transfer must be less is shown by the consistent observation of a thinner active layer under the feature borders—in spite of the fact that the specific heat of the border soil is less.

As shown in the figure, the writer’s estimate of the net heave from September 1954 to September 1955 is 0.03 ft for the borders of the features measured, compared with 0.05 ft for the feature centers.

**Consideration of feature formation time**

Looking at it most simply, we can say that since the total feature heave is 3.2 ft and the yearly heave is 0.03 to 0.05 ft, then the time of heave and feature formation is about 75 years. This reasoning assumes:

a. Feature development started at the same time as ice accumulation at the base of the active layer.

b. The yearly net heave has been constant over the period of heave and 1954-55 is an average year.

Data from Feature 2 indicate that at some time the active layer reached a depth of 9 ft. The original depth of the active layer was then 9 - 3.2 = 6 ft, as compared with the present 3 ft. This is a reasonable comparison when it is considered that the 68% water content soil layer was not originally present to block the penetration of the frost table at 3 ft.

Study of the lithology and gross mineralogy of the stones from the bench mark excavation indicated that the material in the present 0- to 7-ft layer was uniform in composition and presumably was deposited at the same time. The present 0- to 7-ft layer corresponds to the initial 0- to 5-ft layer. This is close enough to the initial 0- to 6-ft active layer to assume that the active layer during the course of this patterned ground development has been the same throughout.

Since it is expected that patterned ground development started as soon after deposition as the nearby glaciological conditions permitted (i.e. melt-water lakes), and a single deposition accounted for the active layer from which the patterns evolved, assumption a is essentially fulfilled.

Assumption b is another case. The development of ice layers requires a soil with a high concentration of fines and it requires that the frost table be at the depth of formation for sufficient time to permit the accumulation of ice at that level. Availability of water is assumed. Without a high water content permafrost table to hold the position of the frost table, it will only be at its deepest point for a short time with small ice accumulation. This was probably the condition during the initial stages of ice accumulation. Also, the high percentage of fines may have been due in part to frost-splitting of particles and the high content of fines presently measured may not have been as high originally. For these qualitative reasons it is likely that the net annual heave has been increasing as the features developed.

There is no way of determining the manner of increase, with time. A linear increase starting with 0, to the values measured would give a time of formation of about 150 years. A parabolic increase, starting with 0, to the values measured would yield 225 years. Since no other data are available, the net heave for the 1954-55 interval will tentatively be accepted as average for present conditions. However, as mentioned previously, the summer of 1954 was warmer than that of 1955 and thus the estimated net heave for this 1-yr interval may be greater than average.
QUANTITATIVE DATA FROM A PATTERNED GROUND

If the above were to be considered as estimates of the total elapsed time since the start of the formation of these features, then two additional assumptions must be acknowledged and investigated. These are:

c. The features are still actively forming.
d. The ground ice accumulation has been continuous since the start of formation.

There is no direct evidence that the features studied are still in the processes of formation. The surveys associated with Feature 4 indicated that radial movements of the surface stones are less than 0.5 in./year, if they are occurring at all. If assumption c is not fulfilled, then ice accumulation is presently occurring without continued feature formation. In this case, the above time estimates would be too long.

It is possible that past weather fluctuations have successively, for an unknown number of times, caused the melting of accumulated ground ice. In such years the yearly ground surface movement would be a settlement rather than the heave assumed. The total ice accumulation may have been much greater than 3.2 ft. Such a failure to fulfill assumption d would result in the above time estimates being too low—perhaps greatly so.

It is the opinion of the writer that the potential errors in assumption d outweigh all others. In this case, the time estimates presented would be minimum formation times. It is, therefore, the writer's opinion that the data and arguments presented indicate that the minimum time required for the formation of the features studied, to their present state, is about 150 years.

Soil grain size distribution within features

Distribuition in plan. When looking at a photograph of any of the sorted circle features in the study area, it might appear that the very coarse feature borders were separated from the much finer centers by some drastic sorting process, the effects of which should be noticeable for a considerable depth into the feature. This does not appear to be the case.

In each of the features investigated for soil grain size distribution, no. 1, 2, 3, and 5, the data showed that once past a depth of about 2 ft there appeared to be no significant differences in soil grain size distribution with radial distance from the center of the feature. This includes under the borders of the feature, although only 13 samples, over a depth range of 2 to 6.25 ft, were obtained from under the borders.

Thus, we have the interesting situation of sorted circles about 10 to 30 ft in diameter, which, while drastically different in soil texture at the surface, are uniform in texture below a depth of about 2 ft. The mechanisms responsible for the surface development of the patterned ground in the study area are confined to a relatively thin veneer (when compared to the plan dimensions of features) near the surface.

Within this veneer there is a distinct increase in coarseness with radial distance from the center. This statement is based on the data from the two features sampled in sufficient detail, no. 3 and 5. Figure 14 shows that the > no. 4 sieve fraction was greater in Feature 3 sampling locations 6 ft from the feature center than at locations only 3 ft from the center. Figure 25 shows that the center sampling holes in Feature 5 had a smaller > no. 4 fraction than the holes at the edge of the feature center. The data from the cobble orientation study presented in Figure 14 indicate that the density of cobbles 3 in. or longer, in the 0- to 6-in. surface layer and not breaking through the surface, averages about 5/ft³ for the center ring and 12/ft³ for the outer of the three rings. The average cobble size is about the same—3.8 in. for the center and 4.2 in. for the outer ring.

Besides the obvious surface difference between the coarse borders and the feature centers, there is a radially increasing concentration of the coarse-grained soil fractions within the centers. Correspondingly, the fine fraction decreases radially outward. This radial sorting occurs only in the 0- to 2-ft depth range of the active layer.

Another question which can be raised is whether or not the general slope of the feature area has any effect on the grain size distribution of the soils within the feature.
Reference to Table XI and the legend for Figure 51 will show that, with the exceptions of the almost circular Feature 5 and the 16' × 13'-ft Feature 8, the dimension of the center of the feature in the direction parallel to the slope is greater than the dimension across the slope. Since the general slopes range from about 0.5 to 1.5 it is surprising that these gentle slopes should so materially influence the feature center dimensions. In view of this, it is even more surprising that Table II (Feature 3) and Figure 24 (Feature 5) indicate no large differences in grain size distribution between the upslope and downslope sample locations within the active layer.

In plan, the sorting processes appear to be predominantly radial in nature—towards the feature borders, with the slope of the general area in which the feature is located playing a minor, if any, role in the sorting processes. Only the several feet at the surface appear to participate in the radial sorting mechanisms.

Distribution in elevation. Only Features 3 and 5 were sampled in sufficient detail to warrant use of their data in an overall study of vertical soil grain size distribution and sorting. Both features are of the depressed center type. The average profiles for three selected soil fractions, from Figures 14 and 25, are presented in Figure 53. Only the feature center is considered.

Consider first the > no. 4, or gravel, fraction. This fraction increases from 10% at the base of the active layer to 50% at the feature surface. Clearly, there is a vertical sorting process moving the coarse soil fraction towards the feature surface. This process is particularly active in the surface layer which is also sorting radially.

The mechanisms accounting for the upward movement of the coarser soil particles will not be discussed here. They are only partially understood. Vilborg (1955) discusses this phenomenon. For the purposes of this report, it is sufficient to state that the effects of such vertical sorting have been observed many times. Its effects were also observed in the study area. The data presented were for the feature centers. However, the feature borders also grade upward from fine to coarse gravel to cobbles to boulders at the surface. Taylor also reports lateral gradation in the borders at depths from 6 to 12 in. to the bottom of the border. This may result from the dish-shape of the borders. It should be noted that the vertical sorting of the coarse soil fraction may occur independently of any radial sorting. The two processes, acting independently, may account for the development of these features.

Why is there the concentration of < no. 200 fines around the base of the active layer and below? A number of explanations seem possible. First, the fines have been washed down from above. This is only possible in the active layer and above the ground-water table. It seems likely only when snow is melting at the ground surface, with the melt water seeping downward—possibly during the spring thaw or during the melt of drifted snow. During most of the summer the water movement in the active layer is more likely laterally downslope, as indicated by Figure 49, or vertically upward due to evaporation at the feature surface.

Another explanation is that the percentage of fines is higher because the coarser soil particles have been removed by vertical sorting. While this is a factor, it cannot be the total answer. The 20- and 50-in. depths have about the same percent of > no. 4 fraction, yet the percentage < no. 200 at 50 in. is 20% more! A third factor to account for the higher percentage of fines at the permafrost table and below is that the numerous cycles of freeze-thaw, as illustrated by Figure 39, mechanically weather the soil by frost-cracking and thereby increase the content of fines. The sudden increase in the < no. 200 fines in the 1-ft zone above the permafrost table, the same zone undergoing the most freeze-thaw cycles, indicates that frost cracking may be a major cause of the concentration of < no. 200 sieve fines.

The < 5µ soil fines show a distribution which may be significantly different than that of the < no. 200 fraction. The averaged data shown in Figure 53 do not show this as clearly as the individual feature data. Figure 14 shows a sudden increase in the < 5µ fraction at about 25 in., while the peak of the < no. 200 fraction is at 40 in. Figure 25 shows the sudden jump at 20 in., compared to a peak < no. 200 fraction at about 27 in. It appears that something happens to the < 5µ fraction that does not happen to the < no. 200 fraction as a whole—or vice versa.
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The < 5μ fines are almost completely absent above the normal summer groundwater table. This may indicate that this soil fraction is fine enough to be washed out by the ground-water flow that occurs at the 0- to 20-in. level during the initial thaw period. Or, it may have been completely sorted downward as part of the upward sorting of the coarser soil fractions. The latter possibility is strongly suggested by the recent work of Corte (1961-62).

On the other hand, it has been shown that the active zone may have been 6 ft thick. The soil fines may have been derived from frost splitting and accumulated with the estimated 3.2 ft of ice.

Radial sorting. It has been shown that the gentle slopes of the study area have a pronounced effect on the feature symmetry—the features are usually elongated considerably in the downslope direction. This was a common observation throughout the Thule-Tuto area. Everywhere there is evidence of the downslope movement of the active layer—a movement so well recognized it has been given the term solifluction. Although the exact mechanisms of solifluction are not known, it is generally believed that this movement is associated with soil conditions during early thaw.

When it is remembered that the soil sorting data indicate that only about the upper 2 ft of soil takes part in the radial sorting process, and that this is the depth of the active layer during the first month of thaw—there is an inference that the radial sorting may be associated with early thaw, and possibly solifluction. In discussions of Features 7 and 8, it was reasoned that it is likely that the borders of these features thaw first. This occurrence could provide a frost line sloping downward, approximately radially, towards these borders. This slope, with little effect from any surface slope (which may be toward the center rather than the border in a depressed center feature), may cause solifluction flow to provide at least part of the radial component of soil movement which obviously accompanies feature development.

CONCLUSIONS

1. The soil materials composing the patterned ground features studied were found to be of common mineralogy, grain size distribution, and plasticity. The chemical nature of the soil materials themselves does not contribute to feature formation in any observed manner. It is the mechanical processes acting on these materials that are important.

2. A sharp rise in the soil water content in the form of ice was consistently noted when passing through the base of the active layer into the present permafrost. An ice content-percent fines analysis indicated that ice concentration below the active layer has resulted from ice lens accumulation during a time when this zone was part of the active layer. The computed present net ice accumulation is about 3 ft.
3. Heave measurements made over a 1-yr period indicated that a net heave occurred at both feature center and border locations. The magnitude of the net heave is about 0.05 ft for the centers and 0.03 ft for the borders.

4. By comparing the above observed net heave with the total heave an estimate was made of the feature age. Necessary assumptions made this estimate one of minimum age—about 150 yr.

5. The distribution of the soil grain size fractions indicated that vertical sorting takes place over the entire depth of the active layer but that radial sorting is confined to approximately the upper 2 ft.

6. Measurements and studies of the ground-water flow indicate that the greater portion of the flow occurs through the feature borders.

7. Studies of the results of thermocouple temperature measurements within selected patterned ground features showed the importance of the magnitude of incoming radiation on the progression of the frost line.

8. At the time of the initial ground thaw, the thermocouple data indicated that the progression of thaw is very rapid. It is estimated that this thaw occurs first under and in the neighborhood of the feature borders. By the end of the summer, the thaw penetration is greatest under the feature centers.

RECOMMENDATIONS FOR FUTURE WORK IN THIS OR SIMILAR PATTERNED GROUND STUDY AREAS

Future research in the present study area, or a similar area, should emphasize continuing study of the following:

Heave and ground-ice accumulation

The concept of a net heave must be further substantiated to determine to what degree this can be considered an annual occurrence. The precise leveling done in Feature 4 should be continued over a period of 5 to 10 yr to firmly establish the magnitude of the yearly net heave. The leveling should be done four times each season—before spring thaw, immediately after the first rapid thaw, about 20 August, and, finally, after freeze-up about 15 September. A similar program in other features would add substantially to the applicability and dependability of the data obtained.

Several more excavations about 10 to 15 ft deep should be made to obtain more information about the total net ice accumulation that has taken place. The present estimate is based almost entirely on the bench mark excavation.

This study determined that the accumulation of ground ice could be an aid to feature development by providing additional drive for solifluction flow. However, it is not known to what extent this accumulation is necessary for feature development. A study of patterned ground in the Thule-Tuto area, or similar areas, to determine under what circumstances ice accumulations are found under existing patterned ground may provide important qualitative information.

Solifluction ground flow

The occurrence of lateral ground movement by solifluction during the spring ground thaw has been inferred from indirect measurements. It would be very valuable, at least for the purposes of checking the possible importance of solifluction, if direct measurements could be made of the factors associated with any such movement.

Horizontal movement. Another effort should be made to detect horizontal movement at the ground surface. As shown by the general failure of the precise triangulation surveys, in spite of the great care used by Taylor, this method is not suitable. It may prove suitable for longer periods between surveys. A horizontal photographic method is recommended. If possible, the photos should be taken as soon as the snow cover clears so that we will know not only how much movement there is, but also when it occurs.

Early frost table. The existing thermocouple installations should be used to attempt to follow the progression of the frost line during its initial rapid penetration (see Fig. 54).
For any new installations of temperature measuring equipment in the soil, it is recommended that thermistors be considered as well as thermocouples. Thermistors may be more rugged and more reliable.

**Additional cobble orientation studies.**

The information obtained from the limited study made in the surface 6 in. of Feature 3 has proved so interesting and potentially important that an extension of this type of study is recommended by both Taylor (personal communication) and this writer. The entire active layer should be sampled in at least one typical raised center and one depressed center feature. It will be necessary to drain the feature to permit this work. Perhaps this can be done by well-points.

Such a study should more clearly define the layer believed subject to solifluction movement, or prove the absence of such movement.

**Grain size distribution.** Orientation studies should be combined with grain size distribution studies made on the non-cobble fraction. This may provide important additional information. More comparative grain size studies are needed to better compare the raised and depressed types of features.

**Feature borders should be subjected to more intensive grain size distribution studies.** Careful sketches may suffice for description of the very coarse fraction in the borders. Quantitative data should be obtained to better understand the transition from borders to the adjacent centers and the soil below.

**Soil water content.** To determine if excess moisture is present to aid the mechanics of feature formation, the water content of the < no. 4 sieve fraction in that soil subject to radial sorting should be determined prior to and during the initial stages of thaw and continued until drainage is complete. Solifluction may be associated with high water content, a wet 0C frost zone, or both.

**Heave.** In conjunction with the above water content study it would be desirable to know the heave pattern for the 0- to 1-ft soil layer. The writer suggests surface disks and heave plates at the 0-ft depth.

**Ground-water washing.** It is possible that the soil fines are being removed by ground-water washing. This should be determined. If this is true, the ground water should be carrying fines which can be trapped. An open cylinder placed at the bottom or sides of the border, with its downslope end covered with a no. 200 mesh sieve, should collect some of the moving fine sands. If the fine sands are moving, then the still finer fractions must be too. The zones of deposition of the fines, if any, should also be determined.

**Incoming radiation and soil albedo.**

For more basic and complete understanding of the energy transfer being accomplished within the patterned ground features, the writer suggests that future studies include a continuous record of the total daily incoming radiation at the study areas. The percent reflectance, or albedo, of the different parts of a feature should also be determined when the ground is very wet during early thaw and again when the ground is about its driest during late summer.

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APPENDIX A.
GENERAL STUDY OF THE HEAT BUDGET OF THE ACTIVE LAYER

It is obvious that since only a small fraction of the total energy falling on a feature is used to thaw at the frost table, other important factors must enter into the thermal energy balance of the active layer. If all other factors remained constant and only incoming radiation were varied, the relationship between $Q$ and incoming radiation would be given by the dashed line in Figure 37. Since this dashed line does not represent actual conditions, some of the other factors in the heat budget must also vary with incoming radiation. It is worthwhile to study this heat budget in more detail for a better understanding of the importance of incoming radiation.

Figure A1 shows the various ways in which heat energy can enter, leave, or be stored in the active layer. It is possible to write equation 6, which expresses $Q$ as the value of incoming radiant energy, less a grouping of energy loss and energy storage terms. Not all of the terms in this grouping are of equal significance. An attempt was made to mathematically evaluate the values of $C_{\text{R}}, R_{\text{lw}}, E_{\text{s}},$ and $H_{\text{sa}}$ at Feature 7, but the radiation-temperature data were not sufficiently detailed. However, to show their relative importance, a table was prepared and included in Figure A1 to show the approximate magnitude of the different terms for a clear day in mid-July at the study area.

The four most significant energy loss terms, accounting for about 90% of the incoming radiant energy, are $C_{\text{R}}, R_{\text{lw}}, H_{\text{sa}}$ and $E_{\text{s}}$. Reflectance depends on the reflecting ability, or albedo, of the surface which the short-wave radiation strikes. It varies considerably with different types of soil (about 0.10 to 0.40)—in general being higher in the coarser, drier, lighter colored soils. The long-wave radiation depends on the fourth power of the absolute ground-surface temperature and does not vary much because of the small range in the absolute temperature of the ground surface. However, it does decrease on days with cloud cover—on the same days incoming radiation is lowered, $H_{\text{sa}}$ depends on the temperature difference between soil and air, and on the wind velocity. $C_{\text{R}}$

Almost all measurements from mid-June to mid-September at Feature 7, string no. 1 (Fig. A2), showed the ground surface to be warmer than the air temperature, indicating that the ground loses heat to the air. On days with high incoming radiation the ground-surface temperature rises and the conduction-convection heat loss increases. With ground-temperature rise the evaporation loss increases too. The above shows that as incoming radiation increases, the major energy losses also increase and account for the difference between the solid and dashed lines in Figure 37.

Now let us consider another possibility—that different parts of a patterned ground feature have different albedos, or different $C_{\text{R}}$ values. A relatively small difference of 0.05 in albedo would mean a difference of 30 cal/cm\(^2\)/day energy available—more than the average heat available for fusion at the frost table. The albedo of the ground surface may play an important part in determining the pattern of thaw penetration under a variable-textured ground surface. For instance, the coarse, light, dry border areas of Feature 7 (Fig. 32) will reflect more of the incident short-wave radiation than the finer, wetter, and darker vegetation-mantled center of the feature.
Heat energy balance for active layer

<table>
<thead>
<tr>
<th>COMING IN</th>
<th>GOING OUT</th>
<th>EITHER IN OR OUT</th>
<th>STORED OR RELEASED</th>
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List of symbols

- C = albedo = % reflectance of incoming short-wave radiation
- E = energy from evaporation of water
- \( H_f \) = heat conduction downward into frozen soil
- \( H_s \) = heat required to change temp. of active layer
- \( H_{sa} \) = heat transfer between soil and air by conduction-convection
- \( R_{lw} \) = long-wave radiation
- \( R_{sw} \) = short-wave radiation
- \( S_{sw} \) = specific heat of water
- \( T_w \) = temp of laterally moving water
- \( W_w \) = weight of laterally moving water
- \( x \) = horizontal distance of lateral water movement

Figure A1. Heat budget of the active layer.

Heat energy budget/unit horiz area/unit time during months of thaw

\[
R_{sw} = CR_{sw} + R_{lw} + E + H_{sa} + H_s + Q + H_f + \frac{WS}{x} (T_{w2} - T_{w1})
\]

\[
Q = R_{sw} - \left[ CR_{sw} + R_{lw} + E + H_{sa} + H_f + H_s + \frac{WS}{x} (T_{w2} - T_{w1}) \right]
\]

Approx magnitude of heat budget terms—clear mid-July day in the study area (cal/cm²/day).

- \( R_{sw} = 600 \)
- \( CR_{sw} = 200 \) (C = 33%)
- \( R_{lw} = 200 \)
- \( H_{sa} = 100 \)
- \( E = 50 \)
- \( H_f = 20 \)
- \( Q = 20 \)
- \( H_s = 5 \)

\[
\frac{WS}{x} (\Delta T_w) = \frac{5}{600}
\]
Figure A2. Difference $\Delta T$ between ground surface and air temperature in °C. Feature 7, string no. 1 (center).