Research Report 55

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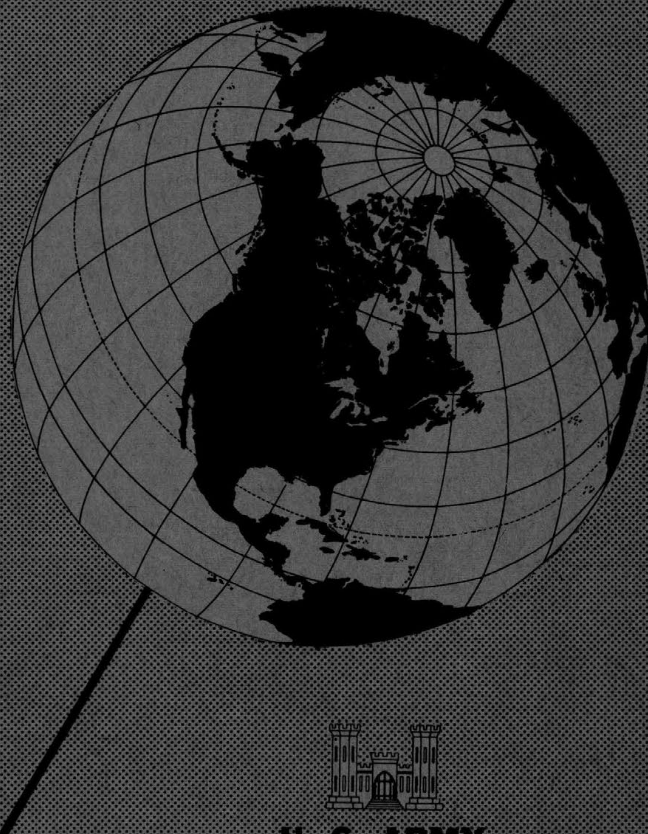
Experimental Formation of Sorted Patterns in Gravel Overlying a Melting Ice Surface



U. S. ARMY
SNOW ICE AND PERMAFROST
RESEARCH ESTABLISHMENT
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Experimental Formation of Sorted Patterns in Gravel Overlying a Melting Ice Surface

by Arturo E. Corte

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Wilmette, Illinois

PREFACE

This is a report of a field study at Thule, Greenland, during the summer of 1957, performed as part of USA SIPRE Project 22.3-5, Field and laboratory study of patterned ground, and Corps of Engineers Project 18. The purpose of this phase of the investigation was to study the behavior of a layer of soil over a melting body of ice, to obtain information of use in understanding the formation of patterned ground. It is reported separately from the principal study since the experiment was done on glacial ice and does not necessarily reflect the manner of pattern formation in soil.

The field work was performed under the direction of the Project Leader, Dr. Corte, Contract Scientist, Frozen Ground Basic Research Branch, assisted by Mr. John T. Tangerman, Project Assistant, Mr. Richard C. Setzer and personnel of the U. S. Army Polar Research and Development Command, then the U. S. Army Engineer Arctic Task Force. The report was prepared by Dr. Corte with the help of Mr. Tangerman. This project was under the supervision of Mr. W. K. Boyd, then acting chief, Frozen Ground Basic Research Branch.

The report has been reviewed and approved for publication by the Office of the Chief of Engineers.

Walter H. Parsons Jr.

WALTER H. PARSONS, JR.
Colonel, Corps of Engineers
Director

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SUMMARY

Experiments were performed to investigate the processes involved in the formation of sorted patterns which occur naturally in unconsolidated sandy gravel deposits covering the edge of the ice cap southeast of Thule, northwest Greenland.

Four different glacier ice surfaces were covered with various thicknesses of sandy gravel in order to observe the effect of differential melting on the formation of sorted patterns. The different stages of pattern formation were recorded by photographs taken at 7-day intervals. A thin gravel cover of 2 in. allowed more rapid melting than did a cover of 6 in., with the result that depressions and mounds were formed. Coarse particles were segregated in the depressions by natural sorting of the various particle sizes when set in motion by differential melting and resulting uneven collapse of the gravel cover. The sorting produced well-developed stone rings in three of the areas, caused directly by the differential insulation provided by the gravel cover. In the fourth area a uniform gravel cover over a smooth ice surface produced no sorted nets, although a poorly developed stone stripe was formed in a melt-stream channel. A stone stripe was also formed in a stream channel cut into the ice along the edge of the test area. This stripe was composed of coarse particles which rolled down from the better insulated heights of the test area.

It is therefore possible that sorted nets and stripes occurring naturally in the moraine deposits on the edge of the ice cap could have been formed by mechanical sorting induced by differential melting of the ice under a non-uniform layer of sandy gravel.

EXPERIMENTAL FORMATION OF SORTED PATTERNS IN GRAVEL OVERLYING A MELTING ICE SURFACE

by

Arturo E. Corte

INTRODUCTION

In the moraine that lies perched on the ice at many points along the edge of the ice cap near Camp TUTO, in the Thule area of northwest Greenland, there are good examples of sorted nets and rings (Fig. 1). These patterns are formed in unconsolidated materials ranging in grain size from boulders to fine sand, which form a cover over the ice varying from several inches to three feet in thickness. Excavations reveal that the concentrations of coarse particles occur above gutter-like depressions in the ice and the finer material above elevated portions of the ice surface (Fig. 2).

Figure 1. Sorted nets in gravel on glacier ice.

Figure 2. Ice surface under nets in Figure 1 exposed to show gutter-like depressions beneath coarse rock fragments.

Washburn (1956) described this type of pattern and suggested that it might be caused by differential thawing and eluviation, with perhaps combined up-freezing of stones and local differential heaving. He considers the differential heat diffusivity of different grain sizes the cause of differential thawing of the underlying ice. Sharp (1949) refers to sorting at the foot of debris-mantled slopes on a glacier in Alaska. No other references to sorted nets or circles in material overlying glacier ice were found in the literature.

Patterns very similar to those found at the edge of the ice cap were also observed by the author in outwash material, formed by the collapse of newly thawed material after the active layer had been removed. Figure 3 shows the sorted nets developed in a 4-in. gravel layer on the edge of the ice cap, and Figure 4 shows the patterns developed in the new active layer over permafrost four years after the active layer was removed and where the depth of the newly formed active layer is greater than 25 in. The mounds of fines in both cases show tension cracks developed by differential melting, a typical feature of such collapse patterns.

It was felt that a study of the behavior of a layer of soil over a melting ice body might provide additional information of use in understanding the patterns developed naturally in the moraine covering the edge of the ice cap and those developed in newly thawed material when the active layer is removed and the permafrost exposed. Therefore, a program of field experiments was designed to study the formation of patterns when layers of morainal material of different thicknesses are superimposed on various ice surfaces and subjected to insolation.

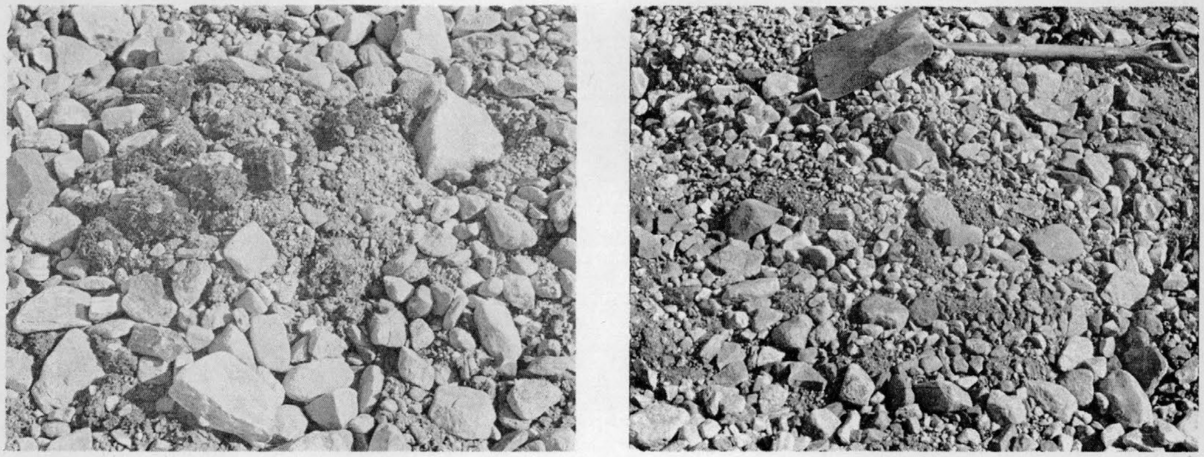


Figure 3. Sorted nets on glacier ice.

Figure 4. Collapse pattern of sorted nets developed 4 years after the active layer was removed from the permafrost.

PROCEDURE

Preparation of test plots

The site chosen for the field experiments is about 300 yd from the border of the ice cap, approximately east northeast of Camp TUTO. The ice was naturally covered by a layer of sandy gravel approximately 4 in. thick and containing cobbles and a few isolated boulders - morainal material which washed down the slope at the edge of the ice cap from the moraines above it. This layer was removed with shovels and piled at one side of the test site for later replacement over the test areas (Fig. 5). An area 25 x 25 ft was cleared on the ice and subdivided into four smaller test plots of 12 x 12 ft each. In order to vary the test conditions each area was modeled differently and/or covered with a different thickness of gravel.

In area A the ice was excavated to form a cross-shaped ditch with four hummocks (Fig. 6). This was covered with a layer of the sandy gravel removed from the site earlier and spread with a smooth surface and slight downward slope out of the test area (Fig. 7). The cross section of area A (Fig. 9) shows the slope and the fact that the gravel cover was thicker over the troughs than over the hummocks.

Area B was a smooth gentle slope with two closed depressions or holes in the ice (one of the depressions is seen to the left of center in Fig. 8). The entire area was

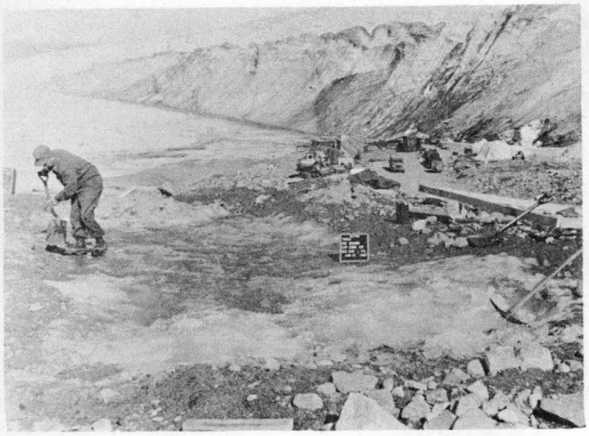


Figure 5. Experiment site being cleared on the ice cap.

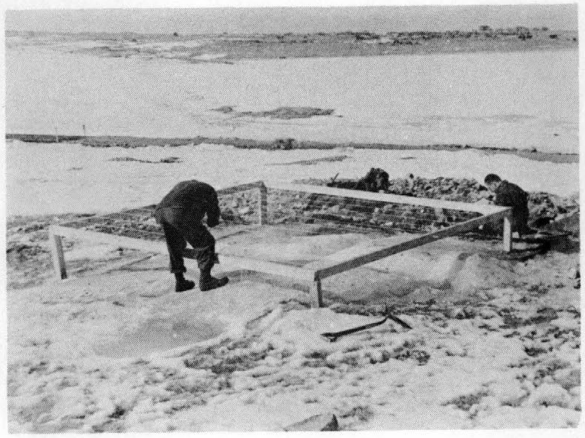


Figure 6. Area A. Ice surface showing cross-shaped ditch and four humps. String grid was used to map ice and gravel surfaces.

Figure 7. Area A after being covered with gravel.

Figure 8. Area B immediately after being covered with gravel.

covered with a more or less uniform layer of gravel, following the contours of the depressions (Fig. 8, 9).

Area C was a smooth slope covered with a uniform layer of gravel (Fig. 9, 10).

In area D the ice surface was made more or less level and covered with a uniform layer of gravel to which four mounds and a small ridge of gravel were added (Fig. 9, 11).

Measurements of ice and gravel surfaces

The prepared ice and gravel surfaces of each area were mapped as completed using a string grid mounted on planks and supported on posts sunk 2 ft into the ice to serve as a reference (Fig. 6). A measurement down to the surface was made from each junction in the string grid. Because of melting of the exposed ice surface during the time of measurement and while the gravel cover was being spread, the measurements cannot be considered more than approximate and relative to the actual conditions at the time the test began. Since the supporting posts used for reference melted out of the ice, it was impossible to remap the areas at the conclusion of the experiment. Therefore, only the profiles constructed from the initial maps are presented (Fig. 9).

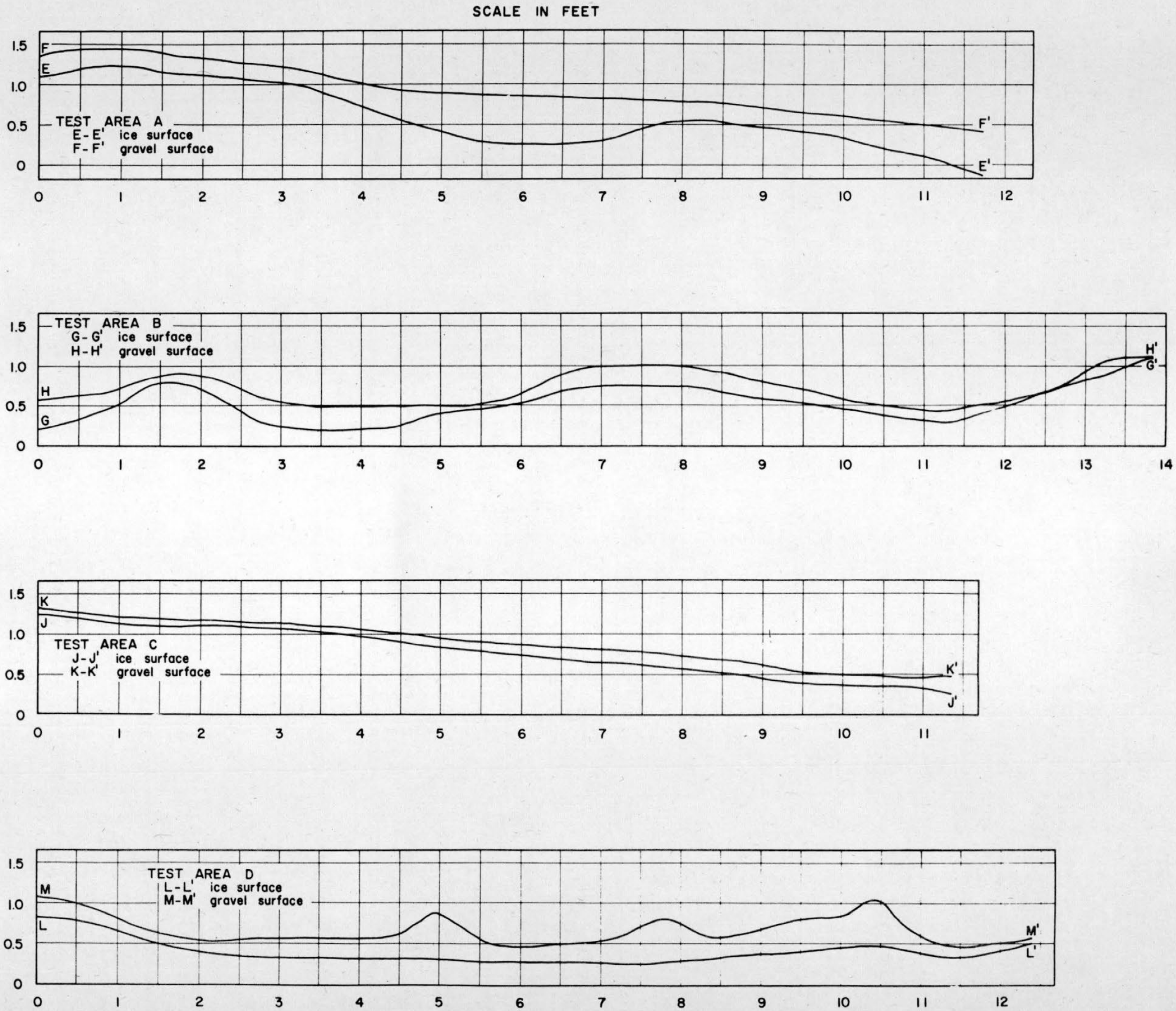


Figure 9. Cross sections of the experimental areas.

Figure 10. Area C immediately after being covered with gravel.

Figure 11. Area D immediately after being covered with gravel.

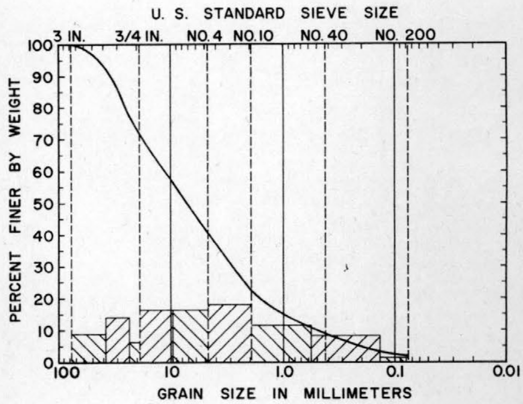


Figure 12. Grain size curve and histogram of the sandy gravel used in the experiment.

Composition of the gravel covering

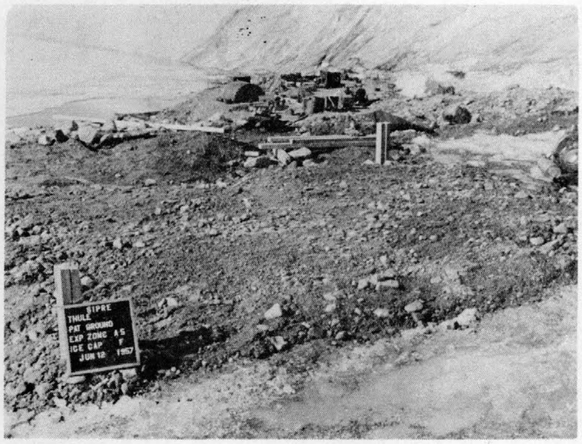
The sandy gravel spread over the test site was the morainal material originally removed from the area. A histogram and cumulative grain-size curve of this material (Fig. 12) shows that there were no silt or clay fractions in the material. The gravel mixture was spread over the ice with a shovel, making every effort to keep it as well mixed as possible. Except in specific instances where mounds of gravel were placed or depressions filled, a general thickness of cover of approximately 2 in. was used.

The changes on the ice and gravel surfaces were recorded by photographs taken every week from the start of the experiment on 12 June until its conclusion on 26 July 1957. Only a selected number of these photographs are presented in this report to illustrate the changes and development of patterns which took place. Because of the preliminary nature of this experiment, no attempt was made to instrument the test sites.

RESULTS

Sorting in a smooth layer of gravel over an uneven ice surface

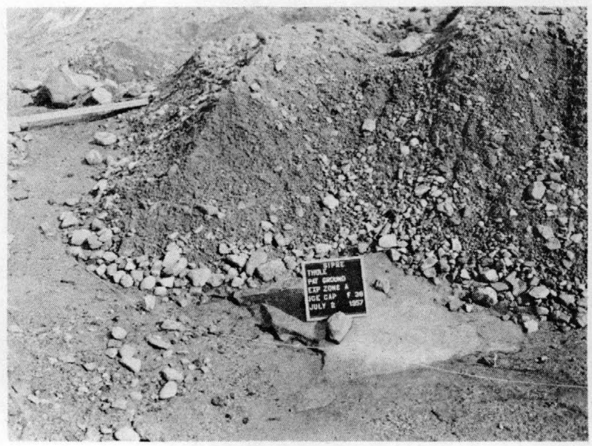
The ice surface of area A was cut by a cross-shaped ditch approximately 4 in. deep and covered by a smooth layer of gravel about 2 in. thick over the humps in the four corners and 6 in. over the ditches. Though not actually a part of the experiment, the ice surrounding the test area provided an interesting comparison during the melting period. The surrounding ice had been cleared, leaving most of it covered by a thin layer of sand a few grains in thickness and a few patches without any cover at all (see foreground of Fig. 6 and 13a). Therefore, four different degrees of insulation were present in area A and the ice surrounding it: 1) a 6-in. cover over the troughs, 2) a 2-in. cover over the humps, 3) a thin cover of sand over the ice surrounding the area, and 4) patches of clean ice without insulation outside the test area. Immediately after area A was covered with gravel on 12 June (Fig. 13a), the surface was smooth over the humps and ditches in the ice and the dirty ice around the test site was at approximately the same level as the gravel covering. Figure 13b shows details of the differential melting and subsidence between the 6-in. and the 2-in. covers after 2 days. More melt



a. Immediately after being covered with gravel.

b. After 2 days. Differential melt has begun to produce uneven collapse of the gravel with the result that tension cracks are formed.

c. After 9 days.



d. After 20 days. Well-developed sorting has been produced at the foot of the gravel mounds at the edge of the area.

Figure 13. Sorting in area A.

had taken place under the thinner cover and tension cracks had developed along the edges of the ridge created by the thicker cover over the original ditches in the ice. After 9 days of melting (Fig. 13c) the ridges of thicker insulation were well-developed and depressions had formed where the insulation was thinnest, along what was formerly the highest part of the humps edging the ditches. The portions of the humps which had a full 2 in. of insulation had melted somewhat, but were still slightly above the areas of maximum melt. Figure 13d shows the edge of the area and a cross section of two high mounds developed through the effect of the 2 and 6 in. layers of insulation after 20 days of melt. Slumping from the ridges and mounds of gravel had produced lateral extension of the features to some extent.

The ice surface adjacent to the test area melted more rapidly because of the very thin insulating cover. However, the small area where the sign was placed had no insulating cover and therefore a higher albedo, so that more of the sun's rays were reflected and less melting took place than in the surrounding ice where the thin layer of sand grains absorbed heat.

A comparison between Figures 13a and d shows the great melt that occurred during 20 days and the considerable sorting which was produced at the foot of the mounds of ice covered with a heavy sandy gravel mantle. The sorting of coarse stones to the bottom of the mounds was due to differential movement on the slopes created by differential melting.

During the experiment approximately 20 in. more ice was melted under the 2 in. insulating cover than under the 6 in. cover. The surrounding ice surface which was covered with a few hundredths of an inch of sand melted about 48 in. more than the heavily insulated ice. Clean ice and ice covered with scattered particles of sand melted more slowly than the ice covered by a thin but continuous layer of sand.

Sorting in a uniform layer of sandy gravel over depressions in the ice surface

Area B was a smooth ice surface with two holes or depressions about 8 in. deep cut into the ice, plus a linear depression or valley of the same depth between the two holes. This surface was covered with a uniform layer of gravel about 2 in. thick, including the bottom of the holes. Figure 8 shows the area immediately after the covering of gravel was spread. The holes filled with melt water very quickly, but the following day the water cut through the rim and drained out. Coarse particles sliding down the walls had already begun to sort themselves around the bottoms of the holes (Fig. 14a). By 21 June a mound developed in the center of the hole had reached the approximate level of the surface surrounding the hole (Fig. 14b), and on 2 July was higher than the surrounding gravel (Fig. 14c). At the end of the experiment on 26 July the center of the hole had become a mound slightly higher than the surrounding surface and ringed by a slight depression into which the coarser particles had sorted, both from the walls of the hole and later from the slopes of the mound (Fig. 14d).

The depression was transformed into a mound by changes in its gravel cover. When the hole was filled with water there was intensive melting and collapse of cover material into the hole. After the water drained out, the hole had a heavier gravel cover than the surrounding ice. The latter, therefore, melted down more rapidly, leaving the former bottom of the hole raised as a mound. A parallel situation was created at the outset of the experiment in area D where mounds of gravel were formed artificially on the insulating cover. Differential melting and collapse of the coarser particles to form a ring around the mound produced the same pattern created in area B by a more roundabout process involving more steps. This sorting is well illustrated by the numbered stones, particularly 5 and 6, in Figure 14. Stones 5 and 6 appeared when the water drained out of the depression, covered for the most part with sand. As the mound developed and the sand settled, the stones were more fully exposed and stone 6 began a noticeable migration down the slope of the mound. Smaller changes in position may be observed in many of the other stones.

The valley between the two holes in area B became a channel for melt water from another area and was therefore incised more deeply than it would have been otherwise. Sorting of coarse particles down the sides of the valley to the center took place in the same way as it did down the slopes of the holes and mounds in this area. The melt stream was then diverted artificially so that the only water flowing through the valley was melt water from the valley walls. Sorting continued in the same way (Fig. 15a, b). Eventually melting at the sides lowered the valley sides and surrounding area to the level of the valley center, which did not melt as fast because of the insulating material washed into it. The valley therefore, was obliterated and became a flat area, though the the lines of coarse particles remained fairly well-defined at the end of the experiment (Fig. 15c).

Melt water from the valley formed a small pond at the edge of the area, observed on 14 July. Sorted nets had formed at the border of the pond by differential melting from the streams entering the pond (Fig. 20, right). As this had not been observed before, the different stages in the sorting were not recorded.

a. One day after gravel cover was spread. Melt water filling the depression has melted out a channel and drained. Sorting of coarse particles down the walls of the depression is already well-developed.

b. Depression seen in a) after 9 days of melting. A mound has begun to form at one edge of the hole due to an increase in insulating cover produced with gravel slumped into the hole.

c. After 20 days of melting. The gravel surface surrounding the hole has sunk through differential melting to leave the mound raised above the general level.

d. After 44 days. The depression has been obliterated, leaving a mound and sorted net.

Figure 14. Sorting in a depression, area B.

Sorting in a uniform layer of sandy gravel over a uniform ice surface

Area C was a smooth, gently inclined ice surface spread with a uniform and smooth layer of gravel as used in the other areas (Fig. 9). During the period of melt very little sorting was observed. A general drainage pattern developed running down the slope in the form of shallow valleys into which coarse material collected to form poorly developed stone stripes, but in general the amount of sorting was very small (Fig. 16). No sorted nets were developed in this area during the period of observations.

Sorting in a non-uniform layer of sandy gravel over a uniform ice surface

A more or less smooth and uniform ice surface was covered by a uniform layer of sandy gravel in area D, to which four conical mounds of gravel about 8 in. above the general surface were added, plus a small ridge of the same height and about 4 ft long (Fig. 9, 11). The sequence of melt, collapse, and pattern formation are shown in

a. Sorting in a melt-stream channel 16 days after the area was covered with gravel.

b. After 28 days. Sorting is intensified as valley walls become steeper.

c. After 43 days. Sorting is less clearly defined because the stream was diverted and further melting served to flatten out valley walls.

Figure 15. Sorting in a melt-stream channel, area B.

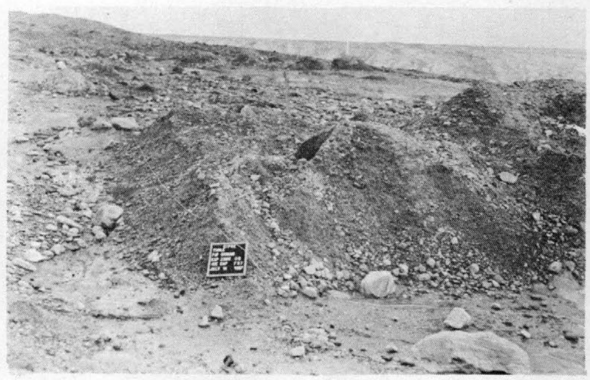
Figures 11 and 17. As in the other areas, the ice on two sides of the area was covered by a fine layer of sand grains, with the result that it melted at a much greater rate than the test area, leaving the latter raised well above the general level of the ice cap surrounding it.

Because of the greater insulation, the ice under the gravel mounds and ridge melted less than the rest of area D, thereby increasing the local relief greatly. The sorting around the bases of the mounds and ridge (Fig. 17b, c), a result of the original topography intensified by differential melting, is analogous to that observed in area B where the mounds developed within the holes. Figures 17b, c also show an accumulation of coarse material at the base of the ice and gravel mounds at the edge of the area, as well as a similar concentration in the shallow but steep-walled valleys which occurred at the edge of the area. A close-up of one of these valleys is seen in Figure 17d. Note also the developing concentration of stones in the valley of the melt-water stream running down along the left side of area D (Fig. 17a-c).

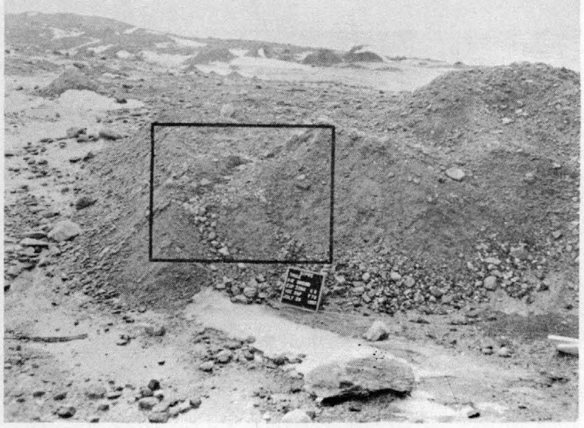
Two of the gravel mounds are seen in Figure 18a immediately after being placed on 14 June. Seventeen days later (Fig. 18b), the mounds had expanded radially while

Figure 16. Area C. Poorly developed sorting in a melt-stream channel 43 days after the ice was covered with gravel.

a. Nine days after being covered with gravel. Melting has progressed rapidly and sorting of coarse material into depressions is readily seen.



b. After 28 days of melting. Concentration of coarse material at the foot of the mounds and in the drainage channel at left is well-developed.



c. The same view seen in a) and b) after 40 days of melting. Boxed area is shown in d).

d. Stone stripe developed in a former drainage channel between two mounds at the edge of the area.

Figure 17. Sorting in area D.

a. Conical gravel mounds immediately after being placed on 14 June.

b. After 17 days. The mounds have joined due to lateral extension. Sorting is already evident on the lower slopes.

c. After 30 days. Sorted nets produced from gravel mounds.

d. After 43 days. The second mound is only partly visible at top center.

Figure 18. Details of sorting in area D.

sorting down their sides had begun to produce a concentration of coarse material around their bases. At the same time the mounds had begun to level out, approaching the base level of the surrounding gravel cover. By 14 July the two mounds had sunk to the base level of the gravel surface (Fig. 18c), leaving two stone rings which touch each other at one point on their perimeters. (In Fig. 18c the second stone ring is only partially shown, in the upper left corner.) Two weeks later (Fig. 18d) the surface was smooth and no further sorting of the material was apparent.

No clear sorting was observed in the other mounds, located at the edge of the area, because differential melting at the borders destroyed the gravel features.

Figures 19 and 20 show the similarities between the sorted patterns produced naturally in a gravel layer over the ice and those produced artificially by differential melting in the field experiments.

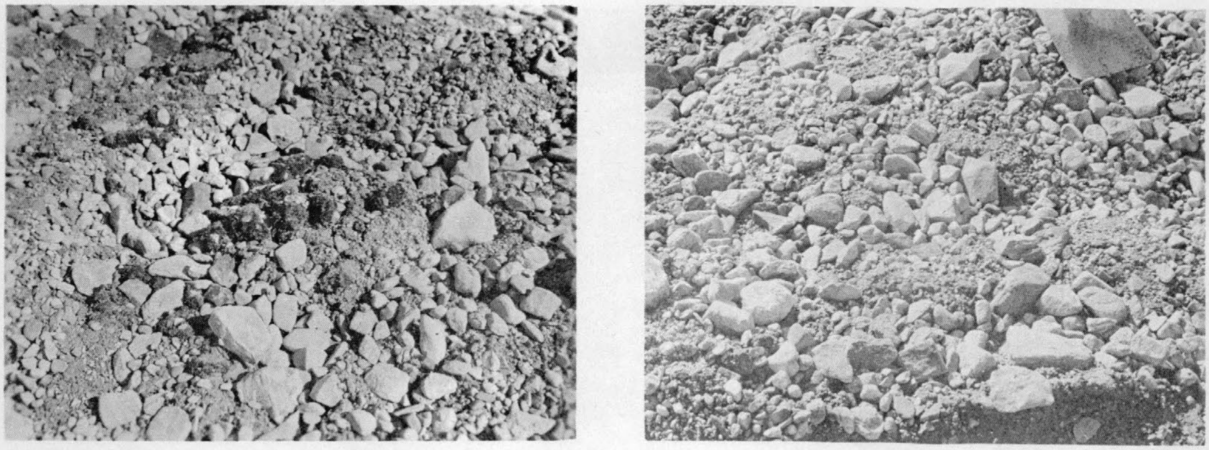


Figure 19. Sorted nets produced naturally in gravel deposits on the ice cap.

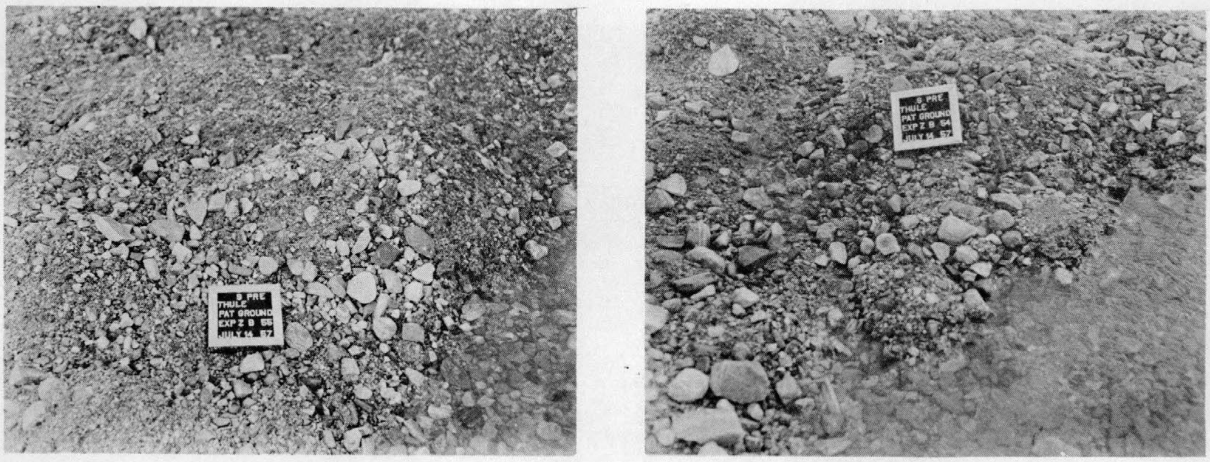


Figure 20. Sorted nets produced experimentally in a layer of gravel overlying ice by differential melting and mechanical sorting.

DISCUSSION AND RECOMMENDATIONS

The experimental formation of sorted nets in a layer of gravel of varying thickness on the ice cap has demonstrated that sorting was produced mechanically upon collapse of portions of the layer due to differential melt of the underlying ice. Concentration of coarse material in melt stream channels cut into the ice is the result of both mechanical sorting and washing out of the finer fractions. For a quantitative evaluation of this process a collection basin was excavated in the ice downslope from the test site, and melt streams from areas A and B were directed into it. After a very few days of melt the basin contained over 2 ft^3 of fine sand. This basin was subsequently destroyed by additional melting of the ice so that actual volumes were not determined. Further experiments are needed to determine what surface slope and particle size are critical in this washing process.

No evidence of a melt trough or depression was discovered beneath the ring of coarse particles developed at the foot of the test area. As its relative height was increased through differential melt of the surrounding ice (Fig. 13d, 17b), it is possible that equilibrium was not reached during the period of the experiment and mechanical sorting continued to move this material in a lateral direction from the test area, thereby preventing the development of depressions.

The test area with a uniform thickness of gravel over a smooth ice surface did not develop sorted nets. Poorly developed sorting occurred along the drainage channel produced by melt water through the center of the area (area C), indicating that differences in insulation are necessary to produce sorted nets. A comparison of the surfaces of the four areas at the end of the experiment, particularly of areas B and D with C, demonstrates clearly that sorting was produced mechanically because of differential melting of the underlying ice surface and resultant collapse of the gravel cover.

As suggested by Washburn (1956, p. 808), differential heat diffusivity of coarse and fine particles might cause the formation of certain sorted patterns formed over the ice. However, in this experiment the gravel cover was well mixed and differential melt was caused by variations in the thickness of the insulating gravel. It is therefore believed that differential heat diffusivity from point to point was negligible and consequently not a primary factor in the formation of these experimentally produced patterns. Further investigation must determine whether the depressions in the ice under stone rings can be explained by differential heat diffusivity, by melt streams flowing more easily through coarse material, or by a combination of these processes. Experiments should also be conducted to determine the actual values of differential heat diffusivity for materials of different grain sizes.

According to engineering standards (Department of the Air Force, 1954), inorganic soils containing less than 3% by weight of grains finer than 0.02 mm in diameter are generally non-frost-susceptible. Since the material used for the experiment was a clean sandy gravel with 2% finer than 0.1 mm, it was therefore non-frost-susceptible. In addition to this fact, the air temperature reached freezing only on ten nights during the experiment for short periods of time and went below 30F on only three nights, two of which were at the beginning of the experiment and one at the very end. Therefore, frost heaving can be ruled out as a factor contributing to the sorting produced.

The similarity between the patterns produced naturally and artificially on the ice cap and those observed in outwash material from which the active layer had been removed and allowed to reform may be explained at least partially by mechanical sorting. Collapse due to differential melting of the ice in the permafrost would provide the same conditions obtained in the ice cap experiment, and therefore allow mechanical sorting of coarse particles into depressions.

Figure 21 is a generalized block diagram showing the stages of differential melting and sorting produced by a non-uniform layer of gravel on a uniform ice surface. Patterns are produced by differential melting beneath gravel cones and by sorting into drainage channels produced by melt water from the area. $\underline{H}$ represents the original thickness of the ice body and $\underline{\Delta h}$ the thickness of ice lost through melt as patterns are formed. ($\underline{H}$ and $\underline{\Delta h}$ do not necessarily represent actual measurements, but rather the principles involved.)

CONCLUSIONS

The following conclusions can be made from the results reported in this paper.

1. Varying thicknesses of a non-frost-susceptible gravel cover produce differential melting of the underlying ice. Coarse particles set in motion by the collapse of the gravel cover are concentrated mechanically into depressions.

2. The sorted nets and stripes produced experimentally were similar to those occurring naturally in the gravel covering the edge of the ice cap. Therefore it is considered that formation of the natural pattern is started by differential melting under a gravel cover of non-uniform thickness.

3. Mechanical sorting produced by differential collapse of the newly thawed permafrost is considered a primary factor in sorted pattern formation in outwash material from which the natural active layer has been removed.

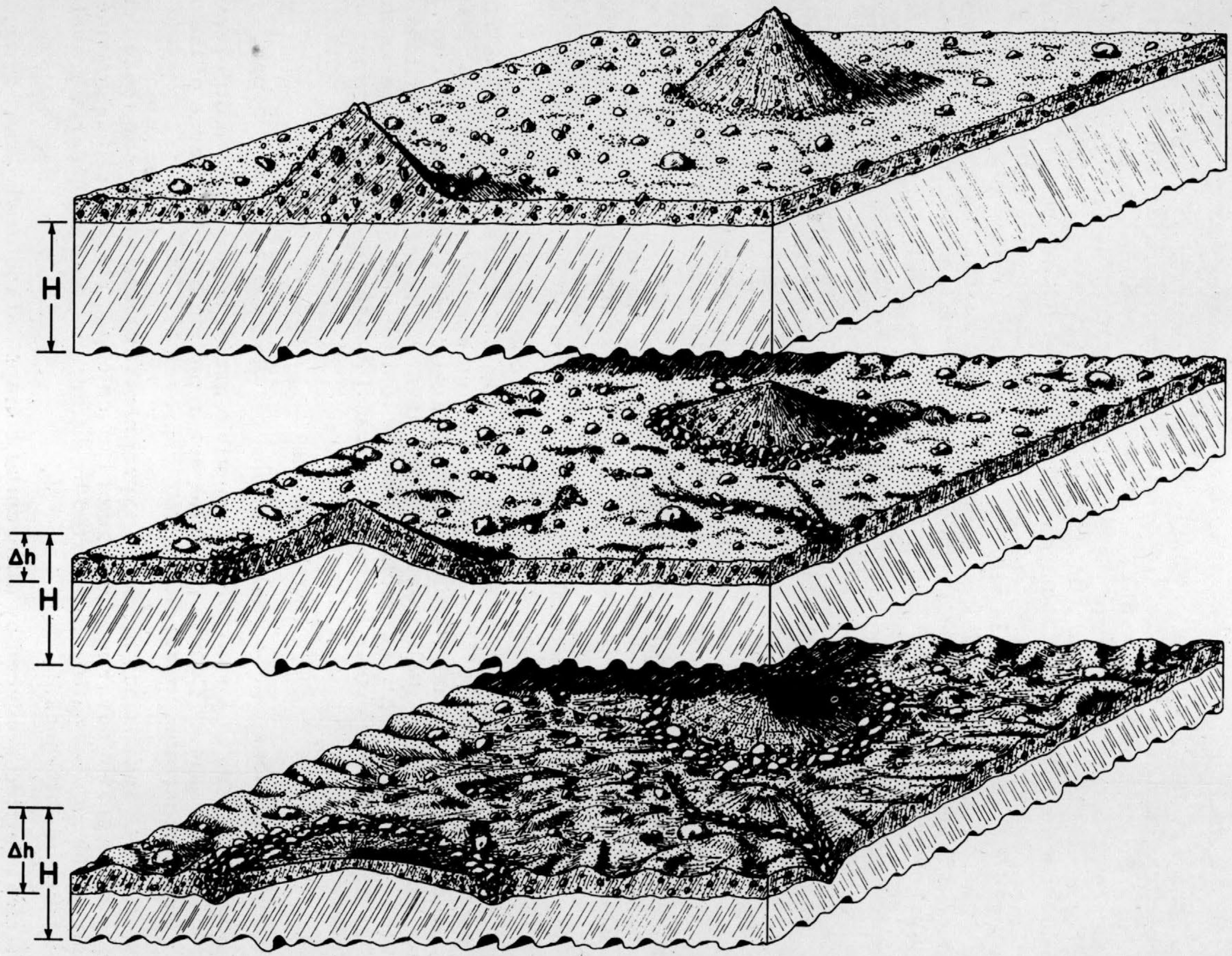


Figure 21. Block diagram showing the process of mechanical sorting in gravel produced by differential melting of the underlying ice. H represents the original thickness of the ice and Δh the amount lost through melt.

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