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

Abstract

Experiments were performed to investigate the processes involved in the formation of sorted patterns which occur in the 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 without fines in order to observe the effect of differential melting on the formation of sorted patterns. A thin gravel cover of 5 cm allowed more rapid melting than did a cover of 15 cm, with the result that mounds and depressions were formed. Coarse particles were segregated in the depressions by a 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 cases where the gravel cover varied in thickness. In a 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 large stone ring formed around the test area as the surrounding poorly insulated ice melted down at a more rapid rate. It is concluded that the sorted nets and stripes occurring naturally in the moraine deposits on the edge of the ice cap were initiated by mechanical sorting induced by differential melting of the ice under a non-uniform layer of sandy gravel. This process very likely plays an important part in the formation of collapse patterns observed in newly thawed permafrost from which the active layer had been removed.

PREFACE

This report presents data and analysis from a field experiment performed during the summer of 1957 on the ice cap near Thule, Greenland. The investigation was part of a comprehensive project conducted by the Frozen Ground Basic Research Branch of the U. S. Army Snow, Ice and Permafrost Research Establishment titled „Field and Laboratory Studies of Patterned Ground". The report was prepared with the help of Mr. John T. Tangerman, Project Assistant, and is published with the kind permission of USA SIPRE and the Government of the United States of America.

INTRODUCTION

Well-developed sorted stone stripes and nets occur in morainic material covering the edge of the ice cap near Thule, northwest Greenland (pl. 1). Removal of the gravel from the ice reveals that coarse material rests in shallow gutters or grooves in the ice and the centers of finer material lie on raised portions of the ice (pl. 2).

Washburn (1956) described this pattern and suggested that it was produced as a result of differential heat diffusivity of the various grain sizes, aided by local differential heaving.

The author observed very similar patterns developed in permafrost rich in segregated ice masses when the active layer was removed (pl. 3). Collapse of the permafrost due to differential metling produced a pattern of elevations and depressions with coarse particles sorted into the depressions. A field experiment was therefore undertaken to investigate the process of pattern formation in gravel layers on the ice cap and its role in patterns formed in thawing permafrost.

PROCEDURE

Four plots of 4 × 4 m each were chosen as experimental areas on the edge of the ice cap and designated A, B, C and D. The gravel naturally overlying the ice was removed (pl. 4) and the ice was smoothed and modelled for the experiment. Since the work was performed rather crudely with shovels and paving breaker, absolutely smooth ice surfaces were not obtained.

The material naturally covering the ice at this location was a sandy gravel with only 2% of the particles finer than 1 mm in diameter.

After the ice surface was prepared, it was mapped, using a string grid mounted on timbers and supported on posts sunk into the ice (pl. 5). The ice was then re-covered with a layer of the gravel originally removed from it and this surface mapped. Due to an unforeseen amount of ablation, the supporting posts were melted out of ice during the experiment and the surface could not be remapped at the end. Therefore, only representative profiles of the four areas will be presented. In these profiles, the relationship of gravel and ice surfaces is not absolute as the latter melted down while being mapped and covered with gravel.

The ice surface of area A was grooved with two troughs to form a cross, as shown in plate 5. Gravel was spread over this to produce a smooth, slightly inclined surface (pl. 6) and a thickness that varied from roughly 15 cm over the troughs to 5 cm in the four corners (fig. 1).

Area B was a slightly inclined smooth ice surface with two depressions. The entire plot, including the bottoms of the depressions, was covered with a uniform gravel layer 5 cm thick (fig. 1; pl. 7).

The ice surface of area C was gently sloping and flat, and was covered with a uniform 5 cm layer of gravel (fig. 1; pl. 8).

Area D consisted of a flat ice surface covered with a 5 cm layer of gravel to which four 15 cm mounds and a ridge of gravel were added, increasing the gravel cover to 20 cm at these points (fig. 1; pl. 9).

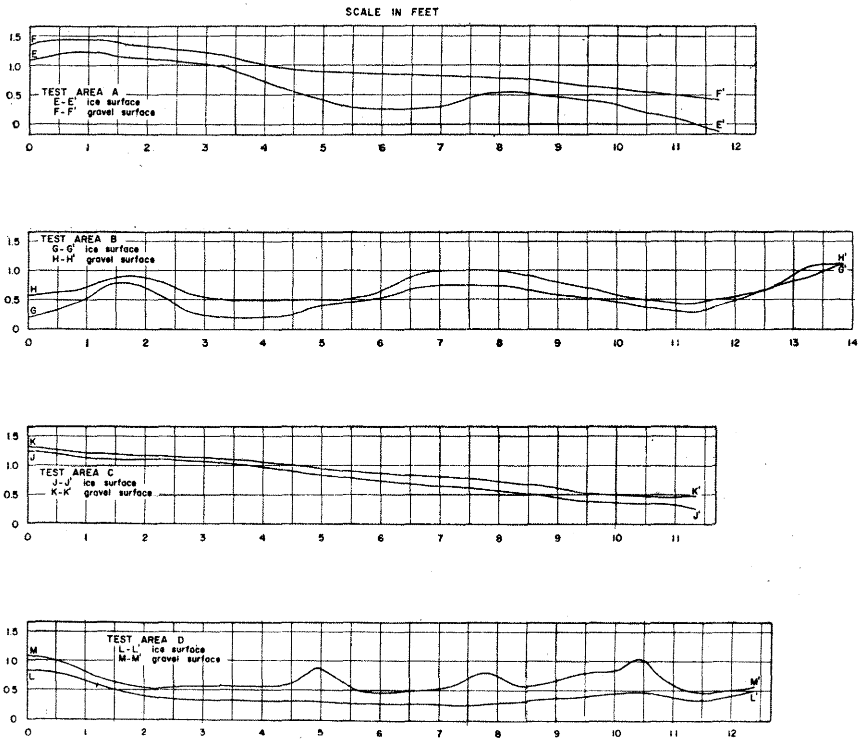


Fig. 1. Cross sections of the experimental areas

Most of the ice surrounding the test area was covered with a thin layer of sand a few grains in thickness, but some patches of bare ice also occurred. Thus the surrounding ice presented two other conditions of insulation and albedo for comparison with the test areas.

RESULTS

Sorting in a smooth layer of sandy gravel over troughs in the ice surface, Area A

This area exhibited the greatest differential melting. The two troughs, having the thickest gravel cover in area A, developed into a raised cross with tension cracks along its sides after ten days of melting (pl. 10). The greatest collapse occurred at the edges of the trough where the insulation was thinnest, and this caused mounds to develop in the four corners of the area where an intermediate thickness of insulation prevailed.

After 20 days of melting, the cross and mounds were large elevations relative to the surrounding area. A remarkable sorting of coarse particles was produced in the depressions and also at the borders of the area, where coarse material rolled down the slopes created by the greater ablation of the surrounding ice (pl. 11).

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

The entire surface of area B had been covered with a uniform 5 cm cover of sandy gravel, including the two depressions. After 9 days of melting, the area did not exhibit any large changes in relief. The small changes in the gravel surface can be attributed to a slightly uneven ice surface due to difficulty in leveling it and slight differences in thickness of the gravel layer.

At the beginning of the experiment, the depressions filled with melt water. Within 2 days, however, the water cut a groove through the rim of the depressions and drained out (pl. 12 a). After the drainage occurred, it was observed that coarse particles had rolled into the depressions and sand had washed in to provide greater insulation relative to the surrounding area. As a result, the depressions began to rise relative to their surroundings because the latter melted more rapidly (pl. 12 b). By the end of the experiment, the depressions had been transformed into mounds with coarse particles concentrated around their bases (pl. 12 c). Coarse particles had also slumped into the drainage channel (indicated by the dashed line in plate 12) to form a stone stripe.

The sorting which occurred during the conversion of the depression into a mound is illustrated by the numbered stones in plate 12. Of particular interest are stones 5 and 6, which were almost completely covered by sand as the depression drained. As the mound developed, these stones were uncovered and stone 6 migrated to the basse of the mound. Radial movement of large stones as the mound developed may be observed to a lesser extent in many of the other stones.

Sorting in a uniform layer of sandy gravel overlying a smooth ice surface, Area C

Area C, a smooth ice surface under a uniform layer of gravel, showed the smallest changes in relief of the four areas. Twenty-eight days after the beginning of the experiment, this area failed to show any well developed sorting, such as observed in the other areas. However, a small stone stripe did develop in a drainage channel which formed through the center of the area (pl. 13).

Sorting produced by gravel mounds and a ridge overlying a smooth ice surface, Area D

At the beginning of the experiment, the four mounds and the ridge of gravel in area D were well separated and distinct from one another. After 18 days of melting, the surrounding gravel surface had collapsed sufficiently to steepen the sides of the mounds so that material moving down the slopes spread radially, causing the perimeters of some of the mounds to join (pl. 14). These mounds had flattened almost to the base level of the area by the end of the experiment, to form simple sorted rings of coarse material (pl. 15).

Due to the lack of insulation, the ice surrounding the test area melted at a much greater rate than the insulated ice of the test area, with the result that a relief of 180 cm was reached by the end of the experiment. The patches of bare ice noted at the beginning of the experiment did not melt quite as fast, due to their greater albedo, as in the case of the ice under the title board in plate 11.

The great difference in rates of ablation between the test area and the ice surrounding it resulted in steep slopes developing between the two levels. Well defined sorting occurred at the bases of these slopes, where a ring of coarse material collected as a result of mechanical sorting down the slopes (pl. 16). A melt stream running down the slope of the ice cap accentuated this sorting by concentrating coarse material in its channel where it ran close beside the test area.

The similarity between patterns developed naturally in a layer of gravel on the ice cap and those produced experimentally (pl. 17) is striking, and indicates that both patterns are formed by essentially similar processes.

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 gravel layer due to differential melt of the underlying ice. Concentration of coarse material in melt stream channels cut into the ice was 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 down slope from the test site and melt streams from Areas A and B were directed into it. Afer a very few days of melt, the basin contained over 2000 cc of fine sand. This basin was subsequently destroyed by ablation 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 (pl. 16). The explantaion is perhaps that equilibrium was not reached during the period of the experiment and that mechanical sorting continued to move this material in a lateral direction from the test area, and therefore such depressions could not develop.

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 due to 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. Whether differential heat diffusivity can account for the depressions in the ice developed under stone rings or whether it is melt streams which can flow through coarse material more easily, or perhaps a combination of both processes, must be determined by further investigation. Experiments should also be conducted to determine the actual values of differential heat diffusivity for materials of different grain sizes.

The material used for the experiments was a clean sandy gravel with 2% finer than 0,1 mm. According to engineering standards (Dep. 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. In addition to this fact, the air temperature reached freezing only ten nights during the experiment, for short periods of time, and went below 30° F 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.

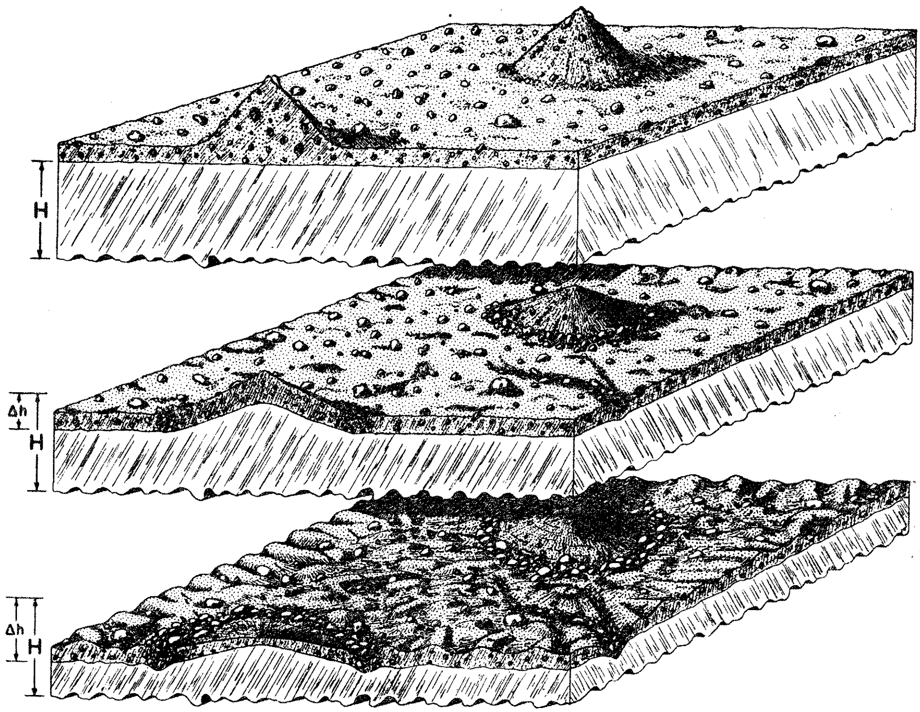


Fig. 2. Block diagram showing the process of mechanical sorting in gravel produced by differential melting of the underlying ice. *H* represents the original thickness of the ice and Δh the amount lost through melt

The similarity between the patterns produced naturally and artificially on the ice cap and those observed in outwash material from which the active layer has been removed and allowed to re-form may be explained at least partly 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 2 is a generalized block diagram showing the stages of differential melting and sorting produced by a non-uniform layer of gravel on an 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. *H* represents the original thickness of the ice body and Δh the thickness of ice lost through melt as patterns are formed. (*H* and Δh 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.

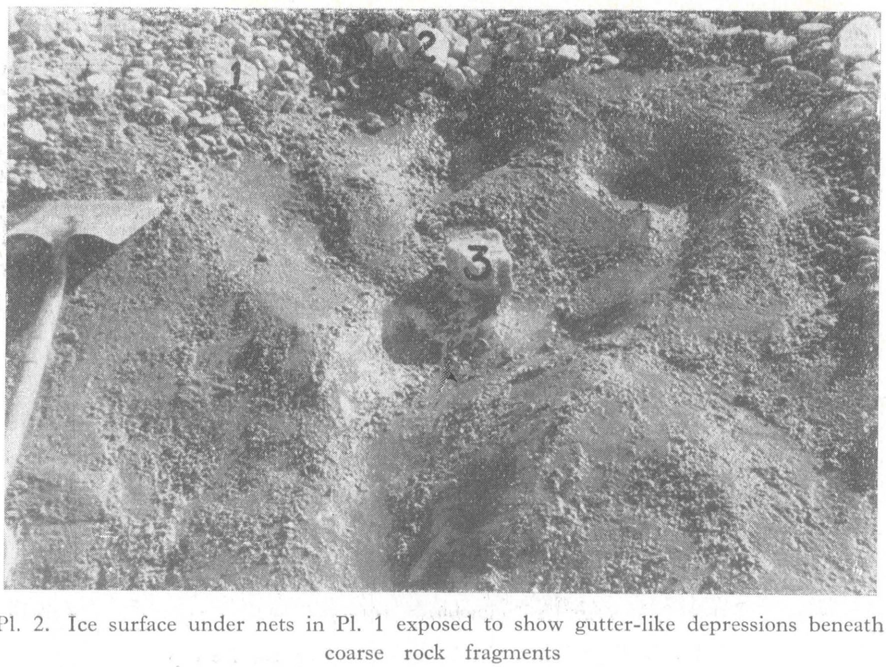
3. Mechanical sorting produced by differential collapse of the newly thawed permafrost is considered a primary factor in sorted pattern formation in outwash material from which the natural active layer has been removed.

References

Washburn, A. L. 1956 — Unusual patterned ground in Greenland. *Bull. Geol. Soc. America*, vol. 67; p. 807—810.

Department of the Air Force, 1954 — Engineering manual for military construction, Part XII: Airfield Pavement Design, Chapter 4: Frost Conditions, (AFM 88—6), Washington, p. 2.

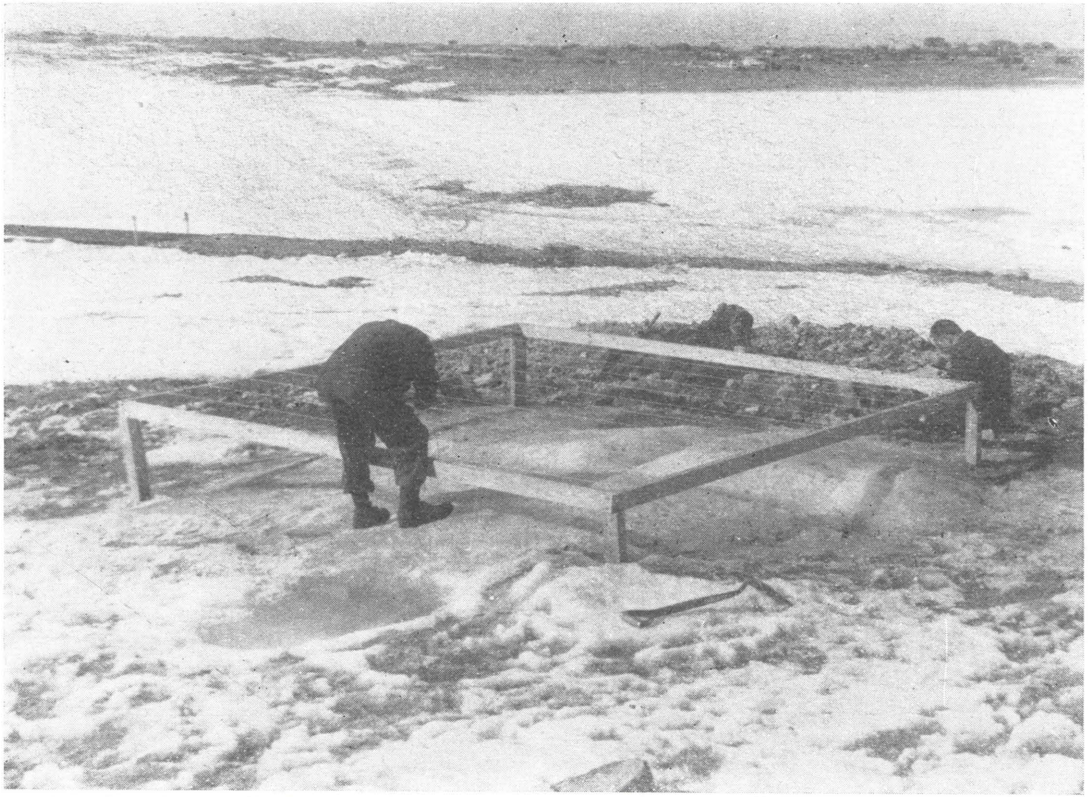
Pl. 1. Sorted nets in gravel on glacier ice



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

Pl. 3. Collapse pattern of sorted nets developed four years after the active layer was removed from the permafrost

Pl. 4. Experiment site being cleared on the ice cap



Pl. 5. Ice surface of area A showing cross-shaped ditch. String grid was used to map ice and gravel surface

Pl. 6. Area A after being covered with gravel

Pl. 7. Area B immediately after being covered with gravel

Pl. 8. Area C immediately after being covered with gravel

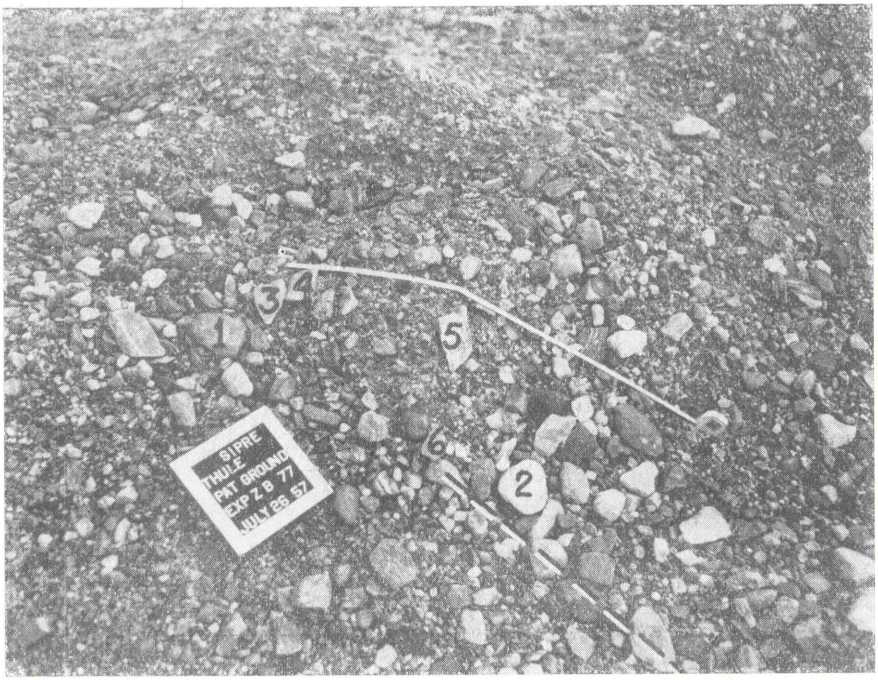
Pl. 9. Area D immediately after being covered with gravel

Pl. 10. Surface of area A 9 days after being covered with gravel. Collapse of least insulated portions has produced tension craks

Pl. 11. Area A after 20 days. Well-developed sorting has been produced at the foot of the gravel mounds at the edge of the area

a

b



c

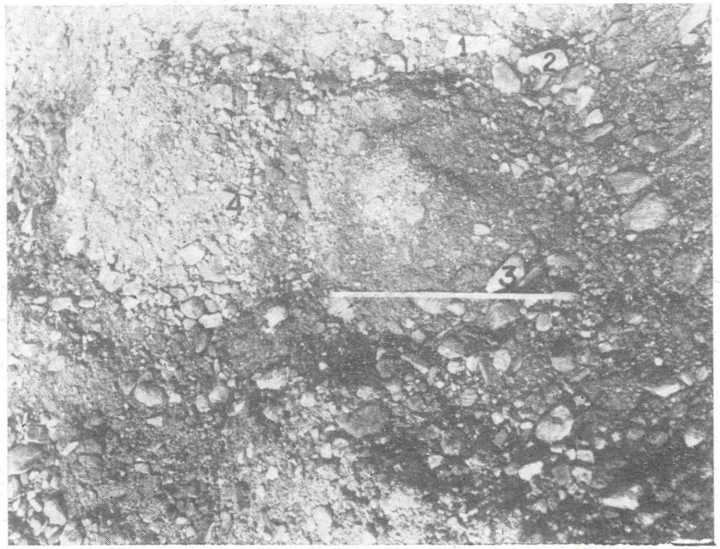
Pl. 12. Sorting in a depression, area B

a. one day after gravel cover was spread. Melt water filling the depression has melted out a channel (indicated by dashed line) and drained. Sorting of coarse particles down the walls of the depression is already well-developed;

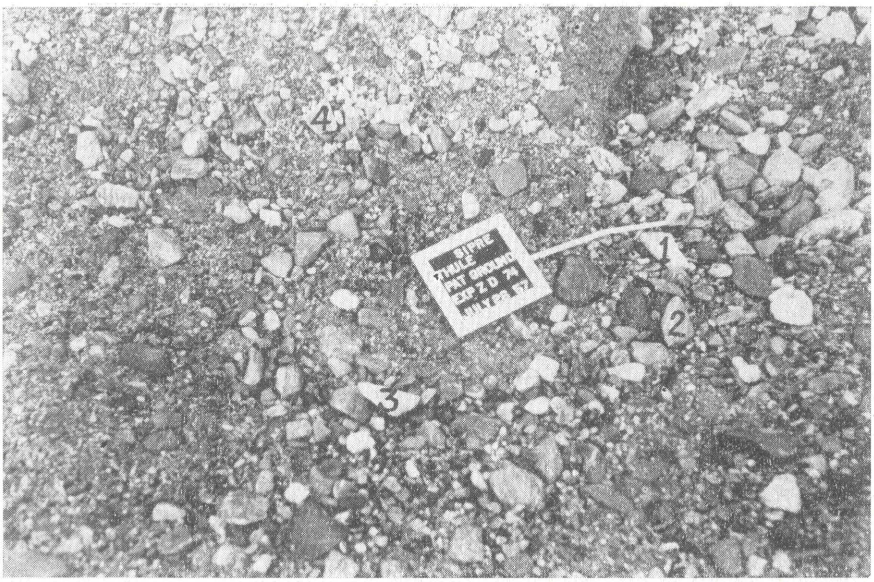
b. after 20 days of melting. The gravel surface surrounding the hole has sunk through differential melting to leave the mound raised above the general level;

c. after 44 days. The depression has been obliterated, leaving a mound and sorted net

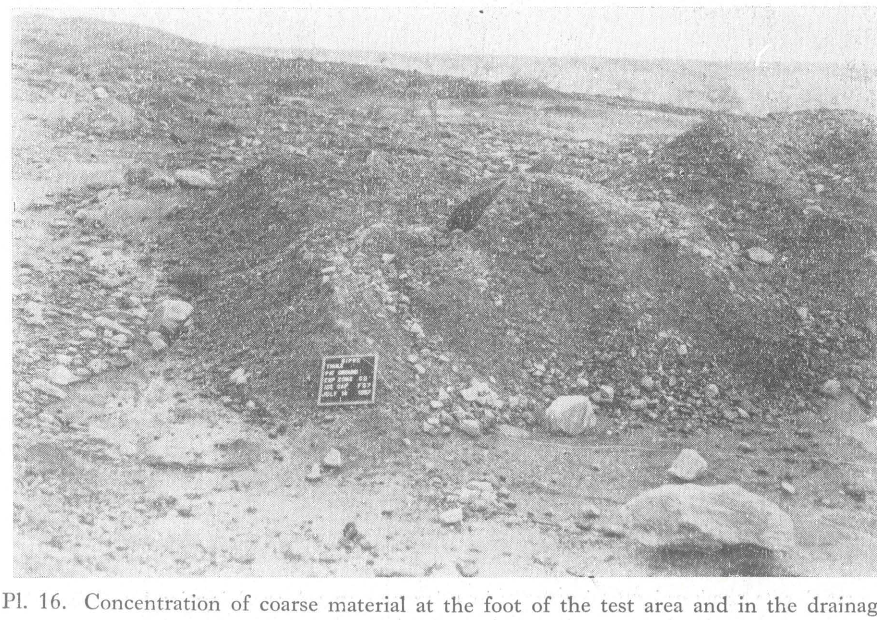
Pl. 13. Area C. Poorly developed sorting in a melt-stream channel 43 days after the ice was covered with gravel



Pl. 14. Area D after 18 days. The mounds have joined due to lateral extension. Sorting is already evident on the lower slopes



Pl. 15. Area D after 43 days. The second mound is only partly visible at top center



Pl. 16. Concentration of coarse material at the foot of the test area and in the drainage channel at left are well-developed

a

b

Pl. 17. Sorted nets produced naturally and experimentally in gravel over ice
a. sorted nets produced naturally in gravel deposits on the ice cap
b. sorted nets produced experimentally in a layer of gravel overlying ice by differential melting and mechanical sorting