INVESTIGATIONS OF PATTERNED GROUND AT SIGNY ISLAND, SOUTH ORKNEY ISLANDS:

I. INTERPRETATION OF MECHANICAL ANALYSES

By M. J. G. CHAMBERS

ABSTRACT. A series of patterned-ground formations on Signy Island were systematically excavated and a large number of soil samples was collected. These samples were subjected to detailed mechanical analysis using sieves and Bouyoucos soil hydrometers. Cumulative grain-size curves were drawn up and used, in conjunction with pH measurements, soil moisture and loss on ignition, to identify the various structures of the patterning and the relationship to the surrounding surface material. Four main pattern types are described according to Washburn's (1956) classification: large sorted circles, large unsorted circles, large sorted stripes and a large extended solitary flow (here termed a "stone stream"). The analyses revealed the distribution of fine and coarse material throughout the patterns, from which some deductions are made as to their origin and the modifying processes which are in operation today. Evidence is drawn from other experimental work on Signy Island in assessing the relative importance of frost-heave and solifluction in these processes.

DURING the course of investigations into patterned-ground and solifluction phenomena at Signy Island, it became evident that observations on surface features alone were inadequate. Some examination of the three-dimensional form of the patterning was essential, and to this end a series of sections was dug through various types of stone polygons, circles and stripes. (Throughout this paper the general classification of patterned ground suggested by Washburn (1956) is adopted.) In this way not only were the structures of the formations revealed but samples were obtained which permitted a detailed analysis of their grain-size distribution. Since patterns largely reflect a sorting of the debris within the active layer, it seemed appropriate that mechanical analyses of the material comprising these features should be carried out. These analyses, in conjunction with moisture-content determinations, pH measurements, ignition tests and observations of soil colour, provide a means of identifying the various soil types of which the patterns and surrounding terrain are composed. (A description of the general Signy Island environment in which this patterning occurs will be given in a future paper by M. W. Holdgate, S. E. Allen and M. J. G. Chambers.)

METHODS

Samples of approximately 0·5 kg. were collected, weighed and oven dried at 105°C, and then re-weighed. No means of obtaining a core of known volume was found to be satisfactory when taking samples of frozen or extremely stony mineral soil, so it was not possible to calculate the air space of the sample,* but water content was determined and is expressed as a percentage of the dry sample weight. Immediately after sampling, pH values were determined by using an electric pH meter, buffered at 4·5, 7·0 and 9·0. A 50 per cent soil/distilled water solution was used for this test.

The oven-dry samples were passed through 16, 8, 4 and 2 mm. sieves and the amount retained by each sieve was weighed. 50 g. of the material finer than 2 mm. was soaked in 25 $cm.^3$ of a 5 per cent "Calgon" solution (sodium hexametaphosphate) for 15 hr. and the mixture dispersed in a high-speed soil mixer with cup baffles for 2·5 min. (Bouyoucos, 1962). "Calgon" is basically a water softener but it has the dual effect of improving the dispersion of the original sample and of preventing flocculation during the later stages of settling. Having made up the total volume to 1 l. with de-ionized water, settling was carried out in a 1 l. measuring cylinder, and density was recorded by means of a Bouyoucos soil hydrometer, according to the method described by Dawson (1949). Readings were taken over a time range of 0·5 min. to 8 hr. and the weight per cent in ten categories ranging from approximately 0·002 to 0·07 mm. was determined. The settled residue was then passed through a further

* The method of using a known volume of fine dry sand to determine the volume of an irregular excavation, described by West (1953), has since been brought to the author's notice.

series of four sieves (1·0, 0·5, 0·2 and 0·1 mm.) and the fractions retained on each were dried and weighed. This allowed a cumulative weight per cent curve to be plotted for each sample with grain-sizes of 0·002 to 16·00 mm. with 18 points on each curve. The appropriate corrections which this settling method incurs were applied during calculation of the corrected grain diameters before plotting.

Large Sorted Circles

In the south-eastern corner of Signy Island a series of peninsulas projects from a broad flat platform known locally as "Clowes Moor", which is at about 30 m. a.s.l. and dips gently south-westwards. This area is completely overgrown with moss, except for the abrupt rocky edges of broad solifluction lobes and a few upstanding rock outcrops. Drainage is poor, so that standing water is commonly found in hollows throughout the summer months.

The only recognizable patterned ground in this area takes the form of isolated stone circles, partly overgrown with moss and some distance from the waterlogged hollows. Two of these circles, 1·5 and 2·0 m. in diameter, were sectioned with the aim of discovering their relationship to the surrounding undisturbed surface (Fig. 1). Situated about 3 m. apart, each was found to have a marked perimeter of coarse stones, and in particular each had a large boulder weighing several hundred kilograms at its north-eastern end, i.e. up-slope of the pattern. The sizes of these boulders were not at all apparent until digging revealed their proportions. Samples were collected throughout the active layer from all parts of the patterns and also from the surrounding undisturbed material.

Three main soil types were identified and found to occur in both circles:

i. A light olive-grey (Munsell coding 5Y 6/2) stony skeletal material which underlay everything and appeared to grade into bedrock, although the permafrost level at 40 cm. to 1 m. prevented confirmation of this assumption.

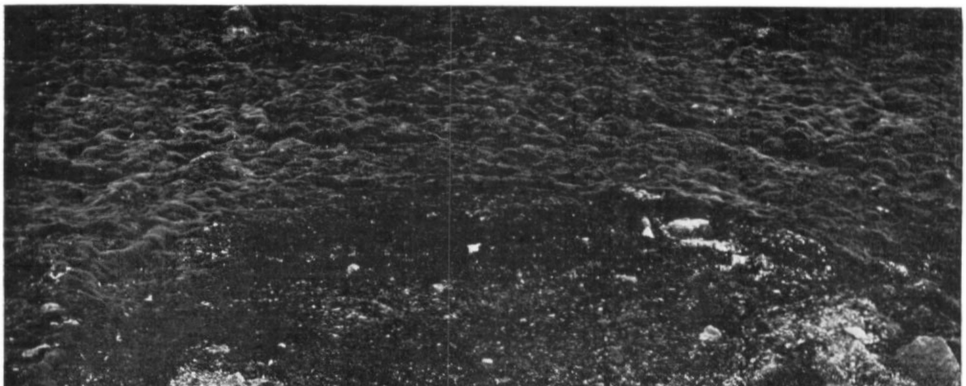


Fig. 1. A large sorted circle partly covered with vegetation; sample site G. The date marker is 20 cm. long.

ii. A dark reddish brown (2·5YR 2/4) peaty gravel, mainly associated with the stone perimeters but also lying in a narrow band on top of the grey material described above.

iii. A dark yellowish brown (10YR 4/4) mineral soil which largely composed the surface material, apart from the coarse stone circles.

These differing soils were not found in level horizons but were distorted beneath the circles into large involutions which died out beyond the rim of the stone perimeter (Fig. 2). One of the

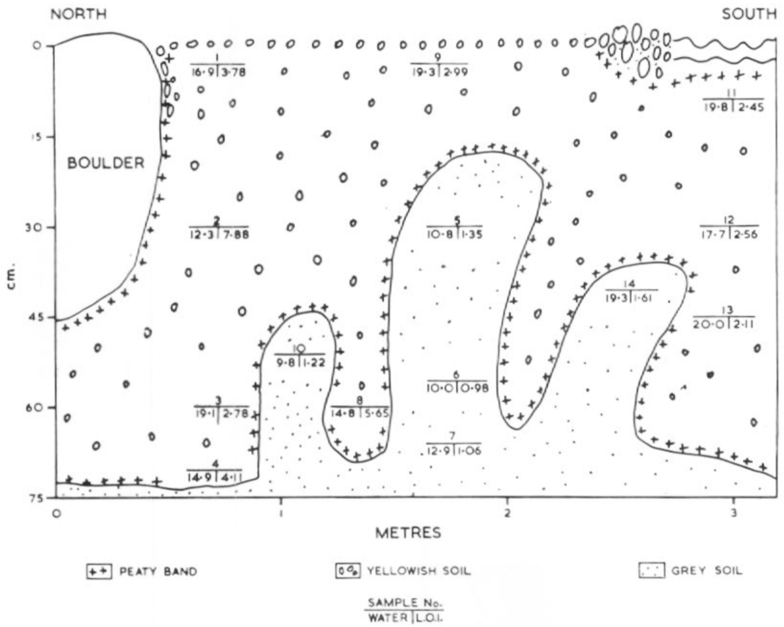
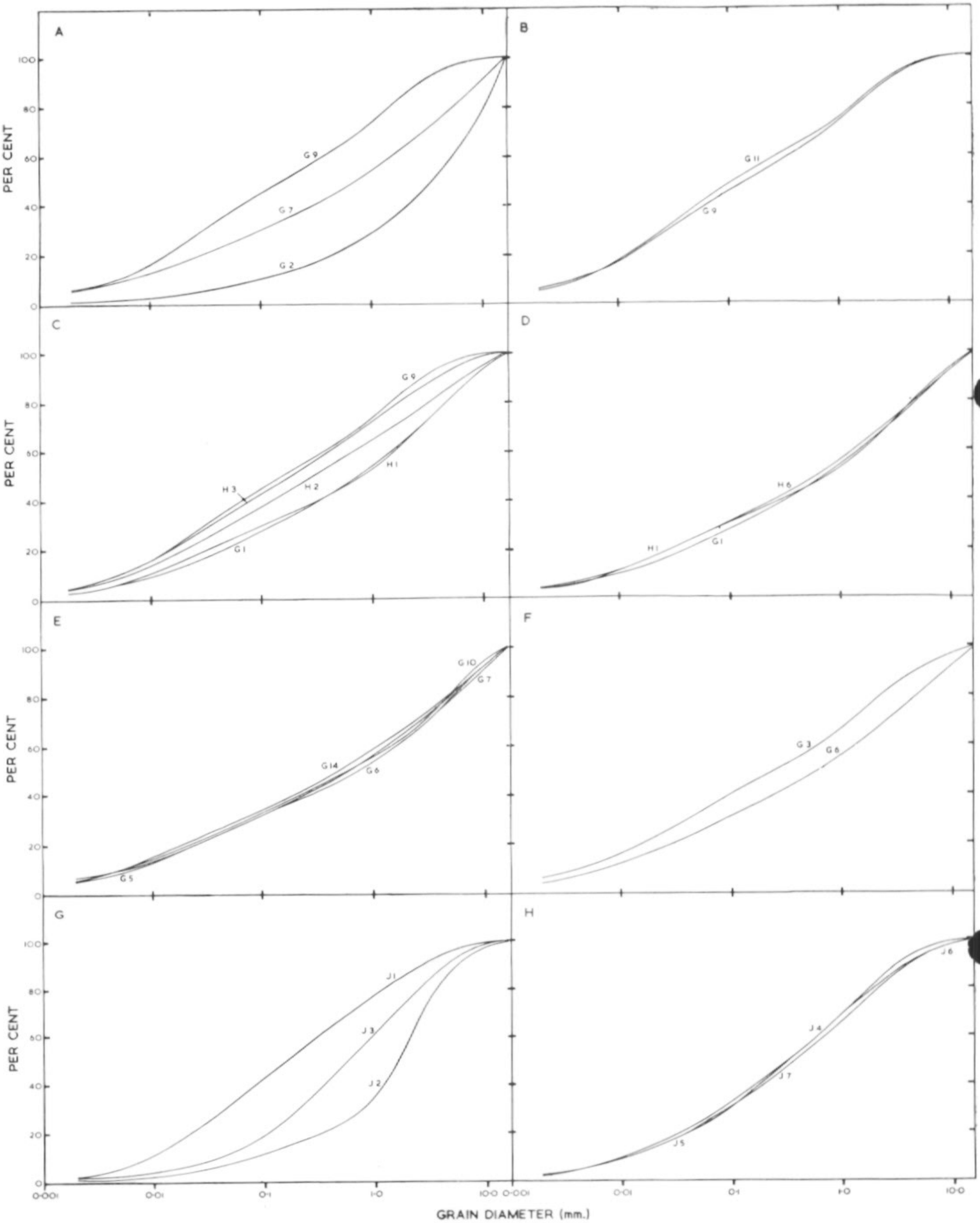


Fig. 2. Diagrammatic cross-section; sample site G. Site H is similar.

main purposes of the mechanical analyses was to correlate the soil types throughout the patterns, since each of the three types has a characteristic cumulative frequency curve (Fig. 3A). It is important to note that, although the curves form a speedy and efficient method of comparing samples, they have distinct limitations. The weight is cumulative, so that between any two grain-sizes on the graph the weight percentage of grains in that range is not represented by the height of the line above the abscissa, but by the angle of the line. If two curves coincide completely throughout their length, then obviously the grain-size distribution of the two samples is similar but, if the two curves are separated, the converse is not necessarily true, since a variation in the clay fraction will offset the curves for their entire length. Thus, in comparing sections of two curves, it is their nearness to being parallel, rather than their degree of superposition, which indicates similarity. It is also essential to remember that two identical size-frequency distributions do not necessarily mean that the samples are derived from the same material. For this reason soil colour, water content, pH value, loss on ignition, relationship to other horizons and, in some instances, the mineral assemblage have all been used in the interpretation of the mechanical analysis results.

Several significant variations and similarities were revealed when comparison was made between samples of the dark yellowish brown superficial material taken from different parts of the circles. Most striking of all was the similarity between samples G9 and G11 (Fig. 3B). The first was taken at the surface in the centre of the large circle, whilst the other was taken immediately beneath the moss mat 50 cm. outside the stone perimeter. Losses on ignition were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G 1
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G 5
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J 3
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0·001
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10·0
GRAIN DIAMETER (mm.)

Fig. 3.

2·99 and 2·45 per cent, respectively, whilst the water contents, expressed as a proportion of the dry sample weights, were 19·3 and 19·8 per cent. In every respect these two samples were virtually identical, yet one overlies the crest of an involution in a zone of general disturbance, whilst the other occurs in an area completely free from such activity, right outside the circle.

Another unexpected feature of the surface material was the contrast between samples taken inside the north-eastern perimeter of the circles (G1, H1; Fig. 3C) and those taken from or near the surface elsewhere in the circles (G9, H2, H3). The north-eastern samples far more closely resembled some taken 40–50 cm. down from the same dark yellowish brown mineral soil (H6; Fig. 3D). This suggests that the gravitational effect of a very slight angle of slope across a circle is sufficient to influence the distribution of fines. The extent of this influence is seen more clearly in the results of a later sample series (site J).

Samples G5, G6 and G7 (Fig. 3E) were taken at descending levels from an involution of the grey skeletal material which protrudes up into the overlying yellowish horizon, and G10 and G14 (Fig. 3E) were taken from two smaller grey intrusions towards the sides of the circle. There is no apparent difference between any of them, but as a group they contrast strongly with the yellowish soil taken from a similar depth (G6, G3; Fig. 3F). This seems to confirm that the plugs of grey skeletal material have been pushed up from below and are not merely irregular colorations of the upper horizon. Some information can be gathered as to the nature of this pushing-up movement, since the form of the plugs shows a very regular and smooth rounded outline, which rather precludes the cryostatic theory of pressure intrusion into weaknesses of the overlying frozen mantle as an explanation of this particular feature (Chambers, 1965). These features are far more compatible with a slow and gentle upwelling under saturated conditions in an unfrozen active layer, where instability is brought about by comparatively dense rocks at the surface. Thus the massive boulder found at the edge of each circle may well have been instrumental in the formation of the involutions.

A further interesting aspect of these excavations was the distribution of the dark red peaty gravel. Although it was found as deep as 70 or 80 cm. below the surface, it had a relatively high organic content, giving a loss on ignition of between 5 and 8 per cent. The association of this organic material with the present stone perimeter is not fortuitous, since it is only when moss grows on a coarse gravel that dead peat is able to fall between the rock fragments and form a definite deposit. Such penetration, without root growth, is impossible into a coherent soil under these conditions, as illustrated by the 2·45 per cent loss on ignition of sample G11 (Fig. 2). The occurrence of a thin layer of this peaty gravel between the grey skeletal material and the overlying yellowish mineral soil, outlining all the involutions, suggests that at one time this junction was in fact at the surface and bearing a layer of vegetation. Brown bands may be found disappearing vertically into the permafrost 1 m. below the present surface, which indicates that involutions had also been formed at an earlier period. This also supports the thesis that the grey material was at one time at the surface, where it would have been far more likely to undergo disturbance than in its present situation in the permafrost zone.

The only alternative explanation of this stained organic band is that peaty water, originally in the gravel of the stone perimeter, has seeped along the junction between the two main soil types. It is not easy to visualize how or why this should have happened, or how the two dis-

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Fig. 3. Cumulative grain-size curves for sample sites G, H and J.

A. G2 30 cm.; brown peaty soil.
G7 65 cm.; grey soil.
G9 5 cm.; yellowish soil.

B. G9 5 cm.; centre of circle.
G11 5 cm.; outside circle.

C. G1 5 cm.; north side of circle.
H1 5 cm.; north side of circle.
G9 5 cm.; centre of circle.
H2 5 cm.; centre of circle.
H3 5 cm.; south side of circle.

D. G1 5 cm.; north side of circle.
H1 5 cm.; north side of circle.
H6 40 cm.; south side of circle.

E. G5 25 cm.; grey plug.
G6 55 cm.; grey plug.
G7 65 cm.; grey horizon.
G10 50 cm.; grey plug to north.
G14 40 cm.; grey plug to east.

F. G6 55 cm.; grey plug.
G3 60 cm.; yellowish brown soil.

G. J1 5 cm.; centre of circle.
J2 5 cm.; south of circle.
J3 5 cm.; north of circle.

H. J4 15 cm.; centre of circle.
J7 30 cm.; centre of circle.
J5 30 cm.; south of circle.
J6 30 cm.; north of circle

tinctive soil types originated *in situ*. It seems far more likely that the area once bore only the primitive grey material supporting a meagre vegetation cover, and that this was later over-run by a broad solifluction lobe from the slightly higher ground nearby. This added load may then have been instrumental in bringing about the involutions observed today. The fact that these involutions are leaning down-slope may well have resulted from a continued slight movement of the upper layer.

Large Unsorted Circles

Immediately to the south-west of Robin Peak is a rocky shoulder jutting westwards at between 150 and 200 m. above sea-level. Where this shoulder adjoins the main mountain mass there is an almost level platform, on which an even cover of relatively fine-grained mineral soil has accumulated. A partial cover of vegetation is supported on this platform, where two distinct zones are apparent. On the lower wetter area a broken cover of dark brown *Andreaea* sp. is completely waterlogged; permafrost is only 15 cm. beneath the surface and this is insulated from summer radiation by the watery conditions. The higher zone is carpeted with bright green *Drepanocladus* sp. and, although it is relatively drier, it is still extremely moist and poorly drained, with the permafrost level at a depth of about 30 cm. The junction between these two vegetation zones, trending north–south across the shoulder, is marked by a series of unsorted circles 1·0–2·5 m. in diameter and completely free from moss (Fig. 4). It appears that the variation of environment, which has given rise to the differing vegetation types, is also critical in the formation of patterns. An examination of the surface beneath the mosses revealed a uniform cover of gravel underlain by a coarse mineral soil and broken only by the circles and by some longer soil flows towards the edges of the platform where the gradient increases.

One of the more evenly shaped and well-formed circles about 2 m. in diameter was chosen for sectioning in a location where the surface dips 3° northwards. Samples were taken down to

Fig. 4. Large unsorted circles surrounded by vegetation; sample site J. The date marker is 20 cm. long.

permafrost level within the circle and from beneath the moss mat 50 cm. to the north and south. It was found that the moss is 20 cm. deep in immediate proximity to the fines, appearing to be banked up adjacent to the bare soil where the *Drepanocladus* gives way to *Dicranum* sp. which appears more resistant to the local disturbance. Elsewhere the moss is only 10–15 cm. deep. Thus the fines within the circle were upstanding about 15 cm. above the level of the general gravel surface, but they were prevented from overflowing by the moss embankment (Fig. 5). In several of the nearby patterns the fines had in fact flowed over this barrier and spilled out on to the surrounding moss.

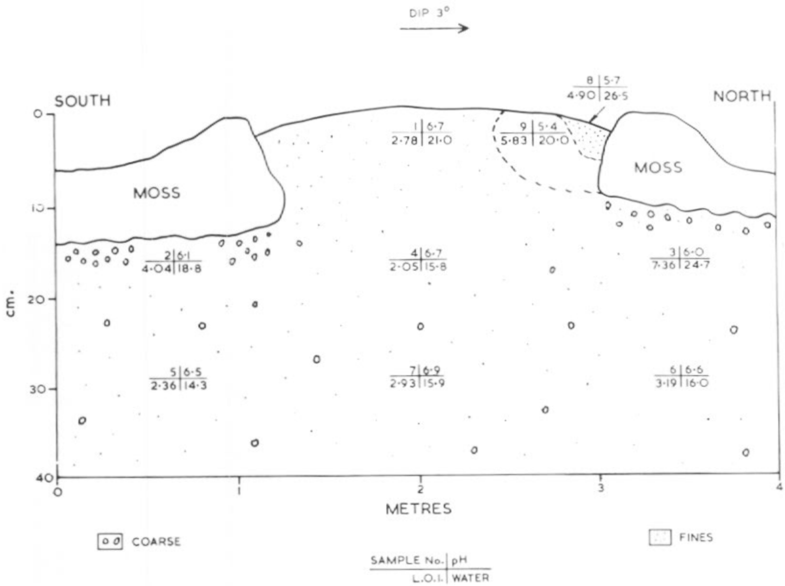
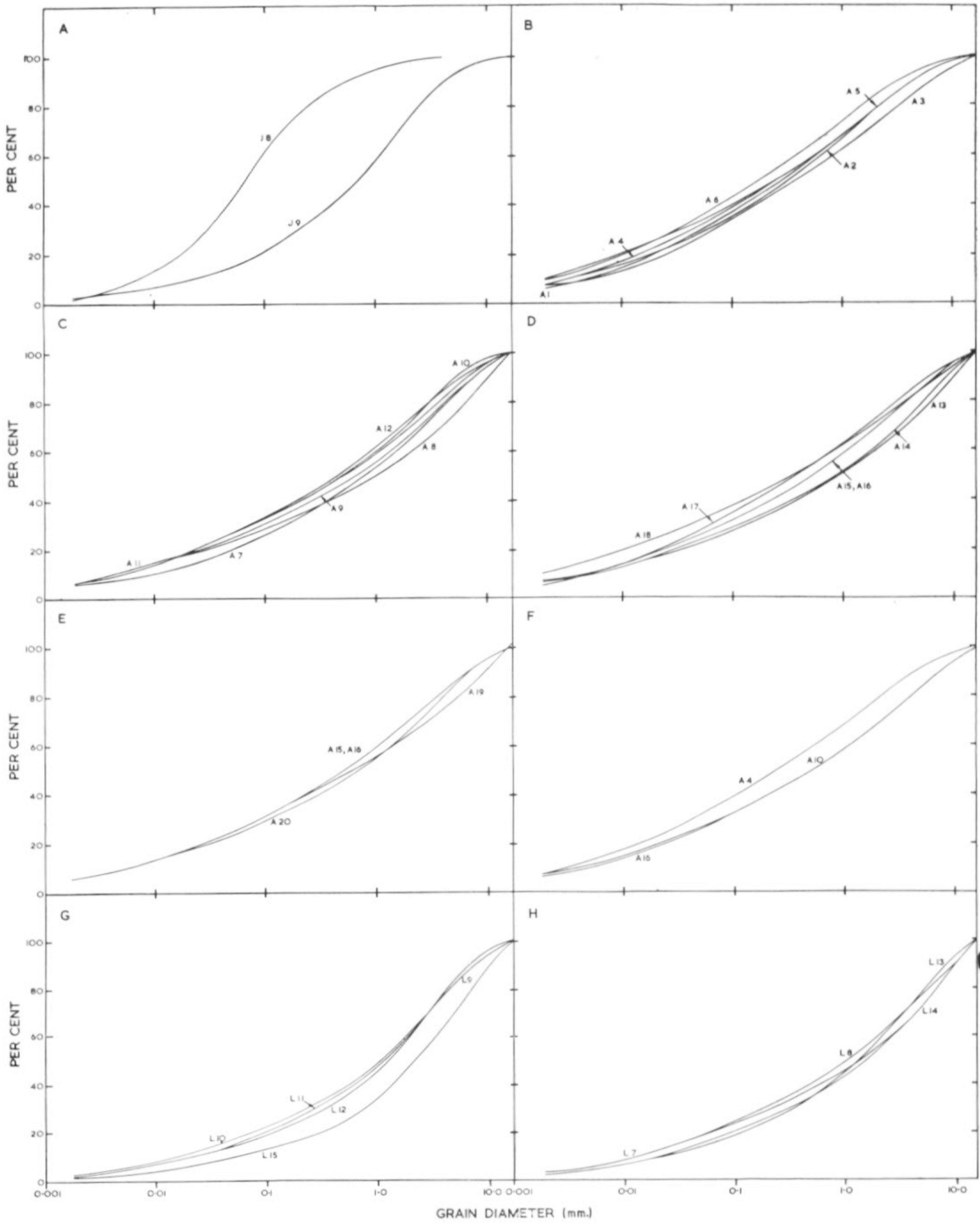


Fig. 5. Diagrammatic cross-section; sample site J.

The mechanical analysis graphs show a concentration of fines at the surface in the centre of the circle, compared with the material immediately beneath the moss mat to the north and south (J1, J2, J3; Fig. 3G). The two sub-vegetation samples are not identical, however, and the down-slope side (J3) shows a much finer and more balanced deposit. At depth these differences are lost and samples taken at the base of the active layer from beneath the circle and vegetation alike show a striking uniformity (J5, J6, J7; Fig. 3H). A further sample taken half-way between the surface and the permafrost level within the circle (J4) may also be classed with the three deeper ones. This shows that the sorting which has taken place is located very close to the surface and cannot be directly related to the annual frost-heave cycle which affects the whole active layer.

As sectioning proceeded a concentration of extreme fines was discovered at the northernmost edge (J8; Fig. 6A) abutting the moss perimeter. Beneath these fines a layer of dead peaty material was discovered (J9), which extended towards the centre and reached the surface about 40 cm. from the moss. The pH of these two samples, when compared with all the others, shows the extent to which the peaty material has influenced them. This buried peat, impregnated with fines, was not found in any other quadrant of the circle, although it was discovered at the down-slope edge of several other circles nearby. It appears that under the conditions of a rapid surface thaw the fines, in a semi-liquid state, have at one time flowed over the moss embankment. A new barrier of living moss has since grown up and now contains the fines once more. The unusually high ignition loss of sample J3 (from beneath the moss to the north), coupled with its high content of fines, suggests that there is not just one stage of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GRAIN DIAMETER (mm.)

Fig. 6.

development revealed here, but that the moss has re-advanced over what was once the extended surface of an earlier formation. On the up-slope side the accumulation of gravel is characteristic of areas which have not undergone such disturbance.

No involutions or signs of cryoturbation were found in the active layer beneath this circle, which seems to indicate that the structures evident beneath the "Clowes Moor" patterns (sites G and H) are not prerequisites of the surface feature. It is possible, however, that the homogeneous nature of the sub-surface material at site J prevented any such formation from being observed. In either case it appears that soil is slowly welling up through this break in the vegetation at a rate which is comparable to that of the growth of the moss. The fines are at present 15 cm. above the gravel surface and, apart from the instance inferred from samples J8 and J9, the moss seems to have kept pace with the upward movement.

Although the local slope angle of 3° has been sufficient to concentrate the flow in one direction, it has not brought about solifluction on a sufficiently large scale to form the regular down-slope movement which ultimately gives rise to a stripe. These were observed quite close to the circle described here, but they are situated towards the edge of the platform where the surface slope angle increases to 8° and more. This influence of the slope is increased by differential frost-heave across the surface. In the centre of a circle, which lacks the insulation of a vegetation cover, freezing takes place more rapidly and more frequently than around it. The water content of the material lacking vegetation is also higher, which gives rise to greater ice segregation, so frost-heaving is concentrated within such circles. Experiments have shown that the centre of a circle may be domed up 5 cm. or more relative to its perimeter by frost-heaving. This differential heave is equivalent to an increase of 3° in the slope angle across a circle 2 m. in diameter, which, in this instance, would cancel the upward slope to the south and double the dip northward. The influence of this dome is still operative as the thaw begins, when semi-liquid fines lie on the extreme surface. Movement will then be concentrated in a northerly direction to an extent which would not have been possible under the influence of the regional dip alone. This may well account for the variations observed across the surface of the "Clowes Moor" patterns (p. 22–26).

Fig. 7 shows the surface expression of a feature which is situated on horizontal ground. This means that flow from the domed-up centre is radial and uniform in all directions. The flow is not inhibited by a dense vegetation mat in this instance, but a far higher concentration of coarse fragments limits the free movement of the fines. The site was sampled when only a few centimetres of the surface had thawed and a dome of frozen fines below was exposed.

Large Sorted Stripes

South-east of Elephant Flats the terrain rises quite gradually from sea-level to a knoll at about 80 m. The slope angle varies from 15 to 6° and the surface is largely free of vegetation, being covered by an irregular series of sorted stone stripes. Measurements across these stripes show that, whilst some are completely stationary, in others on the wetter parts of the slope the

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Fig. 6. Cumulative grain-size curves for sample sites J, A and L.

A. J8 5 cm.; north side of circle.
J9 5 cm.; peaty soil.
B. A1 5 cm.; left of north stripe.
A2 5 cm.; centre of north stripe.
A3 5 cm.; right of north stripe.
A4 5 cm.; left of south stripe
A5 5 cm.; centre of south stripe.
A6 5 cm.; right of south stripe.
C. A7 25 cm.; left of north stripe.
A8 25 cm.; centre of north stripe.
A9 25 cm.; right of north stripe.
A10 25 cm.; left of south stripe.
A11 25 cm.; centre of south stripe.
A12 25 cm.; right of south stripe.
D. A13 55 cm.; left of north stripe.
A14 55 cm.; centre of north stripe.
A15 55 cm.; right of north stripe.
A16 55 cm.; left of south stripe.
A17 55 cm.; centre of south stripe.
A18 55 cm.; right of south stripe.
E. A19 55 cm.; beneath stones.
A20 55 cm.; beneath stones.
A15 55 cm.; right of north stripe.
A16 55 cm.; left of south stripe.
F. A4 5 cm.; left of south stripe.
A10 25 cm.; left of south stripe
A16 55 cm.; left of south stripe.
G. L9 5 cm.; centre of stripe.
L12 5 cm.; south side of stripe.
L15 5 cm.; north side of stripe.
L11 15 cm.; south side of stripe.
L10 30 cm.; south side of stripe.
H. L7 30 cm.; centre of stripe.
L8 15 cm.; centre of stripe.
L13 15 cm.; north side of stripe.
L14 30 cm.; north side of stripe.

Fig. 7. Circle formation in shallow stony soil. The date marker is 20 cm. long.

fines are moving about 15 cm./yr. relative to the stones. Samples were taken across two fine stripes and the intervening stones on one of the most regularly patterned areas (Fig. 8), about 50 m. a.s.l. with a slope of 9° to the north-west towards the bay. The aspect of the site is significant here, since it means that snow patches disappear rapidly under the summer sun, so that after early melt the surface moisture supply is insufficient to permit continued solifluction. Although this section was dug on 10 January 1963, relatively early in the seasonal thaw, moisture levels were down to about 13 per cent of the dry sample weight, which excluded any possibility of solifluction at that time.*

The grain-size frequency graphs show no significant variation across the fines of the two stripes at any depth (Figs. 6B, C, D and 9). It had been expected that some increase in the coarse fraction would be revealed towards the edges of the fines on approaching the stone stripes but no such relationship was found. However, ample evidence of the influence of solifluction was found in the alignment of stones within the fine matrix. The platy fragments of schist are useful indicators of such influences, and in this case all the fragments were lying flat with their long axes parallel to the line of the stripe. Between the depths of 5 and 50 cm. no exception to this alignment was found amongst stones whose axes varied enough to make orientation discernible.

Samples taken from the fines beneath the stone stripe (A19, A20; Fig. 6E) and to each side at the same depth (A15, A16; Fig. 6E) show that there is no significant variation at this level. This substantiates the impression gained during sampling, that below 50 cm. the material is

* An analysis of fines actually in the process of flowing has shown that the weight of water in a sample must exceed 20–30 per cent of its dry weight before movement can take place. The exact figure will depend upon the slope angle and the grain-size of the sample. When the difference in specific gravity between the quartz-mica soils ($\simeq 2\cdot7$) and water is taken into account, it can be seen that water then comprises about 40 per cent of the volume of the fluid mixture. It must be stressed, however, that these figures refer only to the fines which characterize Signy Island's gentler slopes of less than about 18°.

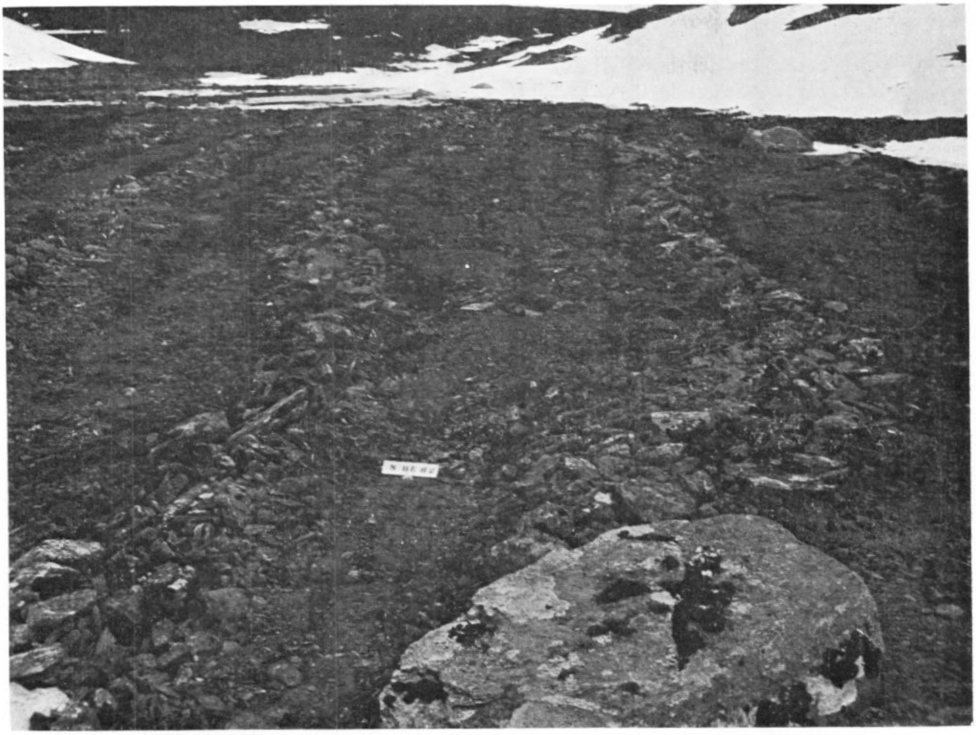


Fig. 8. Large sorted stripes; sample site A. The date marker is 20 cm. long.

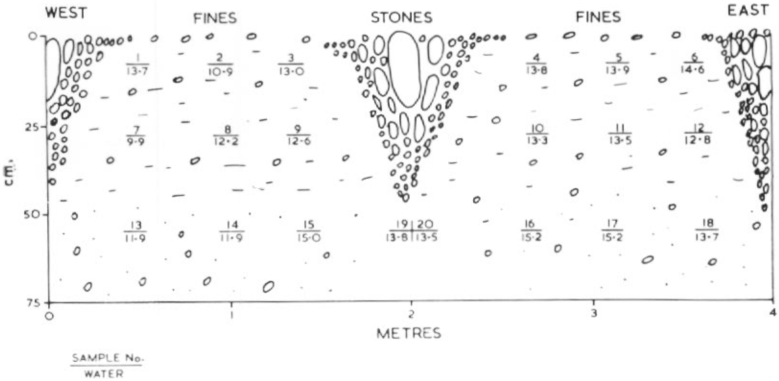


Fig. 9. Diagrammatic cross-section; sample site A.

not sorted, the stones are not oriented and no other evidence of solifluction is to be found, in spite of the fact that the annual thaw extends downward at least another 50 cm. Other field results from stakes planted on solifluction slopes at depths down to 1 m. support this impression that movement does not normally take place throughout the entire depth of the active layer but is concentrated in the upper 50 cm.

The fact that the stone stripes on this site extend to the same depth as the solifluction suggests that there may be some relationship between them. Other experiments have shown that in the horizontal plane movement is greatest along the centre of the fine stripe and gradually sweeps the coarse material to either side, thus adding it to the stone stripe (Fig. 10a). In the vertical plane it has been found that in most cases movement is greatest at the surface. Therefore, the supply of stones to the coarse stripe at either side will, by virtue of the faster movement, be greatest at the surface and will decrease with depth in proportion to the decrease of movement within the fine stripe. The V shape which the stone stripes assume in section supports this hypothesis and is illustrated in Fig. 10b, which shows a stripe lower down the same slope sectioned naturally by a small landslip.

It is for these reasons that some variation in coarse material was expected across the fines, and the apparent uniformity is probably due to the unavoidably small size of the samples, which could not include fragments larger than 16 mm. in diameter. Since the stone stripes are generally composed of these larger fragments, the discrepancy can thus be explained. However, several other problems are raised at the same time, and the mechanism whereby the coarser material is selectively sorted from the fines and where the division between fine and coarse comes in this process remain to be elucidated.

Another feature of the stripe profile which becomes apparent from the mechanical analysis results is the vertical variation of grain-size within the fines. In every case the samples from depths of 25 and 55 cm. are virtually the same but the sample from 5 cm. shows a higher content of fines (A4, A10, A16; Fig. 6F). This may be due to the diminution of particles in the upper layer, because of its more frequent subjection to freeze-thaw activity and the consequent mechanical break-down. On the other hand, it can also be explained by a supply of fines coming from the knoll higher up the slope. This finer material is more liable to solifluction on the rocky slope and would also move at a faster rate than the underlying fines after reaching the stripe. This may therefore be a more recent addition to the soliflual matrix, replacing the earlier surface soil which has moved on down the slope. Further evidence of the influence of source material on the stripe is seen in the overall difference which is apparent between the northern and southern stripes of fines sampled here. At each level the fraction from the northern stripe is coarser than the other (Figs. 6B, C, D), indicating that the influence of diminution under the present climatic conditions is less significant than the source from which the fines are derived.

Stone Streams*

Another formation on Signy Island which apparently owes its origin to solifluction is a type of elongated lobe which has become so extended that it takes the shape of a stone stream, winding down the hillside (Fig. 10c). Sorting has been most efficient so that a stripe of fines is bordered on each side by well-regimented stones, coarse on the extreme edges and smaller towards the central fines. Unlike the normal sorted stone stripes, these features do not occur as a series across a broad slope, but they are found singly, flowing down gullies and other minor corrugations on the hillside. They do not originate on the slope itself or draw their source material from the present-day break-down of steeper rock outcrops, as is the case with the normal stripes described in series A. They appear, rather, to "drain" off the accumulation of mineral soil and rock debris from a higher and flatter catchment area. Fig. 10d shows the coalescence of several normal sorted stone stripes at the head of a gully which proceeds to funnel the debris into one large flow extending about 50 m. down to sea-level at the head of Factory Cove. When the slope lessens towards the bottom and the gully broadens, the flow spreads out into a distinct fan, and the fines diverge along three or four separate channels. An

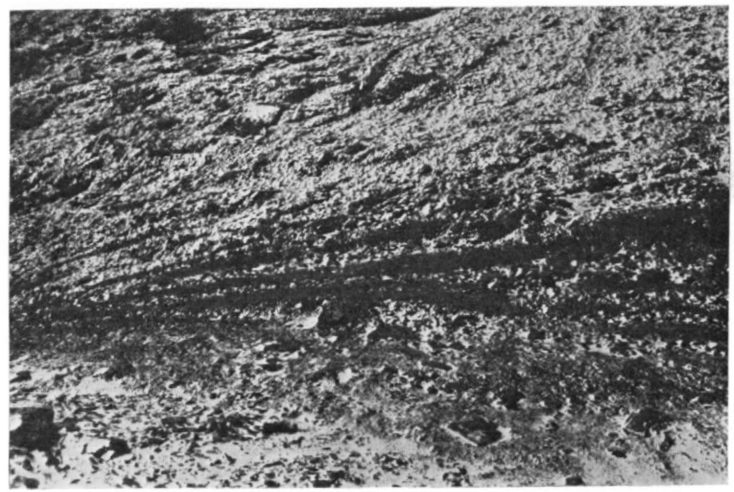
* These features are not included in Washburn's (1956) classification and the term is a new one introduced here.

Fig. 10. a. Differential movement across a large sorted stripe.
b. A large sorted stripe sectioned by a landslip.
c. A stone stream; sample site L.
d. Coalescence of large sorted stripes at the head of a stone stream.
The date marker is 20 cm. long.

a

b

c



d

Fig. 11. Bifurcation of a stone stream. The stake in the centre of the photograph is 120 cm. long.

extreme case of this is shown in Fig. 11, where the flow actually divides on encountering an obstacle in its course.

Movement within these flows follows the same general rule as in the normal stripes, with the most rapid flow at the surface in the centre of the fines and tailing off to either side and below. Fig. 12 shows the displacement of a line of white stones which took place during 16 months in the feature illustrated in Fig. 10c. A section was dug across this stripe with the aim of elucidating its structure and establishing its relationship to the nearby slope deposits. Fig. 13 is a diagrammatic representation of the section, which cut across the main flow and extended 2 m. southwards into the adjoining slope debris. The angle of the stripe at this point is 16° and, although only 1 m. width of fines was visible at the surface, they extended at least 90 cm. towards the sides, covered by a shallow layer of small stones. The depths of the trench depended upon the permafrost limit, which varied between 70 and 130 cm.

It was found from earlier sections that a small slope angle across a pattern had a marked influence on the distribution of fines. There seems to be a similar influence in the present section, caused by a bend in the stream in the same way as a river flows fastest on the outside of a bend. The samples from the centre of the stream and from the outside of the bend to the south (L9, L12; Fig. 6G) showed a much greater concentration of fines than that from the inside of the curve to the north (L15), although the surface material all appeared to be the same yellowish micaceous mineral soil. At depth the difference was maintained, and at 15 and 30 cm. on the south side (L11, L10) the material was similar to that at the surface, but the centre and northern side samples showed a much coarser composition (Fig. 6H). At a depth of 50 cm., however, the samples had a general uniformity right across the section (Fig. 14A) and the grain-size curves for samples L2, L6 and L16 were much the same as the coarse material above (L7; Fig. 6H). Thus, apart from the concentration of fines down the southern side, the samples from the stripe showed a homogeneity suggesting unified movement within the upper 50 cm.

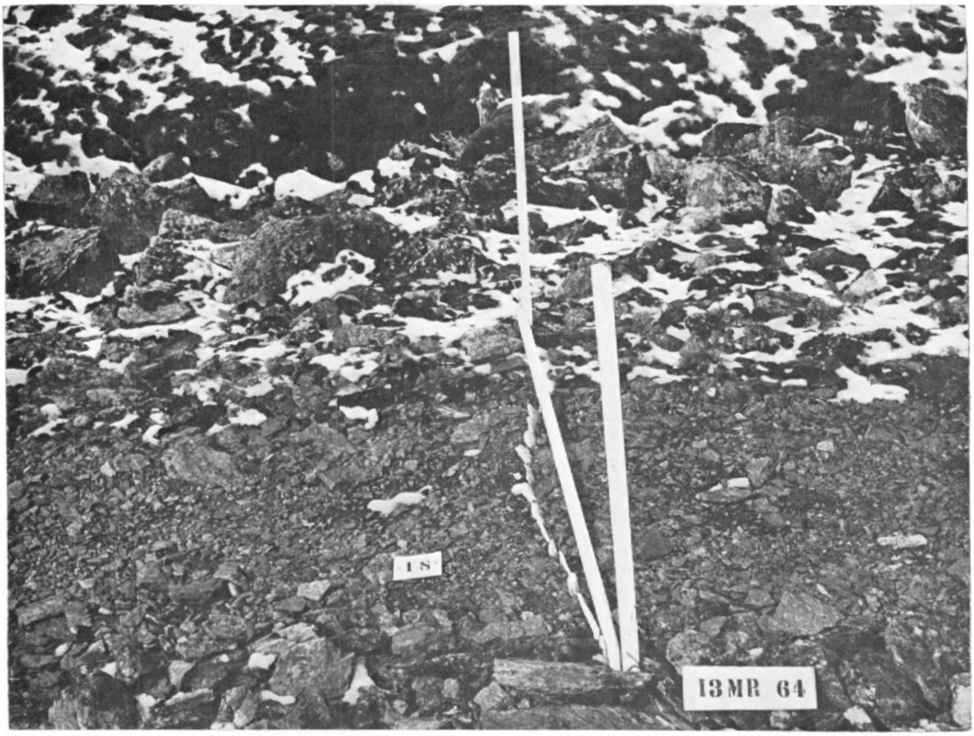


Fig. 12. Differential movement at sample site L.

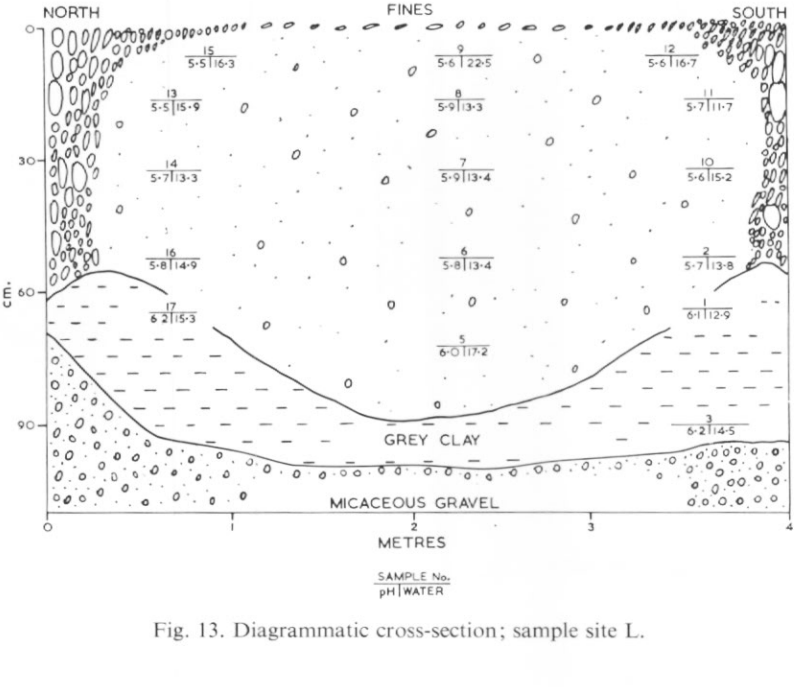


Fig. 13. Diagrammatic cross-section; sample site L.

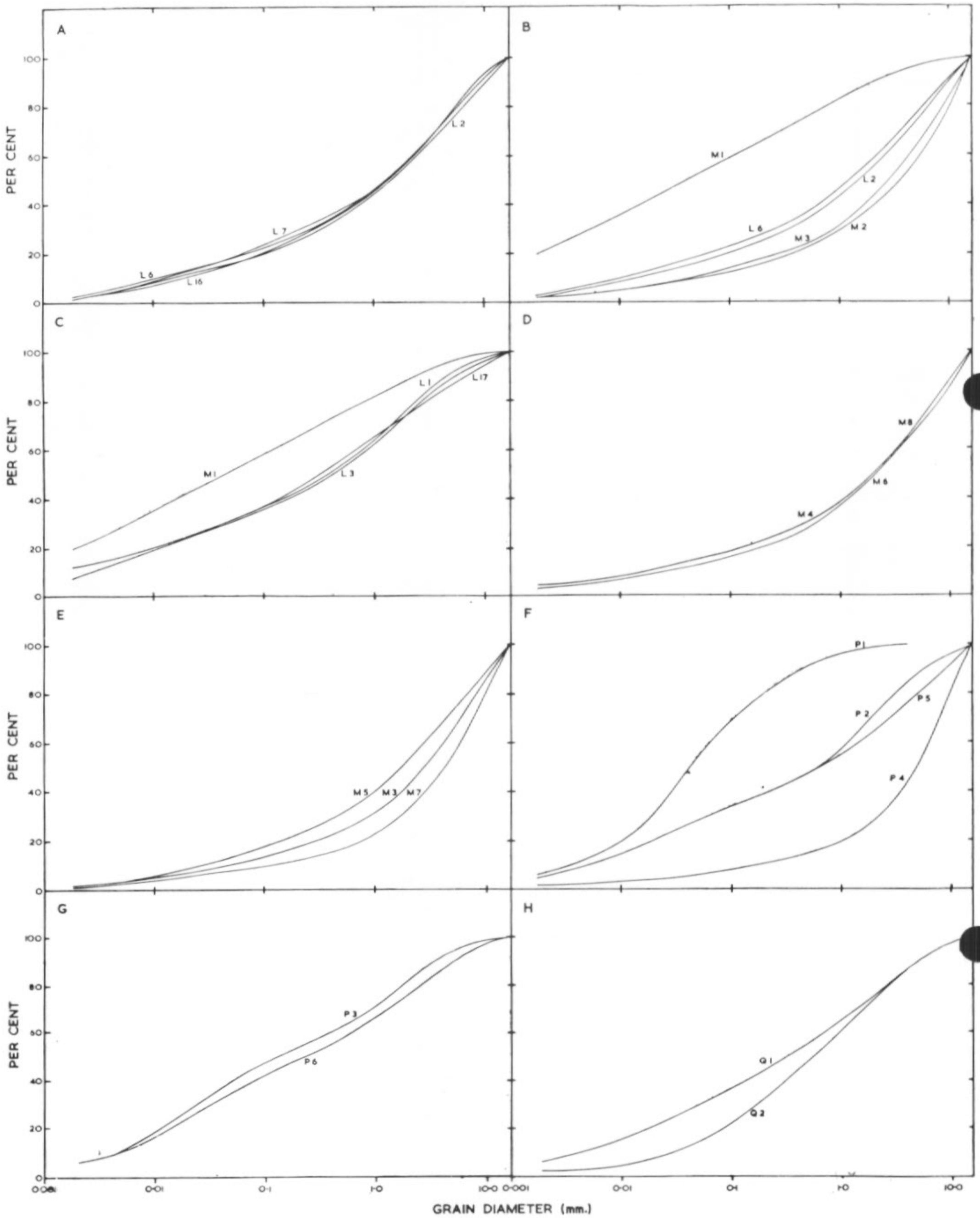

A
B
C
D
E
F
G
H
PER CENT
GRAIN DIAMETER (mm.)
L 2
L 7
L 6
L 16
M 1
L 2
L 6
M 3
M 2
L 1
L 17
L 3
M 8
M 6
M 4
M 5
M 3
M 7
P 1
P 2
P 5
P 4
P 3
P 6
Q 1
Q 2

Fig. 14.

The texture changed completely below 50 cm., where a band of dense grey clay was revealed. This band occurred at a depth of 60 cm. on each side of the flow but it thinned to 90 cm. down beneath the centre. Fig. 13 shows the approximate extent of this band, although its actual outline was irregularly laminated with lenses of coarser yellowish material from above. The relatively impermeable nature of the clay was well illustrated by a stream of water flowing in coarse gravel on top of the clay at about 85 cm. beneath the surface in the centre of the stripe. Ice was encountered 1 m. down and, although sampling was impossible, more micaceous gravel was observed beneath the clay. Some of this gravel was obtained later from the side of the stripe so that a comparison could be made between samples from above and below the clay (L2, M2; Fig. 14B), and with the clay itself (M1). Whilst that from below the clay resembled other samples from the permafrost level in the main slope debris (M3) in grain-size and colour, the material from above the clay bore a far closer relationship to the other samples throughout the stripe (L6). It can therefore be assumed that this clay band marks the limit of foreign solifluction debris which has moved down from the relatively level platform at the head of the stripe. The unique character of the grey clay suggests that it may not be of local origin at all, but it could in fact be an old glacial till. This would then have been the first deposit to undergo solifluction on to the lower slope. An examination of the englacial debris of glaciers flowing into Normanna Strait from Coronation Island revealed a fine grey rock flour, which must give a deposit very similar to the clay found here. The present form of the clay at the base of the stripe may be due to the gradually increasing load of locally derived material which subsequently flowed down on top of the clay, moulding it to form a channel-like feature. The fact that the deepest sample of the clay, which was taken from its southernmost limit (M1; Fig. 14C), showed a considerably finer composition than others higher in the band (L1, L3, L17; Fig. 14C) remains to be explained, although some admixture in the shallower samples is suspected.

This massive flow, with its rocky border, appears to have had some considerable influence upon the adjoining slope debris, which is zoned into curved bands parallel to the stripe (Fig. 15). Stones within the debris are all aligned with their long axes parallel to the maximum slope, but in contrast to the fragments described from site A (p. 30) their flat axes lay in the vertical plane, aligned to the zoning of the various bands. Two vertical columns, 50 cm. apart, were sampled; the first through zoned material close to the stripe and the second in an apparently undisturbed area farther south. This revealed that close to the stripe the samples were quite uniform between depths of 30 to 90 cm. (Fig. 14D), while farther away from the zoned bands wide variations were found in the same depth range (Fig. 14E). It appears that the effect of the stripe has been to squeeze the surface debris sideways by sheer weight at a time when a higher water content than at present prevailed, thus allowing increased mobility. An extension of this section up-slope confirmed that the deformation never extended farther than 150 cm. away from the rocky border of the stripe.

Conclusions and Deductions

Several other patterns were excavated but, on the whole, the results of their analyses merely corroborate the facts described above. Samples taken from three other vegetation-free sorted

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Fig. 14. Cumulative grain-size curves for sample sites L, M, P and Q.

A. L2 40 cm.; south side of stripe.
L6 50 cm.; centre of stripe.
L16 50 cm.; north side of stripe.
L7 30 cm.; centre of stripe.

B. L2 40 cm.; south side of stripe.
M1 90 cm.; south side of stripe.
M2 95 cm.; south side of stripe.
M3 90 cm.; 1 m. away from stripe.
L6 50 cm.; centre of stripe.

C. M1 90 cm.; south side of stripe.
L1 60 cm.; south side of stripe.
L3 90 cm.; south side of stripe.
L17 60 cm.; north side of stripe.

D. M4 90 cm.; zoned bands.
M6 60 cm.; zoned bands.
M8 30 cm.; zoned bands.

E. M3 90 cm.; unzoned.
M5 60 cm.; unzoned.
M7 30 cm.; unzoned.

F. P1 5 cm.; centre of circle.
P4 5 cm.; border of circle.
P2 15 cm.; centre of circle.
P5 15 cm.; border of circle.

G. P3 50 cm.; centre of circle.
P6 50 cm.; border of circle.

H. Q1 5 cm.; centre of stripe.
Q2 5 cm.; under adjacent moss.

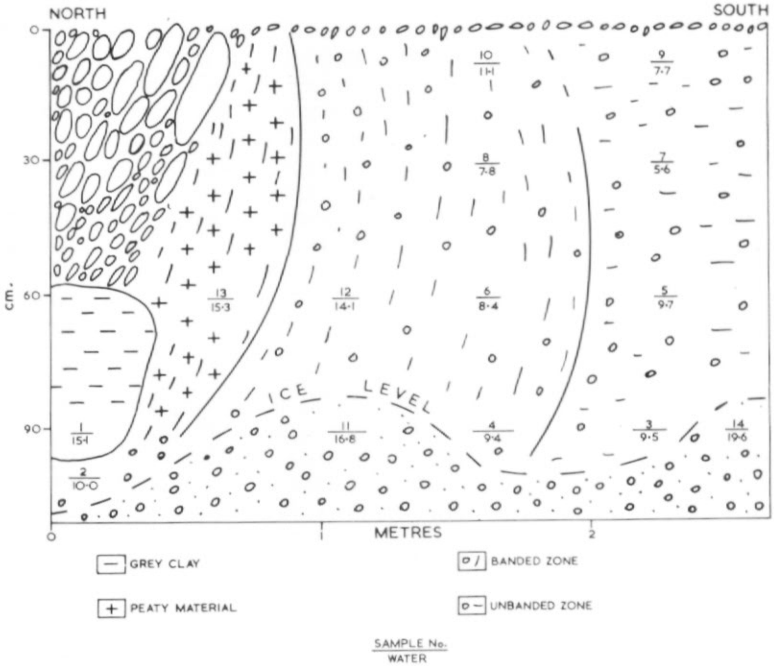

Fig. 15. Diagrammatic cross-section; sample site M, adjoining site L.

stone circles showed equally clearly the zone of undifferentiated material at depths of 50 cm. or more beneath both fines and their stone borders. Such a pattern (Fig. 16) showed surprisingly shallow sorting, in spite of the large boulders forming the perimeter. At the surface the contrast between fine and coarse is clear (P1, P4; Fig. 14F) but at a depth of only 15 cm. the change is almost complete, with the material from the fines showing an increase in the coarse fraction over a sample from the same depth beneath the stones (P2, P5). This suggests that the latter is unsorted, whilst the former has gained the coarse fraction from the extremely fine-grained sample above it (P1). At 50 cm., apart from a slight majority of fines smaller than 0·1 mm. in diameter beneath the centre of the circle, the samples are similar (P3, P6; Fig. 14G).

Further information on the sorting processes at the surface is gained from a pair of samples taken from the centre and side of a shallow soil flow only a few centimetres long (Q1, Q2; Fig. 14H). Here it can be seen that the fraction above 2 mm. in diameter is the same for both samples, but in the fraction below 2 mm. in diameter the centre of the flow has a considerably greater content of fines. It is evident that sorting has only affected the finer part of the samples, and this suggests that there is a relationship between the scale of the movement and the size of the material involved. While this relationship has been generally recognized in respect of pattern size and material, it appears to be more comprehensive, applying to all types of movement. If this is the case, then the conclusion must be that the fundamental sorting process is one of solifluction and not frost-heave. Much of the evidence already discussed supports this hypothesis even when applied to circles and polygons; hence the variations in grain-size across the surface of circles when there is a slight local dip. Other experiments with painted stones have shown that even the upward movement of coarse material to the surface in horizontal patterns is largely a solifluction phenomenon. Nansen (1922) has suggested that this up-freezing of the coarse fraction is due to differential thermal conductivity giving rise to ice segregation beneath stones thus causing them to be up-heaved, and this view has been widely supported. The evidence from Signy Island, however, shows that the formation of ice beneath stones is totally insufficient to account for the rate of upward movement.

Fig. 16. Extreme sorting of fines; sample site P.

A more likely process is that envisaged by Högbom (1910), although his application of the idea was somewhat unrealistic in requiring a radial expansion of a freezing mass of fines, since he was attempting to account for three-dimensional sorting by this mechanism. When applied only to a vertical plane, which is the usual direction of movement of a freezing plane, the idea is far more practicable. Since freezing usually occurs first at the surface and then proceeds downward, any upheaval due to ice segregation will lift a rigidly frozen layer above it. In this frozen layer stones and fines alike will be raised to the same degree. However, on thawing the coherence of the layer is lost, so that the moist fines slump and flow back to their original position, but this time they do not pull the coarse fragments with them. Expansion and deformation due to ice segregation beneath the stones prevents them from falling back into their pre-freezing positions, and by this process they are raised relative to the fines in which they were originally embedded.

Although this process requires frost-action for the general uplift of the surface, it is a solifluction and slump mechanism which actually causes the sorting. Several other experiments investigating the movement of stones relative to fines were carried out at Signy Island, as well as a quantitative study of frost-heave within a large sorted circle. The detailed results of these investigations are the subject of a further paper, but the conclusions from that work generally substantiate the results from the samples discussed here.

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