INVESTIGATIONS OF PATTERNED GROUND AT SIGNY ISLAND, SOUTH ORKNEY ISLANDS: III. MINIATURE PATTERNS, FROST HEAVING AND GENERAL CONCLUSIONS

By M. J. G. CHAMBERS

ABSTRACT. Several experiments designed to test the validity of various hypotheses concerning the origin and current activity of patterned ground are reported. Miniature sorted patterns were destroyed and photographed regularly over a 3-year period. Observations show that there is much movement of coarse material across the surface of pattern nets located on slopes of 6° or more but, in spite of such movement, individual cells of fines appear to re-form in their original positions. The conclusion is that the general pattern outline is determined by a series of desiccation cracks, whilst the form of individual cells depends upon the disposition of coarse material.

Other experiments showed that the upward freezing of stones is not due to the heaving of ice crystals beneath the stones but to the general uplift of the surface fines which grip the stones and then, on thawing, fail to return them to their original positions. The rate of such up-freezing was found to decrease rapidly with depth owing to the failure of any but the annual freeze-thaw cycle to penetrate more than about 10 cm.

A piece of apparatus was constructed over a large sorted circle in order to measure the frost heave within the fines of the circle. Results show that a uniform level of heave is attained in all but the outermost ring of fines, creating a gradient of up to 15° around the edge of the circle. This gradient was found sufficient to promote outward radial movement of fines by solifluction at the beginning of the spring thaw. A further experiment showed that stones are also moved outward radially from the centre of a sorted circle by the same process.

A general conclusion, drawing upon results described in the earlier papers of this series, stresses the dual nature of the active layer. Solifluction, ice segregation and sorting were all found to be concentrated in the upper 40–60 cm. of the active layer, leaving a similar depth below which played no apparent role in the formation or current activity of patterned ground on Signy Island.

THE work described in this paper was carried out as part of a programme designed to investigate the various forms of patterned ground found on Signy Island. A general description of the soils, vegetation and climate of the island has been given by Holdgate, Allen and Chambers (1967), whilst detailed accounts of pattern excavations and the temperature regime of the active layer form earlier parts of this series of papers (Chambers, 1966*a*, *b*).

MINIATURE PATTERNS

Miniature patterns are defined here as those with circles, polygons, stripes or intermediate forms not exceeding 15 cm. across each unit. Whilst their appearance is similar to that of the larger patterns, there is sufficient controversy about the processes which form them to justify separate treatment. It has commonly been recognized that these smaller patterns occur in less severe climatic zones than their larger counterparts, and such areas as the Alps (Conrad, 1946), the Pyrenees (Philberth, 1964) and even the English Lake District (Hay, 1943) have all been the sites of experimental work on miniature polygons and stripes. Hollingworth (1934) maintained that the variation in climatic regime associated with smaller forms suggested a somewhat different process to that which determines the large sub-polar forms and, although this differentiation has not been maintained in current literature, the basic assumption seems justifiable. The fact that these miniature forms also occur in many sub-polar regions suggests, however, that the processes which result in their formation are operative, to some extent, in these more severe environments, concurrently with the activity which gives rise to the large patterns. The common occurrence on Signy Island of large patterns with their surfaces subdivided by a miniature sorted network allows for two alternatives. It is possible that some environmental change has altered the scale of the patterning processes so that the large ones are stagnant and the small ones are still active, or it may be that both scales of pattern are formed simultaneously. The observations discussed here indicate that both scales of pattern are currently active on Signy Island, so it is evident that the superimposition of one upon the other is no safe indication of climatic change.

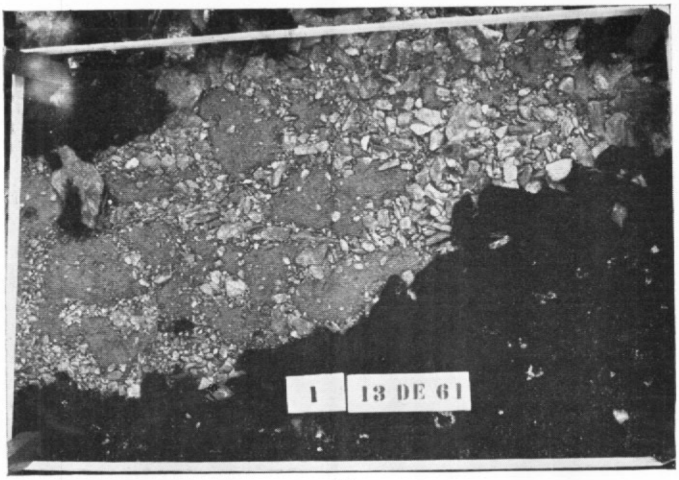
The factor which appears to correlate most satisfactorily with patterning on these two different scales is the depth of freeze-thaw activity. In temperate places, where only small features are found, the frost penetration is slight, amounting to only a few centimetres, and the most common cycle of freeze-thaw is diurnal. Where both large and miniature patterns occur in the truly periglacial regions, winter freezing extends downwards for 1 m. or more and is usually associated with permafrost, but at the same time there are still frequent diurnal freeze-thaw cycles in autumn and spring, which give rise to the shallow frosts associated with patterning in lower latitudes. It has also been suggested that the dimensions of polygons are directly related to the depth of the material in which they occur (Romanovsky, 1939; Pissart, 1964*a*), although others (Bout, 1953) have not found this to be true in the field. Observation of miniature patterns on Signy Island, in areas where the active layer is 150 cm. thick, show that such a relationship is certainly not found there. Others have put forward theories that miniature stripes are related to rill wash (Hay, 1943), although Troll (1944) has found this is not the case in his experience. Gradwell (1957) and Klatka (1961) have proposed that desiccation and contraction cracks determine the size and form of the patterns, while Klatka has suggested that rill wash then amplifies the cracks once they are formed.

In the light of these conflicting statements, a series of experiments was designed to elucidate the processes that are occurring in the active miniature patterns on Signy Island. The primary method of data recording was photographic, with the camera located immediately above the sites of the experiments. Photographs were taken at approximately 1 month intervals during the snow-free season, which usually extended from December until April. Most of the experiments were initiated in December 1961 and the final photographs were taken in January 1965, so that the total period of observation was 3 years. Six sites bearing miniature patterns were selected so as to include a range of features from irregular sorted polygons to well-formed sorted stripes and also the intermediate transitional forms. The only regular miniature polygons found on Signy Island were non-sorted and hence they were unsuitable for this experiment.

Site 1. Irregular polygons

Site 1 was located on the ridge east of the British Antarctic Survey hut. This site was on the ridge crest about 50 m. a.s.l. which was covered by an almost level but uneven moss mat broken by large rocks and occasional bare patches of stony soil. The particular bare patch chosen was divided by an irregular network of stones which formed the boundary to several mounds of fines, each about 8 or 10 cm. in diameter. On 13 December 1961, the surface of the patch was raked lightly to a depth of 5 cm. so that the patterning was completely obliterated and the stones were distributed randomly over the surface (Fig. 1a and b). Throughout the summer months no changes were observed and the photograph taken on 7 April 1962 shows that, although some drying had taken place, there had been no relative movement over the surface. In November 1962, immediately after the winter snow had cleared, the site was completely saturated with melt water. The stones which had been lying on the surface appeared embedded into the fines. As drying took place during the summer, the fines formed increasingly distinct centres which were raised up above the stones. By March 1963 there were quite clear concentrations of stones between the centres of fines. A comparison with photographs taken in 1961 showed that already some movement of smaller stones from the fines towards the concentrations of stones had taken place. When the winter snow had cleared towards the end of December 1963 the junctions between stones and fines had become increasingly distinct (Fig. 1c), a development which was maintained throughout the early months of 1964 as the surface dried. The final photograph in the series, taken on 31 January 1965, shows little change from the previous year, apart from the appearance of several small stones (less than 1 cm. in diameter) at the surface of the fine mounds, and in one case a small mound had been completely obliterated by the accumulation of stones upon it.

Fig. 1. a. Site 1. Original pattern; 13 December 1961.
b. Site 1. Pattern destroyed; 13 December 1961.
c. Site 1. Patterned surface after 2 years; 11 January 1964.
The date marker is 20 cm. long.



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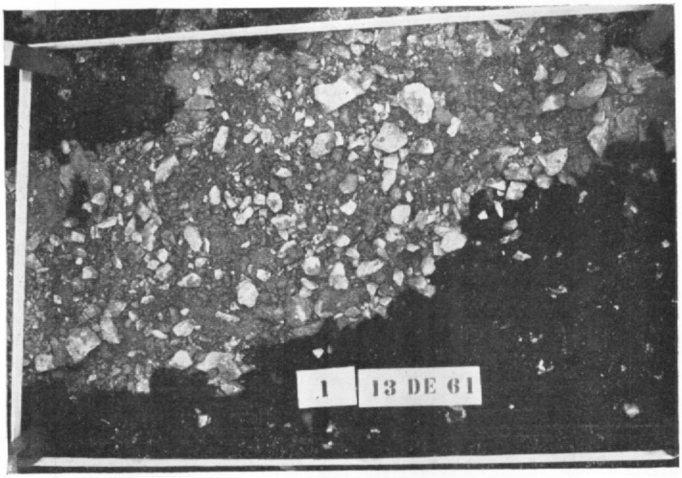

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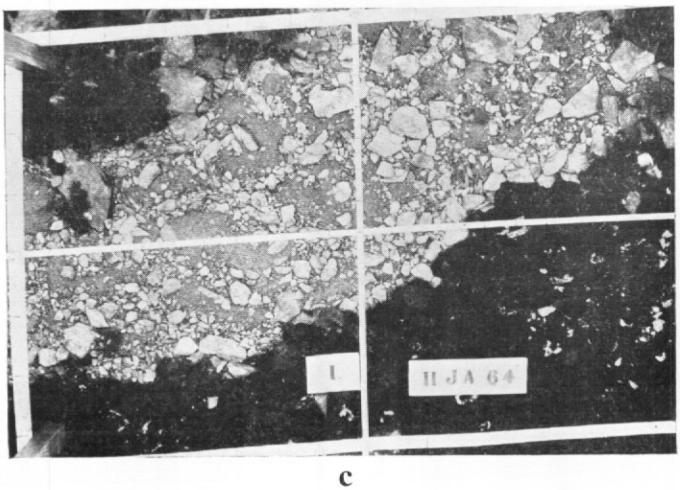

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Comparison of the original patterning with the newly formed sorting shows that the latter is far less complete and the network of stones is less regular. At first it appeared that the new mounds of fines were determined in their location and shape by the stones which lay on the surface after raking. Whilst this is partly true, it is evident from the photographs that the main centres of fines had re-formed in virtually the same places as the original fines. Where a large stone (3 cm. in diameter) had been raked on to the site of a previous fine cell, the stone had hindered the re-formation of the original shape but not the presence of a new cell altogether. By 1965 the larger stones showed signs of movement towards the edges of the new cell, making the resumption of the initial pattern outline more and more complete. Other large stones, which already lay in the line of the coarse net, did not undergo such movement.

Site 2. Transitional nets

Site 2 was situated only a few metres from site 1 but towards the edge of the ridge crest, where the gradient was 2° or 3°. The patterning was therefore of a transitional nature, the fine mounds being elongated down-slope. The coarse material comprised small irregular rock fragments rarely more than 2 cm. in diameter. These stones were so abundant that, rather than forming a network around the mounds of fines, the fines appeared to be isolated amongst a layer of stones. The right-hand side of the site was churned up so that not only was the patterning destroyed but the unsorted material beneath was disturbed to a depth of 12 cm. The left-hand side of the site was untouched to allow comparison and to record any natural development in the patterning during the period of observation. This experiment was commenced on 13 December 1961 and within 5 weeks of the initial destruction of the pattern a series of desiccation cracks had appeared within the disturbed material on the right-hand side of the site. The cracks in no way resembled those which form in drying mud but they rather assumed a roughly circular shape around coherent lumps of soil. After another 3 months these cracks had almost disappeared from the surface, due to the summer rain washing down fines. In November 1962, whilst the surface was still saturated with melt water, it was noted that several small stones had appeared at the surface, which had not been present in April of the same year. This up-freezing of stones was not only seen in the disturbed part of the site but also within the fine centres of the untouched patterning. As the surface dried out in the following month, differentiation between stones and fines became increasingly apparent. Already distinct concentrations of fines, surrounded by a network of stones were evident, although at this stage there were fewer stones at the surface than in the original pattern. Later in the summer, when the concentrations of fines were considerably drier, desiccation cracks appeared once again in similar locations to those which were observed soon after the experiment began, except that now parts of the cracks were obscured by the accumulations of stones. The first photograph after the winter snow, taken on 28 December 1963, shows that all the cracks had disappeared and the relief between fines and stones was at a minimum. As the moisture level dropped in the early part of 1964, the areas of concentrated stones became depressed relative to the mounds of fines, accentuating the newly formed patterns. A comparison with the initial 1961 photographs reveals several changes within the undisturbed side of site, including slight variation in the form of the fines and the movement of small stones into the main areas of coarse material. A year later, when the last photograph was taken in January 1965, the sorting on the disturbed side had, if anything, become less marked, owing to the up-freezing of more stones to the surfaces of the elongated mounds of fines. Most significant of all, however, was the fact that these mounds of fines were located in almost identical positions to the ones which were destroyed at the beginning of the experiment. There was also an obvious relationship between some of the newly formed sorted patterns and the desiccation cracks which occurred a few weeks after the surface was disturbed.

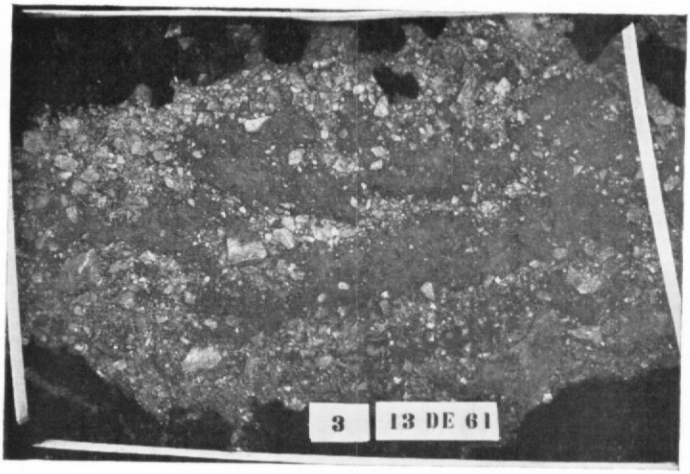
Site 3. Transitional nets

Site 3 was located on the same ridge as sites 1 and 2 but even farther towards the steep eastern flank of the ridge which drops almost sheer into the sea. The slope angle across the bare patch chosen for this experiment was about 6° and the vegetation-free surface was patterned by irregular stripes of coarse and fine material. The stones here tended to be larger than those at site 2 and the greater slope caused the fine stripes to be 30 or 40 cm. long, although still very irregular in outline (Fig. 2a). In December 1961, the left-hand side of the patch was lightly raked to destroy the sorting but not to disturb the soil below, whilst the right-hand side was thoroughly churned to a depth of 15 cm. (Fig. 2b). The effect of this disturbance on the right-hand part of the site was not merely to destroy any sub-surface structure which might be determining the form of the patterns but also to bury many of the stones which had been concentrated at the surface. The significance of this is seen in the photograph taken only a week after the destruction of the pattern. On the lightly raked side the stones remained at the surface and had dried out rapidly, but on the deeply churned part the soil remained dark and moist with only a few dry stones visible. Although some tiny desiccation cracks formed around the individual clods of soil, they were smaller and not nearly so marked as those at site 2. By the end of the summer of 1962 most of these cracks had disappeared, the remaining few being associated with stones lying on the surface. It was noted that the photograph for April 1962 showed several stones which were not readily apparent immediately after the pattern was destroyed. A close inspection of the early stage reveals just the occasional corner of these thinly covered stones and it seems likely that they were washed clear of fines by rain during the summer.

At the end of the 1962 winter, the picture taken of site 3 in December showed surprisingly little change, apart from the appearance of one or two more stones at the surface. This time it is likely that their appearance was due to up-freezing, although it is again possible that their upper surfaces were washed clean by melt water. Later in the summer more desiccation cracks occurred on both sides of the site, once more along the weaknesses apparent during the previous summer. The line of these cracks had become increasingly plain owing to the accumulation of small stones along them. This movement of coarse material into the cracks seemed to take place mostly in the summer months as the surface dried out, when the relief between the mounds of fines and the surrounding stones was at its greatest. Some similar movement was observed between the last photograph before the winter and the first photograph after the snow had cleared, but it was impossible to determine specifically when it occurred. This problem was particularly evident at site 3, since it was located on an east-facing slope that accumulated deep snow drifts in winter which, during the second year of the experiment, did not clear until the end of January 1964. Several changes were apparent since the last photograph in March 1963 but there was no means of determining exactly when they occurred. There was a similarly large time interval between the last two photographs in the sequence, which revealed an ever-increasing number of small stones at the surface, particularly on the right-hand side of the site. Here an entirely new scheme of sorting had formed, bearing no relationship to the original stripes. These features could hardly be described as patterning since there was no organization or regularity to them. Small mounds of fines of all shapes, separated by stones and patches of gravel (Fig. 2c), were distributed unevenly across the surface. The only consistent thing about the surface was that the mounds of fines were all asymmetrical with their steepest sides down-slope. It was along these abrupt edges that the cracks occurred in summer. This shape appeared to be due to the influence of the slope angle when the fines were in an almost fluid state at the beginning of the thaw. Other indications of gravitational movement across the site were cracks on the down-slope side of the large stones and the slight movement of some of them relative to the wooden corner stakes of the observation frame.

Site 9. Stripes

The fourth experiment in this series, completing the transition from polygons to stripes, was site 9 which was located on the eastern side of Moraine Valley on a well-drained slope of 10°. The surface material was at least 1 m. deep overlying a mass of large boulders, so that after the initial spring thaw there was rarely any surface water to be found. However, there was clearly some solifluction, as seen in the heaps of debris piled up behind rocks which were obstructing the down-slope movement. Immediately below such accumulations, moss had colonized the more stable coarse areas but the surface was elsewhere free from vegetation. Several patches of well-formed miniature stripes were present on this slope and one such



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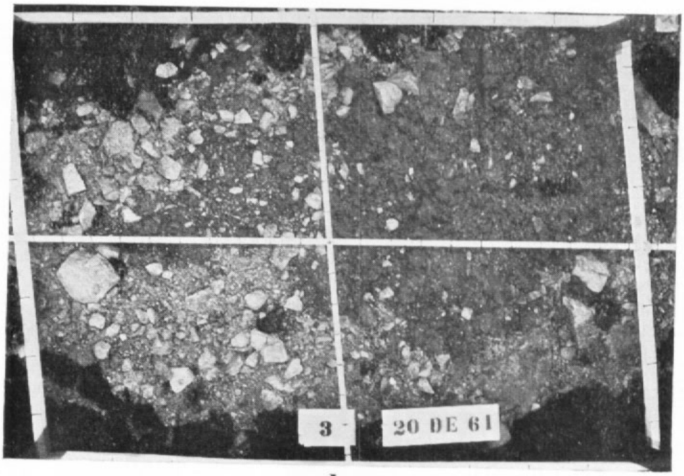

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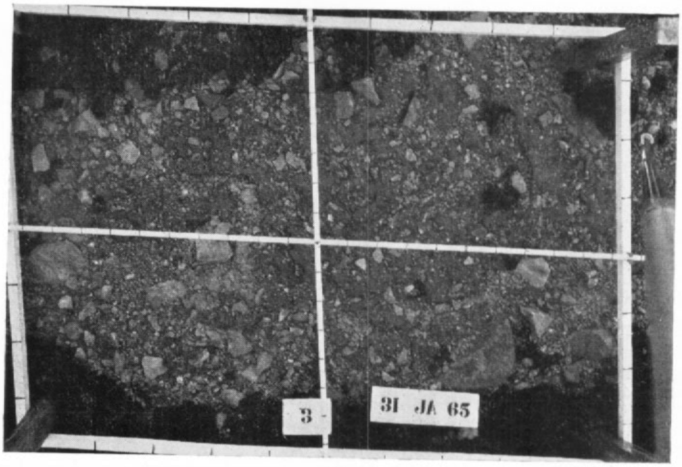

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pattern was chosen for experiment (Fig. 3a). The whole area covered by the wooden frame was raked to a depth of 5 cm. so that the stripes were obliterated and the fresh surface was randomly spread with coarse and fine material (Fig. 3b). Although there was an abundance of gravel, there were no stones greater than 5 cm. in diameter. At the time when this experiment was started, on 18 January 1962, the fines were moist and crumbly. During the rest of the summer months drying continued, so that shortly before the winter snow came the surface showed several desiccation cracks in roughly circular form, exactly similar to those which were observed on the other more level experiment sites. When the snow had cleared again and while the surface was still saturated, these cracks were not visible, but the areas which they enclosed showed up as concentrations of fines, still having a more or less circular outline. A down-slope movement of 3 cm. since the last photograph was evident after the first winter. Even at this stage (on 12 November 1962), only 10 months after the pattern was destroyed, a vague distinction between zones of fines and small stones was visible. As the surface dried out, this became increasingly apparent. The impression given by this incipient sorting was that in some areas the fines had been washed from amongst the stones, rather than the stones ejected from the fines. No cracks were observed during the summer of 1963, although this may merely indicate that these particular photographs were taken after wet periods. The 1963 winter brought an additional down-slope movement of 2 cm., whilst small stones lying on the fine areas had moved into the gravel concentrations, and at the same time other stones had appeared at the surface of the fines (Fig. 3c). Desiccation during the summer caused the formation of cracks along the stony channels which by now were clearly orientated down-slope. A year later (in January 1965) when the next photograph was taken, the formation of miniature sorted stripes was found to be very similar to those which had been destroyed in 1962 (Fig. 3d). The patterning was far from complete and there were individual variations to the outline of the stripes due to the disposition of larger stones, but in spite of this the photograph taken in 1965 shows a remarkable similarity to the original lay-out of fine and coarse material. During the 3 years of observation, a down-slope movement of 10 cm. was observed across the surface of the site, and yet still the miniature stripes formed in the same places. This suggests very strongly that the factor which determines this patterning is not the superficial distribution of stones, although this may influence the precise outline of the stripes.

Site 5. Planted stones on a polygonal net

The final experiments carried out on miniature patterns were designed to reveal the movement of stones during the year-round cycles of moisture and temperature variation. Two adjacent sites were selected for this work, the one almost horizontal and the other sloping at an angle of 6° to 8°. The coarse material in the stony areas of the two patterns comprised flat platy fragments of schist, 1 to 3 cm. in diameter, so similar fragments were chosen for the experiments. A number of these were painted white and laid upon the surface and their movements recorded photographically for 3 years. At the horizontal site 5, where there was a series of well-formed irregular polygons ranging in diameter from 5 to 12 cm., 18 white stones were laid flat upon the mounds of fines and upon the surrounding coarse network. A further 16 stones were embedded on edge into the miniature patterns. At the time the experiment began, in December 1961, the mounds were raised 2 or 3 cm. above the peripheral stony areas. By the end of that summer the stones planted on edge were already protruding by about 1 cm. and one of the flat-lying stones had been moved by an unknown agent into a stony belt over 10 cm. away. Immediately after the winter a surprising degree of movement was observed. All but one of the stones which had been on edge were now lying flat and had fallen in the direction of the slight local dip. The only exception was a stone wedged in the crack between two mounds of fines, which was presumably unaffected by frost-action. Of the stones laid flat, all but two of those placed in the sorted mounds had moved towards the edges, whilst those

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Fig. 2. a. Site 3. Original pattern; 13 December 1961.
b. Site 3. Pattern destroyed; 20 December 1961.
c. Site 3. Patterned surface after 3 years; 31 January 1965.
The date marker is 20 cm. long.

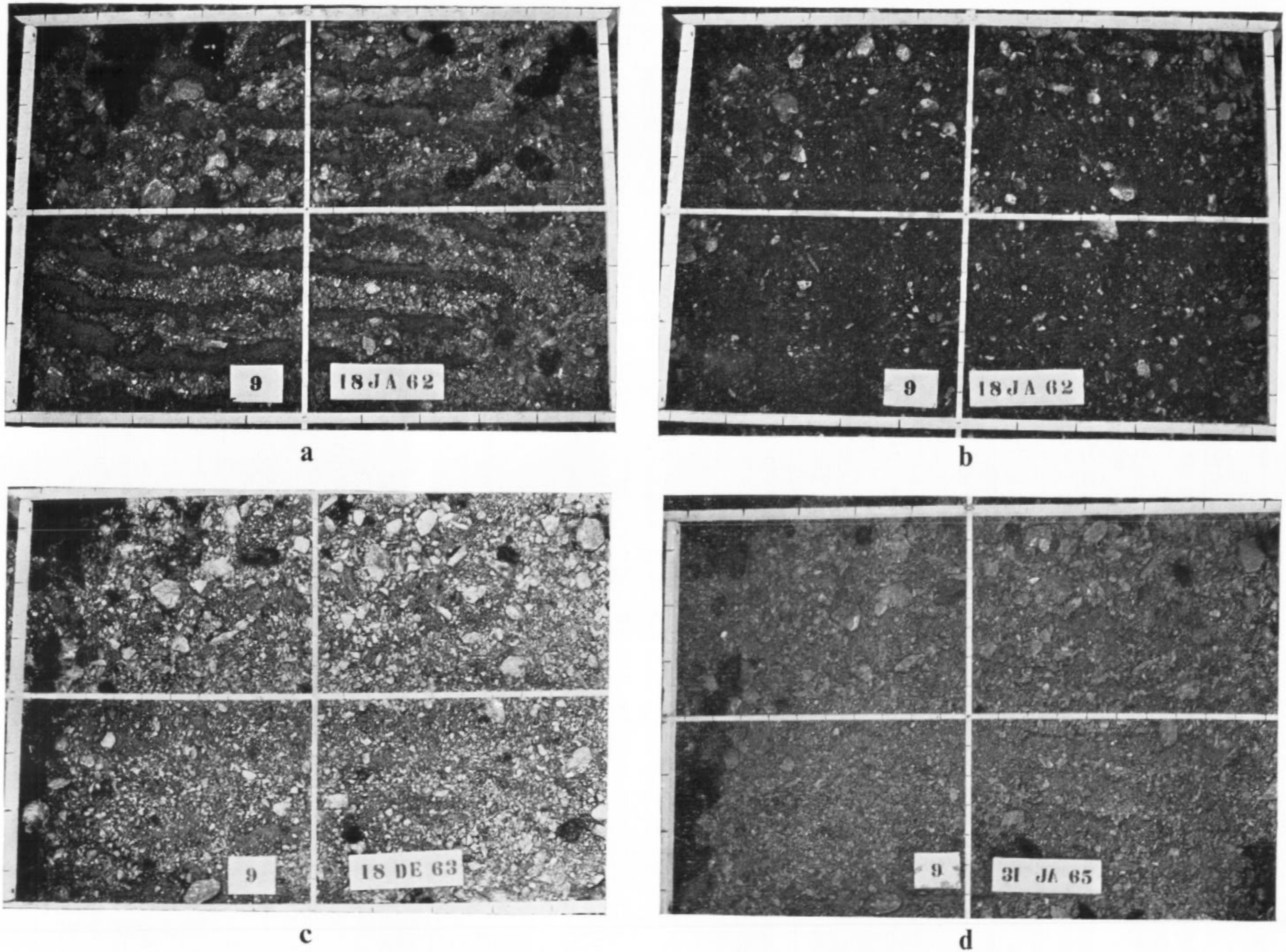
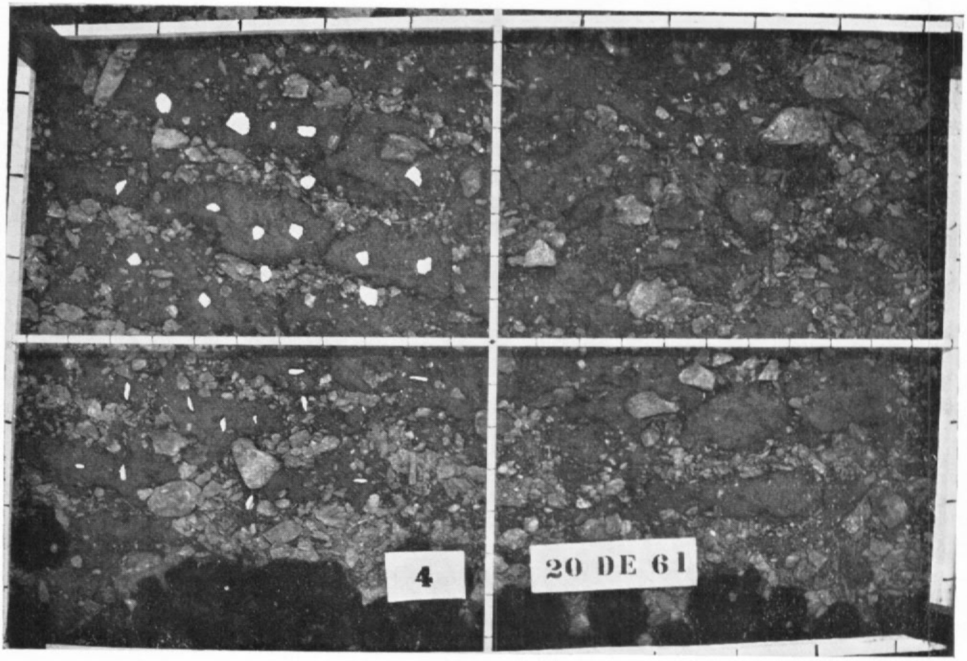


Fig. 3. a. Site 9. Original pattern; 18 January 1962. b. Site 9. Pattern destroyed; 18 January 1962.
c. Site 9. Surface after 2 years; 18 December 1963. d. Site 9. Surface after 3 years; 31 January 1965.
The date marker is 20 cm. long.

laid on the coarse zones all showed signs of being buried by either the adjacent fines or other stones. Throughout the summer the desiccation of the surface fines continued, so that by March 1963 the cracks between the mounds were at their widest. During this period, changes in the positions of the stones were limited to the falling of two into adjacent cracks. By the end of the 1963 winter all but four of the 18 stones which had originally been placed on the fine polygon centres had migrated into the surrounding crevices. The next summer saw three more move into the stone borders, and by January 1965 the remaining one was still on its mound of fines, although in 3 years it had travelled 5 cm. across the surface. Every one of the stones planted on edge lay flat at the end of that time, and several others which were not painted white and were part of the original patterning showed movements of several centimetres. Some variations in the shape of the mounds were also observed, suggesting that these miniature patterns are by no means at a stage of equilibrium.

Site 4. Planted stones on a transitional net

At site 4 an experiment exactly similar to that described above was carried out on a sloping plot where the fine sections were extended into mounds up to 20 cm. long and from 5 to 10 cm. across. These mounds were aligned so that there was a series of discontinuous stripes across the plot parallel to the line of steepest dip. Each unit of fines was separated from those at either end by only a narrow crack, whilst at each side of the mounds a distinct band of stones about 3 cm. wide was formed. In December 1961, 15 small white stones were laid flat upon the patterning, 12 on fines and the remainder amongst the stone sectors, whilst 11 stones were planted on edge (Fig. 4a). In addition, four were buried flat at depths of 3 to 5 cm. in one corner of the plot. The same photographic procedure was adopted as for the adjacent site 5. By the beginning of April 1962 four of the stones planted on edge had already been lifted out of the fines and lay flat on the surface. By the end of the winter three others were lying flat, so that only one of the stones planted on edge in the fines remained in its original position. Of those which were placed flat on the fines, three had moved more than 2 cm. while the others showed signs of minor disturbance. The direction of this movement was not down the nearest side of the mounds as might be expected, but down-slope parallel to the long axis of the upraised mounds. This suggests that the movement observed was brought about by solifluction rather than the tumbling of the loosened stones into depressions. The latter process appeared to operate during the summer months, when several of the stones located somewhat precariously at the edges of the mounds were found to have fallen into the adjacent cracks—possibly dislodged by raindrops or disturbed by diurnal freeze-thaw cycles. The following winter brought even more significant changes, and the photograph taken in December 1963 shows that of the 20 stones placed on the fines, either on edge or flat, only three remained. All of those originally placed on the stone borders showed signs of disturbance too and several of them were partly buried by this stage, but others had moved down-slope along the lines of coarse material. This movement took place at all seasons of the year and it was by no means limited to the winter period. Several of the unpainted stones, as well as those planted for the experiment, showed a migration along channels of coarse material during the early months of 1964. By January 1965 it was noted with surprise that several stones which had been in the cracks were now moving down-slope on to the fines (Fig. 4b). Comparing the last photograph with the one taken in December 1961, it was evident that almost all the stones on this site were migrating down-slope, often right across the pattern of contrasting coarse and fine material. Fragments 5 cm. in diameter or more had travelled over 10 cm. during the 3-year period, and as they moved the fines adapted their outline accordingly. In spite of these major movements of the coarse material, the centres of fines remained in their original positions, apart from the minor adjustments of shape as dictated by the larger stones. Once the stones had moved on down-slope, the earlier form of the mound was resumed. Nothing further was seen of the four white stones buried in one corner of the plot and their fate is unknown. It may be that on this particular site drainage was so efficient that ice segregation was minimal, which would hinder their upward movement. Quite apart from the buried white stones, there was an almost complete lack of other fragments appearing at the surface during the course of the experiment, which seems to support the above explanation.



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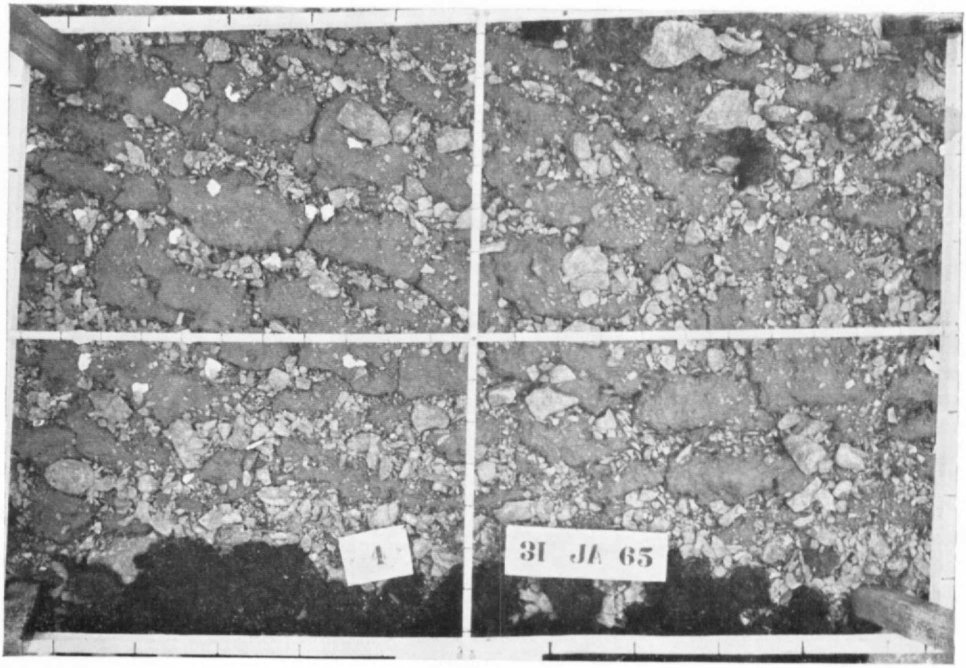

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Fig. 4. a. Site 4. Original position of white stones; 20 December 1961.
b. Site 4. Position of white stones after 3 years; 31 January 1965.
The date marker is 20 cm. long.

On reviewing the results of the six experimental sites discussed here, several conclusions may be drawn concerning the processes which operate in the miniature patterns on Signy Island. The major factor which appears to influence the outline of the patterns is the formation of desiccation cracks during the summer months. On horizontal or gently sloping surfaces these cracks assume a more or less regular polygonal pattern, but with an increase in the slope angle the cracks tend to form most strongly parallel to the slope, with only minor breaks normal to the major lines. The volume of coarse material present at the surface also affects the outline of the pattern and, if it is sufficiently great, it prevents the formation of patterns. The formation of mounds of fines raised up above the level of the stones appears to be due to differential frost heaving. The concentrations of fine silt and clay retain more moisture than the stones and thus undergo greater expansion when freezing takes place. But before this differential heaving can take place sorting must occur within the surface material. Although in a few instances such heaving was observed in random concentrations of fines after the destruction of the miniature patterns, it was 2 or 3 years before any regular mounds were found. Prior to the formation of true patterns it was necessary for a system of cracks to develop. Once this had taken place, the heaving of the surface followed the weaknesses, giving rise to a series of mounds separated by the pre-existing network. The accumulation of stones within these cracks appears to take place in three ways. The presence of coarse material at the surface often influences the positioning of the initial desiccation cracks, so that the two coincide from the start. Secondly, as the cracks appear, the stones on either side are dislodged and fall down into them. Ice needles, raindrops and strong winds have all been observed to cause these movements. The third means is the transport by solifluction of small stones towards the edges of upheaved mounds during the period of melt, when the soil is in a fluid state, although of necessity this process cannot take place until some sort of mound has already formed. The relative importance of each of these three explanations is difficult to assess but there is no doubt that each one plays a significant part.

A fact that became evident after continuous observation of these miniature patterns was that the maximum relief between the tops of the mounds and the lowest part of the dividing stone network did not necessarily occur when the surface was frozen. An examination of the upraised mounds revealed that they possessed a vesicular texture, being full of small air bubbles. This meant that even after the ice segregations had thawed and the melt water had drained away the mounds remained in their elevated form. This uncompacted nature of the superficial fines within miniature patterns was only found in those areas where the relief was maintained after thawing, so it would appear that the two are related. The precise means whereby these air bubbles form is not certain, although observations on small mud flows suggest that it is the result of drainage of melt water in association with rapid surface heating. The outer crust of the soil is consolidated by strong insolation, so that collapse cannot occur as the underlying moisture drains away. Gradwell (1957) has suggested that these bubbles are of air which has been trapped among ice needles and it is released by rapid thawing, but on Signy Island the bubbles were observed in areas where there was no great amount of ice-needle formation. The loss of this moisture must either bring about a considerable decrease in overall volume, or the occupation of the pore space by air instead of water. In most instances the surface subsides, but it appears that in these miniature patterns the rapid desiccation of the extreme surfaces prevents collapse. It is also possible that extreme heating of the surface fines causes some vaporization of the soil moisture, bringing about the formation of the bubbles. Whatever the exact mechanism, the result of this consolidation in an expanded state is to promote the sorting of stones into the depressed sections of the patterns throughout much of the year. Once the upraised character of the fines has been established, the mounds appear to be permanent and not dependent upon special conditions of rapid drying each summer.

Observations from elsewhere

The conclusions reached by Hay (1943) concerning the relationship between miniature sorted stripes and erosion channels in the English Lake District do not appear to be valid for Signy Island. Although there is no doubt that melt water occupies the depressed stone sections of the stripes, thus tending to wash out any fines which may have accumulated there, the perfect transition between the polygonal patterns on horizontal areas and the stripes on slopes makes it impossible to suggest that rill wash is the sole agent in the sorting process. If this were the case, then it is unlikely that the miniature stripes would have re-formed in the precise locations of those which had been destroyed. Klatka (1961) found deep desiccation cracks associated with miniature stripes and he concluded that the sorting resulted from the movement of stones into cracks to be later emphasized by rill wash. This appears to be a more satisfactory explanation for the Signy Island patterns, but there is still need for carefully controlled experimental work on this topic.

It is not easy to visualize how valid laboratory experiments could be carried out, since so many factors are both variable and of unknown significance. The most useful work to date has been done by field observations, but even then conclusions are surprisingly different. During his detailed work in New Zealand, Gradwell (1957) found a consistent movement of stones into shrinkage cracks in a manner and degree very similar to that found on Signy Island. Gradwell also found a considerable down-slope movement of the stones involved, with a direct relationship between slope angle and rate of movement. In accounting for this down-slope movement, however, he attributed it entirely to creep caused by the uplift of stones by needle ice. He stated that needles reached an aggregate thickness of 3 to 4 in. (7·6 to 10·2 cm.). In view of this degree of ice segregation, it seems very unlikely that there was no solifluction when thaw took place. To account for the observed degree of movement, he calculated that as many as 50 freeze-thaw cycles each year would be necessary. While such a frequency of cycles may well be possible in an alpine environment, much of the observed movement could be accounted for by solifluction with far fewer cycles.

Pissart (1964*b*) has described the radial movement of stones across the surface of a large sorted circle over a period of 16 years. In the course of this movement, the marked stones were found to have crossed several miniature patterns, travelling from fine centres to stone borders and on to fines again. A corresponding movement was observed to a lesser degree on experimental site 4, where some of the white stones were found to have moved on to the centres of fines in the general down-slope direction of the site. It is clear from these observations that the network of miniature patterns is established independently of the presence of coarse material. The photographs show that, in spite of a steady down-hill movement of stones across fine and coarse sections, the individual cells remained in precisely the same positions. Though much of the migration of stones may be attributed to creep, there is no doubt that some solifluction takes place at the extreme surface of the fine mounds. For this to happen, and yet at the same time for the cells to remain stationary, means that the pattern must be controlled by a deep-rooted network which is unaffected by these superficial disturbances. The only satisfactory explanation of this sub-surface control is a system of contraction cracks which occurs along the same lines of weakness year after year. This conclusion is substantiated by many observations on Signy Island, whilst further support comes from workers in Spitsbergen (Klatka, 1961), New Zealand (Gradwell, 1957) and the Pyrenees (Philberth, 1964). The other processes involved in the sorting, i.e. up-freezing of stones, creep and solifluction, are all of secondary importance. From this it may be inferred that the occurrence of miniature sorted patterns is not necessarily a periglacial phenomenon (Troll, 1944), although conditions for their formation are particularly favourable in this environment.

Signy Island Frost-heaving Experiments

During the discussion of miniature patterns and also in the first part of this report (Chambers, 1966*a*), several references were made to frost heaving of the ground surface and to the up-freezing of stones which was observed during the course of various experiments. While such isolated notes provided useful details, it was also necessary to attempt some sort of quantitative analysis of the vertical movement which takes place as the active layer freezes and thaws. For this purpose a metal framework of similar principle to that used by Heywood (1961) and Matthews (1962) was constructed over a large sorted stone circle (Fig. 5). The horizontal framework, supported about 1·5 m. above the ground, was made of slotted angle-iron connected to four legs concreted and bolted to rocks and pickets which were embedded in the permafrost. Through the holes in the angle-iron were passed vertical aluminium rods

Fig. 5. Site of the frost-heave experiment.

bearing a plate 2·5 cm. in diameter which rested on the ground. These rods could then move up or down with the surface, sliding through the supporting frame which was used as a datum against which the positions of the rods were measured (Fig. 6). Some of the rods were partly buried in an attempt to discover details of deeper movement. A total of 20 rods was placed all over the circle, which measured 3 by 2 m., and was situated along the course of an ephemeral melt stream that flowed amongst a mass of large boulders where the local gradient was 6°. The surface of the circle was almost horizontal but it showed slight doming in the centre with a maximum slope of 2°. The fines of the circle were contained within a ring of large boulders which showed no signs of having been sorted from the fines, but rather it appeared that these fines had moved upwards from below and had been retained by the pre-existing rim of coarse rocks. Several other such circles were found along the course of the stream and each bore more or less the same form, except that in some cases the fines had overflowed the rims of boulders and had elongated into an irregular stripe.

The surface of the circle in question was divided into a miniature sorted net which had formed in the top 3 cm. of the surface material. Rods H, P and S (Fig. 7) were placed directly on top of the stones which formed this irregular grid, whilst rods J, N and Q were placed at the edges of the circle where the fines lay immediately over the surrounding boulders. Rods B, F, G and L were buried to depths of 10 and 15 cm. within the fines, whereas the remaining ten rods were placed on the surface fines in a way which would give as comprehensive a picture as possible of the movement within the circle. It was feared that the stems of the buried rods would freeze to the surrounding soil, so these were sleeved with polythene tubing and lubricated with silicone grease. This allowed the surface to rise freely all around without gripping the rod itself until the descending freezing plane reached the plate at the bottom of the rod. This means of recording sub-surface movement proved surprisingly effective and, as far as is known, it has provided the first available data of its kind.

The recorded movement of the rods throughout one month at the onset of the winter in 1964 is shown in Table I. After 26 April no significant movement took place until the beginning of January 1965, when the snow melted from the site. Since the surface was unfrozen when the

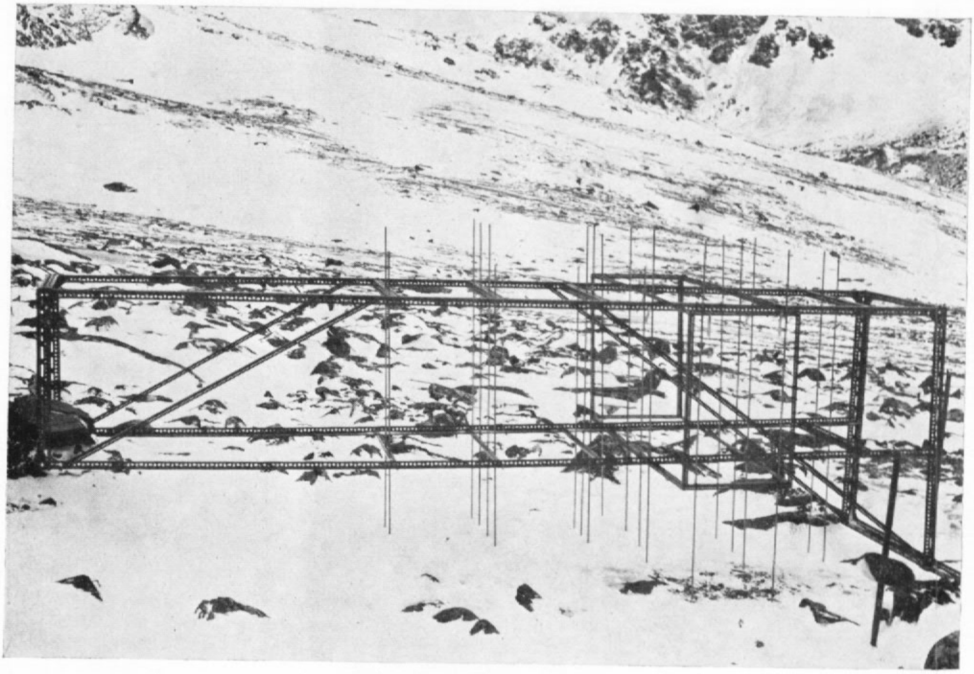

Fig. 6. Frost-heave recording apparatus.

readings were first made, on 25 March 1964, the movement shown represents the entire heave for that winter. From an examination of the buried rods, it can be seen that rod L at 15 cm. did not start to heave until 4 April and rods F and G, also at 15 cm., had not started heaving on 6 April. Rod B, at 10 cm., did not start moving until 5 April, being later than the 15 cm. rods due to a drift of snow which caused some insulation over the eastern sector of the circle. It may be safely assumed that the beginning of heave at these depths indicates the arrival of the freezing plane at the soil beneath the plates at the bottom of the rods. During these first 2 weeks, when the freezing plane was descending from the surface to a depth of 15 cm., Table I shows that almost 75 per cent of the total frost heave took place. By dynamiting several non-sorted circles, Williams (1959) was able to examine the frozen soil for ice segregation, which he found to be concentrated in the upper 10 cm. The Signy Island soil-temperature records show that, after a month of freezing at the beginning of winter, only the upper 40 cm. or so are affected (Chambers, 1966*b*). Since no significant movements were recorded after 26 April, when the freezing plane must have been at about 40 cm., it may be concluded that there was no ice segregation, apart from the non-heaving concrete type, in the active layer below this depth. The total thickness of the active layer at this site was between 120 and 150 cm.

The fact that ice segregation is here concentrated in the upper part of the active layer means that the downward movement of fines ahead of the freezing plane, by the process which Corte (1963) described, would be confined to this zone. The up-heaving of coarse material through fines would similarly be limited to this upper level.

Another interesting feature of these results is the negative movement recorded by the buried rods, particularly G and F. This would suggest that, at the same time as the upward heaving is taking place, a downward force is also exerted which is sufficient to cause compression of the unfrozen material below the freezing plane. This would lend substance to the cryostatic theory described by Washburn (1956) who proposed just such a pressure as this. The evidence put forward here is slight, however, and it is still dubious whether sufficient pressure could be exerted to cause flowage. In all the patterns sectioned on Signy Island, the zone immediately

Table I. Frost heave in circle for one month, March–April 1964

Rod	March 25	26	27	28	29	30	31	April 1 (mm.)	2	3	4	5	6	12	26	Total heave (mm.)
A	254	+4	+6	+3	+3	0	+1	−1	+1	+2	+3	+2	+3	+6	+3	+36
B	173	0	+2	0	+1	−2	0	−1	+1	0	0	+1	+1	+4	+3	+10
C	283	+5	+5	+2	+2	+2	+1	0	0	+3	+3	+2	+3	+8	+2	+38
D	275	+4	+6	+3	+3	+1	+1	−2	+2	+3	+3	+2	+3	+8	+3	+40
E	283	+3	+7	+3	+3	+1	0	−3	+3	+3	+3	+3	+2	+9	+3	+40
F	137	0	−1	−1	−1	−1	0	−1	+1	−1	−2	−1	−1	+3	+1	− 5
G	106	0	+1	−1	0	−2	0	−1	+1	−1	−2	−1	0	+6	+1	+ 1
H	283	+2	+8	+3	+3	+2	+2	+1	+1	+2	+2	+3	+3	+9	+2	+43
I	294	+4	+7	+4	+4	+2	+1	−1	+3	+2	+2	+3	+2	+9	+2	+44
J	209	+4	+7	+2	+2	+1	+3	−2	+2	0	+1	+3	+1	+3	+1	+28
K	264	+5	+8	+5	+4	+3	+1	+1	+2	+1	+2	+3	+2	+8	+2	+47
L	134	0	0	0	−1	0	0	0	0	−1	+1	+2	+3	+7	+1	+12
M	291	+4	+10	+5	+5	+3	0	−2	+4	+2	+1	+2	+2	+7	+1	+44
N	296	+4	+9	+2	−1	0	0	−3	+3	0	0	+1	0	+4	0	+19
O	242	+5	+11	+6	+4	+3	+1	−1	+3	+1	+1	+3	+1	+7	+1	+46
P	254	+3	+7	+8	+6	+2	+2	−4	0	+3	+2	+2	+2	+7	+1	+41
Q	270	+5	+7	+2	−1	−1	−1	−3	+2	0	0	0	+1	+4	−2	+13
R	195	+5	+8	+4	+3	+2	−2	−3	+3	+1	+2	+2	+1	+4	+1	+31
S	194	+1	+3	+5	+4	+2	−1	0	+1	+2	+2	+1	+2	+3	+1	+26
T	272	+4	+11	+7	+4	+2	0	−2	+3	+1	+1	+2	+1	+5	+1	+40
Air temperature (°C)	+1	−4	−4	−5	−3	−1	+1	+2	−7	−8	−4	−4	−4	−7	−9	

above the permafrost, where the two approaching freezing planes would meet, was composed of relatively coarse gravelly material.

The placing of various rods upon the stones and fines, which together formed an irregular sorted net, revealed a surprising lack of difference in the frost heave they underwent. These differences are shown in Table II, which compares the movement of the rods placed on the miniature stone network with that in each adjoining centre of fines. The maximum differential heave between the fine and coarse sectors of this patterning was 0·5 cm., which is totally inadequate to allow gravity sorting of coarse material down the sides of frost-heaved mounds. It is also barely sufficient to promote solifluction on the same scale. It seems likely that the freeze-thaw activity which causes relative movement within these patterns takes place at the end of the winter, when the fines are saturated and the freezing plane is still close to the surface.

TABLE II. DIFFERENTIAL FROST HEAVE IN MINIATURE PATTERNS

On stones (cm.)		*On fines* (cm.)		*Difference* (cm.)
H	+4·3	I	+4·4	0·1
P	+4·1	O	+4·6	0·5
S	+2·6	R	+3·1	0·5

Whilst differential heave on a miniature scale proved to be small at this site, over the entire pattern it was considerable. The central fines were uplifted between 4 and 5 cm. above the stone perimeter, emphasizing the domed profile which existed even before freezing. It can be seen from the rod locations in Fig. 7 that this heaving did not form a gentle gradient from the periphery to the centre of the circle. The maximum heave was found as a fairly uniform level over all but the extreme outer ring of the fines, so that rods such as O, situated only 30 cm. from the stone rim, were uplifted 4·6 cm. This means that the gradient created by the differential heave is concentrated in a strip about 25 cm. wide at the edge of the fines, which must then slope outwards at the surprising angle of about 15°. This gradient is maintained throughout the winter and it is not until thawing starts that the force exerted by gravity plays any part. As the snow melts, the top 2 or 3 cm. of the soil are also melted even before the surface is actually clear. This soil, saturated with water and disturbed by the collapse of small ice segregations, is rendered quite mobile and then flow takes place down the frost-heave gradient towards the edges of the circle. As the thaw penetrates more deeply, more and more of the ice segregations are melted and the gradient decreases accordingly. Thus gravity flow within circles of this nature is confined to the very early period of the thaw in the upper 4 or 5 cm. of the surface material.

Another experiment was devised to examine this type of movement across the surface of sorted patterns, for such a process would account for the accumulation of the coarse material around the edges of the cells. A number of white stones were laid flat over the surface fines of a sorted circle in January 1962. Within a few weeks the stones had sunk until their upper surfaces were level with the fines, but after that no further vertical movement occurred. By the following spring it was evident that the stones which had been touching each other at the beginning had begun to disperse radially. This movement continued throughout the next 2 years until the outermost stones had joined the coarse material at the perimeter of the fines. Total movement of the 11 stones ranged from 3 to 10 cm. in 3 years. The positions of the stones were noted at the beginning of each winter and as soon as the snow had cleared in the spring, by which time the surface fines were already liquid. It was found that the movement occurred in the winter period with little or no change in the summer months. This suggests that either the stones were moved by ice action or that solifluction during the early thaw was responsible. That such a movement could be caused by ice was proposed by Cholnocky (Washburn, 1956) but no satisfactory explanation has ever been put forward for this mechanism. It seems far

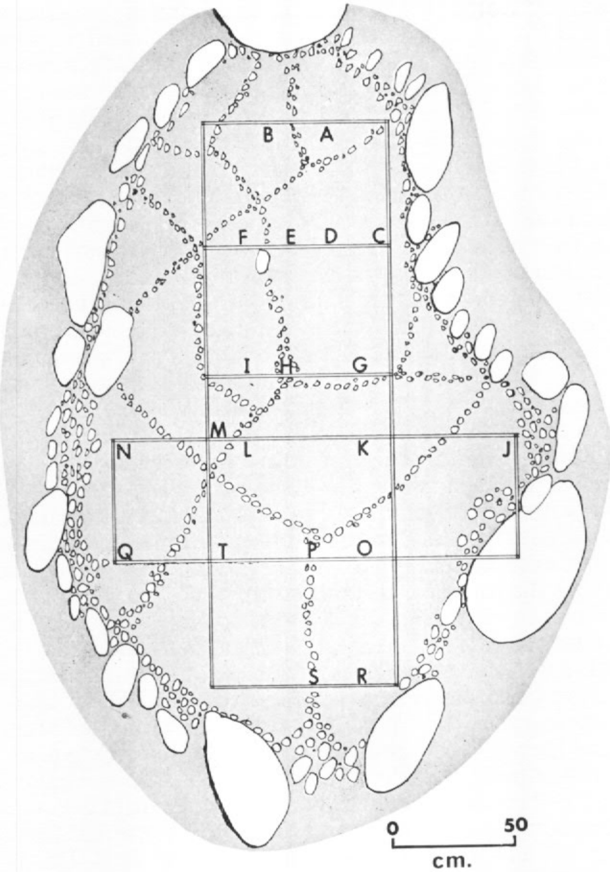

Fig. 7. Plans of rods on a sorted circle for a frost-heave experiment.
Rods A, C, D, E, I, K, M, O, R and T sited on surface fines.
Rods H, J, N, P, Q and S sited on surface stones.
Rods B, F, G and L buried in fines.

more likely that the stones were carried along by the saturated fines as they moved outwards. It has already been established from the frost-heave experiment described above that moist fines are domed up in the centre of a circle or polygon when frozen, and that when thawing first takes place there is sufficient gradient to permit solifluction towards the edges. A similar experiment to this, but operated for a much longer period, has been described by Pissart (1964*b*), when painted stones placed at the surface of a stone circle 1·5 m. in diameter were found to have moved outwards between 7 and 21 cm. in a period of 16 years.

The outward radial movement of fines across the surface of large circles appears to be coupled with an upwelling at the centre of the pattern. This is illustrated by several sample sites discussed in an earlier paper (Chambers, 1966*a*), where, at site J the fines were raised above the general surface level, being only contained by a narrow embankment of moss. Similarly, the continued flow of fines down-slope from an extended circle, with its origin in just such a pattern as site J, can only imply that there is a continued upwelling of material at the source in order to maintain the movement. The form of fines in the sorted circle used in the frost-heave experiment described above also gives the impression of having migrated upwards through the surface boulders, resulting in the feature shown in Fig. 5.

Other experiments were designed to examine the way in which stones within the centres of fines are moved. Two adjacent circles approximately 1·5 m. in diameter were chosen for an attempt to clarify the up-freezing process which brings stones to the surface. This had been proved experimentally by Corte (1961) under ideal laboratory conditions but the validity of the concept under a natural periglacial environment remained in some doubt. Numerous researchers had invoked this process in explanations of various pattern forms but field experiments were still lacking. Jahn (1961) has quoted details of work conducted in Spitsbergen, but upward movement was recorded by wooden stakes protruding from the surface, so although these data give useful information on the extent of the frost-heave cycle, the results do not confirm or measure the movement of stones. It was decided to plant small white-painted stones at different depths within the fines of large sorted circles and to record the time taken for the stones to reach the surface. The stones varied in size from 2 to 4 cm. in diameter and they were planted in two circles, at 5 and 10 cm. beneath the surface, respectively. After 12 months there appeared to be no change in either circle and no white stones were visible. After 2 years, however, eight of the ten stones planted at 5 cm. had appeared, showing minimum annual differential movement between stones and fines of 2·5 cm. in the upper part of the active layer. At the end of the third year no more stones had appeared and the fate of the two remaining stones planted at 5 cm. is unknown, although it is most likely that they were trapped beneath other coarse material at the surface and thus hidden from sight. The non-appearance of the stones at 10 cm. was only to be expected in view of the paucity of frost-heave cycles at that depth, as revealed later by soil-temperature measurements (Chambers, 1966*b*).

Another up-freezing experiment, similar to that described by Jahn (1961), was carried out in a large sorted polygon, with a series of stakes and stones inserted vertically to depths of 10 to 100 cm. Two stakes were inserted at each depth, one with the end pointed and the other with the end cut square, but each of these pairs showed identical uplift regardless of their shaped ends. This indicates that the force which uplifted the stakes came from the side and not from below. These conclusions confirm Högbom's (1910) original suggestion that coarse material is carried passively by fines subjected to heaving, rather than the later idea expounded by Nansen (1922) and Beskow (1930) that ice segregates beneath stones and thrusts them out of the fines, which has been commonly accepted in texts such as that of Cailleux and Taylor (1954). If the Nansen theory were true, then wooden stakes with low thermal conductivity and sharpened bases would not have been forced upward from below by growing ice crystals. Elongated stones were inserted in the pattern at the same time as the wooden stakes and they underwent exactly the same uplift as the stakes. The results of this experiment are summarized in Table III, the upward movement being measured relative to the surface of the fines. It may be observed that in all cases the movement was greater during the second year. This is probably due to the heavy rainfall in April 1963, which left the ground wetter when it froze than in the previous year, thus permitting more ice segregation and frost heaving. It would appear that the stakes and stones were gripped by the fines at the extreme surface when freezing first started, so that as the surface was lifted the stakes were drawn up at the same time. In this way the stakes were

TABLE III. UP-FREEZING OF STAKES AND STONES, 1962 AND 1963

Depth (cm.)		*Upward movement, 1962* (cm.)	*Upward movement, 1963** (cm.)	*Mean movement* (cm./yr.)
Stones	10–15	†	5	5·0
Stakes	10	4	5	4·5
	15	5	6	5·5
	20	5	6	5·5
	25	2	4	3·0
	50	1	3	2·0
	100	1	2	1·5

* Stakes returned to original depth after 1962.
† Movement not recorded in 1962.

drawn upwards for a distance equivalent to the amount of expansion which occurred in the surrounding fines. As the freezing plane reached the base of each stake, differential movement ceased and fines and stakes were heaved up together. The results of the frost-heave experiment described above show that after the upper 20 cm. were frozen further heaving was slight. Thus the stakes inserted to 15 and 20 cm. were moved most, while those at 10 cm. revealed the movement only within the top 10 cm. of the fines. From this it would be expected that all the deeper stakes should show at least the same movement as those at 20 cm. and the reason for their failure to do this is not certain. It is probable, however, that the friction with the soil throughout their greater length was sufficient to hinder their uplift.

Winter observations on soils revealed a concentration of ice beneath the stones which had been noted previously and used to support the Nansen theory of stone uplift (Williams, 1959). It was noticed frequently, however, that these ice crystals were not compressed, which would be expected if they had exerted sufficient force to push up the stones into the already frozen layer of fines above. Often there was a small cavity between the ice crystals adhering to the bottom of the stone and the underlying fines. The crystals gave every indication that the ice had formed within the cavity. This fact, together with the evidence of the uplift of the sharpened wooden stakes, gave rise to the following theory. As the freezing plane descends to the level of a stone contained within a mass of fines, the top of that stone is gripped by the freezing fines. The freezing plane continues to descend with consequent ice segregation and heaving, so that the stone is lifted with the already frozen material above. Beneath the stone is left a hollow which represents the degree of expansion that has taken place within the fines while the freezing plane was descending from the top to the bottom of the stone. Further descent of the freezing plane may heave both stones and fines but it will not alter their relative positions. The hollow beneath the stone is then deformed by the pressure of ice expansion, which prevents the space being re-occupied when the soil thaws, releasing the stone. From this it may be concluded that the maximum upward movement of any stone in one frost-heave cycle is equal to the total amount of vertical expansion which takes place in the zone of fines surrounding the stone in a horizontal layer of equal thickness to that stone. Since these conclusions were first formulated, confirmation has come from Kaplar (1965), who has demonstrated with the aid of a time-lapse camera the validity of every stage of the movement described above.

In view of these results, further deductions may be made concerning the upward movement of white stones within the large sorted circle described earlier. This showed that stones at a depth of 5 cm. were uplifted through 2·5 cm. in a year, but the frost-heave experiment revealed that in the top 15 cm. of fines there is approximately 3 cm. of expansion as the freezing plane descends. From this it can be calculated that the maximum movement of the white stones, each about 2 cm. thick, during a frost-heave cycle is $3 \times 2/15$ cm. $= 0 \cdot 4$ cm. This indicates that a minimum of six or seven freeze-thaw cycles per year is necessary to achieve the observed rate of uplift, although this is a very approximate calculation. The water content and grain-size of the fines, the thickness of the stone and the freezing rate all affect the degree of ice segregation and heaving around the stone. The soil-temperature data which were recorded from a sorted stone circle only a few metres from the site of this experiment show that at a depth of 5 cm. within the fines a total of 13 frost-heave cycles were recorded in the 2 years January 1962 to December 1963, which is exactly the number required by the calculations above. Since the occurrence of such cycles decreases with depth, as a stone approaches the surface its speed of uplift will accelerate according to the increased frequency of the cycles. This means that the stones planted at 10 cm. may take 6 or 7 years to reach the surface.

General Conclusion

One of the most important facts emerging from this study is the dual nature of the so-called "active layer". It has been found that in the upper zone, which appears to be 40 to 60 cm. deep, are concentrated sorting, ice segregation and solifluction, whereas below this there is a relatively passive zone which plays little or no part in current geomorphic processes. Often the separation between these two is sufficiently distinct to be marked by a line, especially on slopes subject to solifluction. A change in colour of the fines, and a lack of sorting and orientation of coarse material below all indicate this junction. The close similarity between the depth of sorting and the depth of solifluction in areas of large sorted stripes suggests that they are related. Likewise, the accord between the depth of ice segregation and the depth of sorting within large circles and polygons promotes the same conclusion. Thus it appears that the upper mobile part of the active layer is the zone in which large sorted patterns are formed.

As to the actual processes involved in the formation of these patterns, there is no doubt that the upward movement of coarse material to the surface by frost-action is one of the most important factors. This up-freezing is relatively slow in material deeper than about 10 cm. which undergoes freezing only once each year but, according to the processes outlined above, the greater the vertical extent of a stone, the faster will be its upward migration, which would account for the concentration of coarse material at the surface. If such a process were to operate upon a rock fragment which was tilted in the vertical plane, then as it was drawn upward year by year with the annual cycle of frost heave it would be moved into an increasingly vertical position as the bottom of the stone moved in the line of least resistance, i.e. the place previously occupied by the top. In this way the presence of standing stones, so commonly associated with regions of patterned ground, may be explained. Though there is no field evidence for this hypothesis, it provides a satisfactory account of a hitherto unexplained phenomenon.

The actual movement of coarse material to the surface is well documented and the rate of this movement is discussed above. The evidence from observations made on Signy Island points to the fact that this coarse, relatively dense material which has been sorted from the fines below is responsible for the load deformation that is expressed in the upwelling of plugs of fines. Where these plugs break through to the surface, sorted circles are formed, and where such circles occur in juxtaposition a polygonal pattern results. One of the points favouring this hypothesis is that it requires no special postulation of concentrations of fines and stones within the active layer before the pattern-forming processes operate. Another factor of importance which Washburn (1956) indicated is that the surface load which brings about the displacement of the underlying fines may merely be due to a difference in moisture content, so that intergranular pressure is less at depth. In this way, one of the greatest objections is overcome, since a uniform layer of coarse material at the surface is not a prerequisite of pattern formation. Many areas of sorted polygons have been reported where the stone borders are relatively narrow and could not possibly be the concentration of an entire surface covering of such coarse material. Other unnecessary criticism of the concept has been provoked by the use of the word "convection" to describe this process. The movement is not a circulation but the upwelling of fines in plugs, and a far more gentle and less obvious settling of the surface material. Once an equilibrium is reached, movement will cease. This equilibrium stage may be represented by "anchored" polygons, where the coarse material extends to the base of the active layer.

With respect to the formation of large sorted stripes, the up-freezing of stones is equally important. Whether any upward movement of fines takes place is difficult to determine but the efficient drainage of such slopes makes it unlikely. The dominant process in bringing about the patterning appears to be the streamlining of solifluction in areas unobstructed by large boulders. Even in the area of most regular sorted stripes on Signy Island, the fine sectors are of varied width and the stripes are often interrupted by obstacles (Chambers, 1966*a*). These facts tend to confirm the idea that the original movement down the slope was of a random nature. The movement of stones to either side of the fine sectors has been demonstrated experimentally and the fact that this movement decreases with depth has also been established. This motion, continued in vertical and horizontal planes, accounts satisfactorily for the observed "V" form of the stone sections of the stripes, where the maximum width occurs at the surface, decreasing downwards until the sorted stones cease altogether at approximately the same depth as the limit of solifluction.

The assumption that the processes which operate within miniature patterns are dissimilar to those found in large patterns appears to have been justified. The dominant influence of contraction cracks in both polygons and stripes on a miniature scale did not occur in their larger counterparts. Again, it must be stressed that these observations are confined to Signy Island, and no reference is made to the giant ice-wedge polygons which are also systems of icefilled contraction cracks. Miniature sorted stripes were found to be influenced more by creep than by solifluction in the movement of stones down-slope, although the latter process was evident to some extent. In the large sorted stripes, on the other hand, solifluction played the major role in such movement. Some doubts have been raised as to the relationship between normal desiccation cracks and the miniature sorted patterns on account of the contrast in lattice form between the two. The observation is valid, although the difference is not genetic. The regularity of the miniature patterns is due to small-scale solifluction within individual cells, so that the cracks outlining each unit are emphasized but those tending to penetrate the mounds are obscured. This process takes place in the early stages of pattern formation, and once the regular system of cracks is established they are maintained. The speed of movement within the miniature patterns may be attributed to the frequency of freeze-thaw action, since a total of 20 cycles per annum was observed in the top centimetre of the surface material.

There is no doubt that the effects of frost-action and solifluction combine to form one of the most geomorphologically active landscapes in the world. While mass wastage is found in almost every environment, it is in the maritime periglacial regions of abundant moisture and disturbed unvegetated surfaces that it becomes predominant.

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