

THE MORPHOLOGY OF SOME PERIGLACIAL FEATURES ON SOUTH GEORGIA AND THEIR RELATIONSHIP TO LOCAL ENVIRONMENT

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ABSTRACT. Small sorted stripes, large vegetated unsorted stripes, large unsorted circles and two types of solifluction lobes are described by means of vertical sections and particle-size analysis. Where possible, vegetation is related to periglacial morphology. Soil temperature patterns and depth and duration of snow lie are related to periglacial activity for some features. Sorting in the stripes appears to be only superficial and takes place almost wholly in autumn. There is little sign of downslope movement of the solifluction lobes. The role of needle ice is discussed.

INTRODUCTION

The main geographical emphasis in the voluminous literature on periglacial activity and patterned ground morphology has been on the northern hemisphere. Although a recent bibliography (Walton, 1980) lists 368 references on Antarctic and sub-Antarctic pedology and periglacial processes, apart from some work in Victoria Land (e.g. Berg and Black, 1966; Black, 1973) and on Signy Island, South Orkney Islands (Chambers, 1966*a, b*, 1967, 1970), detailed published information for the Antarctic region is relatively poor. Periglacial data for the sub-Antarctic islands often appear as minor notes in geological papers. South Georgia, despite its apparent suitability for a study of patterned ground, has been little studied until recently. Descriptive notes are to be found in papers by Clapperton (1971), Clayton (1977), Skidmore (1972) and Stone (1974, 1975) but the only published process study has been a limited estimate of the depth of penetration of the frost front and its heaving effects (Smith, 1960). Against this inadequate background, a preliminary survey of the distribution of various types of patterned ground around the island was made in 1975–76 (Thom, 1981). The survey was principally descriptive and few new data on rates of periglacial processes were obtained.

More recently (1978–82), in a programme principally concerned with plant colonization of patterned ground (Heilbronn and Walton, 1984), considerable data were collected on certain types of periglacial features on South Georgia. This paper describes the morphology and particle distribution in four periglacial features, reports on some local climatic data that may influence cryoturbation and discusses the South Georgia data in the context of other Antarctic periglacial information.

METHODS

The cold, moist sub-Antarctic weather, together with a heavily glacierized terrain, provides good conditions for frost shattering and periglacial movement at South Georgia. The bedrock is mainly fine-grained greywackes and tuffs (Stone, 1980) and is highly fissile.

All the features described were in the Cumberland Bay area of South Georgia but were typical of the periglacial forms throughout the island (Thom, 1981). Since each

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feature was represented by many examples, one good specimen of each type was chosen for analysis. The following features were examined:

1. small sorted stone stripes
2. large unsorted stone stripes
3. large unsorted circles
4. solifluction lobes,
 - a. with bare terrace
 - b. completely vegetated

Classification is based on Washburn (1979).

Morphological descriptions

Each feature was photographed undisturbed. Vegetation descriptions were prepared where appropriate. The feature was sectioned vertically and the soil profile photographed and sketched. Measurements were made of the range of sizes shown by each feature. By means of a 1-cm quadrat frame (Kershaw, 1958) a 2-m transect was used to record the detailed microtopography of small-scale sorted stripes.

Mechanical analysis

To simplify comparison of results, the methods of Chambers (1966a) were followed where possible. Soil samples of approximately 500 g were collected from each distinct horizon and were kept dried until analysis. Subsamples were used to determine loss on ignition at 550°C. Forty grams of the fraction below 2000 μm was dispersed in a mixer with 5% sodium hexametaphosphate solution before wet sieving through a nest of sieves passing particles from 1000 to 63 μm in diameter. The silt and clay fractions were determined using the Bouyoucos soil hydrometer method over a period of 12 h. Corrections for meniscus, temperature, dispersant and water density were applied to the hydrometer readings before calculation of the percentages of specific particle sizes (Head, 1980).

Environmental data

Snow depth was recorded over a two-year period above several patterned ground features. In addition, regular measurements of soil temperatures were made over a period of 22 months, at depths of up to 30 cm, in small scale sorted stripes, a turf-banked solifluction lobe and an unsorted circle. Measurements were made with Gulton 32TD thermistors and a portable meter. Accuracy was ± 0.2 deg.

RESULTS

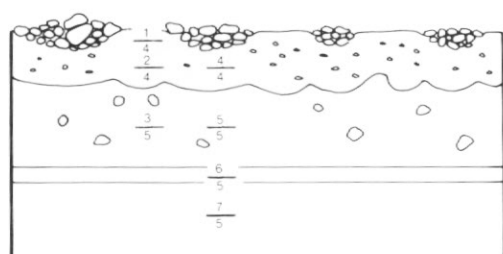
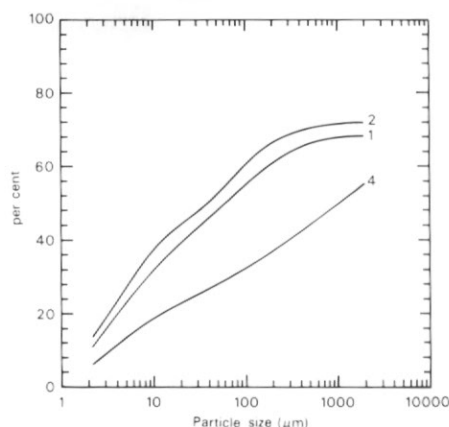
Morphology of features

Small sorted stripes. The stripes shown in Fig. 1 were in Bore Valley at an altitude of 75 m and had a SW aspect. They were considered typical of the small-scale stripes found throughout the Cumberland Bay area.

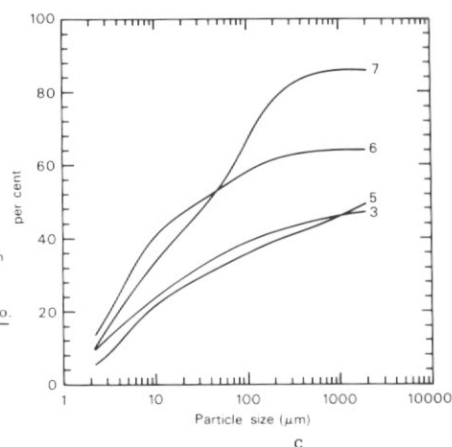
Sorting did not extend very far into the regolith, usually 6–7 cm, and the amplitude of the stripes was 10–20 cm. The microtopography point quadrat data, when subjected to spectral analysis, showed three major wavelengths at 120, 55 and 21 cm. The active 21 cm stripes were found over a wide range of altitudes, from near sea level to over 250 m, generally on slopes of 6–18° with a northerly aspect. Vegetation cover was generally sparse and was predominantly composed of isolated plants of *Phleum alpinum*, *Festuca contracta*, *Deschampsia antarctica* and *Acaena tenera*. *Polytrichum piliferum* was the commonest moss, often occurring as isolated stems but most other cryptogams present were associated with the flowering plants.



a



b



c

Fig. 1. a. Small-scale stone stripes in Bore Valley showing depth of sorting.

b. Diagrammatic vertical section showing major horizons and sample points: 1 – medium brown; 2 – light sandy brown; 3 – grey sand and silt; 4 – orange brown sandy. (L.O.I. = percentage loss on ignition.)

c. Distribution of particle size classes at sample points.

On the more gentle slopes, a series of transitory phases from polygonal nets through 'ovals' to stripes were found, whilst 'damming' of material in the stripes was frequently caused by single, large and very slow moving clasts. Plant growth, especially of *Phleum*, produced small steps as fine material accumulated around the rhizomes and root ball (Heilbronn and Walton, 1984).

The distribution of particle size classes down the profile (Fig. 1c) shows a higher percentage of fine material in the two samples from beneath the coarse material (4). No differences are evident between the lower samples (3, 5) but there is a marked decrease in the >2 mm class in the lower horizons (52% in 5, 36% in 6, 14% in 7).

A survey of small sorted stripes, all on 14° slopes but at a range of altitudes, showed some interesting features (Fig. 2). The percentage of >2 mm in both coarse and fine samples appeared to increase with altitude, possibly as a result of greater downwash, or deflation, of fine material from the more exposed upland sites. Sites 1 and 2 showed an almost linear distribution of particles across size classes in the fine samples

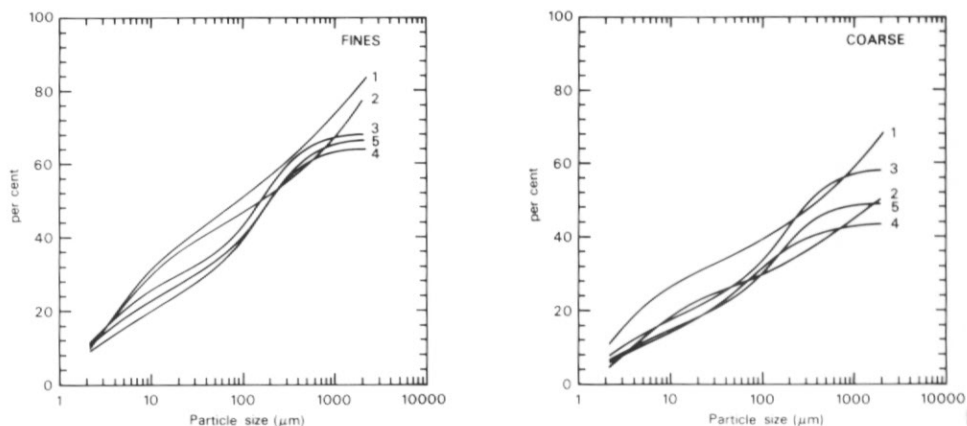


Fig. 2. Small-scale sorted stripes: particle size class distribution in specimens taken from fine and coarse areas at five sites of differing altitude and aspect: 1, 75 m, East; 2, 83 m, South-west; 3, 120 m, South; 4, 190 m, West; 5, 225 m, South-west.

whilst sites 3–5 appeared to have virtually no material in the range 250–2000 μm . This applied also to the coarse samples. Clay content in all samples was in the range 4–10%. In general terms the principal difference between the coarse and fine material at all five sites was an increase of 20–25% in the proportion of material <2 mm in the fine. Loss on ignition showed only a small change with altitude, from c. 3.5% of the dry weight at the lowest two sites (sites 1 and 2) to c. 1.5% at the highest sites.

Needle ice was observed on several occasions beneath the fines. The needles often showed banding, suggesting formation by more than one freezing event, and lifted the frozen soil crust by several centimetres.

Large unsorted stripes. These features are especially well developed in the Cumberland Bay area (Fig. 3), occurring on a wide range of slope angles from almost level ground to c. 30° and mainly at sites with northerly and north-easterly aspects. At a site on the south side of King Edward Cove (Fig. 3b) a vertical section was sampled. The wavelength from crest to crest was 90–120 cm with a trough depth varying between 15 and 30 cm. All the stripes were completely vegetated. Quadrat analysis of plant cover (Table I) showed the dominance of the grass *Festuca contracta* on the drier crests and banks, with mosses and liverworts predominating in the moister troughs.

Although only four soil horizons are shown in Fig. 3b, it was possible in some sections to see further subdivisions, especially in the grey–brown horizon. In some stripes, the A horizon ran under the trough whilst in others it lay only under the hummock. In some sections an extra B horizon was present, coloured olive to grey and rarely more than 3 cm thick. The C horizon was of variable colour, from red–brown to dark brown, often with a number of large clasts below 40 cm.

Excluding the humic rooting layer, with its 32% loss on ignition, particle distribution (Fig. 3c) showed close similarities between A and C horizons with only 3% clay and 50% >2 mm in both. The B horizon had more clay (8%) but only 32% >2 mm. Although not sampled, the soil just beneath the trough showed, in some cases, accumulations of large clasts. These were most common on the steeper slopes and suggest that water erosion may have carried away most of the original fine material.

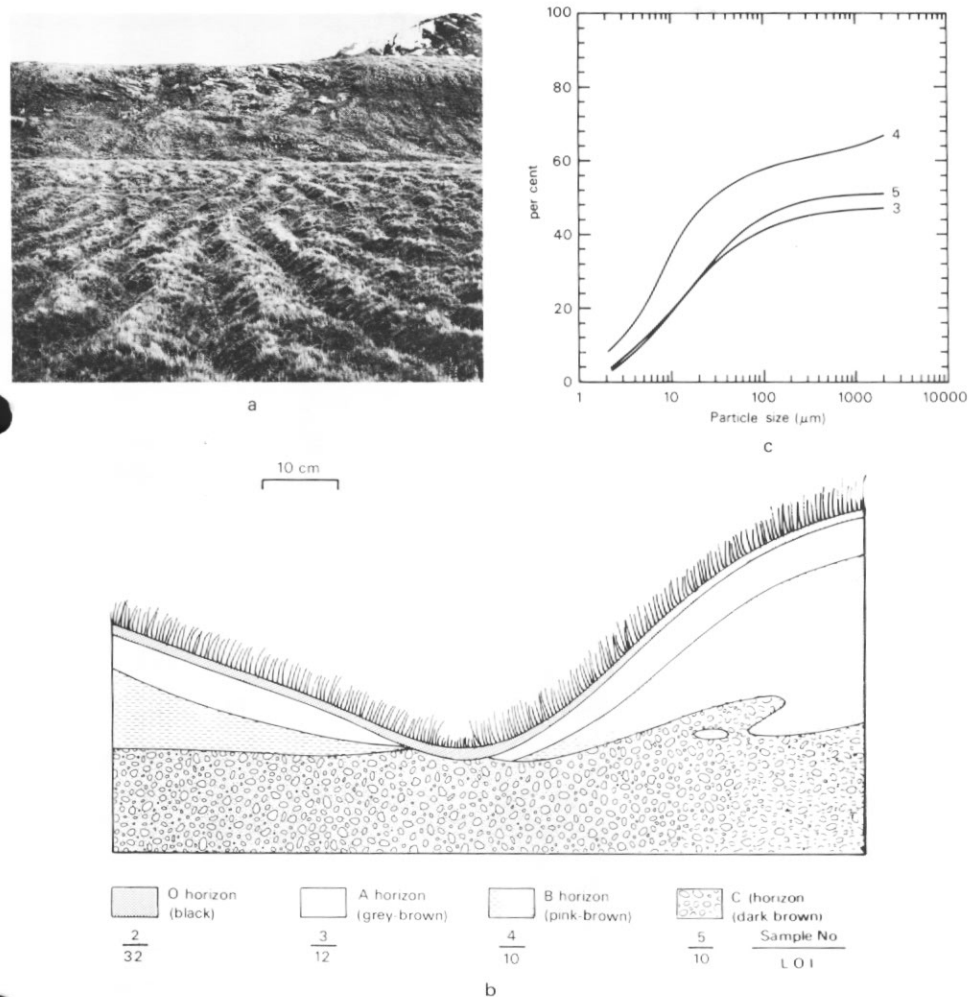


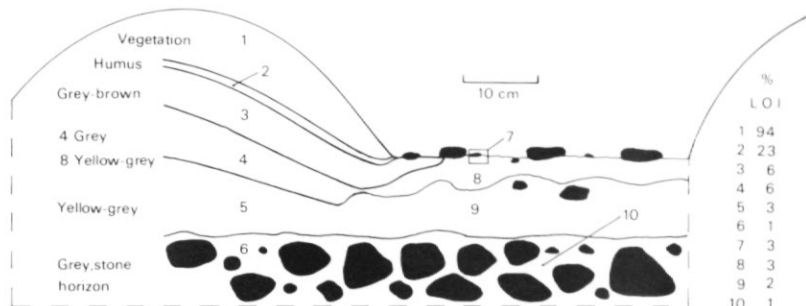
Fig. 3. a. Large-scale unsorted stripes, Dartmouth Point (photo R. I. Lewis Smith).
 b. Diagrammatic vertical section showing major horizons and location of sample points.
 c. Distribution of particle size classes at sample points.

Table I. Percentage distribution of vegetation on nonsorted large stripes.

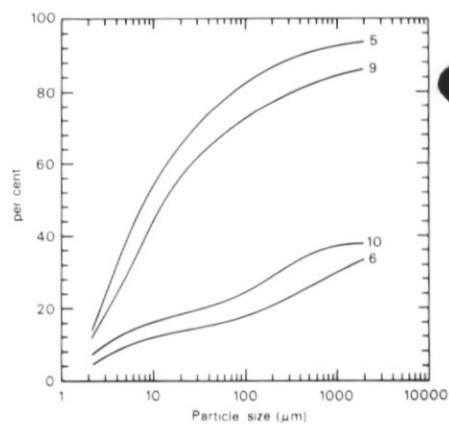
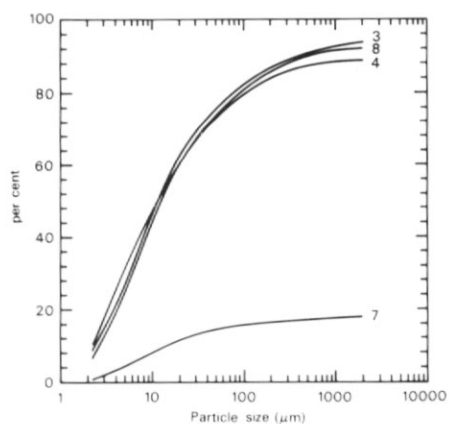
	Crest %	Bank %	Trough %
<i>Acaena magellanica</i> (Lam.) Vahl	15	10	5
<i>Acaena tenera</i> Alboff	5	10	10
<i>Festuca contracta</i> T. Kirk	30	30	5
<i>Phleum alpinum</i> L.	<5	5	<5
<i>Tortula</i> cf. <i>robusta</i>	25	20	25
<i>Chorisodontium aciphyllum</i> (Hook. f. et Wils.) Broth	5	5	5
<i>Polytrichum alpinum</i> Hedw.	10	15	30
<i>Cladonia</i> sp.	5	<5	<5
Liverworts	5	5	20



a



b



c

Fig. 4. a. Unsorted circles, Hestesletten.

b. Diagrammatic vertical section showing major horizons and location of sample points.

c. Distribution of particle size classes at sample points. (L.O.I.=percentage loss on ignition.)

Table II. Percentage distribution on the rim of non-sorted large circles.

	%
<i>Acaena magellanica</i> (Lam.) Vahl	<5
<i>Acaena tenera</i> Alboff	5
<i>Festuca contracta</i> T. Kirk	25
<i>Phleum alpinum</i> L.	5
<i>Rostkovia magellanica</i> (Lam.) Hook. f.	<5
<i>Chorisodontium aciphyllum</i> (Hook. f. et Wils.) Broth.	5
<i>Conostomum pentastichum</i> (Brid.) Lindb.	15
<i>Polytrichum</i> spp.	<5
<i>Cladonia</i> spp.	40
Liverworts	<5

Large unsorted circles. A considerable area of the outwash plain at Hestesletten is covered with large unsorted circles (Fig. 4). The plain is virtually flat with many old dry stream channels. Some of the circles are completely vegetated but others have bare centres, sometimes with poorly sorted small-scale nets. Virtually all have raised rims 20–30 cm high, which are dry enough to be covered by *Festuca* and lichen dominated vegetation (Table II). Where the centres are not covered by vegetation, considerable needle-ice activity was observed and they usually contained only scattered mosses. When they are vegetated, the mosses generally dominate with scattered plants of *Festuca contracta* and *Juncus scheuchzerioides* Gaud.

The shapes of the features are variable, usually circular or oval, but sometimes polygonal. Clapperton (1971) describes them as circles but Thom (1981) calls them polygons. The diameter varies from 1 to 2 m with a bare area of 50–80 cm in diameter. There are considerable differences in the details of the soil horizons between parts of the area. There may be more than the five horizons shown in Fig. 4b. Thom (1981) has recorded up to ten distinct horizons. He also noted the occasional occurrence of an iron pan amongst the basal sands and gravels.

Solifluction lobes. These lobes and benches are frequent features on South Georgia. They vary greatly in size and detail with both turf-banked (Fig. 5a) and stone-banked (Fig. 5b) types being found. Two types of turf-banked lobe were

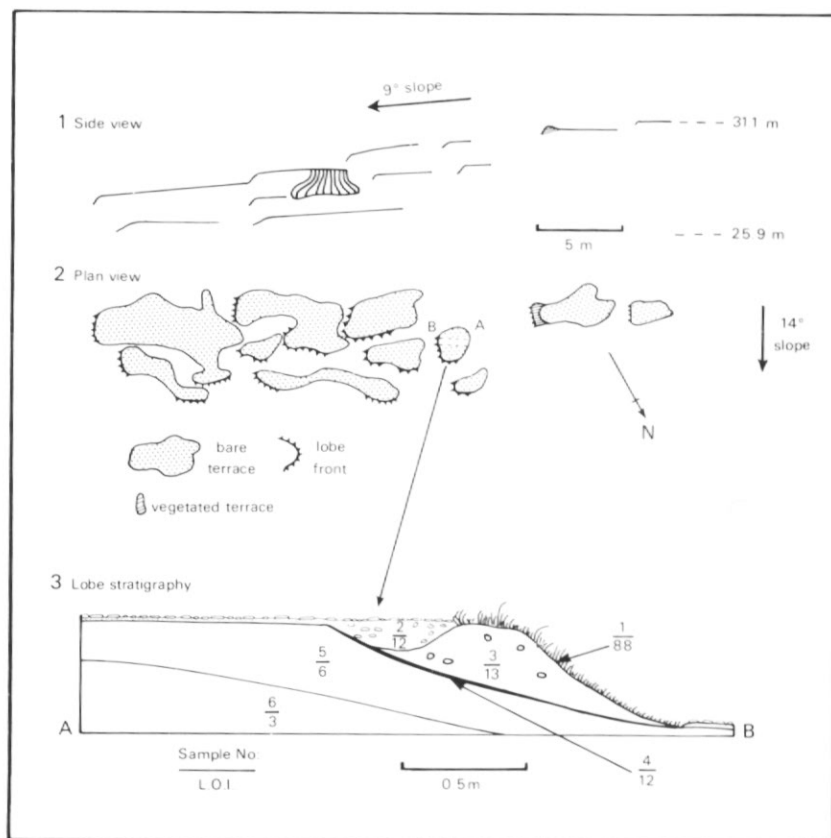


a

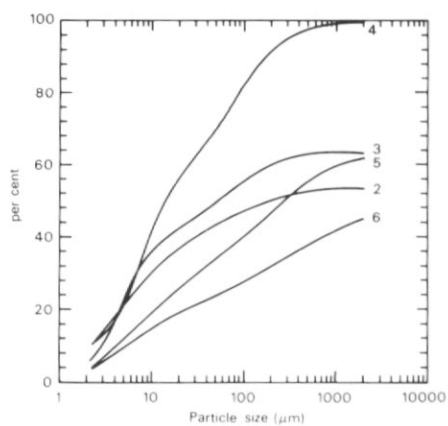


b

Fig. 5. Solifluction lobes: a, turf banked, near Horese Head; b, stone banked, beside Gull Lake.



a



b

Fig. 6. Solifluction lobe with open terrace: a, diagrammatic vertical section showing major horizons and location of sample points; b, distribution of particle size classes at sample points.

examined – firstly, those with bare terraces and, secondly, those that had become completely vegetated. The terraces shown in Fig. 6 are on the south side of King Edward Cove and are one form of the turf-banked type. The risers are 25–80 cm high with well vegetated fronts and crests. There appears to be a positive correlation between increasing riser height and an increasing slope of the terrace. The vegetation composition of the lobe front sectioned in Fig. 7 was 30% *Polytrichum* spp., 25% *Festuca contracta*, 15% *Acaena magellanica*, 10% *Tortula robusta*, 5% each *Acaena tenera* and lichens and 10% bare ground extending back to the front of the next lobe upslope. Some sorting does occur in these terraces and poorly sorted, small-scale nets are quite common. Isolated *Phleum* plants and occasional clumps of moss are scattered over the bare area.

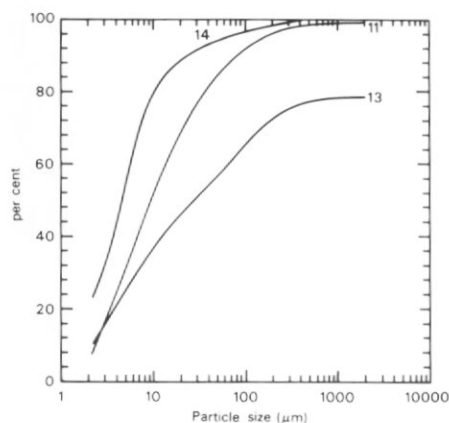
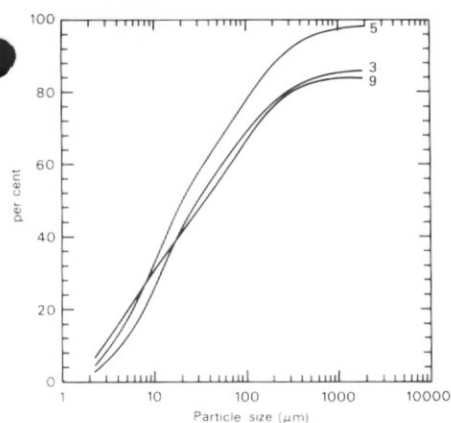
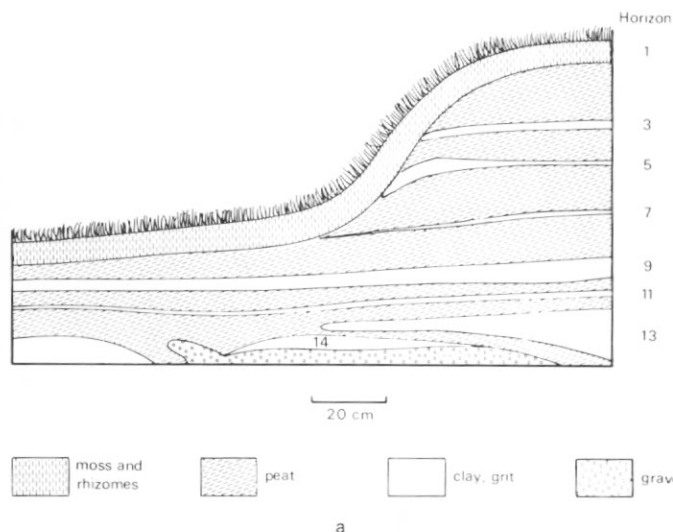


Fig. 7. Solifluction lobe completely vegetated: a, diagrammatic vertical section showing major horizons and location of sample points; b, distribution of particle size classes at sample points.

Within the lobe, the particle analysis (Fig. 6b) shows little evidence of any sorted stratigraphy. The front of the lobe has 40% >2 mm, as has the reddish-brown stratum 5.

Separating the two strata is a thin, grey layer, almost entirely composed of silt and clay and probably due to a sudden downwash of sorted material from an area upslope. The soil filling the bare terrace area has 50% >2 mm and 10% clay content with some evidence of sorting.

This terrace appears to have been built up by at least three separate events. The initial event may have been a major downslope flow of saturated mixed material (stratum 5) over the basal material in stratum 6. Small-scale downwash of clay and silt followed and some plants became established on this grey layer later. Gradual accumulation of downwashed material in the bases of these plants resulted in the slow formation of the front of the lobe. The area behind filled up later, again as a result of a major downwash of material. Although this feature is described as a solifluction lobe, it has some features more typical of a sorted step. Further field investigation is necessary to elucidate the origin of these terrace forms.

The second type of lobe is much more characteristic of solifluction lobes found elsewhere in the world (Fig. 7a). The concavity of the riser is presumably due to erosion of the original edge by wind and water, together with a redistribution of this material to adjacent areas downslope. The regular banding within the profile and the highly organic nature of the alternate bands suggests that the lobe is a product of a number of separate solifluction events. The particle size analysis for the inorganic layers show that they all fall within the frost susceptible category (as described by Williams, 1957) and therefore have been liable to ice segregation and consequent downslope movement.

Although there was no obvious evidence of current movement of the fronts, e.g. convex or broken risers, an attempt was made to measure this directly using deeply inserted stakes. It is unlikely that the system adopted would measure less than 5 mm movement and nothing of this scale was detected over a two-year period.

Local environmental data

As far as stone sorting and frost creep are concerned, the most important factor is likely to be the effect of the depth and duration of snow lie on needle-ice formation. The deeper the snow the higher the ground temperatures remain during the winter and any extension of the period of snow cover is likely to reduce the number of freeze/thaw cycles in spring and autumn.

For 1981, snow lie on the sorted stripes corresponded very closely to the period during which the soil was frozen (Fig. 8). With a snow depth in excess of 40 cm for over three months, soil temperatures were generally very close to zero for much of the winter. This blanketing effect is also clearly demonstrated in the mid-month temperature profiles (Fig. 9). The deep snow in August, September and October produced almost isothermal profiles around 0°C but in June and July temperatures were much lower with snow depth down to only 20 cm.

Strong summer radiative heating can penetrate quite far into the ground. The warmest months, January and February, showed temperatures of 10°C down to almost 20 cm (Fig. 8). In winter, the steepest temperature gradient is normally between the ground surface and the snow surface. In summer it generally occurs from the ground surface down to c. 5 cm. Surface temperatures can reach 24°C and higher in January (Fig. 9) with concomitant drying effects, which produce desiccation cracking in fine soil.

Although it is not possible to deduce the number of freeze/thaw cycles from these

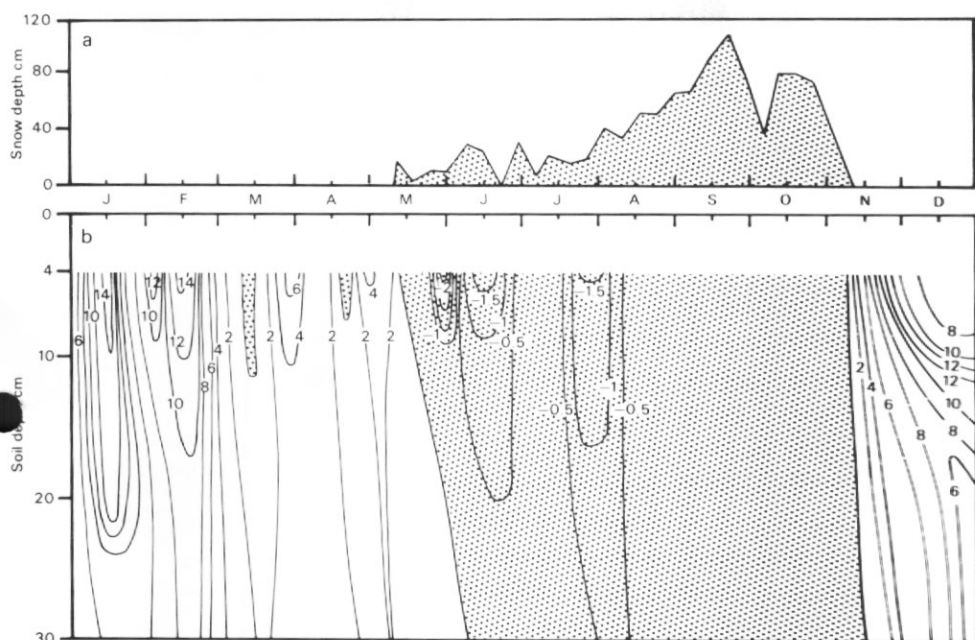


Fig. 8. a, Depth and duration of snow lie; b, ground temperature patterns (stipple denotes frozen ground), at a small scale sorted stripes site in Bore Valley.

data, it is clear that the freezing of the profile in May took much longer than the thawing in November. Also important in this context were the two freezing periods in March and April. Thus, it would appear likely that any creep or sorting due to frost heave or needle ice is most probable in autumn, while mass downslope movement by solifluction is probably restricted mainly to a short period in spring at snow melt.

Snow depth on a nearby turf-banked solifluction lobe reached 160 cm in September 1981 (Fig. 10). The lobe front was 60 cm high, which was sufficient to hold a small snow bank at the bottom of the vegetated face for up to ten days longer than on the bare area at the top. Snow cover for the two years differed in duration and distribution but not much in depth. In 1980, winter snow lay continuously from mid-May to mid-October, with new snow cover established for three weeks in November. In 1981, although snow cover began early in May, there was a complete melt in early June. Re-establishment of snow in mid-June then gave continuous snow cover until late November. As far as frost heave activity is concerned, it seems likely that the broken snow cover in April–May 1980 allowed more freeze/thaw cycles to occur than the June 1981 melt period.

The unsorted circle surrounded by *Festuca* grassland showed a pattern of snow depth and duration very similar to that of the solifluction lobe. From the 4-cm soil temperatures taken in the centre, at the edge of the bare ground and in the vegetated margin, some patterns can be deduced. Generally, during the winter, the centre is warmer than either the edge or the margin. In summer, when temperatures are rising, the centre is again warmer than the margin but, with falling temperatures, it loses heat more rapidly and soon becomes colder than the vegetation. The edge of the circle tends to lag behind in both changes.

The most critical periods are both spring and autumn, when frost heave and needle-ice formation can occur, keeping the centre of the feature free of vegetation.

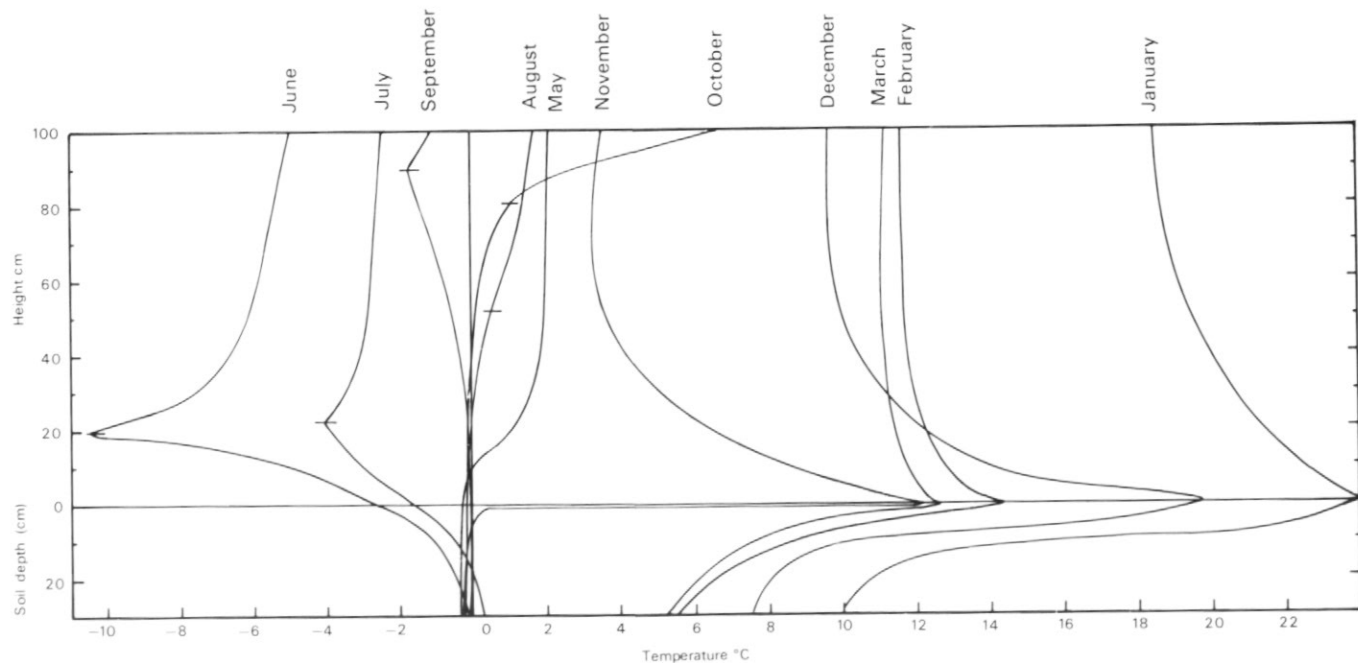


Fig. 9. Air and soil temperature profiles at midday for the middle of each month at a small scale sorted stripes site in Bore Valley. The depth of any snow is indicated by a horizontal line across the temperature profile.

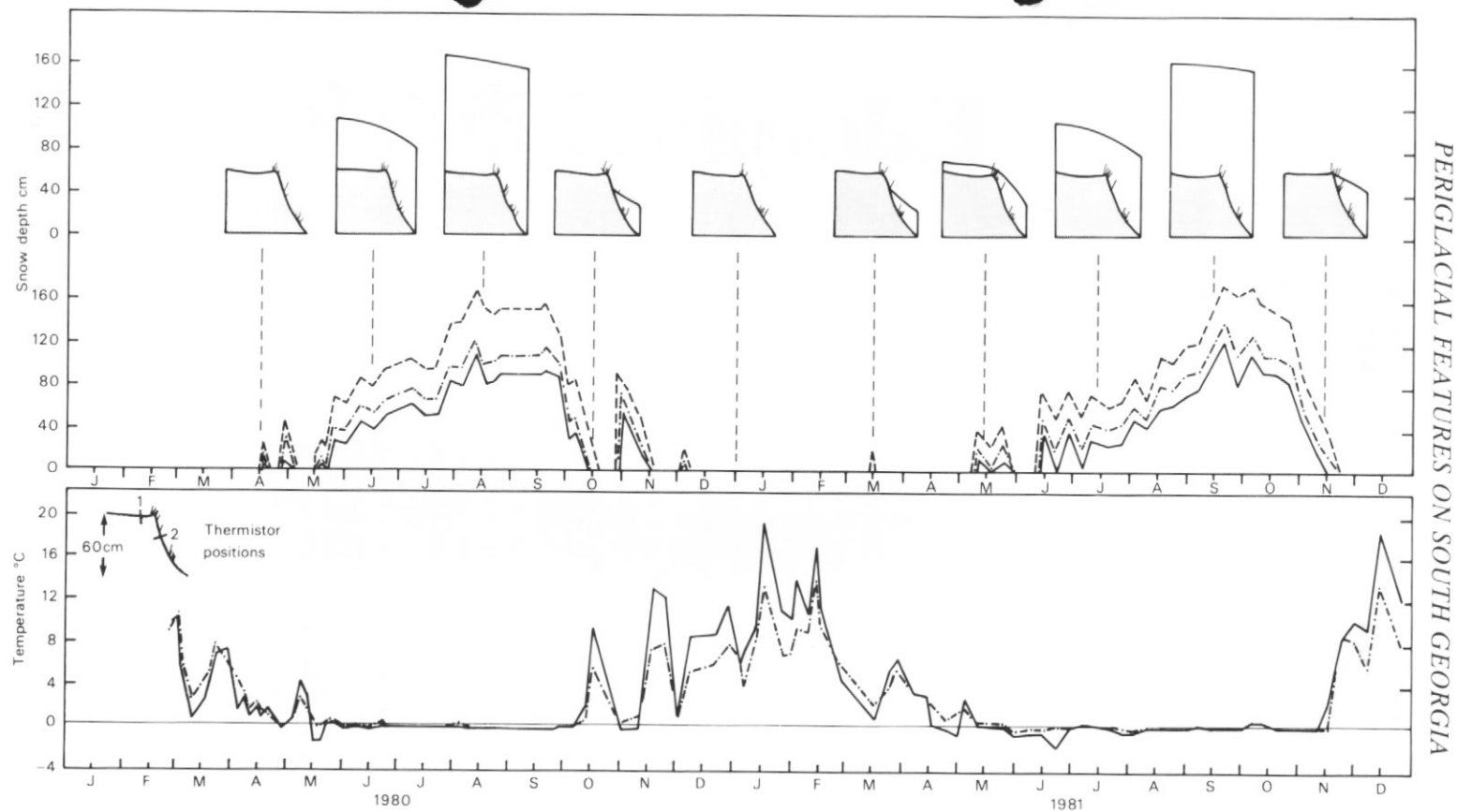


Fig. 10. Ground temperatures at the top and on the face of a solifluction lobe in Bore Valley over a two year period, together with data on the position of snow accumulation, its depth and duration. Key: — top, —·— face, --- base.

In spring 1980, both the centre and the edge were warmer than the vegetation, probably because of a delay in the melting of the icy crust that often forms in the litter layer. Snow showers during the summer accumulated around the edge of the circle and depressed the soil temperature there. In autumn 1981 the early light snow in May depressed the temperature of the centre to c. 0°C, while the edge and margin remained above zero and, as the vegetation cooled down to below -2°C, the centre remained within 0.5 deg of 0°C.

This situation changed as snow accumulated and, when snow depth exceeded 40 cm, all temperatures remained at -0.2°C.

Thus, from this limited data, it appears that maximum frost heave in the circle is likely to be in autumn and early winter, with little activity in spring. The summer snow showers have little effect but snow accumulation to a depth greater than 40 cm smooths out differences between the vegetated and bare areas. Temperatures at 4 cm deep in the centre of the circle can reach at least 18°C in January but rarely fall below -3°C in winter.

DISCUSSION

All the features described in this paper are on glacial till, as are the majority of patterned ground features (Goldthwait, 1976). The small scale of the active features agrees well with a lack of permafrost at present and only a single deep freezing event as Goldthwait (1976) found for sites in the Arctic.

The origin of the large unsorted vegetated stripes appears to be obscure. Stone (1975) recorded totally unsorted stripes on South Georgia with *Poa flabellata* tussocks on them, but they seem to be a special case. His explanation of their formation by downwash seems untenable for the stripes in Cumberland Bay. The only analogous feature from elsewhere appears to be the 'stripe hummocks' reported by Lundqvist (1962) from Sweden. Thom (1981) failed to find a convincing explanation for their formation, concluding that the South Georgia patterns might represent the 'extreme end of the spectrum of unsorted pattern ground requiring a particular combination of site variables in order to develop'. Our data do not allow us to shed any further light on this.

A detailed investigation of the effect of differences in annual snow cover on downslope movement of clasts in small-scale stripes on South Georgia (Walton and Heilbronn, 1983) has shown important short-term differences but a virtually linear trend over a period of seven years. This suggests that movement rates based on single sites and single seasons, as were Smith's (1960) original soil movement data, may considerably misrepresent the true long-term trend of movement if measurements happen to be made in an untypical season.

Although mass flow events are all referred to in this paper as solifluction, mass movement in early spring may take place over frozen ground and is thus more correctly described as gelifluction. As yet there are no adequate data from South Georgia to partition the total annual downslope movement between solifluction/gelifluction and frost creep. Studies on needle ice (unpublished) have, however, indicated that creep may be a major factor at some sloping sites. The frequency of needle-ice formation in the unsorted circle is not known but its exposure of plant roots to desiccation after heaving seems an adequate explanation for the continued existence of this feature.

The activity of needle ice produced by freeze/thaw cycles has been suggested here both as the major factor in the formation of small scale stripes and in keeping the centres of unsorted circles free of vegetation. Bunt (1954) suggests a similar

explanation for stripes on Macquarie Island as does Aubert de la Rue (1959) for stripes on Îles Kerguelen. Bellair (1969) concluded that freeze/thaw activity on the volcanic debris of Îles Crozet, was of less significance in stripe formation than wetting/drying cycles. This is surprising since Hall (1979) concluded that needle ice was of considerable importance in stripe formation on a similar substrate on Marion Island, although his data suggested an effect of wind on stripe orientation. In more recent studies on stripes in Îles Kerguelen (Hall, 1983), he also found strong evidence for wind effects on stripe orientation in some areas. There does not appear to be any major effect of wind on stone stripe direction on South Georgia but, on steeper slopes, channelling of water through the coarse stripes is likely to accelerate the loss of fine material and consolidate the form of the stripes as Bunt (1954) has suggested.

On both Marion Island (Hall, 1979) and Îles Kerguelen (Hall, 1983), correlations have been found between stripe width and altitude, and between the width of coarse and fine stripes. Although our qualitative observations on South Georgia agree with Hall in stripe width and coarse/fine ratio increasing with altitude, the more detailed quantitative survey by Thom (1981) found no statistically significant relationship. This seems surprising since other workers have established that stripe width is related to mean clast size, and clast size on South Georgia generally increases with altitude. Interestingly, the width of most stripes (coarse plus fine) on Marion Island and on Îles Kerguelen (Nougier, 1970) appears to be c. 20 cm, very similar to the 21-cm wavelength (coarse plus fine) found on South Georgia.

More statistical investigation is necessary to assess the relative importance of frost heave by ice lens formation against needle ice production for particular features. The ability of certain plant species to colonize periglacially active areas (Heilbronn and Walton, 1984) suggests that the establishment of closed vegetation in these areas may be principally limited by frost generated movement in the upper soil layers.

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