C. K. BALLANTYNE *

St. Andrews

# NONSORTED PATTERNED GROUND ON MOUNTAINS IN THE NORTHERN HIGHLANDS OF SCOTLAND

Abstract

The characteristics of nonsorted patterned ground on two massifs in the Northern Highlands of Scotland are described and discussed with particular reference to age and mode of formation. On the frost-susceptible regolith of the Ben Wyvis massif, earth hummocks on level ground and gentle slopes grade into hummock stripes (bands of hummocks aligned downslope) then relief stripes ("ridge and furrow" features) as gradient increases. These features appear to have formed through modification by mass displacement of nonsorted vegetation-defined patterns of Lateglacial age, and are essentially inactive at present. On the An Teallach massif (where the regolith is not frost-susceptible) equivalent features are absent, but large sand hummocks have developed within the last 100 years on recent niveo-aeolian deposits. These are interpreted as having formed through the trapping of niveo-aeolian sand by tussocks on slopes that are sufficiently steep to allow eluviation of sand from between the tussocks by nival meltwater. The wider significance of these findings is discussed with reference to previous literature on nonsorted patterned ground in upland Britain.

## INTRODUCTION

Three types of nonsorted patterned ground have hitherto been reported on the mountains of Great Britain. The most common type consists of earth hummocks (thufur), which generally occupy flat or gently-sloping sites and may be defined as vegetation-covered domes of predominantly fine material separated by a network of depressions. On slightly steeper slopes earth hummocks sometimes become aligned downslope in parallel bands to form the second type, here termed hummock stripes (equivalent to the "stripe hummocks" described by LUNDQVIST, 1962). With further increases in gradient individual hummocks merge to form nonsorted relief stripes (*sensu* NICHOLSON, 1976) consisting of alternating ridges and furrows aligned downslope. The three types described above therefore constitute a slope-controlled continuum (Fig. 1).

Various conflicting opinions have been expressed concerning the age and genesis of these forms on British mountains. GALLOWAY (1958, 1961) interpreted "ring" (hummock) and stripe patterns on Ben Wyvis (Fig. 2) as features inherited from sorted patterns that formed under a climatic regime more severe than that of the present. GOODIER and BALL (1969) considered that small relief

* Department of Geography, University of St. Andrews, St. Andrews, Fife, KY16 9AL, Scotland, U.K.

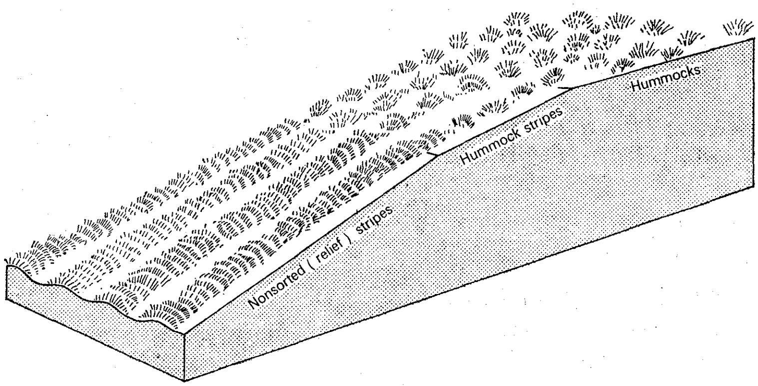



Fig. 1. The transition from earth hummocks via hummock stripes to nonsorted relief stripes. Based on field sketches

stripes on the Rhinog Mountains in North Wales were formed during the Little Ice Age of the 16th to 18th centuries A.D., a conclusion based on the relationship between the stripes and what they supposed to be a medieval wall that had undergone solifluction. In a later paper (BALL and GOODIER, 1970) the same authors described further examples of relief stripes in Snowdonia but offered no explanation of mode of formation although they noted (following LUNDQVIST, 1962) a possible relationship between relief stripes and earth hummocks. This was confirmed by BIRKS (1973), who described the transition from hummocks to stripes on gently-sloping plateaux above 600 m on Skye and attributed both forms to differential ground freezing and consequent upheaval as envisaged by BESKOW (1930) and LUNDQVIST (1962). TUFNELL (1975) subsequently described, classified and analysed the distribution and dimensions of earth hummocks in the northern Pennines, but apart from stating that these are "similar to the Icelandic thufur and [...] consequently of periglacial origin" (p. 365) he offered no explanation of hummock formation. He considered that hummocks may form under present conditions, noting that "small hummocks occur on ground which must have been disturbed in the late 1940s/1950s when the radio station and masts (on Great Dun Fell) were built " (p. 367). This conclusion is supported by reports of hummocks of apparently recent origin on relatively low ground in the central and southern Pennines (COTTON, 1968) and the Vale of Eden (PEMBERTON, 1980). The latter author concluded that "all the hummocky microrelief has been formed within historical times" (p. 500) and that "although the exact mechanisms of formation remain uncertain, earth hummocks are clearly the product of frost penetration". Yet he added that "earth hummocks [...] are not periglacial features", although he failed to explain why he considered this to be so. It is notable that of the three types of nonsorted patterned ground described earlier, only earth hummocks have been reported at low altitudes; all of the sites at which hummock stripes and relief stripes have been observed lie above 600 m in altitude.

The present paper reports the results of research into the characteristics of well-developed nonsorted patterned ground on mountains on the Northern Highlands of Scotland, with particular reference to the age and genesis of such features.

## THE STUDY AREAS

The study areas consist of two mountain massifs that reach similar altitudes but are of very different lithological composition. The An Teallach massif (57° 49'N, 5°16'W, Figs 2, 3) reaches an altitude of 1062 m and consists largely of Precambrian Torridon Sandstone comprising red arkosic grits with occasional conglomeratic layers (PEACH *et al.*, 1913). The Ben Wyvis massif (57°41'N, 4°35'W, Figs 2, 4) lies 43 km E.S.E. of An Teallach and rises to an altitude of 1046 m. The rocks of Ben Wyvis consist of Moine schists and gneisses, Precambrian metasediments that range from fissile muscovite-biotite schists to massive quartz-biotite granulites (PEACH *et al*,. 1912).

Evidence provided by high-level striae and erratics suggests that both massifs were largely if not entirely covered by glacier ice when the last British ice-sheet (the Late Devensian ice-sheet) reached its maximal extent ca. 18,000 B.P.

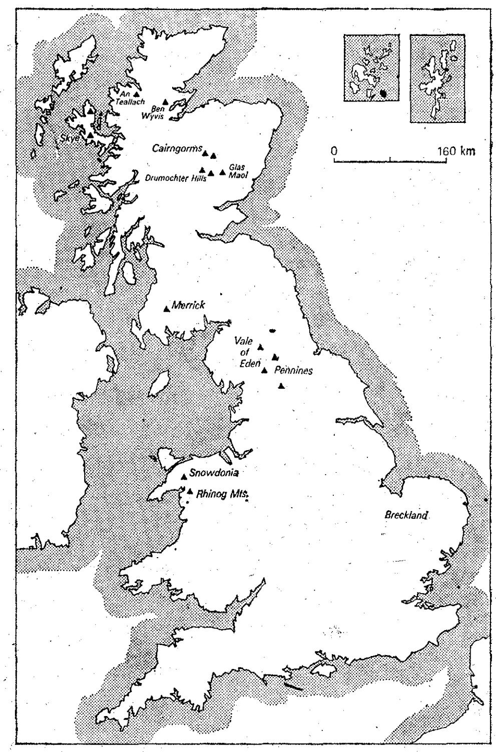



Fig. 2. Location of the study areas and other sites mentioned in the text

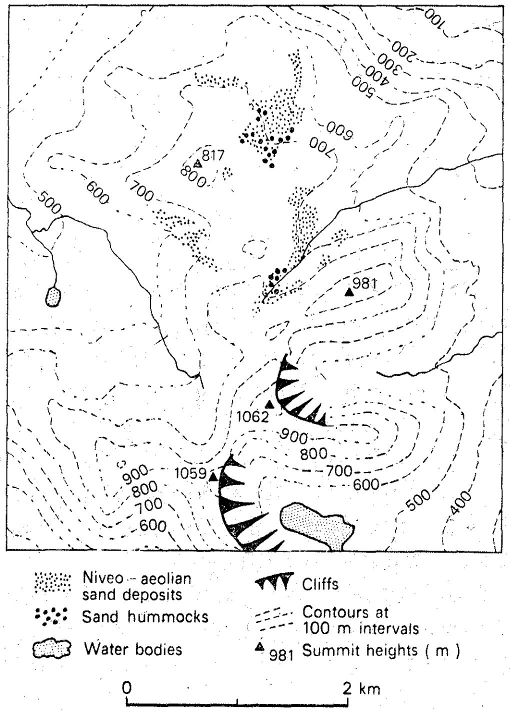



Fig. 3. The An Teallach massif, showing the location of niveo-aeolian sand deposits and "sand hummocks" developed on such deposits

(PEACH *et al.*, 1912, 1913; PHEMISTER, 1960; SISSONS, 1976). The higher parts of the massifs subsequently became exposed to severe periglacial conditions both during the downwastage of the Late Devensian ice-sheet and later during the Loch Lomond Stadial (ca. 11,000—10,000 B.P.). During these two Lateglacial cold periods a shallow (generally less than 1 m thick) mantle of frost-weathered debris accumulated on the plateau areas and slopes of the massifs (BALLANTYNE, 1981). Although in both cases this mantle consists of clastic detritus of variable size embedded in a predominantly sandy matrix, the granulometry of the matrix material is strongly influenced by lithology. On the Torridon Sandstone of An Teallach, rock breakdown has produced a matrix predominantly composed of medium and coarse sand with a negligible silt fraction (Fig. 5). The soil mantle on An Teallach is consequently not frost-susceptible in terms of commonly-employed indices of susceptibility (e.g. TERZAGHI, 1952; WASHBURN, 1979, p. 68). This is borne out by excavations of the weathered mantle during winter freezing: these revealed interstitial pore ice but no ice lenses. In contrast, the matrix of the weathered mantle developed on the Moine schists of Ben Wyvis consists mainly of fine sand, with over 6% by weight of silt (Fig. 5), and is consequently frost-susceptible; excavation of the soil on Ben Wyvis under winter conditions revealed well-developed ice lenses at shallow depth.

The present air temperature regime of the study areas is relatively mild (BALLAN-

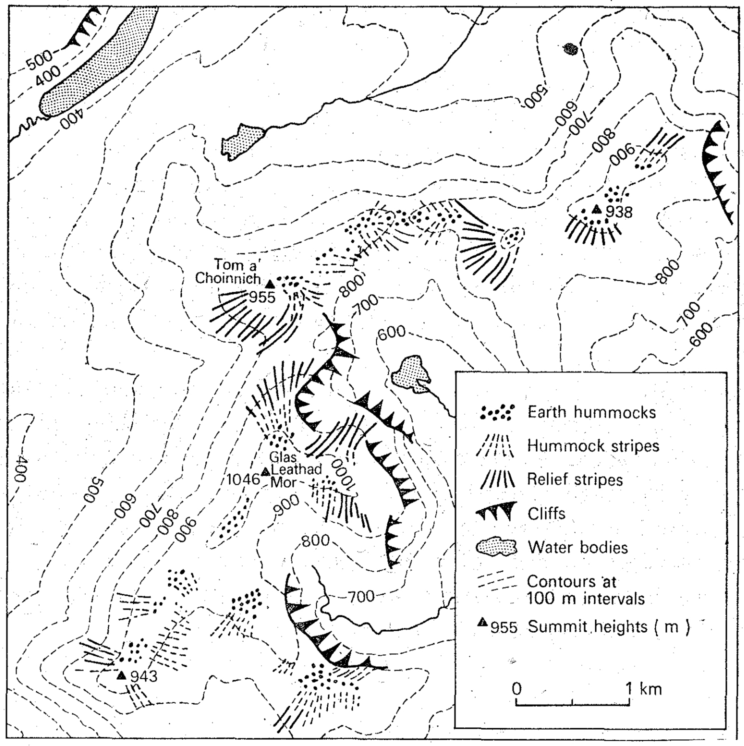



Fig. 4. The Ben Wyvis massif, showing the locations of earth hummocks, hummock stripes and relief stripes

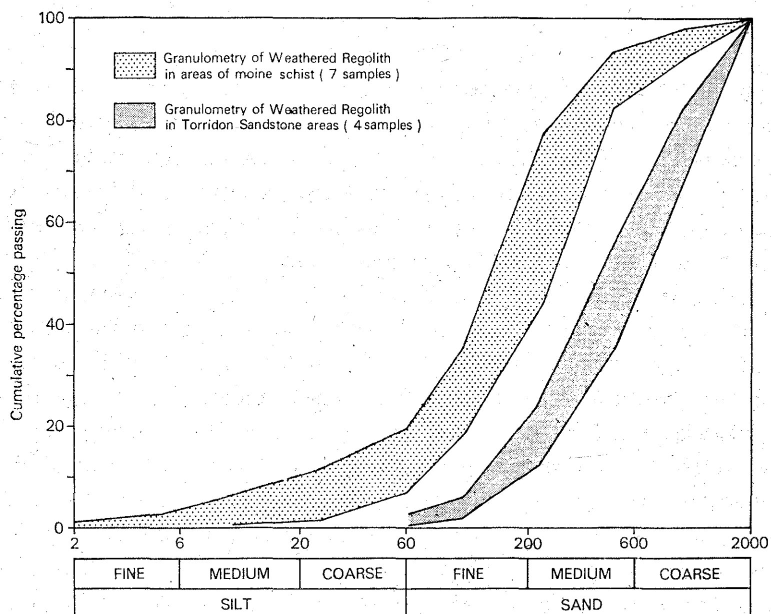



Fig. 5. Grain-size envelopes summarizing the granulometric characteristics of frost-shattered detritus on moine schist (Ben Wyvis) Torridon Sandstone (An Teallach)

TYNE, 1981). Even at 1000 m, temperatures below −10 °C are rare, and mean monthly air temperatures are below 0 °C for only six months of the year. Frost penetration is consequently shallow, and the ground is rarely frozen to depths of more than 50 cm. The severity of climate on these massifs relates more to extreme exposure and wetness than to low temperatures. Mean annual precipitation at 670 m on An Teallach is 3577 mm but rather less (around 2100 mm) at the same altitude on Ben Wyvis. The mean duration of snow-lie (>50% cover) on An Teallach increases linearly from 36 days at sea level to 135 days at 700 m and 177 days at 1000 m. Strong westerly winds frequently sweep over both massifs; on An Teallach gusts exceeding 40 $ms^{-1}$ have been recorded at only 600 m altitude.

Although bare ground is rare on the Ben Wyvis plateau, deflation of the cohesionless coarse sandy detritus that mantles the northern plateau of An Teallach inhibits vegetation colonization so that exposed areas resemble a desert colonized only by small clumps of grass and heather, and complete vegetation cover is restricted to sheltered lee slopes. The species and associations characteristic of the two massifs also differ. The summit plateau of Ben Wyvis supports a *Rhacomitrium* heath (*Rhacomitrium lanuginosum* and *Carex bigelowii*) that grades downslope into a bilberry heath (*Vaccinium myrtillus* and *Empetrum nigrum* with grasses and sedges). In contrast, *Calluna vulgaris* is dominant on the high ground of An Teallach, with *Deschampsia flexuosa, Festuca ovina, Juncus triffidus, Alchemilla alpina* and *Vaccinium myrtillus* covering well-drained lee slopes.

## NONSORTED PATTERNED GROUND ON BEN WYVIS

### DESCRIPTION

All of the categories of patterned ground described in the introduction are well represented on Ben Wyvis (Fig. 4). As on Skye (BIRKS, 1973) the nonsorted patterned ground on Ben Wyvis occurs on *Cariceto-Rhacomitrium lanuginosi* summit heaths, with the sedge *Carex bigelowii* occupying sheltered locations between or on the lee (east) side of hummocks or stripes whose exposed flanks are covered with *Rhacomitrium lanuginosum.* Earth hummocks on Ben Wyvis vary widely in size (Tab. I) and, although fairly similar in dimensions to those described by BIRKS on Skye, are much lower than hummocks measured on An Teallach and somewhat larger than the features described by TUFNELL (1975) on the Pennines. Hummock stripes on Ben Wyvis tend to be broader than individual hummocks, with ridges typically 1.0 m in width separated by furrows 0.4—0.7 m across. Relief stripes are often broader still, with repeat distances (crest to crest) around 2.0 m and heights of 10—30 cm (Pl. 1). Hummock stripes and relief stripes tend to follow the direction of maximum slope, although they often meander slightly (particularly on gentle slopes) and divide where the slope is concave (outward) in plan or join where the slope is convex in plan, thereby maintaining a roughly equal spacing. Individual stripes are traceable for up to 110 m downslope.

Table I

Dimensions of some turf hummocks in upland Britain

| Site | Sample size | Height in cm | | | Diameter in cm | | |
|---|---|---|---|---|---|---|---|
| | | min. | mean | max. | min. | mean | max. |
| An Cabar, Ben Wyvis | 50 | 6 | 16 | 32 | 32 | 63 | 127 |
| Glas Leathad Beag, Ben Wyvis | 50 | 9 | 18 | 44 | 28 | 65 | 118 |
| Coire nan Tota, An Teallach | 50 | 20 | 49 | 92 | 24 | 71 | 156 |
| Skye (BIRKS, 1973, p. 194) | — | 15 | — | 30 | 40 | — | 120 |
| Great Dun Fell (TUFNELL, 1975, p. 360) | 88 | — | 20 | — | — | 35 | — |
| Knock Ore Gill (TUFNELL, 1975, p. 360) | 166 | — | 15 | — | — | 37 | — |

The transition from hummocks to hummock stripes to relief stripes (Fig. 1) takes place over a fairly wide range of slopes: 1° to 6° in the first case, 6° to 11° in the second. Relief stripes are poorly developed on slopes steeper than 20° and absent on slopes steeper than about 25°. The lower limit of nonsorted patterned ground on Ben Wyvis is around 770 m, but appears to be determined by availability of suitable peat-free slopes rather than climatic factors. Stripes tend to occupy the same slopes as solifluction sheets and lobes and ploughing boulders, and sometimes appear to terminate downslope near the risers of solifluction sheets or even to define the margins of small lobes.

## STRUCTURE AND CONSTITUTION

Trenches were dug across three south-facing relief stripes at 910 m altitude on a slope of 11° S.E. of Tom a'Choinnich (Fig. 4) and across two hummocks at 1010 m S.W. of Glas Leathad Mor. Both revealed well-developed podzols (Pl. 2 and Fig. 6) with clearly-defined soil horizons following the undulations of the ground surface. The stripe section displayed a concentration of clasts near to the surface (a feature of the stripes in North Wales described by GOODIER and BALL, 1969), but this was not evident in the hummock section. The clasts in both sections were generally flat-lying with no obvious preferred orientation and an absence of erected stones. Most interestingly, the concentration and size of clasts underlying the troughs were no different from those of clasts underlying the ridges (Fig. 6).

Several inferences can be made from these observations. First, the similarity in structure between relief stripes and hummocks suggests, like the transition via hummock stripes, that relief stripes and hummocks are genetically related. Secondly, the development of mature podzols and the lack of thrust or erected stones indicates that cryoturbation is presently ineffective, as frost churning

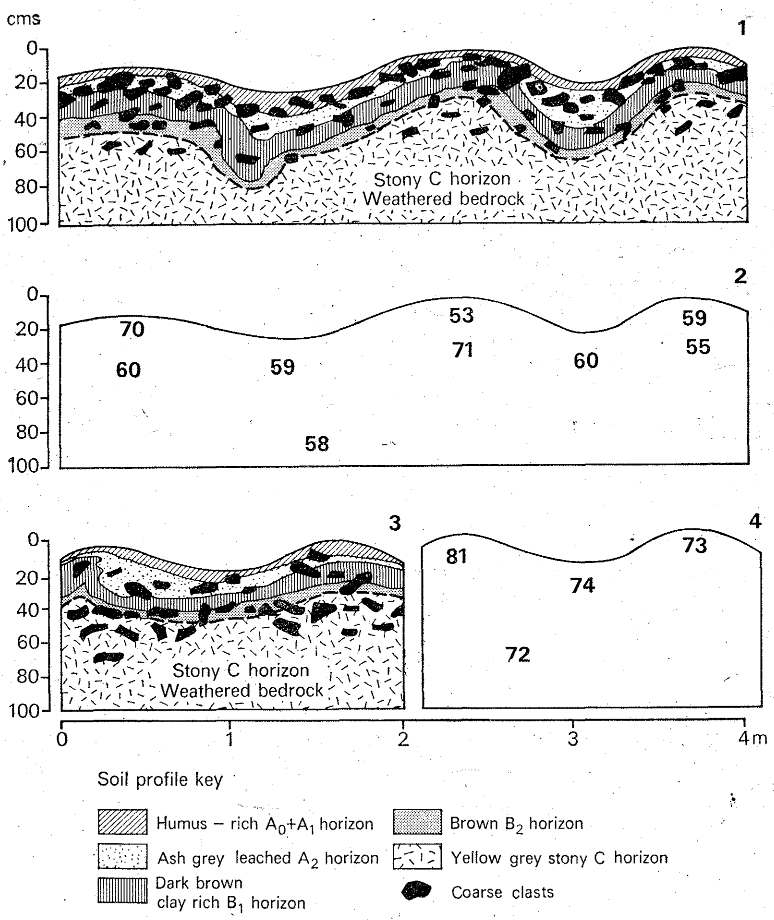



Fig. 6. Cross-sections through nonsorted relief stripes (diagrams 1 and 2) and hummocks (diagrams 3 and 4) on Ben Wyvis. The figures on diagrams 2 and 4 refer to the mean intermediate axis lengths of clasts sampled at the points shown (in millimetres)

would presumably disrupt the soil horizons (Tarnocai and Zoltai, 1978). Thirdly, preservation of podzolic horizons and the lack of any preferred orientation of clasts indicate that recent solifluction has not been important at the stripe site despite the association of stripes and solifluction features elsewhere on Ben Wyvis. Finally, the absence of differences in clast concentration and size between the hummocks or ridges and adjacent depressions conflicts with Galloway's (1958, 1961) claim that these represent vegetation-covered fossil sorted stripes and circles.

Soil samples taken from a depth of 30 cm under troughs and crests at both sites also proved similar in constitution (Fig. 7), comprising in all cases over 60% by weight fine and medium sand (60—600 $\mu$) with a relatively high (ca. 20%) silt fraction and negligible clay content. Samples taken from hummockless terrain on the Ben Wyvis plateau proved relatively deficient in silt (6—14%).

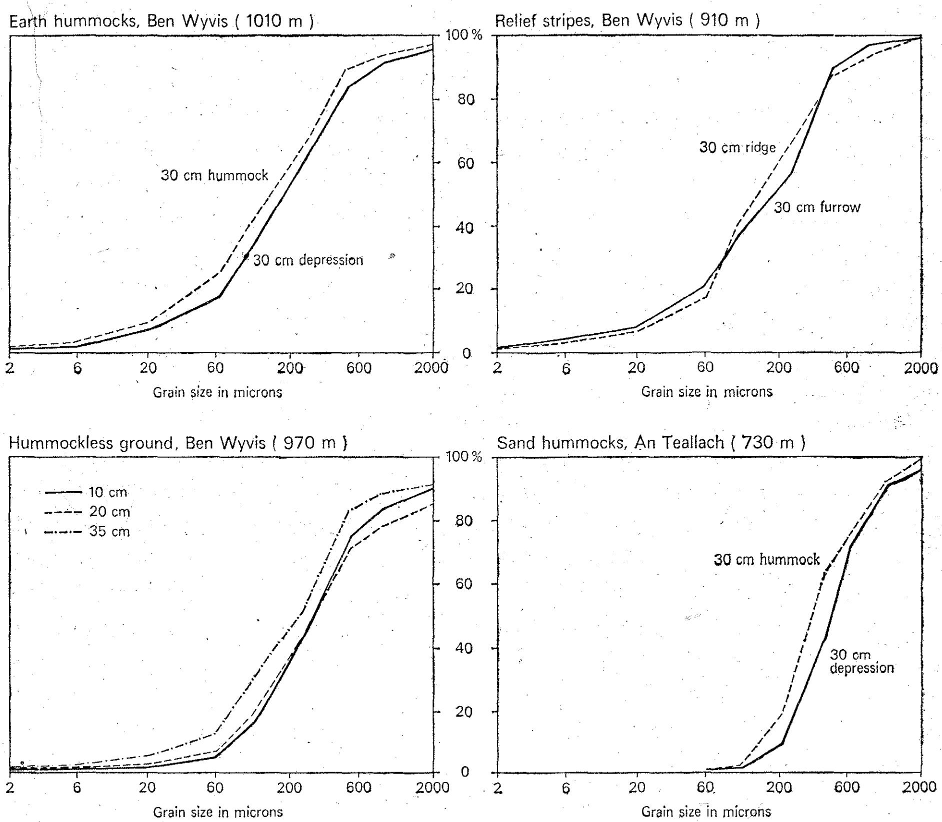



Fig. 7. Grain-size distribution for samples of fine material collected from relief stripes, earth hummocks and hummockless ground on Ben Wyvis and sand hummocks on An Teallach. The figures in centimetres refer to the depths at which sampling was carried out

This difference may explain the irregular distribution of nonsorted patterned ground on Ben Wyvis (Fig. 4), as a high silt content is likely to promote more effective ice segregation and therefore greater frost heave and mass displacement, which are widely believed to be responsible for hummock formation (see below). This conclusion must be regarded as tentative, however, as the stripe and hummock samples were collected from $B_1$ horizons that may contain illuviated silt particles.

## FORMATION

In view of the transitional nature of earth hummocks, hummock stripes and relief stripes, it is reasonable to assume that all three types of feature are the products of the same underlying processes. That stripes occupy slopes whilst hummocks are restricted to level or nearly level ground indicates either that stripes represent hummocks subsequently modified by mass-movement (solifluction) or that the formative processes affected slopes and level areas in different ways. The first possibility is rejected for the following reasons. First, although it is possible to envisage "stretching" of hummocks by post-formation solifluction, the development of regularly-spaced relief stripes demands that irregularly spaced hummocks migrate laterally across the slope to form the ridges of the stripe pattern, which seems unlikely. Secondly, solifluction creates fabrics with a strong preferred downslope orientation (BENEDICT, 1976), but clasts in the excavated stripes apparently lack orientational preference. Thirdly, hummock stripes occur on slopes of only 1°, well below the lowest gradient (6°) for slopes occupied by solifluction features on Ben Wyvis. Finally, it seems improbable that hummocks could survive over-riding by solifluction sheets, which tend to bury pre-existing soil and vegetation (BENEDICT, 1966, 1970, 1976; WORSLEY and HARRIS 1974; BALLANTYNE, 1981).

Although earth hummocks are probably polygenetic (BESCHEL, 1966) it is widely accepted that hummock formation is initiated by local small-scale variations in soil constitution, moisture content, topography (swells and depressions or a crack pattern) or vegetation cover (e.g. THORODDSEN, 1913; BESKOW, 1930; HOPKINS and SIGAFOOS, 1954; ZAWADZKI, 1957; LUNDQVIST, 1962; RAUP, 1965; SCHUNKE, 1975, 1977). Such differences result in an uneven pattern of frost penetration, with pockets of unfrozen ground surviving amid frozen soil and/or slower frost penetration and consequently greater ice segregation and frost heave in some areas than others. Unfrozen pockets of soil are subject to mass displacement (defined by WASHBURN, 1969, as "the *en masse* local transfer of mobile mineral soil from one place to another within the soil as the result of frost action") but the mechanism responsible is uncertain (WASHBURN, 1979, p. 96—100 and 167—168). NICHOLSON (1976) argued that the establishment of oblique freezing planes is sufficient to cause upward migration of material in the unfrozen soil, but this was refused by WASHBURN (1979, p. 99) who contended that unless adjacent soil was frozen to an impermeable base (such as a permafrost table), freezing stresses would be relieved by uplift of frozen soil as a unit. Others (e.g. HOPKINS and SIGAFOOS, 1954; SCHUNKE, 1977; TARNOCAI and ZOLTAI, 1978) have favoured cryostatic pressure as the mechanism responsible for upward mass displacement and consequent hummock formation. These authors evisaged that water-soaked material trapped beneath and both sides by freezing (and therefore expanding) soil would be forced upwards, forming surface mounds. MACKAY and MACKAY (1976), however, pointed out that in fine-grained frost-susceptible soils migration of water from unfrozen ground to the freezing plane results in desiccation that reduces plasticity in the unfrozen material and allows release of cryostatic pressure through compaction. They also observed pressures developed in clayey soils are greater during thawing than during freezing, which led MACKAY (1979) to propose that wetting and expansion of the desiccated material during thaw results in upward mass displacement as the surrounding frost-heaved ground melts.

Although it is impossible to assess the nature of the mechanism responsible for mass displacement and consequent hummock and stripe formation on Ben

Wyvis, the association of hummocks with presumably contemporaneous stripes allows inferences to be made regarding the nature of hummock and stripe initiation. Random soil and microtopographical variations can be ruled out; although these may constitute an irregular „net" pattern on level surfaces, they are unlikely to consitute a regular stripe pattern on slopes. Likewise, seasonal frost cracking (THORODDSEN, 1913; WOO, 1975) or desiccation cracking (ZAWADZKI, 1957) may conceivably produce a regular net, but are unlikely to result in the formation of stripe forms. On the other hand, vegetation cover on slopes in relatively arid arctic environments often takes the form of alternating stripes of vegetated and unvegetated ground (nonsorted stripes *sensu* WASHBURN, 1956) where the vegetation is nourished by subsurface percolines (Pls, 3, 4). On Ellesmere Island in the eastern Canadian arctic the writer observed instances of transition from nonsorted vegetation-covered circles on level ground to vegetation-defined stripes on slopes, giving patterns strikingly similar in scale and appearance to those on Ben Wyvis. A similar transition has also been described by WASHBURN (1947) on Victoria Island, and TARNOCAI and ZOLTAI (1978) reported replacement of hummocks by nonsorted stripes with increasing gradient elsewhere in the Canadian arctic. WASHBURN (1979, p. 153) suggested that the relief stripes described by GOODIER and BALL (1969) in North Wales and the Breckland stripes of eastern England (WILLIAMS, 1964; WATT *et al.*, 1966; EVANS, 1976) represent forms derived from nonsorted vegetation-defined stripes. The similarities in plan form of the features on Ben Wyvis and nonsorted vegetation--defined patterned ground in relatively arid arctic areas also suggests that the former may have evolved from the latter.

Although little is known of palaeoclimatic conditions during the period of ice-sheet downwastage in Scotland, climatic reconstructions based primarily on the survival of ice-wedge casts and the altitudes of the firn lines of former glaciers (SISSONS, 1976, 1979a) suggest that during the Loch Lomond Stadial of ca. 11,000—10,000 B.P. much of Scotland experienced permafrost conditions and that there was a pronounced west-east decline in precipitation which amounted to only 500—600 mm $y^{-1}$ at 1000 m altitude in the N.W. Cairngorms (Fig. 2) at this time; effective precipitation was probably greatly reduced by high evaporation rates resulting from strong insolation and high winds. Similar conditions are likely to have prevailed on the higher parts of Ben Wyvis. It is by no means improbable, therefore, that features that presently occur in the more arid parts of the Canadian arctic should have occupied the upper slopes of Ben Wyvis during the Loch Lomond Stadial.

The nature of the metamorphosis from nonsorted Lateglacial features defined essentially by concentrations of vegetation into the forms that presently occur on Ben Wyvis must of necessity be speculative, but a possible evolutionary model is depicted in figure 8. The envisaged sequence of development is as follows.

1. Under the arid periglacial conditions that prevailed during the Loch Lomond Stadial, irregularly-spaced vegetated circles and regularly-spaced

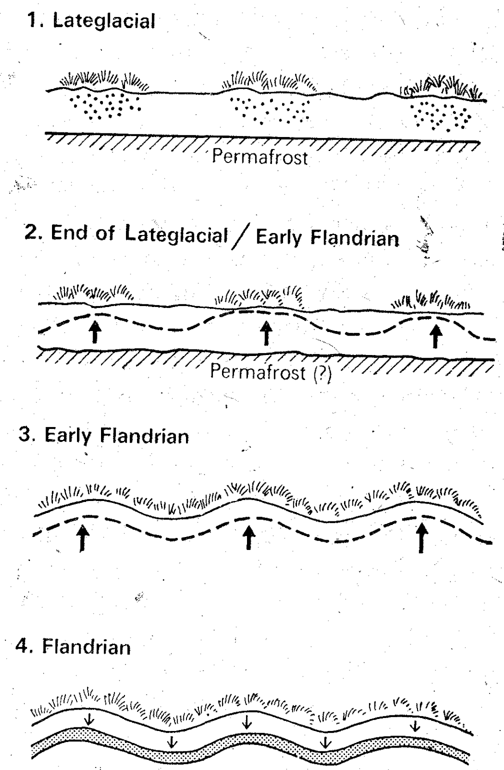



Fig. 8. Possible evolution of hummocks, hummock stripes and relief stripes on Ben Wyvis
1. Under arid periglacial conditions, irregularly-spaced vegetated circles and regularly-spaced vegetation-defined stripes develop in zones of moisture concentration in the active layer; 2. The insulating effect of vegetation cover results in more rapid frost penetration under bare ground. The resulting undulating freezing plane induces mass displacement under conditions of increasing wettness; 3. Hummocks and stripes formed by upward mass displacement may have continued to develop as surface topography perpetuated irregular frost penetration; 4. Podzolization results in depletion of clay and silt in the A horizon, rendering the top ca. 20 cm of the soil less frost-susceptible. Frost action is consequently diminished

vegetation-defined stripes develop in zones of moisture concentration (percolines on slopes) in the active layer above a permafrost table.

2. With the onset of wetter conditions at the end of the stadial, mass displacement is induced through the formation of an undulating freezing plane that results from more rapid frost penetration under unvegetated ground.

3. Mass displacement results in the formation of earth hummocks, hummock stripes and relief stripes; the resulting changes in microtopography perpetuate the survival of differential freezing so that mass displacement may have continued into the Flandrian despite climatic amelioration and the formation of a complete vegetation cover.

4. The formation of podzol soils during the Flandrian results in the depletion of silt and clay in the A horizon (Fig. 6) of stripes and hummocks, rendering the top ca. 20 cm of the soil less frost-susceptible; frost action is consequently diminished.

Although speculative, this sequence accounts for all of the observed features of the Ben Wyvis stripe-hummock system, including the transition from hummocks to stripes, the regular spacing of stripes (which are assumed to have initially followed regularly-spaced percolines, like those depicted in plates 3 and 4) the meandering of stripes on gentle slopes and the apparent lack of recent activity. It also explains the layer of clasts found immediately below the surface in the stripe section (Fig. 6; GOODIER and BALL, 1969): instead of being heaved out of the soil (as with sorted stripes) these would have been trapped by the existing root mat and hence would have accumulated immediately below the surface.

One further point that deserves consideration concerns the morphology of earth hummocks on Ben Wyvis and other British mountains. In the author's experience, earth hummocks in arctic environments tend to be knob-like in shape and closely spaced together, with narrow inter-hummock depressions (Pl. 5; see also TARNOCAI and ZOLTAI, 1978, Fig. 2; WASHBURN, 1979, Figs 5, 9). In contrast, the hummocks on Ben Wyvis and other British mountains are characteristically dome-like and separated by rather broad depressions (Pl. 2; see also BALL and GOODIER, 1970, Fig. 4a; TUFNELL, 1975, Pls 1, 2, 4). The wide spacing of many areas of hummocky microrelief on the upper slopes of British mountains favours interpretation of these features in terms of inheritance from randomly-spaced concentrations of vegetation, whereas the much closer spacing and steeper sides characteristic of arctic hummocks suggests that their formation is initiated in some other way, possibly as a result of seasonal frost-cracking (THORODDSEN, 1914; WOO, 1975). It is notable that arctic hummocks are not generally associated with relief stripes on steeper ground, which also suggests that the hummocks on Ben Wyvis are genetically different from those of arctic areas.

## NONSORTED PATTERNED GROUND ON AN TEALLACH

### DESCRIPTION

Of the three types of patterned ground described in the introduction, only hummocks occur on An Teallach. Moreover, the An Teallach hummocks differ from those of Ben Wyvis in certain respects. Not only are they generally much higher (Tab. I), but they are also rounded rather than dome-shaped in profile and much more closely-spaced (Pls 6, 7). Furthermore, they occur on slopes of 4—18° rather than on level ground and are not associated with hummock stripes or relief stripes. The vegetation on the An Teallach hummocks is also different. The windward sides and exposed crests of hummocks are occupied by long-stemmed grasses and sedges, but the lee sides and interhummock troughs are typically covered by a *Calluna vulgaris* — *Vaccinium myrtillus* association (Pl. 7; Fig. 9).

The An Teallach hummocks are limited in distribution to gentle and moderate

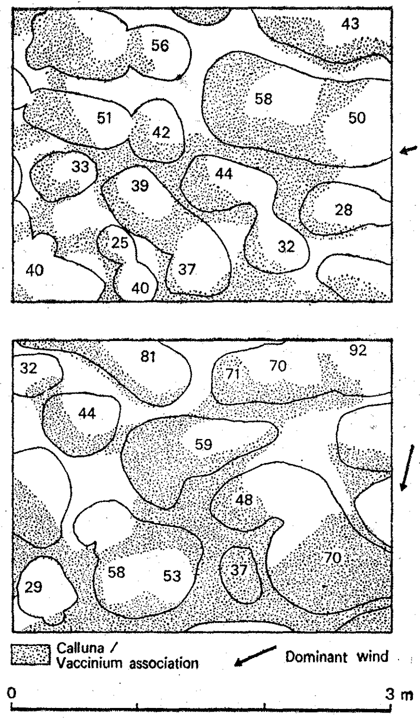
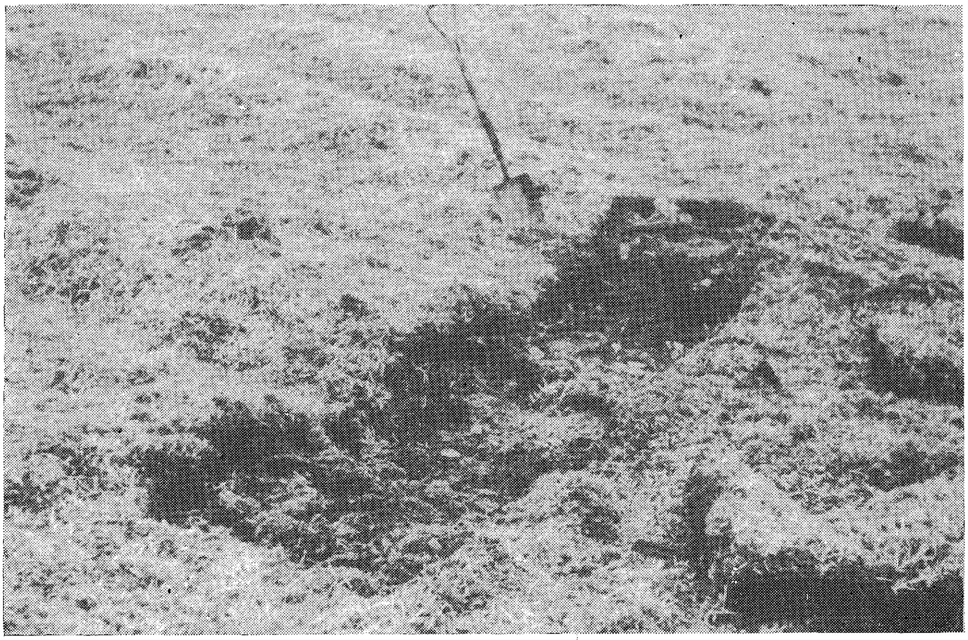



Fig. 9. Vegetation cover on hummocks, An Teallach. The unshaded areas are mainly covered by long-stemmed grasses and sedges. The figures refer to hummock heights above the lowest points in the surrounding depressions (in centimetres)

lee (east-facing) slopes on which a thick (>1.0 m) cover of niveo-aeolian sand has accumulated (Fig. 3). In the areas occupied by the hummocks, the niveo--aeolian sand deposits consist of two well-defined units: a lower weathered unit that accumulated slowly during the Flandrian, and an upper unit of fresh sand that accumulated rapidly on lee slopes as a result of the erosion of pre-existing sand deposits on exposed cols upwind (Ballantyne, 1981). As this erosion appears to have been triggered by overgrazing following the introduction of hill sheep to the mountain at the end of the last century, both the upper sand unit and the hummocks that have developed on the upper sand unit must have formed within the last hundred years or so.

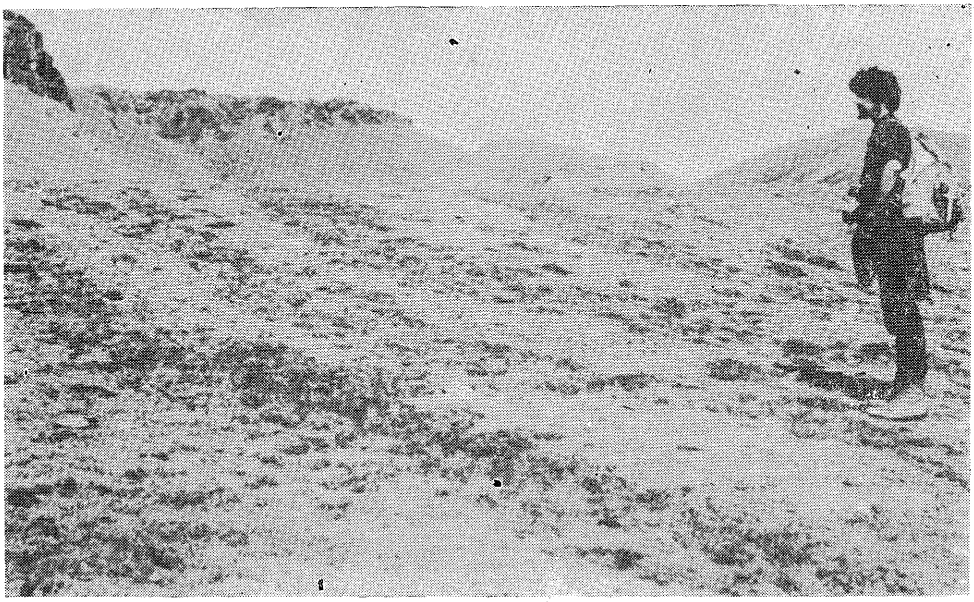
## STRUCTURE AND CONSTITUTION

Sections were cut through 8 hummocks at 4 different locations. All excavated hummocks were found to consist of structureless, predominantly medium to coarse sand (Figs 5, 7; Pl. 8) of similar granulometric composition to that of hummockless niveo-aeolian sand deposits elsewhere on the mountain. The lack of clay, silt and fine sand in these hummocks indicates that they are unlikely to

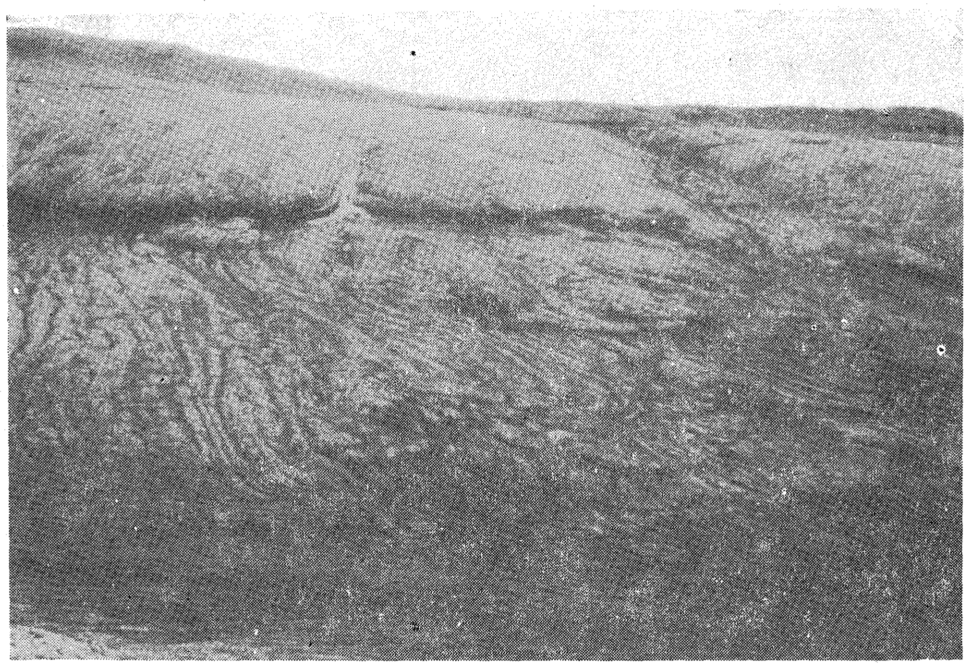


Pl. 1. Relief stripes on Ben Wyvis, showing the absence of subsurface sorting

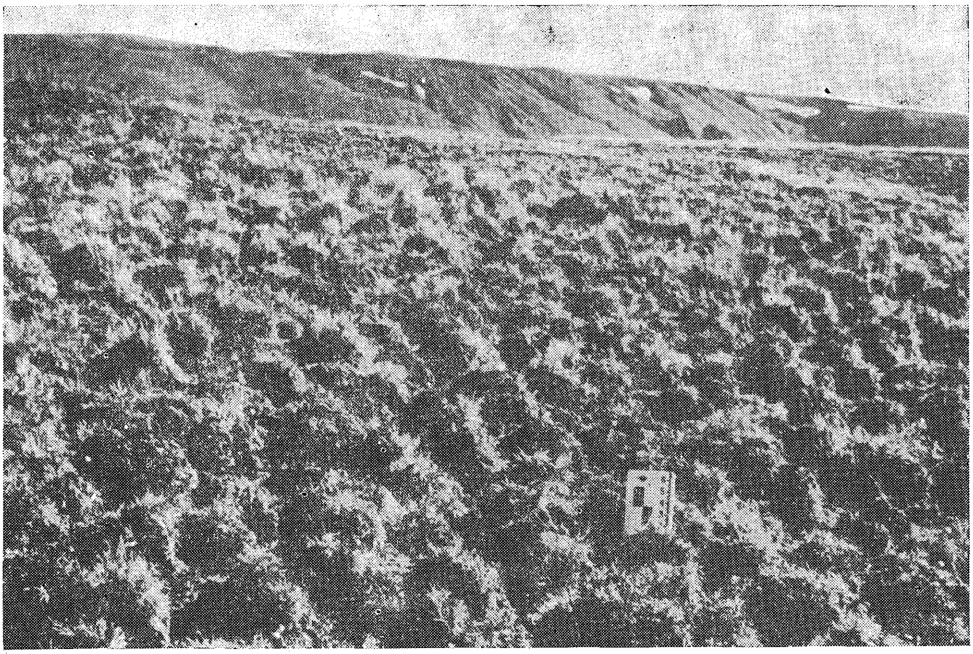
Pl. 2. Section cut through two earth hummocks on Ben Wyvis, showing the development of a podzolic leached A horizon parallel to the ground surface and the absence of subsurface sorting



Pl. 3. Nonsorted stripes consisting of alternating bands of vegetated and unvegetated ground, Ellesmere Island, N.W.T., Canada



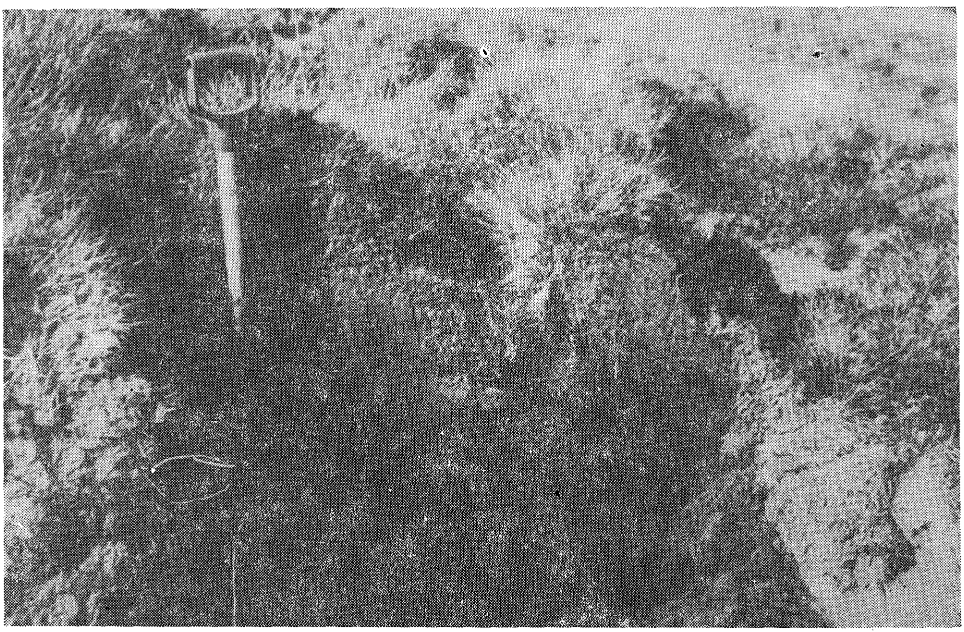
Pl. 4. Vegetation-defined nonsorted stripes and gelifluction sheets on a slope in Ellesmere Island, N.W.T., Canada. The vegetated stripes follow subsurface percolines



Pl. 5. Earth hummocks in a arctic environment, Ellesmere Island, N.W.T., Canada

Pl. 6. Sand hummocks on An Teallach

Pl. 7. Sand hummocks on An Teallach, showing the concentration of long-stemmed grasses and sedges on hummock crests



Pl. 8. Section cut through two sand hummocks on An Teallach, showing the structureless sand on which such hummocks are developed

be frost-susceptible even if sufficient water were retained in the sand to allow ice segregation, and excavation of frozen hummocks revealed pore ice but no lenses. The hummock sands are therefore unlikely to have experienced pronounced frost heave or mass displacement, and a different explanation must be sought for hummock genesis.

## FORMATION

The manner in which the hummocks developed is suggested by the following observations. In winter, large quantities of sand are blown by strong westerly winds off the relatively snow-free unvegetated plateau of An Teallach and deposited on the snowcover on lee (east-facing) slopes. This annual supranival

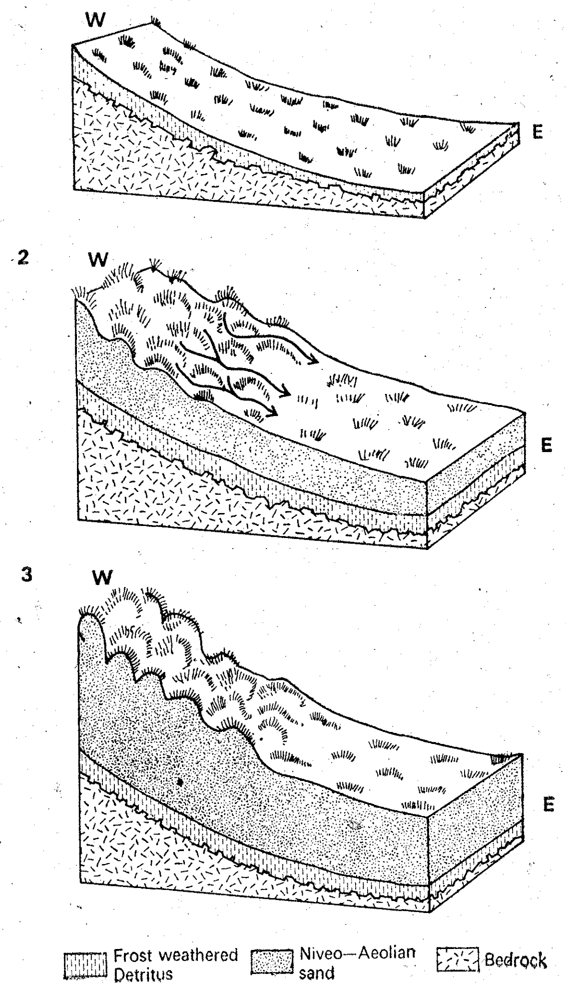



Fig. 10. Hummock evolution through preferential accumulation of niveo-aeolian sand on tussocks and flushing of sand from between tussocks by nival meltwater (schematic)

sand deposit is thickest on ground immediately adjacent to the plateau source areas, and has through time built up the deep deposits of niveo-aeolian sand on which the hummocks are found (BALLANTYNE, 1981). When the snow melts in spring, supranival sand is deposited on the underlying vegetation cover. On hummock crests it becomes trapped amongst long-stemmed grasses and sedges that grow on the exposed parts of the hummocks. The inter-hummock troughs, however, form the routeways for snowmelt runoff, and sand deposited in such locations is transported via a network of troughs to be deposited in a thin spread over more level ground (*cf.* WOO, 1975).

On adjacent areas of level or gently-sloping hummockless ground, grasses and sedges tend to grow as tussocks that also trap sand during snowmelt. However, on slopes of less than 4—5° the gradient is apparently too low to allow eluviation of sand from between the tussocks, so that sand accumulates on and between the tussocks at similar rates and no hummocks are formed. This evidence suggests that hummock genesis is due to preferential accumulation of niveo-aeolian sand on slopes that are sufficiently steep to allow nival meltwater to flush out sand from the areas between the grass tussocks. This interpretation is illustrated in Fig. 10 and explains not only the differences between the An Teallach and Ben Wyvis hummocks, but also the restriction of the former to thick non-frost-susceptible niveo-aeolian sand deposits that have recently accumulated on lee slopes adjacent to plateau areas. Although similar hummocks have been reported by ROBINSON (1977) on the Torridon Sandstone hills of Applecross (50 km S.S.W. of An Teallach) the circumstances under which these features appear to form severely limit their distribution; the writer knows of no examples on lithologies other than Torridon Sandstone. Adoption of the term "sand hummock" to describe such features may serve to distinguish them from features formed by frost action.

## DISCUSSION

The conclusions reached in this study may be summarised as follows.

1. The earth hummocks, hummock stripes and relief stripes on Ben Wyvis appear to have formed through modification by mass displacement of nonsorted vegetation-defined patterned ground of Lateglacial age. These features are essentially inactive at present and both morphologically and genetically different from nonsorted patterned ground forms in arctic environments.

2. The sand hummocks of An Teallach, although superficially similar to earth hummocks, are not frost action phenomena. They are interpreted as having formed over the last century as the result of the trapping of niveo-aeolian sand by tussocks on slopes that are sufficiently steep to allow eluviation of sand from between the tussocks by nival meltwater.

A number of supplementary conclusions may be drawn from comparison of the characteristcs of the features described above with accounts of nonsorted patterned ground in other parts of Britain. Although sand hummocks such as those on An Teallach appear to be restricted in distribution to niveo-aeolian sand accumulations on sandstone mountains, features corresponding to the hummocks, hummock stripes and relief stripes on Ben Wyvis appear to be fairly common on a range of lithologies. The relief stripes described on the Rhinog mountains (GOODIER and BALL, 1969) and Snowdonia (BALL and GOODIER, 1970) are clearly similar in form to those on Ben Wyvis, and the association of hummocks and stripes on Skye reported by BIRKS (1973) is apparently identical. Other examples of earth hummocks grading into hummock stripes and relief stripes with increasing slope occur at 825 m altitude on the Merrick, at 800—900 m on the Drumochter Hills and at 900—1000 m on Glas Maol (Fig. 2). WASHBURN's suggestion (1977, p. 152) that the features here termed hummock stripes and relief stripes are "uncommon" may be true of arctic environments, but it is not true of the mountains of Great Britain. Similarly, the assertion by TUFNELL (1975, p. 354) that earth hummocks are "uncommon" in Britain deserves qualification; whereas this may be the case in North Wales and Northern England, it is not true of the Scottish highlands, where hummocky microrelief is widespread on many plateau areas.

Not all of these hummocks are associated with stripe forms on steeper ground, however. TUFNELL (1975), for example, reports earth hummocks on slopes as steep as 17°, whereas those on Ben Wyvis are replaced by stripe forms on slopes of 1—6°. No hummock stripes or relief stripes are reported by TUFNELL, so the sequence of development summarised in Fig. 8 cannot hold for the formation of nonsorted patterned ground in the northern Pennines. Similarly, the "low elevation earth hummocks" described by PEMBERTON (1980, Fig. 1) not only appear to be much lower and flatter than the forms on Ben Wyvis (and those described by TUFNELL), but also occur on slopes of up to 14° and are again not associated with stripe features. Although the hummocks studied by TUFNELL and PEMBERTON may indeed be frost-action forms (as both authors concluded), these hummocks are clearly genetically distinct from the hummock and stripe features described in this paper. Significantly, both TUFNELL and PEMBERTON favoured a recent origin for the features they described, whereas the hummocks and associated stripes on Ben Wyvis have apparently experienced prolonged inactivity (as evidenced by intact podzol soil horizons) and are here inferred to have originated at the end of the Lateglacial period some 10,000 years ago. It appears that even morphologically similar hummocks on British mountains comprise at least three chronologically and/or genetically diferent types of feature, and that none of these types is strictly analogous to the hummocky microrelief of arctic environments.

A final point concerns the relationship between earth hummocks produced by frost action and the nature of the soil mantle on which such hummocks are found. COTTON (1968) and TUFNELL (1975) noted that although earth hummocks occur on sedimentary rocks in the Pennines, the regolith developed on crystalline formations may not favour hummock development. PEMBERTON (1980) found that not all superficial deposits are conducive to hummock formation, and related the distribution of earth hummocks to the frost-susceptibility of the parent material. The evidence presented here supports this interpretation, for although frost-action nonsorted patterned ground is widespread on the frost-susceptible soils of Ben Wyvis, it is completely absent from the non-susceptible regolith of An Teallach. In the author's experience widespread development of frost-action hummocks in the Scottish Highlands is restricted to rocks that have broken down to form a frost-susceptible diamicton (particularly micaceous schists), but similar forms are rare or absent on lithologies that have weathered to produce regolith with a coarse sandy matrix (such as granite and Torridon Sandstone). Frost susceptibility would appear to be a *sine qua non* for the development of nonsorted patterned ground by frost action in upland Britain.

## ACKNOWLEDGEMENTS

The research reported here was carried out whilst the author was in receipt of a scholarship from the Carnegie Trust for the Universities of Scotland. Dr. J. B. Sissons of the University of Edinburgh contributed useful comments on an earlier draft of this material.

## References

Ball, D. F., Goodier, R., 1970 — Morphology and distribution of features resulting from frost action in Snowdonia. *Field Studies*, 3; p. 193—217.

Ballantyne, C. K., 1981 — Periglacial landforms and environments on mountains in the Northern Highlands of Scotland. Unpub. Ph. D. thesis, Univ. of Edinburgh; 593 p.

Benedict, J. B., 1968 — Radiocarbon dates from a stone-banked terrace in the Colorado Rocky Mountains, U.S.A. *Geogr. Annaler*, 48A; p. 87—93.

Benedict, J. B., 1970 — Downslope soil movement in a Colorado alpine region: rates, processes and climatic significance. *Arctic and Alpine Research*, 2; p. 165-226.

Benedict, J. B., 1976 — Frost creep and gelifluction features: a review. *Quatern. Res.*, 6; p. 55—67.

Beschel, R. L., 1966 — Hummocks and their vegetation in the high arctic. *U.S. Nat. Acad. Sci., Nat. Res. Council Pub.*, no. 1287; p. 13—20.

Beskow, G., 1930 — Erdfliessen und Strukturböden der Hochgebirge im Licht der Frosthebung. Prelimäre Mitteilung. *Geol. Fören. Stockholm Förhandl.*, 52; p. 622—638.

Birks, H. J. B., 1973 — Past and present vegetation of the Isle of Skye: a palaeoecological study. Cambridge Univ. Press; 415 p.

Cotton, D. E., 1968 — An investigation of the structure, morphology and ecology of some Pennine soil microtopographic features. Unpub. Ph. D. thesis, Univ. of Lancaster; 203 p.

Evans, R., 1976 — Observations on a stripe pattern. *Biuletyn Peryglacyjny*, 25; p. 9—22.

Galloway, R. W., 1958 — Periglacial phenomena in Scotland. Unpub. Ph. D. thesis, Univ. of Edinburgh; 287 p.

Galloway, R. W., 1961 — Solifluction in Scotland. *Scott. Geogr. Mag.*, 77; p. 75—87.

GOODIER, R., BALL, D. F., 1969 — Recent ground pattern phenomena in the Rhinog Mountains, North Wales. *Geogr. Annaler*, 51A; p. 121—126.

HOPKINS, D. M., SIGAFOOS, R. S., 1954 — Role of frost thrusting in the formation of tussocks. *Amer. Jour. Sci.*, 252; p. 55—59.

LUNDQVIST, J., 1962 — Patterned ground and related frost phenomena in Sweden. *Sver. Geol. Unders.*, 55, no. C583; 101 p.

MACKAY, J. R., 1979 — An equilibrium model for hummocks (nonsorted circles), Garry Island, Northwest Territories. *Canada Geol. Surv. Paper*, 79—1A; p. 165—167.

MACKAY, J. R., MACKAY, D. K., 1976 — Cryostatic pressures in nonsorted circles (mud hummocks), Inuvik, Northwest Territories. *Can. Jour. Earth Sci.*, 13; p. 889—897.

NICHOLSON, F. H., 1976 — Patterned ground and description as suggested by Low Arctic and Subarctic examples. *Arctic and Alpine Research*, 8; p. 329—344.

PEACH, *et al.*, 1912 — The geology of Ben Wyvis, Carn Chuinneag, Inchbea and the surrounding country. *Mem. Geol. Surv. Scotland;* p. 189.

PEACH, B. N., *et al.*, 1913 — The geology of the Fannich Mountains and the country around upper Loch Maree and Strath Broom. *Mem. Geol. Surv. Scotland;* 127 p.

PEMBERTON, M., 1980 — Earth hummocks at low elevation in the Vale of Eden, Cumbria. *Trans. Inst. Br. Geogr.*, New Series, 5; p. 487—501.

PHEMISTER, J., 1960 — Scotland: The Northern Highlands. British Reg. Geology, H.M.S.O.; Edinburgh; 104 p.

RAUP, H. M., 1965 — The structure and development of turf hummocks in the Mesters Vig district, Northeast Greenland. *Medd. om Grønland*, 176; 216 p.

ROBINSON, M., 1977 — Glacial limits, sea-level changes and vegetational development in part of Wester Ross. Unpub. Ph. D. thesis, Univ. of Edinburgh; 239 p.

SCHUNKE, E., 1975 — Neue Beobachtungen zur Periglazialmorphologie Islands (Ein Forschungbericht). *Gesell. Erdkunde Berlin Zeitschr.*, 106; p. 47—56.

SCHUNKE, E., 1977 — Zur Genese der Thufur Islands und Öst-Grönlands. *Erdkunde*, 31; p. 279—287.

SISSONS, J. B., 1976 — The geomorphology of the British Isles: Scotland. Methuen, London; 150 p.

SISSONS, J. B., 1979a — Palaeoclimatic inferences from former glaciers in Scotland and the Lake District. *Nature*, Lond., 278; p. 518—521.

SISSONS, J. B., 1979b — The Loch Lomond Advance in the Cairngorm Mountains. *Scott. Geogr. Mag.*, 95; p. 66—82.

TARNOCAI, C., ZOLTAI, S. C., 1978 — Earth hummocks of the Canadian arctic and subarctic. *Arctic and Alpine Research*, 10; p. 581—594.

TERZAGHI, K., 1952 — Permafrost. *Boston Soc. Civil Engineers*, 39; p. 1—50.

THORODDSEN, T., 1913 — Polygonböden und „Thufur" auf Island. *Petermanns Geogr. Mitt.*, 59; p. 253—255.

TUFNELL, L., 1975 — Hummocky microrelief in the Moor House area of the northern Pennines, England. *Biuletyn Peryglacjalny*, 24; p. 353—368.

WASHBURN, A. L., 1947 — Reconnaissance geology of portions of Victoria Island and adjacent regions, Arctic Canada. *Geol. Soc. Amer. Mem.*, 22; 142 p.

WASHBURN, A. L., 1956 — Classification of patterned ground and review of suggested origins. *Bull. Geol. Soc. Amer.*, 67; p. 823—865.

WASHBURN, A. L., 1969 — Weathering, frost action and patterned ground in the Mesters Vig district, Northeast Greenland. *Medd. om Grønland*, 176; 303 p.

WASHBURN, A. L., 1979 — Geocryology: a survey of periglacial processes and environments. Arnold, London; 406 p.

WATT, A. S., PERRIN, R. M. S., WEST, R. G., 1966 — Patterned ground in Breckland: structure and composition. *Jour. Ecol.*, 54; p. 239—258.

WILLIAMS, R. B. G., 1964 — Fossil patterned ground in eastern England. *Biuletyn Peryglacjalny*, 14; p. 337—349.

WOO, M-k., 1975 — The formation of earth hummocks in south-central Ellesmere Island, N. W.T. Abstract of paper presented at meeting of Canadian Assoc. of Geographers, Vancouver, 1975; 2 p. (unpub.).

WORSLEY, P., HARRIS, C., 1974 — Evidence for neoglacial solifluction at Okstindan, north Norway. *Arctic*, vol. 27; p. 128—144.

ZAWADZKI, S., 1957 — Badania genezy i ewolucji gleb błotnych węglanowych Lubelszczyzny. *Ann. Univ. M. Curie-Skłodowska*, sec. E, 12; p. 1—86.

*Manuscript received: November, 1981*