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MORPHOLOGY AND DISTRIBUTION OF FEATURES RESULTING FROM FROST-ACTION IN SNOWDONIA

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Frost-action in the Pleistocene period, in historically recent times and at the present day, has been a major factor in the development of many landforms, types of patterned ground, and other surface features in the mountains of Snowdonia, North Wales. These features are described, classified in a broad morphological system, and related to the formative processes of gelifraction, gelifluction and cryoturbation. Their variety and distribution emphasizes the importance of frost-action in the glaciated uplands of Britain in the past and present and also the significance of the great climatic range found in Snowdonia today. The present account can, it is believed, form a basis for regional study and for detailed investigations of the features which have been identified and described.

CONTENTS

INTRODUCTION

THE effects of glacier ice on the landscape were recognized in North Wales by some of the earliest British workers in this field (e.g. Ramsey, 1860) who described the resultant features from such classic localities as Nant Ffrancon, Cwm Idwal and Snowdon. It took much longer for it to be appreciated that processes associated with severe frost climates had been important in shaping the detail of landforms in mountain areas of Western Britain. It has, however, become increasingly recognized that conditions involving frost-action and freeze-thaw were not confined during the

Pleistocene to zones of Britain which always lay outside the glacier limits (where their results had been identified at least as long ago as 1851 by R. A. C. Austen), but were also important geological factors in the glaciated regions of Britain, (see e.g. Fitzpatrick, 1958, and Galloway, 1961, for Scotland; Tufnell, 1966, for northern England; and Watson, 1969, for mid-Wales). In highland Britain, frost-action in the Pleistocene period, in historically recent times, and also locally at the present day, has produced and is still creating features of surface physiography and pattern, and has greatly modified, by erosion and transport of till deposits and frost-shattered rock, the landscape that was present after the disappearance of glacier ice.

Examination of aerial photographs combined with ground survey in Snowdonia has made clear to us that a wide range of deposits, landforms and patterned ground resulting from frost-action is to be found there. The region discussed can be defined as the uplands, having an altitude range from about 150 m. (500 ft.) to 1,085 m. (3,561 ft.), within the Snowdonia National Park in the counties of Caernarvonshire and Merionethshire, North Wales. Specific examples of such features have previously been described from this area (Tallis and Kershaw, 1959; Ball, 1966, 1967; Ball and Goodier, 1968; Goodier and Ball, 1969) but no general account has previously appeared. A comprehensive regional study which we have found very valuable for comparison is that from Scandinavia by Lundqvist (1962), and an important classificatory work is that of Washburn (1956). Embleton and King (1968) provide a good general text which covers periglacial geomorphology.

The present paper attempts a regional review of frost-action features, with type examples drawn so far as possible from north Caernarvonshire, but does not consider the nature and distribution in the area of landforms and deposits resulting from erosion and transport by glacier ice. We consider also that, in Snowdonia, contemporary slope erosion is dominantly due to periods of excessive rainfall, although frost-action may be a subordinate causative factor. The results of this erosion, which include gully, sheet and slip erosion scars, although of considerable interest, justify separate consideration rather than attention here among the definite frost-action features.

The description *periglacial* has been widely applied to most or all of the features described in this paper, but we feel that the connotation of "peripheral to a glacier" makes it unsuitable for general use in the present context. Although many of the features were formed during the Pleistocene period, especially in the Late Glacial, and are therefore at least sometimes periglacial in a strict sense, others have been formed in relatively recent historic time or are actively forming or being maintained today, when neither permanent ice nor snow patches are found. We prefer therefore to employ *frost-action* as a general term to identify the range of processes and resulting features substantially caused by repeated freeze-thaw cycles. The processes can be broadly sub-divided into three categories:

(*a*) *Gelifraction* — The breaking down of outcrop rock into smaller particles by freeze-thaw action. The word is a synonym for frost-shattering.

(*b*) *Gelifluction* — (After Washburn, 1967.) Down-slope mass creep or flow of water-saturated material resulting from seasonal thaw (*gelifluction*) is a sub-category of *solifluction* ("the slow flowing from higher to lower ground of masses of waste saturated with water" (Andersson, 1906)). Gelifluction is distinguished by Washburn from *frost creep*, the former involving downslope saturated flow,

PLATE 1a.
Mountain-top detritus in foreground on summit of Garnedd Uchaf at c. 900 m. altitude (SH 687669); screes on slope of Carnedd Llywelyn in background; Carneddau mountain group, Caernarvonshire.

PLATE 1b.
Small sorted polygons at 945 m. altitude near Foel Grach; Carneddau mountain group, Caernarvonshire. (SH 690656).

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the latter a step-wise process in which there is a heave of rock and mineral particles normal to the slope on freezing and a vertical drop of these when their supporting ice crystals thaw. While some features are clearly due to one or the other process, frost creep for example being probably dominant in scree accumulation, the distinction between the effect of the two modes of movement in non-contemporary deposits may be difficult to make. For simplicity in this paper we treat all frost-action downslope movement under the term gelifluction.

(*c*) *Cryoturbation* Redistribution or re-orientation of the component fractions of a deposit *in situ*, or differential vertical movement as a result of heaving by frost-action.

We have not considered it necessary to present detailed evidence here proving that the features we describe are due to frost-action, because much published work from present-day strict periglacial environments as well as experimental laboratory studies (e.g. Corte, 1966) have made this case convincing enough. We do, however, discuss the relevance of probable processes in consideration of the individual features and relate the features to examples previously described from Britain and elsewhere. We have also not attempted to define the climatic conditions likely to have been, or to be, required for formation of the various features (see e.g. Williams, 1961), since this is a most complex field in the interpretation of past events, while adequate contemporary climatic data are at present entirely lacking for the area.

Classification, description and discussion of frost-action features in Snowdonia

Classification

Table 1 classifies the major features recognized and these are subsequently individually described and discussed. We have indicated what formative processes we consider to be dominant and also the periods of formation, definite and probable, for those features now seen, but these indications must be considered in part provisional and liable to improvement with increased knowledge. Late Glacial is used in the accepted sense to include Zones I and III during which periglacial action was widespread. Recent historic time is used to cover the period from about A.D. 1500 to 1800.

Although a few features can be said to form dominantly as a result of one of the types of frost-action process defined above, in most cases two are involved, and a classification based purely on process would not be satisfactory. There is some correlation of feature characteristics, mainly their size, scale and the altitudes at which they occur, with known or postulated period of formation, but small-scale older surface features would of course be less likely to be preserved than those of larger scale so that a classification based on the period of formation would give a false impression of their original distribution.

We have therefore chosen, although it is admittedly not ideal, to follow the principles of Washburn and other specialists, and use a grouping which is neither genetic nor chronological but is crudely morphological. We base Table 1 on an initial sub-division into Major Physiographic Features, Minor Physiographic Features and Modification of Drift Fabric. The first two categories cover features

Table 1. *Classification of frost-action features in Snowdonia*

	Dominant Process or Processes			Formation Period/s of Features as Found Today*		
	Geli-fraction	Geli-fluction	Cryotur-bation	Late Glacial†	Recent historic time	Present day
A. *Major Physiographic Features* A1. Tor-like summits	✓	✓		✓	?	?
A2. Mountain-top detritus ..	✓	✓		✓	?	?
A3. Scree slopes..	✓	✓		✓	?	?
A4. Valley-side gelifluction terraces		✓		✓		
B. *Minor Physiographic Features* Lobate forms B1. Stone-banked lobes		✓	?	✓	✓	✓
B2. Turf-banked lobes		✓		✓	?	?
B3. Terracettes		✓		?	✓	?
Regular patterned forms B4. Large sorted stripes		✓	✓	✓		
B5. Small sorted stripes		✓	✓		✓	✓
B6. Small unsorted stripes ..		✓	✓		✓	?
B7. Large sorted polygons ..			✓	✓		
B8. Small sorted polygons ..			✓		?	✓
Irregular forms B9. Earth hummocks			✓		?	✓
B10. Stone pits			✓		?	✓
B11. Stone lenses			✓	✓	✓	?
B12. Gliding blocks		✓			✓	?
C. *Modification of Drift Fabric* C1. Frost shattering, involutions and wedge casts	✓		✓	✓	?‡	?‡
C2. Development of laminated structure and "pinhole" fabric in indurated till ..			Freeze-thaw *in situ* with little vertical heaving	✓		
C3. Development of downslope orientation of stones in transported till, head and scree	✓	✓		✓	?	

* *Small-scale features, e.g.* B5, 6, 8, 9, 10, 12 *were almost certainly also formed in the Late Glacial period but are unlikely to be preserved to the present day.*

† *Frost-action features also formed at earlier periods during the Pleistocene and some large-scale examples may be relicts from that time (e.g.* A1 *and* A2).

‡ *Frost-shattering only.*

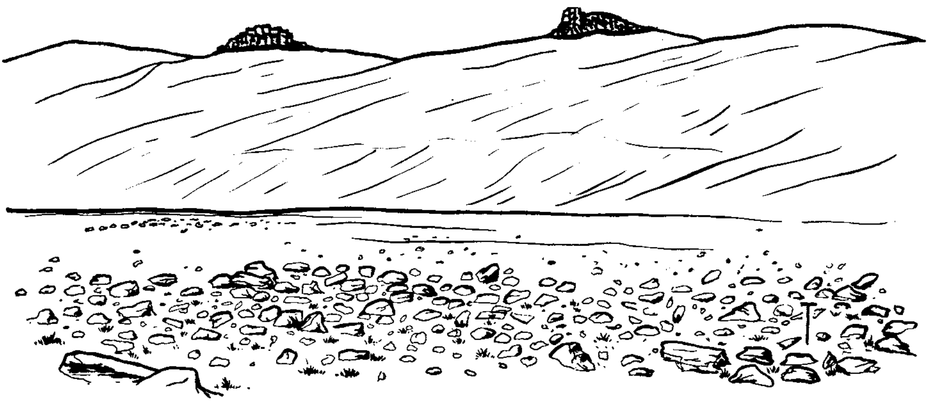

Fig. 1a

Fig. 1b

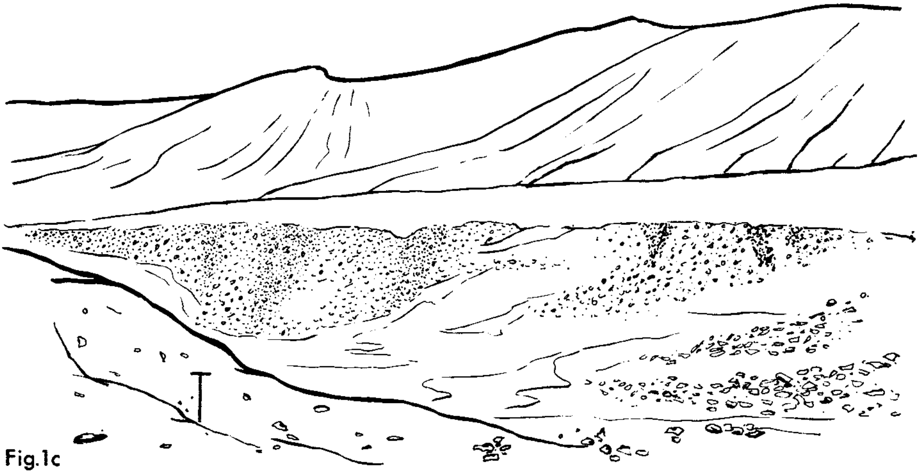

Fig. 1c

FIG. 1a.

Tor-like summits in the background at about 800 m. altitude on the Drosgl-Bera Bach ridge (SH 668679), Carneddau mountain group, Caernarvonshire, with mountain-top detritus in the foreground.

FIG. 1b.

Cross-section of scree slope at 8 m. altitude at Coed Camlyn, Merionethshire (SH 657398).

FIG. 1c.

Valley-side gelifluction terrace in middle distance on north-eastern side of Cwm Llafar at c. 500 m. (c. SH 662648), Carneddau mountain group, Caernarvonshire.

seen at the surface although they may also have a recognizable internal structure, the third category is to allow discussion of internal structures observed in sections of unconsolidated deposits, which may have no, or less obvious, expression in surface morphology. The division of Major from Minor Physiographic Features is clearly subjective but is intended to distinguish so far as possible those features which result in large relief amplitudes, or have a major effect on large areas of ground surface, from those which are either less extensive or, if extensive, have low relief amplitudes and a less extreme influence on the form of the ground surface. The category of Minor Physiographic Features has been further sub-divided into Lobate Forms, Regular Patterned Forms and Irregular Forms.

Features resulting from quasi-permanent snow, such as snow-patch moraines (pro-talus ramparts) and nivation hollows, which are on the borderline of glacier-ice and frost-action features, are excluded from this account, as also is any discussion of possible periglacial (or niveo-fluviatile) valley formation, due to the difficulties of distinguishing these in our area from valleys produced by glacial drainage or post-glacial stream erosion.

Description and Discussion

A. Major Physiographic Features

A1. Tor-like Summits (Fig. 1a).

A tor was originally defined from a local name on Dartmoor (see Amer. Geol. Inst., 1957) as an outcrop with rounded ice-worn surfaces (i.e. it was considered synonymous with roche moutonée) and was also used to describe upstanding rock masses considered to be remnant features left after ice had removed surrounding more strongly-weathered rock. Subsequently the equivalence with roche moutonée has been dropped. Linton (1955) showed that tors in their type area have a complex origin, resulting from non-uniform weathering of bedrock in pre- or inter-glacial periods, followed by removal of the softer more deeply weathered material by gelifluction. The name has more recently been extended to cover upstanding shattered rock outcrops attributed to non-uniform gelifraction which has acted on rock of variable joint or cleavage development, again followed by removal of the more deeply shattered material by gelifluction, without Linton's essential pre-requisite of deep pre- or inter-glacial chemical weathering (e.g. in the Yakutsk region of the U.S.S.R. (Demek, 1968)). Such features occurring on "Pleistocene periglacial slopes" have alternatively been called "surface remnants" but also attributed, in an important Canadian general work (Hamelin and Cook, 1967), to non-uniform gelifraction. Complex origins for tor-like features have been suggested in Charnwood Forest, Leicestershire, by Ford (1967) and in Tasmania by Caine (1967).

It seems preferable in England to confine the meaning of tor to its original usage where the dual cause of origin has been demonstrated. The general types of craggy shattered rock masses which project as isolated features above the surrounding hill level are therefore defined here under the more non-committal term "tor-like summits", in a similar manner to the use of "tor-like weathering forms" by Dahl (1966). There is a hint that pre-glacial weathering may have been significant in the Welsh mountains in the recognition of a narrow zone of deeply-weathered granite containing gibbsite which was found on Llymllwyd, 750 m. (2,450 ft.) above Nant Ffrancon, Caernarvonshire (631609) (Ball, 1964), but this evidence is not yet strong enough to decide whether tor-like summits in the Welsh mountains have a similar origin to those of Dartmoor.

There are very many examples in Snowdonia of tor-like summits rising above the peaks and summit ridges, for example on the Glyders and the Carneddau and also on lower mountains such as Bera Mawr (675683, c. 789 m. (2,588 ft.)) and Mynydd Craig-goch, c. 610 m. (1,996 ft.). Except on the most fissile rocks (e.g. slates) at the highest altitudes these features are not apparently being substantially modified today. Tor-like summits on Glyder Fach, Foel Grach (689659) and Garnedd Uchaf (688670) are referred to by Whittow and Ball (in press) in a review of glacial stratigraphy in North-West Wales, and the probability is suggested that their formation, together with that of associated mountain-top detritus, will have extended through a longer time in the Pleistocene Period than just the Late Glacial.

A2. Mountain-top Detritus (Plate 1a, Fig. 1a).

Mountain-top detritus is in a broad way generally taken in Britain as synonymous with blockfield or felsenmeer, and used to describe extents of boulders, covering areas, of level ground or gentle slopes, on hills in glaciated and periglacial areas. Strictly, blockfields refer to accumulations of angular frost-shattered stones more or less *in situ*. Because mountain-top detritus is rather wider in meaning, covering deposits with a wider range of stone sizes and shapes, it is preferred here and blockfields and mountain-top detritus are not treated fully as separate features.

In the formation of mountain-top detritus it is generally assumed (see e.g. Hamelin and Cook, *op. cit.*) that fracture of underlying rock by gelifraction gives accumulations of angular stones, from among which the finer material is removed by gelifluction. Where a cover of glacial drift has been present the mountain-top detritus will include rounded stones as a lag deposit from erosion of the finer fractions of the till.

It is an interesting speculation to consider whether not simply the surface deposit of stones, but the landform itself, in such areas as the shoulder between Carnedd Llywelyn and Foel Grach (c. 687655, c. 915 m. (3,000 ft.)) or the ridge of Gledrffordd in the same area of North Snowdonia (c. 705650, c. 760 m. (2,500 ft.)), is due to frost-action. These landforms may be comparable to cryoplanation terraces, defined by Demek (*op. cit.*) as erosional forms created by complex processes including gelifraction and gelifluction as defined here. Further study of the detailed morphology of these and similar areas and their surroundings with this consideration in mind would be most valuable.

There have been important investigations of hill-top deposits in the Southern Uplands of Scotland by Ragg and Bibby (1966). They demonstrated a passage from stony surface horizons through finer textured material before the solid rock is reached, a succession which they attribute to cryoturbation processes sorting coarser from finer fractions. To enable such sorting, freeze-thaw cycles operating through the entire depth of the unconsolidated material are, presumably, essential (e.g. Charlesworth 1957, p. 575). It is believed that such sorting is also present on some at least of the areas of mountain-top detritus in Snowdonia but again more investigation is necessary.

It is certain that the greater part of these deposits were formed before the Post Glacial period—the example from Gledrffordd only in recent times being exhumed from beneath a thickness of a couple of metres of peat. Locally on the higher peaks with moderately sloping approaches and particularly fissile bedrock, such as on

Y Garn above Idwal (632593, c. 915 m. (3,000 ft.)), there may be contemporary accretion of freshly gelifracted material which forms a blockfield in a more strictly defined sense.

A3. Scree Slopes (Plate 1a, Fig. 1b (section)).

One of the most extensive frost-action landforms has resulted from the formation, by a combination of gelifraction and gelifluction, of the screes which, beneath soil and vegetation cover, give a uniform steeply sloping mantle to many valley sides in the Welsh uplands, including Snowdonia. The scree consists of closely packed angular stones with their long axes oriented dominantly downslope at angles in the general range of 25–30°, a slope followed by that of the ground surface. The characteristics of such scree have been described and discussed by Ball (1966) with particular reference to a type section at Coed Camlyn near Maentwrog, Merionethshire (655397).

Scree (derived from an old Norse word meaning rubble that slides when trodden on (Holmes, 1965)) can be defined as consisting only of angular stones, with a minimal quantity of fine matrix in the sand, silt and clay size ranges. In contrast, *head* (named by de la Beche in 1839), which has been defined as crudely stratified solifluction deposits partially derived from country rock and soils and partially from re-sorted till (Dines *et al.*, 1940), contains a substantial proportion of the smaller size fractions. Gradations between these two types of deposit exist with a high stone content but with fine material which has been incorporated either when the deposit accumulated, or subsequently due to washing down of material from the surface and to weathering of the stones *in situ*. Where the fine fractions are clearly subordinate and the fabric of the deposit is due to the packing together of oriented stones, we prefer to continue to consider these as scree, since their formation has essentially depended on gelifraction of outcrop rock. The stratified screes, consisting of closely alternating beds of finer and coarser material, recorded in Southern Snowdonia and mid-Wales (Watson, 1965), have not been seen by us in Northern Snowdonia.

Numerous deep exposures of coarse slaty scree which are seen in the Conway Valley along the B5106 road between Betws-y-Coed and Llanrwst are typical cross-sections of scree slopes. The sections show, among dominantly angular local stone, an incorporation of occasional rounded stones derived from drift cover which must have existed prior to the period of intense frost action responsible for the scree accumulation. Some glaciated upland valleys in Snowdonia also show extensive slope deposits of scree or intergrade head-scree material, a good example of the latter being Cwm Dudodyn, north of Nant Peris (c. 615605, c. 460–610 m. (1,500–2,000 ft.)).

Where scree cover is less thick the contribution of the two formative processes can be seen in exposures. Jointed or cleaved massive rock passes up into frost-shattered but *in situ* material, the orientation of which follows that of the cleavage or jointing in the rock below. Within a thickness of about 25 cm. the long axes of the rock fragments have become oriented down-slope. The close packing of the stones and the orientation of finer material around occasional larger contained boulders supports the conclusion that flow, probably due to gelifluction contemporaneous with the frost-shattering, is important in the build up of the scree mantle. Such an exposure made recently where road-surfacing material had been removed from a cutting above Dolgarrog in the Conway Valley, on the Moel Eilio road (c. 757663), was brought to our notice by Dr. R. Elfyn Hughes.

The relic character of the screes overlain by mature soil profiles and continuous vegetation cover is obvious. At higher altitudes, exposed screes are less immediately easy to date and probably still receive minor accretion of material as a result of contemporary frost-shatter and other weathering processes. In such cases, slope angles are generally steeper and the stones are packed less tightly together than in the vegetated scree slopes. The evidence given by Ball (1966), however, indicates that, certainly for exposed scree at lower and middle altitudes, and probably even at the highest altitudes, most of the material results from a Late Glacial period of formation and that re-sorting of this material, rather than accretion of freshly shattered rock, is the dominant contemporary process.

A4. Valley-side Gelifluction Terraces (Fig. 1c).

Gelifluction operates in present-day periglacial areas by the mass downslope movement of water-saturated debris as a plastic solid after surface thaw (Hamelin and Cook, *op. cit.*, p. 179). Flow is probably limited to a short period in spring when meltwater from snow and from ice in the upper active layer of the deposit saturates this above the permafrost (perennially frozen ground). Rates of movement are of the order of a few centimetres a year, dependent on slope, surface morphology and climatic factors; for example in Norway Rapp (1960) has shown movements of c. 2 cm. a year in a 25 cm. thick layer of fine-grained meltwater-saturated material. Flow takes place when shear stress produced by gravity with its downslope component exceeds the yield limit of the material.

If, therefore, a slope is mantled by till and a period of permafrost conditions with seasonal thaw of an upper "active" horizon ensues after ice retreat, the till will be moved gradually downslope, to create an accumulation near the foot of the slope, a downslope orientation of the long axes of contained stones, and a smoothing of surface relief into a uniform slope contrasting with the hummocky relief characteristic of fresh till sheets. Obviously, when gelifluction has continued for a sufficient period, till cover can be completely removed from valley sides, thus allowing valleys such as Cwm Dudodyn, which was previously mentioned in connection with scree slopes (A3), to develop their present characteristic form of rock outcrops on the upper slopes and head or scree on the lower slopes. However, if the drift cover is initially thick and the periglacial period was not of sufficient duration or intensity to cause complete removal of the gelifluted material, then thick gelifluction deposits form benchlike terrace features on the lower valley slopes. It has been suggested from studies in Greenland (Everett, 1967) that "solifluction" sheets form over smooth bedrock and "solifluction" lobes over channelled bedrock but in the Welsh examples this does not appear to be the controlling factor (however, see also B2).

Gelifluction terraces can be of large scale, measured in hundreds of metres in breadth and kilometres in length, as in the examples described and discussed from South Wales (Crampton and Taylor, 1967). In Snowdonia, although they appear less widely developed than in South Wales, they have been recognized in some upland tributary valleys, such as Cwm Llafar, south-east ofBethesda (c. 660650, c. 450–530 m. (1,500–1,750 ft.) and, less well-defined, in Cwm y Llan, Snowdon (c. 617520, c. 365 m. (1,200 ft.)). As noted by Crampton and Taylor (*op. cit.*) the remains of terraces below south and west facing slopes may be more prominent than are those at the foot of north or east facing slopes because of more intense seasonal transport of material by gelifluction processes on the former. Gelifluted till resulting in smooth slopes, although not conspicuous bench features, can also be identified in Snowdonia above areas of younger morainic till deposited by Late Glacial cwm glaciers, for example in the Cwm Dyli sector of Snowdon (Ball, Mew and Macphee, 1969).

B. Minor Physiographic Features

Lobate Forms

B1 Stone-banked Lobes (Fig. 2a).

These are tongue-shaped or lobed terraces oriented with their curved fronts downslope and bounded on their sides and especially on their frontal downslope faces by steep banks of imbricated stones. They result from gelifluction flow in a non-uniform sheet.

Their scale and form is variable since, as a morphological category, they include both relatively large features which are of Late Glacial age and formed over a long period, smaller features which in some cases, although of apparently recent origin, are inactive today and finally others which are being formed at the present day only at the highest altitudes in Snowdonia. Although the division of major from minor features is subjective in our classification, the general scale of lobes is sufficiently small to give preference to their grouping in the latter category. The larger stone-banked lobes are generally terrace-like with multiple lobed fronts of lengths along the contour up to 100 m. and downslope lengths of some tens of metres, and with their frontal banks about 1 to 3 m. in height. The recent and contemporary features are generally much smaller, with lengths along the contour of up to ten metres, downslope lengths of up to the same order and frontal banks usually not exceeding about 0·5 m. Most of the small scale features of this type found in Snowdonia do not appear to be active at present as the frontal imbricated stone banks are moss and lichen covered. However, active examples formed on unvegetated or sparsely vegetated terrain are to be found near the summit of the highest peaks. Many of the recent or active lobes have a very high stone content and are almost pure stone lobes rather than simply stone-banked lobes, as is the case with the lobate forms produced in a collapsed medieval wall on Y Llethr at c. 670 m. (2,200 ft.), 661258, (Goodier and Ball, 1969). A general morphological characteristic of these features is that the surface of the lobes has a rather gentler slope than the surrounding ground, to give a downslope step but a merging boundary on the upslope side, so that the marked breaks of slope are at the sides and especially the front of the feature. Stone-banked lobes can be considered, although they are of much smaller scale, as having some affinities to gelifluction terraces (A4).

Such features, named as "lobate soils (steps)", by Hamelin and Cook (*op. cit.*, p. 155) have been described elsewhere under the name "stone garlands" (e.g. by Sharp (1942) from the Yukon). Galloway (1961a) has illustrated impressive stone-banked lobes from Cuidhe Crom, Lochnagar, Aberdeenshire, Scotland, which he attributes to past periglacial conditions. Rather larger and less lobate forms which have a general similarity to those discussed from Snowdonia have been described from Otago, New Zealand (McCraw, 1959) where the association between the features and long lasting snow patches is interpreted as showing the significance of localized gelifluction movement in the creation of lobate forms. The same author (McCraw, 1967) illustrates and discusses examples from Antarctica where lobate forms with stone scarps of an average height of 60 cm. occur on debris slopes of 8°+,

Fig. 2a

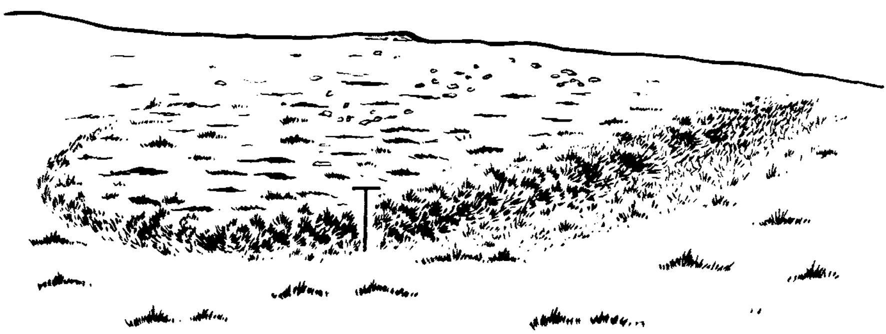

Fig. 2b

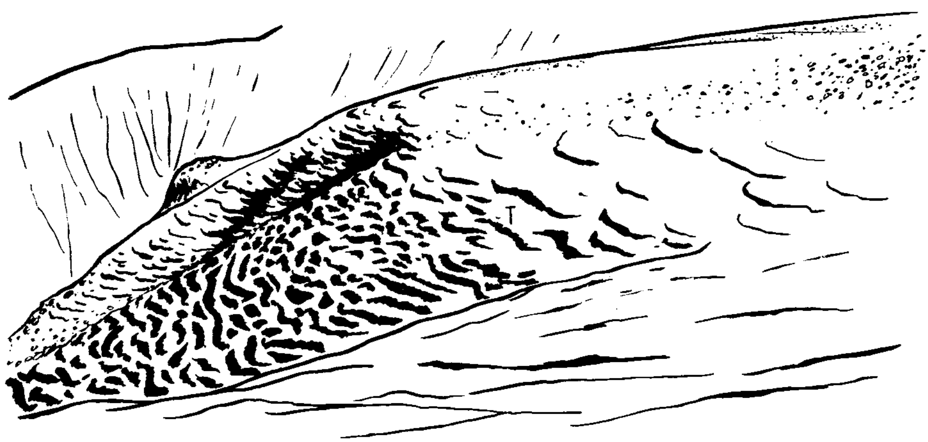

Fig. 2c

FIG. 2a.
Stone-banked lobe at 1,000 m. altitude on south-east slopes of Carnedd Dafydd, Caernarvonshire (SH 665630).

FIG. 2b.
Turf-banked lobe at 1,000 m. altitude on south-east slopes of Carnedd Dafydd, Caernarvonshire (SH 665630).

FIG. 2c.
Terracettes at 800 m. altitude on steep east facing slopes of Glyder mountain group, Caernarvonshire (SH 628608).

saturated with meltwaters from snowfields and glaciers. In Norway, Williams (1959) has also shown stone-banked lobate "terraces" to be associated with late snow patches, the stone borders being attributed to washing out of fine materials. The alternative role of cryoturbation in producing the sorted stone borders is uncertain. Active stone banked lobe formation is also described from Spitsbergen by Dutkiewicz (1967). Many good examples of large-scale relic and smaller recent and contemporary stone-banked lobate features are found on the upper slopes of the Carneddau and Glyder mountain groups, particularly on Carnedd Llywelyn and Y Garn above 835 m. (2,750 ft.).

B2. Turf-banked Lobes (Fig. 2b).

Forms of similar shape to stone-banked lobes, differing only in absence of the stone margins, are named turf-banked lobes, and occur in the Carneddau mountain group (for example near points c. 667629 and 693655 at c. 950 and 760 m. respectively (3,100 and 2,500 ft.)). In some cases they may be found to be buried stone-banked lobes with soil, peat, and/or vegetation covers but in others appear to represent genuine cases of localized earthflow (gelifluction) without sorting of marginal stones. They can be considered as a lobate form of the more continuous terracette-like features (B3) but in the latter it is difficult to disentangle the influences on their formation of gelifluction, frost-creep, recent soil creep and treading by animals. Although the treading effect of animals certainly plays a part in formation of some terracetted slopes it is improbable that this could produce lobate forms.

In the formation of turf-banked lobes it is likely that, on a slightly uneven gentle to moderate slope, snow patches will naturally last longest in hollows so that, by greater gelifluction influence on the downslope margin of such patches, lobate structures can be built up which, though slowly mobile under suitable climatic conditions, remain essentially as units rather than merging into sheet movements (see Everett, 1967). If the frequency of freeze-thaw is not adequate to cause cryoturbation, then the sorting of stones to the borders of such lobes cannot take place through this means, although this process is not necessarily the only cause of such sorting. Williams (1959*a*) illustrates actively forming unsorted "soil tongues" of turf-banked lobe type from the Rondane area of Norway. A suggestion of Galloway from Scottish studies is that turf-banked lobes are associated with material lacking large stones. This is probably not a general explanation but the relationship between turf-banked and stone-banked lobes in Snowdonia is not clear.

B3. Terracettes (Fig. 2c).

Closely spaced, small terraced features formed parallel to the contour on steep slopes and having a characteristic scale of risers averaging 25–45 cm. in height and treads averaging 45–60 cm. in width are, on lower slopes and valley sides, generally attributed to the treading action of farm animals using regular pathways which they create along the contours (e.g. Thomas, 1959; Rahm, 1962). Although this is a reasonable general assumption, the structure of features of this type, called terracettes, is being studied in Snowdonia and elsewhere in an attempt to decide the relative physical and biotic influences in particular cases.

At high altitudes in Snowdonia where livestock numbers are generally fewer, examples of less uniformly spaced and less continuous terracette-type features which may have a natural physical origin occur on slopes of angles between about 25° and

35°. We have referred elsewhere to such terracetted ground below the stone-banked lobes of the medieval wall on Y Llethr (Goodier and Ball, 1969 and B1 above). These terracettes were attributed to gelifluction, as have been the similar "frost action small slip terraces (terracettes)" described and illustrated from an 18° slope at 700 m. on Broadlaw in southern Scotland by Ragg and Bibby (*op. cit.*). These high-level terracettes appear to differ from those more probably attributable to stock treading on the lower valley sides in having more sloping and broader treads, and forming a honeycomb pattern of small slip features rather than a closely spaced parallel pathway system. Although they are not as lobate in form as categories B2 and B3, they can most conveniently be considered here in our morphological grouping.

In the Yukon it is considered by Sharp (*op. cit.*) that heave by differential freezing beneath a vegetation cover, associated on moderate to steep slopes with a degree of orientation caused by gelifluction, can produce terracette-like forms which are there named turf-banked terraces. The problem of the origin of these features in Snowdonia is, however, less certainly resolved than are those of the lobate forms discussed above and the majority of the patterned ground forms described below.

Regular Patterned Forms

B4. Large Sorted Stripes (Fig. 3a).

It is generally considered that stone polygons and stone stripes both owe their formation dominantly to cryoturbation but that stripes form on moderate slopes where gelifluction assists downslope orientation of the frost heaved stones, while polygonal patterns occur on level ground. The scale of the stripe pattern, that is the repeat distance between coarse stone zones, is thought to depend in part on the size of available stones in the initially unsorted deposit and in part on the length of time available for soil formation.

Fine examples of large-scale sorted stripes have recently been described by Ball and Goodier (1968) from slopes at c. 450 m. (1,400 ft.) (c. 643286) west-south-west of Rhinog Fawr in Merionethshire. Their detailed structure need not be discussed again here but in summary they consist of downslope oriented bands of exposed boulders of Cambrian grit in a size range generally from 60–150 cm. (24 to 60 in.), the long axes of individual stones also having a preferred downslope orientation, separated by virtually stoneless fine earth zones in which mature podzolic soils have developed. The repeat distance for the pattern is between 5–8 m. (15 to 25 ft.).

Stripes of remarkably similar appearance and scale have been illustrated from Virginia, U.S.A., by Clark (1968). There is no doubt that both the American and the Snowdonian examples are relic features, in the Rhinogs possibly dating from a rather earlier stage in the Pleistocene than the Late Glacial (Ball and Goodier, *op. cit.*). An important point emphasized by Clark (*op. cit.*) is that if relic features are to be preserved on slopes there must have been slope stability over the post-formation period. This therefore gives evidence of the absence of any intense gelifluction subsequent to stripe formation. It is thought that the Welsh examples were protected beneath a peat cover, relatively recently removed by erosion, and it can be seen on aerial photographs that the stripes continue as sub-surface features beyond the limits of visible ground exposure.

The Rhinog examples are the only such stripes so far located in Snowdonia, and are of a scale larger than described elsewhere in upland Britain. They are, however,

Fig. 3a

Fig. 3b

Fig. 3c

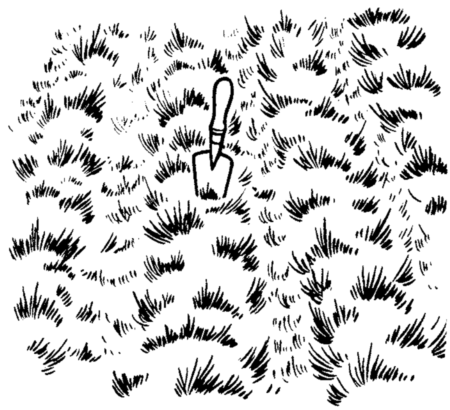

Fig. 3d

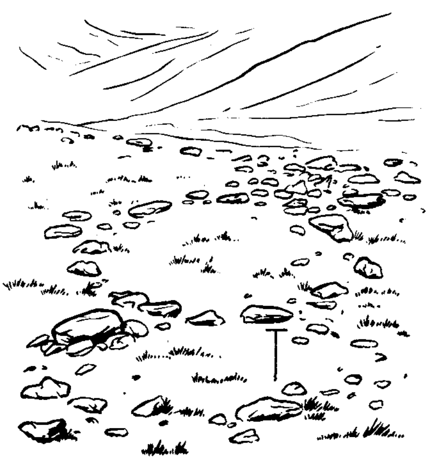

Fig. 3e

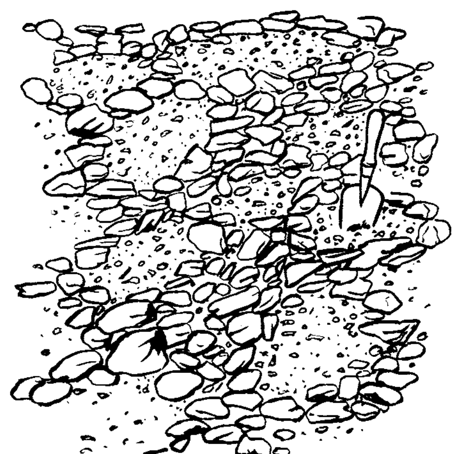

Fig. 3f

Fig. 3.

(a) Large sorted stripes at 450 m. altitude on south-west facing slope near Foel Ddu, Rhinog mountain group, Merionethshire (SH 643286).

(b) Small sorted stripes (vegetated type) at 750 m. altitude on upper south-east facing slopes of Cwm Clyd, below Y Garn, Glyder mountain group, Caernarvonshire (SH 635597).

(c) Small sorted stripes (bare-ground type), at 945 m. altitude near Foel Grach, Carneddau mountain group, Caernarvonshire (SH 690656).

(d) Small unsorted stripes at 680 m. altitude on Y Llethr, Rhinog mountain group, Merionethshire (SH 659262).

(e) Large sorted polygons at 500 m. altitude near Foel Ddu, Rhinog mountain group, Merionethshire (SH 646287).

(f) Small sorted polygons at 945 m. altitude near Foel Grach, Carneddau mountain group, Caernarvonshire (SH 690656).

of comparable size to large sorted polygonal patterns present on Scottish peaks, and similarly large stripes and polygon patterns are known as fossil features in midland and eastern England (e.g. Williams, 1964).

B5. Small Sorted Stripes (Figs. 3b, 3c).

Although one would reasonably assume that stripe patterns of a wide size range can occur according to lithological and climatic variations and the period of time available for formation, there are no well-documented or presently identified examples in Snowdonia between the large stripes near Rhinog Fawr and the widespread occurrence of patterns with average repeat distances of 45–75 cm. (18–30 in.).

To account for this discontinuity in stripe scale, we may need to postulate a third formative factor in addition to those discussed above in relation to large stripes, namely that of the depth of ground subject to seasonal freeze-thaw cycles. There is here a distinction to be made between the ground conditions of periglacial times and of the present day in the zones of frost-action in Snowdonia. True periglacial cryoturbation and gelifluction takes place during seasonal freeze-thaw and mass-flow operative in the upper horizons of deeply frozen ground. The contemporary and historically recent case is quite different. There is now a permanently non-frozen subsoil, but a surface horizon, of depths to a maximum order of 20–30 cm. at the present day, which probably remains frozen continuously for a few months every winter but which each autumn and spring passes through one or perhaps more freeze-thaw cycles. There have been no observations of soil temperature in Snowdonia to determine how the temperature regime in areas of active stripes differs from that found in otherwise closely similar topographic and lithological situations which do not have patterned ground. Such observations pose difficulties of instrumentation, observation and cost but they would be valuable in removing some of the speculative views on the conditions for formation of active patterned ground in the region. Caine (1963) considered formation of stripes to depend in some cases not only on frost-action and pointed out that he had recorded fifty occurrences of active stripes in the Lake District compared to only 14 occurrences of small active polygons, suggesting that preferential water flow in the summer probably assists in developing and maintaining stony stripe patterns.

Goodier and Ball (1969) have recorded moderately sorted small stripes on steep (25–30°) slopes of south-easterly exposure on Y Llethr (c. 661258) in the Rhinog mountains of Merionethshire. Elsewhere in Snowdonia, good examples of small sorted stripes are found near the crest of a ridge leading to Y Garn above Cwm Idwal in North Snowdonia (632598, c. 760 m. (2,500 ft.)) (Fig. 3b) and on Moelwyn Mawr, Merionethshire. Both these examples can be distinguished on aerial photographs at a scale of 1:10,000. The stone stripes contain exposed bare stones of 10–30 cm. general size range but the depth to which sorting extends is quite shallow, of the order of 15–25 cm. The fine earth zones consist of very open structured porous soil, with vegetation cover. The most active stripes are readily recognized by the ease with which a soil auger (or other rod) can be pushed into the raised vegetated zones. The stripe patterns are maintained when these zones are puffed up by seasonal needle-ice formation. This can lead to thrusting upwards of stones which subsequently slide down the sides of the raised ridges into the troughs. The average height difference between fine-earth ridge and stone trough is between 15 and 30 cm. The rather unstable surface created by the loose fluffy structure of the vegetated zones and the bare stone lines separating these ridges increases the susceptibility to erosion of steeper striped ground slopes under a grazing regime. The results of this can be seen in the extension of eroded re-sorted stony ground into the area of the stripe pattern on Y Garn. Sorted stripes can also occur on ground devoid of vegetation, for example in association with the polygon areas described below (B8) (Fig. 3c), and on slaty screes.

Numerous other areas of active small sorted stripes have been found in Snowdonia at heights above 500 m. (1,750 ft.). It is impossible to say whether they have remained active continuously or whether they have active and quiescent years or periods of years according to annual and periodic temperature fluctuations. It is probable that small stripes on steep slopes would not remain as totally inactive features for a long period before disappearing, although stripe patterns which are no longer active may be preserved on gentler slopes (see B6).

Small sorted stripes are probably the most widely described contemporary frost-action features in the British mountains (e.g. Hollingworth, 1934; Hay, 1936; Miller, Common and Galloway, 1954, and Caine, 1963) and they occur widely in other mountain areas, such as in Czechoslovakia (Sekyra, 1961). Pearsall (1950, Fig. 9, p. 28) shows diagrammatically the general character of sorted stripes with reference to small active features but does not emphasize that active frost heaving can occur on vegetated stripes, as in the Snowdonian examples.

B6. Small Unsorted Stripes (Fig. 3d).

Parallel stripe patterns, of similar scale to the small sorted stripes, occur in which the pattern is due entirely to relief and vegetation differences without any marked sorting of the mineral material into alternate finer and coarser textured zones. The surface features and internal characteristics of such a stripe pattern have been described by Goodier and Ball (*op. cit.*) from a 15–25° slope at about 640 m. (2,100 ft.) on Y Llethr in the Rhinog mountains, Merionethshire. These stripes, which have a pattern of vegetation cover accentuating the underlying relief difference, are believed to have been formed in relatively recent time (between the sixteenth and eighteenth centuries) when stone-banked lobate features developed from a medieval wall on the same site (see B1). They are apparently inactive today, in contrast to the sorted stripes with more broken vegetation cover and thinner organic surface horizons found on steeper slopes at similar altitudes elsewhere on the same mountain.

Why unsorted stripes form is not obvious, since those on Y Llethr contain suitable stones to create stone lines. The literature is not clear-cut on this issue either, for although both Washburn (1956) and Hamelin and Cook (*op. cit.*) indicate that unsorted stripes have alternate vegetated and non-vegetated bands this is not found to be the case in North Wales (however this may be because the examples here are inactive) and, according to Lundqvist (*op. cit.*), this characteristic is also rare in Scandinavia. In general, unsorted stripes seem to be formed on vegetated moderate slopes where there is a high proportion of fine material in the soil, but this is a broad situation also covering many unstriped areas and again the climatic factors are not fully understoood. It is considered by Lundqvist (*op. cit.*) that unsorted stripes are probably the slope equivalent of the earth hummock form found on level ground; indeed Lundqvist's term, "stripe hummock" is probably a better descriptive name than unsorted stripe for the most usual form found in North Wales. Good examples can also be found near the summit of Moelwyn Mawr (659449) at about 700 m. (2,300 ft.), but they are less frequent in Snowdonia than are small sorted stripes.

B7. Large Sorted Polygons (Fig. 3e).

By analogy with large sorted stripes, polygonal features of similar scale should be found on level ground as relics of Late Glacial periglacial activity. However, although large-scale polygonal features are present on a number of Scottish peaks such as Ben Wyvis (Galloway, 1961) and the granitic mountains of the Isle of Rhum, no definite examples have been described from Welsh mountains. Above the area of large stripes described previously from near Rhinog Fawr (B4), there is a suggestion on gentler slopes of polygonal patterning of 6–10 m. (20–30 ft.) average diameter. These features are not fully convincing even in the presence of the stripes and require more study than they have yet received. The category is included here as one of which traces are thought to occur and of which better examples probably remain to be found.

B8. Small Sorted Polygons (Plate 1b, Fig. 3f).

The presence of small-scale sorted polygons associated with stripe patterns in Snowdonia was recorded by Pearsall (*op. cit.*) from nearly level ground between Foel Grach and Carnedd Llywelyn (c. 690654, 945 m. (3,100 ft.)). He described them as consisting of central areas of mud associated with small rock detritus, surrounded by polygonal boundaries of larger stones. Subsequently, Tallis and Kershaw (1959) reported that the patterned ground showed rapid re-arrangement due to the redistribution of coarse and fine materials by the erosive influence of wind and rain, even in the summer season.

We have examined this area over several seasons. The general vegetation of the summit ridge is of *Juncus squarrosus* with *Festuca ovina*, but unvegetated bare areas of almost level ground occur ranging in size up to the order of 850 m^2. Mosses form a thin cover at the margins of these bare areas which expose mixed size range stony material. In this material, cryoturbation has, through sorting, developed patterns which vary in shape from well defined polygons, through elongated polygons, to rather sinuous sorted stripes (see Fig. 3c) of, in each case, a scale of repeat distance of the general order of 30–45 cm. (12–18 in.). Pearsall (*op. cit.*) says that the polygons become stripes "as soon as the surface acquires an appreciable slope". Observations suggest that the relationship between slope and pattern at this site is not simple. It has recently been possible to initiate quantitative study of the main area of these polygons and stripes, including their distribution and their relation to ground slope, through the work in 1969 of a survey party from the Department of Geography, University of Reading, led by Drs. J. Hardy and J. Whittow.

Our information suggests that the patterns are in general now more stable than was found during the observation period of Tallis and Kershaw (*op. cit.*). During the 1968–1969 winter the ground became frozen at this site to a depth of from 20 to 30 cm. in late November and remained so until March. Active cryoturbation could only take place in the periods shortly before and after the period of permanently frozen ground. A sample 2 m. square area of polygonal patterned ground was dug over, broken up and uniformly mixed after several weeks of hard freezing. At this time the frozen surface layer was between 15 and 20 cm. thick, the fine earth zones being hard frozen and the coarse zones dry and loose with only non-cementing ice skins on individual stones. The depth of sorting of coarse from fine material in these patterns was of the same order as that of the freezing, restricted to a maximum depth of about 20 cm., with immediately below this depth a continuous horizon of gritty loam comparable to that of the fine earth zone. In June 1969 after the opportunity of cryoturbation only during the one spring, the disturbed area showed a crude commencement of sorted polygon formation though not the sharp distinction of fine and coarse zones found on the adjacent undisturbed control plot. The course of development of this plot will be followed.

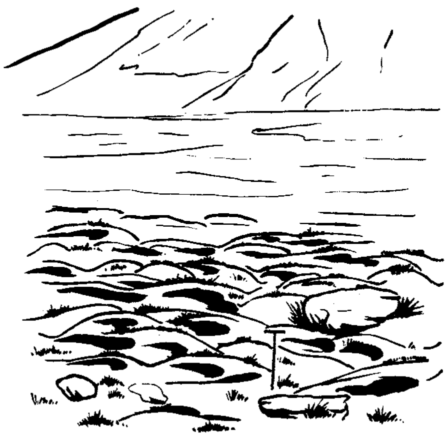

Fig. 4a

Fig. 4b

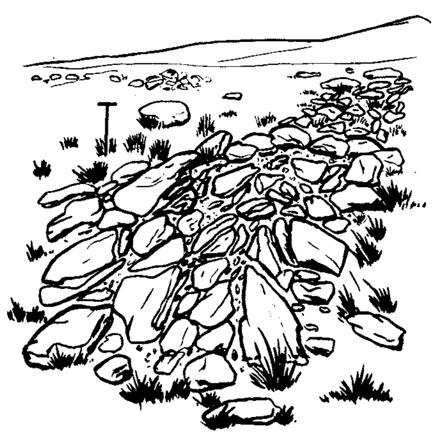

Fig. 4c

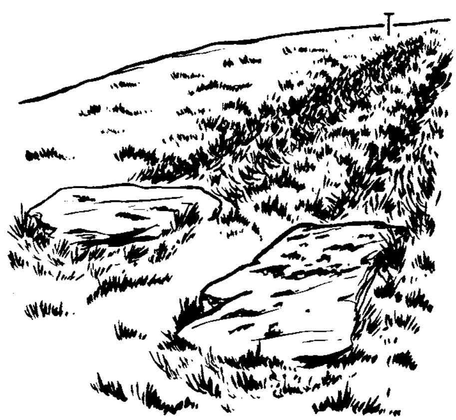

Fig. 4d

Fig. 4a.
Earth hummocks on polygon area at 945 m. altitude near Foel Grach, Carneddau mountain group, Caernarvonshire (SH 690656).
Fig. 4b.
Stone pit at 970 m. altitude on Foel Grach, Carneddau mountain group, Caernarvonshire (SH 689659).
Fig. 4c.
Stone lens at 450 m. altitude on Foel Ddu, Rhinog mountain group, Merionethshire (SH 634286).
Fig. 4d.
Gliding blocks at 680 m. altitude on north-facing slope of Y Llethr, Rhinog mountain group, Merionethshire (SH 661261).

It is of interest that the ridge of Gledrffordd (see A2), immediately east of the polygon site but at a lower altitude, c. 750 m. (2,500 ft.), shows no sorting developing on its bare, stony detritus surfaces. It can be suggested, therefore, that the present climate in Snowdonia is only just able to produce patterned ground on suitable level sites at the highest altitudes, although active sorted stripes can form on slopes at lower altitudes.

Other good examples of active polygons have not been recorded in our study area but they are a widespread feature in present day frost-climate regions, very similar polygons being described from Spitsbergen by Dutkiewicz (*op. cit.*), and from the Carpathian ridges in Czechoslovakia by Sekyra (*op. cit.*).

Irregular Forms

B9. Earth Hummocks (Fig. 4a).

The term earth hummock was used by Sharp (*op. cit.*) to describe "low rounded knobs of fine material covered by . . . (vegetation)" in the Yukon, where they occurred on tundra slopes and flats. The description has also been employed in Scandinavia (Lundqvist, *op. cit.*), in Canada by Hamelin and Cook (*op. cit.*), and, under the variant of "frost-hummocks of grass-covered type with mineral soil centres" by Williams (1959*a*). Earth hummocks average 15–25 cm. in height above general ground surface and 40–100 cm. in diameter. The term is synonymous with the Icelandic name thufur or thurfur but is more self-explanatory in English and therefore preferred here. G. Beskow quoted in Lundqvist (*op. cit.*) suggested a mode of formation which is widely accepted. If there is local micro-unevenness of ground and vegetation, the thicker vegetation gives greater protection of ground from frost. Surrounding ground freezes first and, following this, ice which penetrates beneath the unfrozen patch forces it upwards to commence a hummock formation. During winter the hummocks are frequently found to contain much needle-ice. Johnson and Billings (1962) have observed that "frost hummocks" are always associated with a seasonably high water table and suggest that their scale is connected in some way with depth to ground water, while in earlier work in Wyoming, Billings and Mooney (1959) said that degradation of earth hummock features can lead to the development of sorted polygons following initial thrusting of stones by cryoturbation through eroded hummock tops.

Earth hummock areas of the type illustrated in Lundqvist (*op. cit.* Fig. 13) and from c. 1450 m. in Czechoslovakia by Sekyra (*op. cit.*) have been observed on Scottish mountains, but they have not been seen by us in well-developed hummock fields in Snowdonia. Scattered earth hummocks can however be seen on the Carneddau and Glyder summit ridges. On a few of the areas of small sorted polygons previously discussed (B8) from the Carnedd Llywelyn-Foel Grach ridge (c. 690654, 945 m. (3,100 ft.)), a probable variant of the earth hummock has been noted as particularly well displayed in the spring after thaw. Here small moss-covered hummocks which have a fine earth core are found with patches of bare ground between them.

B10. Stone Pits (Fig. 4b).

Roughly circular patches of bare ground, typically from 30–100 cm. in diameter, consisting of stones, many of which show a trend towards vertical orientation of their long axes, within generally vegetated ground cover, are described here as stone pits. These features are those discussed in detail as "stony earth circles" by Williams

(1959*b*) but this name has otherwise been used as synonymous with sorted circles, the circular form of sorted polygons (e.g. Hamelin and Cook, *op. cit.*). Stone pits were so named by Lundqvist (1962) following Washburn (1956), and such features giving "a strong impression of a pit filled with loose stones" have been recorded by McCraw (1959, 1967) from New Zealand and Antarctica. Smith (1968) has described similar features as "boulder clusters" and has concluded that both frost-induced segregation and rearrangement of materials, and secondary denudation of fine materials by water-erosion, are involved in their formation.

As with earth hummocks, stone pits are not concentrated in our area in extensive fields, but they are not individually uncommon in the Carneddau and Glyder mountain groups in Caernarvonshire, for example near Foel Grach summit (c. 690657, 947 m. (3,100 ft.)) on slopes above the small sorted polygon zone. It is not clear what relative part is played in their formation by damage to surface cover by wind erosion (see Williams, 1959*b*), by water action as indicated by Smith (*op. cit.*), and by frost heave and sorting processes. They appear to represent smaller, but more clearly frost-heaved, forms of the features described below as stone lenses although the size range at which the two categories is divided must be arbitrary until more adequate morphological or genetic comparison is possible.

B11. Stone Lenses (Fig. 4c).

These features have much in common with stone pits but we use the term to refer to considerably larger exposures of generally ovoid or elongated shape consisting of bare stones surrounded, as are stone pits, by areas of vegetated ground with finer textured or organic soils. Typical dimensions of these areas are of the order of 30–40 m. in length and 3–7 m. in width, but gradations of size between the 30–100 cm. stone pits and this typical size range occur, as has been noted above. The transitional character of the relation between the two groups has also been recorded by Lundqvist (*op. cit.*), the stone lenses as named here appearing to be, at least in part, the features called "boulder depressions" by Lundqvist. We prefer to emphasize the morphological similarity between the two categories by the nomenclature.

Good examples of stone lenses have been noted in the Rhinog area of Merionethshire west of the large-sorted stripes discussed previously (B4), and also above the valley of the Afon Scethin in the south of the Harlech Dome at about 305 m. (1,000 ft.) near grid reference 616218. In both these cases, which are at a lower altitude than are the recorded stone pits, cryoturbation effects are less evident and they are clearly not contemporarily active features. Their formation must again have resulted from a combination of frost-sorting and water erosion and they also may represent an incomplete development of the mountain-top detritus of higher altitudes.

B12. Gliding Blocks (Fig. 4d).

When single large stone blocks rest on a sloping surface they can, by sliding on unstable water-saturated or loosely frozen ground, move downslope over the ground surface. In such movement the blocks gouge out furrows in the material along their path and eventually come to rest with a small "bow-wave" of transported material ahead of them and shallow embankments along the furrow they have created behind them. In some cases movement may have happened in one episode, in others there may be intermittent reactivation of the downslope movement. A combination of a moderate slope and widely scattered boulders is necessary to allow this movement to be unimpeded.

From Y Llethr in the Rhinog Mountains, Merionethshire, Goodier and Ball (*op. cit.*) have described the parallel movement of two adjacent gliding blocks on a 27° slope, the largest block, 1·6 m. long, having travelled a total distance of 13 m. during its period of active movement which was of unknown duration. There are many other examples of gliding blocks above the 610 m. (2,000 ft.) level in North Wales, often on slope crest positions, e.g. on the margins of the Carneddau and Glyder plateaux, and on the Moelwyn mountains. Association of gliding blocks with other frost action features supports their classification here as due mainly to gelifluction processes during seasonal thaw, perhaps initiated by lift of the block by needle-ice during freezing, with subsequent movement on thawing. Once substantial movement has taken place, the "bow-wave" of soil and vegetation ahead of the block is likely to reduce or prevent further movement.

We have suggested that movement on Y Llethr may be dated as taking place between the sixteenth and late eighteenth centuries, whether in one move, or gradually over a period we do not know, but some gliding blocks in Snowdonia are possibly moving at the present day, as has been found with similar boulders at above 450 m. (1,500 ft.) in the Southern Uplands of Scotland by Galloway (1961*a*) and by Ragg and Bibby (*op. cit.*), and in northern England (where they are described as "ploughing blocks") by Tuffnell (*op. cit.*).

C. Modification of Drift Fabric

C1. Frost-shattering, Involutions and Wedge Casts.

It will have been obvious from many preceding descriptions of physiographic features that gelifraction has been significant in providing the raw material on which gelifluction and cryoturbation can act. Holmes (*op. cit.*) points out that water on freezing expands by 9 per cent of its volume, creating pressure of the order of 141 kg./cm.^{2} (2,000 lb. per sq. in.). If therefore a rock is fissile as a result of closely spaced joints or cleavage planes, or has a porous fabric, freeze-thaw cycles can create angular shattered rock fragments. Many exposures where the surface morphology is inconclusive in deciding the origin of the deposit, show in section clear evidence of gelifraction in a passage from massive rock to a progressive degree of frost shatter and reorientation of the shattered fragments. Illustrations of such gelifraction are given by Fitzpatrick (*op. cit.*) and Galloway (1961*b*) and its influence has been particularly referred to in sections A1, A2 and A3 above.

Where cryoturbation has acted on a gelifraction deposit, in particular on one containing many angular non-equidimensional rock fragments such as scree or head derived from shale, one can find the result of this frost-heaving within a section, although again there may be no evidence on the ground surface. Involution, a term used in structural geology to describe complex overfolding, has been applied in periglacial geology to describe contortion and folding brought about in unconsolidated deposits by a mixture of frost-heave and downslope movement in a solid state, in contrast to movement as "liquid" or plastic flow. A complexity of nomenclature exists to describe the range of forms which can be included under the general category of involutions. All we wish to do here is to draw attention to the existence of folded zones with patchy vertical orientation of contained stones in deposits such as screes, for example near Cwm Eigiau, Caernarvonshire (723647), and near Esgairgeiliog, Merionethshire (754054), where the upper metre of bedded scree contained involutions (see Ball, 1964, esp. Plate 3). Crumpling or sliding downslope of previously accumulated scree or head can produce involutions and is likely to take place (Galloway, 1961*c*) under a worsening climate in which pressure differences are set up by ice masses within the deposit while lower horizons are permafrosted and the surface is without a rigid ice cover.

Wedge casts caused by the former presence of ice tongues or desiccation cracks which produced open fissures thinning downwards, that were later infilled by material differing in texture or other characteristics from the surrounding material, are also typical expressions of frozen ground phenomena which can be seen in section (and sometimes in plan view) in unconsolidated deposits. Although identified in sandy deposits of the north-west Wales coastal areas, they have not been found to be conspicuous in the uplands of Snowdonia but a well-defined example in scree near Tremadoc, Caernarvonshire, has recently been recognized and is being studied (Dr. M. Hornung, *pers. comm.*).

C2. Development of Laminated Structure and "Pinhole" Fabric in Indurated Till.

In deposits of till (or head) it is frequently found that there occurs an indurated horizon, initially hard and impenetrable to spade or auger but which, when eventually broken up, gives clods that then crumble quite readily in the hand. The characteristic fabric of this material includes discontinuous small spherical pores of "pinhole" type, and its structure is a platey or laminated one in which the structural units have longer horizontal than vertical axes. The essential characteristics of this material were recognized in Scotland by R. Glentworth and its identification as a fossil permafrost horizon was made by Fitzpatrick (1956). Fitzpatrick showed, with reference to earlier work by S. Taber, that the laminar structure and pinhole fabric could be produced experimentally by freezing a wet mass of soil. Everett (1966) in studies of frozen ground in Alaska demonstrated that formation of horizontal ice lenses or "sirloin freezing" took place in any mineral soil containing fine fractions, beneath the surface horizon in which water crystallized as needle-ice. As the "sirloin freezing" ice melted, the pore spaces between the compacted mineral material remained, becoming accentuated in successive freeze-thaw transitions to a state of structural permanence.

Such structural and fabric features, previously recorded in mid-Wales (Stewart, 1961), have been recognized to depths of several metres in drift sections in Snowdonia, for example in the "gravel pit" which is indicated on the 1 in./1m. O.S. sheet 107, on the Watkin Path leading to Cwm y Llan, Snowdon (c. 625513), and can be confidently attributed to relics of a permafrost condition during the Late Glacial periglacial period. There is no evidence for subsequent deep seasonal freezing in post-glacial time in areas of thick drift cover, while even on the highest summit areas the recent and contemporary freezing appears dominantly to give surface needle-ice rather than deeper sirloin ice freezing.

C3. Development of Downslope Orientation of Stones in Transported Till, Head and Scree.

Although there are some inconsistencies, caused for example by folding or thrusting of till sheets, it is generally true that the orientation of long axes of stones in till is parallel to the direction of movement of the depositing ice. Where either downslope flow or creep processes, including those due to frost-action, have been operative, the direction of orientation of long axes of contained stones becomes dominantly parallel to the direction of ground slope. This has been shown by Rapp (*op. cit.*) to be the case in both "talus-creep" on scree slopes and in "creeping till" or head in a contemporary periglacial environment in Norway.

By examining exposed faces of unconsolidated deposits, it is possible to measure the orientations of a large enough number of stones (probably of the order of 50 to be statistically accurate) and determine whether they have a preferred downslope orientation. If the stones are sub-angular and till derived, great caution should still be taken in describing the deposit as unmodified till if the orientation is downslope, although there are of course localities where ice movement was in this direction. Where stones are angular and result from gelifraction of local rock, as in scree and most head material, downslope orientation is useful support for other evidence for a frost-action origin of drift deposits.

Conclusion

Previous works had discussed specific results of frost-action in Snowdonia in greater or lesser detail, but no comprehensive review had been attempted. The present paper emphasizes through descriptions and a morphological classification that a very wide range of frost-action features are present, including types not previously recorded from the area. It considers correlations with other regions and, in a broad way, relates characteristics of the features to the causative processes of gelifraction, gelifluction and cryoturbation.

As has also been shown in published work from other areas of upland "glaciated" Britain, the range and distribution of these features in Snowdonia emphasizes the important role both of true periglacial conditions in the Pleistocene period, particularly in the Late Glacial, and of recent and contemporary frost-climate conditions in modifying the surface relief and the cover of unconsolidated deposits in mountain regions of Britain.

It is not yet possible to say that every type of frost-action feature in Snowdonia has been discovered, nor can we provide a comprehensive assessment and interpretation of the regional distribution of those which are discussed, but we are confident that this paper provides a framework from which further regional study and more detailed investigations of the various individual phenomena can proceed. An analysis of distribution, based on aerial photographs supported by ground survey, would help more fully to understand the causative factors by defining more accurately the localities of formation of many features. Such surveys, together with information on the contemporary climate and more detailed morphological studies of individual features, are potentially productive topics for future field work.

There is particular interest in the fact that, in spite of all the changes affecting the region through post-glacial time, it is still possible to detect, in some cases superimposed on each other, a succession of features of different periods of formation starting from stabilized relic Late Glacial or even earlier Pleistocene features, through products of temporarily harsher climates in historic time, to the important morphological effects caused near and on the summit ridges by contemporary freeze-thaw processes. This present-day frost-action emphasizes clearly the very great climatic zonation compressed into an accessible altitudinal range in Snowdonia and the scope this gives for continuation of qualitative and development of quantitative studies in the field of frost-action features and their relation to the environment, both from the point of view of their physical causes, and of their pedological and ecological effects.

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