Periglacial geomorphology of parts of the Grampian Highlands of Scotland

By

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In accordance with the University of Edinburgh postgraduate study regulation 2. 4. 15 the following declaration is made :

This thesis is composed by me and is based on my own work.

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Abstract

This thesis presents a study of a number of periglacial features of three parts of the Grampian Highlands of Scotland : the Drumochter hills, the Creag Meagaidh hills and a part of the Cairngorms.

The three areas were first studied stereoscopically on aerial photographs at c 1:25,000 scale. All identifiable geomorphological features were mapped on the basis of a comprehensive classification using appropriate symbols.

From the wide variety of periglacial features gelifluction lobes and sheets, turf-banked terraces, ploughing blocks and two types of small-scale patterned ground feature (small sorted circles and turf hummocks) were studied in detail. The gelifluction lobes were classed into three categories in terms of component material, namely debris lobes, boulder lobes and vegetation-covered small (solifluction) lobes. The three major types of turf-banked terrace are : normal terraces, lobate terraces and oblique terraces. The study of gelifluction lobes and sheets, turf-banked terraces and ploughing blocks involved (a) the investigation of relationships with altitude, aspect and hillslope angle using the Ordnance Survey 100m grid on the photogrammetrically surveyed (1:10,000 scale) maps with 10m contour intervals and (b) the investigation of morphology and structural characteristics, which was carried out in the field on a selected sample size from each type. Hillslope angle was found to be the major controlling factor for lobe and terrace distribution while ploughing blocks responded markedly to altitude. The formation and mechanism of the lobes and terraces are attributed to frost action and gelifluction activities on varying scales. Some debris lobes, vegetation-covered small lobes, turf banked terraces and ploughing blocks show some amounts of contemporary movement, while boulder lobes were found to have been preserved in relict form.

Turf hummocks and sorted circles are largely restricted to the summit areas. The study was concerned with their size characteristics and structure. The hummocks were found to be largely inactive at the present day while a superficial sorting, predominantly by needle-ice activity during the early spring was, found for the small sorted circles.

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CHAPTER 1

Introduction

1.1 Definition of periglacial and scope of study

The term "periglacial" was first proposed by W. Lozinski (1909, 1912) to describe the climate and frost weathering conditions adjacent to the Pleistocene ice-sheets and glaciers. Since frost activity and the occurrence of frozen ground phenomena are not found only in proximity to ice margins, many geomorphologists have subsequently widened the use of this term (e.g. Butzer, 1964; Dylik, 1964a, 1964b). Many have proposed its replacement (e.g. Bryan, 1946; Linton, 1969). However, since Lozinski's introduction of the concept of a periglacial zone it has been widely accepted that frost action is the most important weathering process in periglacial environments. A general treatment of periglacial conditions was attempted by Peltier (1950) who considered the periglacial morphogenetic region to be characterized by an annual average temperature of -15^{o} to -1^{o} C and an annual average rainfall of 130mm (5 inches) to 1400mm (55 inches). Tricart (1967) and Péwé (1969) considered permafrost to be the common denominator of the periglacial environment.

Now neither any quantitative parameter of climate nor the existence of permafrost is regarded as the limiting factor for identifying a periglacial environment. Washburn (1979, p. 4) identified periglacial as '... primarily terrestrial, nonglacial processes and features of cold climates characterized by intense frost action regardless of age and proximity to glaciers'. The term periglacial is employed in this broad sense in the present study.

The effect of periglaciation on the landscape of Great Britain is extremely variable. It is well established that periglacial processes operated much longer in the southern part of the country beyond the limits of Pleistocene glaciation. Geologists involved in mapping southern England and Wales in the nineteenth century reported very thick superficial deposits which were assumed to have been produced in a much colder climate. For this type of unsorted debris in Cornwall De la Beche (1839) used the term 'head'. North of the late Devensian ice limit the influence of frost action on the ground has been limited. The features that developed inside this limit on high ground during Late-glacial and Post-glacial times present a marked contrast with the head deposits of southern Britain. They include gelifluction lobes, terraces and other related slope deposits and various types of patterned ground feature. Such features in upland Britain, particularly on the Scottish mountains, began to be identified from the early part of this century by Geological Survey officers. Over the last quarter century periglacial phenomena in Scotland have received increasing attention. A systematic understanding of the effect of periglaciation in parts of the Grampian Highlands of Scotland is the principal aim of this study.

1.2 Selection of the study areas

After consulting aerial photographs and relevant literature three parts of the Grampian Highlands were selected for detailed study. These are the hills on either side of the Pass of Drumochter (56° 52'N, 4° 15' W), the Creag Meagaidh hills (56° 58' N, 4° 33' W) and a part of the Cairngorms (57° 06' N, 3° 43' W) (Fig. 1.1). The areas together cover approximately one hundred square kilometres. These areas were selected since they give reasonable accessibility to a wide variety of periglacial features. The hills of the Drumochter and the Creag Meagaidh areas constitute largely schistose rocks while the Cairngorm area is formed of granite. These geological differences offered an opportunity for a comparative study.

1.3 Aims and methodology

The aim of this study is to establish characteristics of

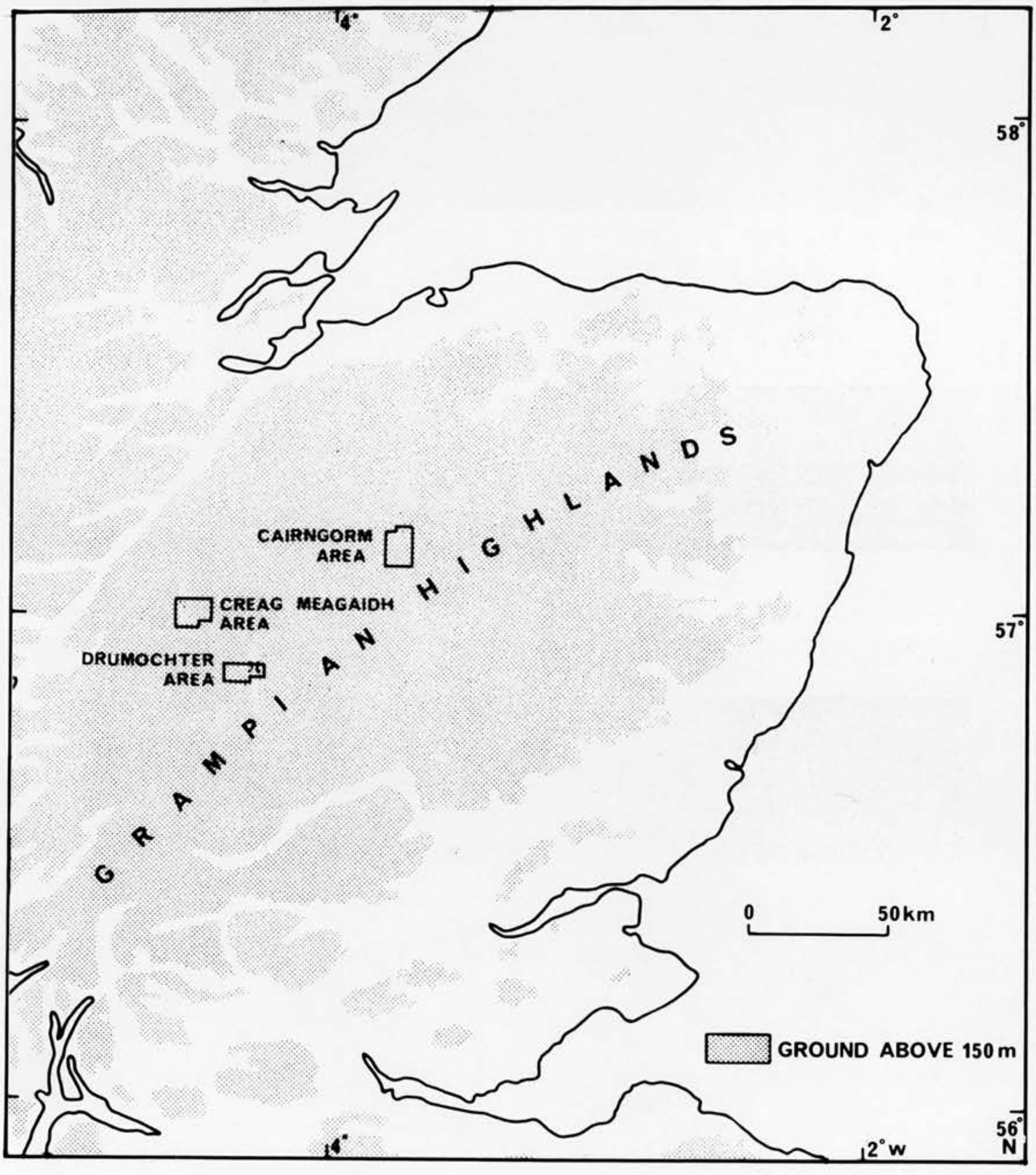


Fig. 1.1 Locations of the study areas.

past and present periglacial landforms, processes and environments in the three sample areas of the Grampian Highlands. More precisely it is concerned with : (i) the range of periglacial phenomena in the study areas and their classification, (ii) the distribution of periglacial landforms and their environmental controls and (iii) past and present periglacial processes and the possible age of the related landforms and deposits.

The initial investigation of the areas was based on aerial photographs at c 1:25,000 scale using a mirror stereoscope with low and high magnification. The first field season was devoted almost entirely to the mapping of geomorphological features. A comprehensive classification of the periglacial features was adopted. The classification was generic, being based on morphology and other surficial characteristics. Among the widely varied periglacial features four major forms, namely gelifluction lobes and lobate sheets, turf-banked terraces, ploughing blocks and two types of patterned ground feature (small sorted circles and turf hummocks) were selected for detailed study. The features were first surveyed in the field to relate morphology and environment and then the structure in each case was investigated by digging trenches and subsequently analysing constituent materials. In order to understand the present-day activity of movement through the lobes and the terraces measurement sites were installed on the Drumochter hills in the first field season (May-September, 1978). A number of sites were also installed for the recording of ploughing block movements in this area on varying slope angles. Movements of the lobes and the terraces were recorded twice a year, in the early summer and the late summer during the period 1979-80. Movements of the ploughing blocks were recorded annually, in the late summer, during the same period.

SECTION I BACKGROUND OF THE STUDY

CHAPTER 2

Climatic changes in Scotland in the Lateglacial and Flandrian

2.1 Introduction

Scotland underwent pronounced environmental changes during the Late-Devensian and Early Flandrian. The major part of this chapter is a discussion of the published literature on environmental evolution in Scotland, with special reference to the Grampian Highlands, from the time when the last ice-sheet reached its maximal extent to the beginning of the Flandrian. It was during this time that the present periglacial landscape was mainly fashioned. The minor part of the chapter is concerned with the Flandrian.

2.2 Lateglacial climate

At the height of the Late-Devensian glaciation, between 17,000 and 20,000 years ago, the Grampian Highlands were submerged beneath an ice-mass of at least 1,000m in thickness which is considered to have extended as far south as Holderness (Penny *et al.*, 1969). Very little is known about the temperature over the Scottish Highlands or of other parts of Great Britain at this time of maximum glaciation. Fossil ice-wedges found in East Anglia and in other parts of the English lowland are of special value as an indicator of past climatic conditions. Following Péwé (1962, 1966), Williams (1975) suggested that mean annual temperature was no more than -8° to -10° C when the ice-wedges formed. From the evidence of the European ice-wedges much lower late-glacial temperature has been suggested by many workers, e.g. -14° to -16° C in Denmark (Christensen, 1974), -12° to -13° C in Sweden (Svensson, 1976). Whatever may have been the exact temperature in Britain at that time it can be accepted that a very low temperature permitted the occurrence of extensive permafrost throughout the country. The evidence of the Lateglacial and Early Flandrian climatic changes in the Scottish Highlands, as elsewhere in Europe, has been deduced from the study of biostratigraphic, lithostratigraphic and geomorphic changes (e.g. West, 1968; Iversen, 1973).

There is a general agreement that within north-west Europe the Late-Devensian glaciation was followed by a marked climatic amelioration at about 13,000 years B.P. (Mangerud et al., 1974; Coope, 1977; Gray and Lowe, 1977; Berglund, 1979). If the radiocarbon dates are correct, the ice in Scotland had retreated from the Lockerbie area of the Southern Uplands and from the Loch Droma area of the

North-West Highlands by a little after 13,000 years B.P. (Bishop, 1963; Kirk and Godwin, 1963), while the Spey Valley in the vicinity of Abernethy Forest was free of ice by 12,700 ± 270 yr B.P. (Vasari, 1977). A very similar radiocarbon date of 12,750 ± 120 yr B.P. was obtained from the Tynaspirit basin near Callander (Lowe and Walker, 1977). The basal organic deposits of Loch Etteridge in the central Grampians gave a date of 13,151 ± 390 yr B.P. (Sissons and Walker, 1974). These findings are in agreement with the view that around 13,000 years ago large areas, if not all, of the Grampian Highlands were free from glacier ice. However, basal radiocarbon dates have certain limitations (Sutherland, 1980) and it is possible that deglaciation was somewhat later.

Coope and Brophy (1972) and Coope (1977), from the study of coleopteran remains from North Wales, in association with radiocarbon dates, inferred that, at about 13,000 years B.P. an intensely cold continental climate suddenly gave way to a period with summer temperatures as warm as those of the present day or slightly higher, a mean July temperature of 17° C being proposed for lowland Britain. They also maintained that this value of 17° C declined to about 12°-13° C by the end of the Lateglacial Interstadial. The present sea-level temperature difference between the central Grampians and the English Midlands is 1.4° C (Walker, 1975a). On the higher ground of the hills and plateau surfaces of Scotland, however, conditions would have been more severe and, therefore, interstadial highland temperatures would have been considerably below those proposed for the English Midlands. Bishop and Coope (1977) also constructed a curve of mean July temperatures throughout the Lateglacial for South-West Scotland based on coleopteran evidence. The curve shows that around 13,000 years B.P. the mean July temperature of the South-West was about 15° C, which is similar to the present value.

Before the publication of a radiocarbon date of 12,810 ± 155 yr B.P. with a pollen diagram from the organic layer in the sediment of Loch Droma in northern Scotland (Kirk and Godwin, 1963) there was a misconception that most of northern Scotland was occupied by glacier ice until the end of the Loch Lomond Stadial. Since 1963 lake sediments have been investigated in many locations in or near the Scottish Highlands, either by cores obtained from open water (Pennington and Lishman, 1971; Pennington *et al*., 1972; Birks, H. H., 1972; Pennington, 1977) or by peat boring through the marginal infill of lakes or into the deposits of completely infilled lakes (Birks, H. H., 1970; Birks, H. J. B., 1973; Walker and Lowe, 1979a, 1979b).

Pollen and diatoms provide evidence for the existence of terrestrial and aquatic biota before 13,000 years B.P., and a change in sediment composition at about this date denotes the end of permafrost on low ground at least.

The thinning and retreating ice, during the declining stage of the Late-Devensian glaciation, exposed much of the Grampian Highlands for rapid colonization by heaths typical of open habitats (e.g. *Rumex* and *Artemisia*) of steppe or tundra affinities (Walker, 1975a; Lowe and Walker, 1977) with large areas of relatively unstable bare ground. The stratigraphy and composition of the basin sediments of Loch Ettridge (Walker, 1975a, 1975c) indicate that there was a progressive stabilization of the central Grampian landscape as the Lateglacial progressed. The initial vegetation partly gave way to *Betula* and *Juniperus*, which are characteristic temperate flora. This change is much more pronounced in pollen diagrams from Blelham Bog and Low Wray Bay (Windermere) in the Lake District published by Pennington (1975a, 1977), who assigned the period between 13,000 and 12,000 years B.P. to a 'Bölling chronozone'. It has been suggested (Iversen, 1954) that the presence of *Betula pubescens* in local flora implies a mean July temperature of at least 12° C. The microfossil records of this species from Abernethy Forest and from Skye (Vasari, 1977; Birks and Mathewes, 1978) and also the development of tree birch copses in many areas of Scotland during the Lateglacial Interstadial (Gray and Lowe, 1977) indicate that temperatures of about or in excess of 12° C were maintained long enough to permit the immigration of tree birch (Lowe and Walker, 1977).

Pennington (1977) also advocated a second part of the Lateglacial Interstadial corresponding with the 'Allerød chronozone' (11,800 - 11,000 years B.P.) which was separated from the former by a short cold episode (12,000 - 11,800 years B.P.), equivalent to the Older Dryas. This last was recorded by a reduction of pollen production by woody plants and by a temporary increase in the rate of soil erosion, but Pennington said that there was no renewal of deep periglacial weathering during this short period.

The Allerød chronozone or the second part of the Interstadial has been identified by Pennington in northern Scotland. She investigated nine lakes from the Great Glen northwards and inferred slight climatic warming from the maximum rates of characteristic pollen taxa deposition in the sediment profiles. Palaeoecological studies at Abernethy Forest (Birks and Mathewes, 1978) demonstrated vegetation changes from grass-sedge to Empetrum associated with climatic warming during Allerød time.

The close of the Lateglacial Interstadial is rather problematic. A most likely boundary for this has been placed by many workers at or about 11,000 years B.P. (Mangerud et al., 1974; Pennington, 1975a; Gray and Lowe, 1977; Berglund, 1979). It has been shown that the Allerød interlude was terminated as oceanic polar water spread southwards once again to reach the latitude of south-west Ireland (Ruddiman et al., 1977) or as far south as the Bay of Biscay (Duplessy *et al*., 1981). The associated cold period, approximately equivalent to the Younger Dryas of Scandinavia (between 11,000 and 10,000 years B.P.) is the Loch Lomond Stadial in the British Isles (Sissons, 1979d). The mean July temperature curve for the Lateglacial constructed by Bishop and Coope (1977) for South-West Scotland from coleopteran evidence shows a marked deterioration, possibly in two steps, which culminated in a Loch Lomond Stadial July temperature of 8°-9° C.

The Younger Dryas or Loch Lomond cold episode, when glacier ice developed again in many corries and valley-heads and on some plateaux in Scotland, is characterized biostratigraphically by *Artemisia* pollen. Relatively high values of *Artemisia* have been recorded over a considerable part of the Highlands during this cold spell (e.g. Vasari and Vasari, 1968; Pennington *et al*., 1972; Birks and Mathewes, 1978). The rapid change in vegetational communities coincided with an equally rapid lithological change to minerogenic sedimentation in Scottish lakes (Pennington, 1975b, 1977). In lakes outside the limits of glacial advance but sufficiently close to glaciers to be supplied with turbid glacial materials, such as Loch Maree, Ness and Stack, varved sediments accumulated.

Pollen diagrams from the Loch Etteridge site of the central Grampians (Walker, 1975a, 1975c), the Upper Spey Valley (Macpherson, 1980) and eastern Scotland (Walker, 1975b; Lowe and Walker, 1977; Caseldine, 1980) all show high values of Artemisia and Rumex, and demonstrate that during the stadial temperatures were far below those of the present day.

Although the pollen zonation systems are climatically based, it remains difficult to employ them to describe past climate except in general terms. Some quantitative evidence of climatic changes during the Lateglacial, particularly for the Loch Lomond Stadial, comes from non-botanical sources, for example the record of cirque glaciers (Colhoun and Synge, 1979), lithostratigraphic evidence of erosion and solifluction (Craig, 1978) and evidence for ocean surface temperature changes from the study of foraminifera (Ruddiman et al., 1977). The most detail information on climatic conditions in Scotland during the Loch Lomond Stadial, however, relates to the use of reconstructed firn-line altitudes for the glaciers of that time (Sissons, 1974b, 1976a, 1976b, 1980; Sissons and Sutherland, 1976).

Using this firn-line altitude method for the former glaciers, Sissons (1976a, 1980) estimated the temperature conditions in parts of Scotland during the Stadial. A mean July sea-level temperature of about 7.5° C and a January value no higher than -9° C were suggested for the central Grampians. This implies a mean annual temperature range of at least 16° C, which is 50% greater than the present range. Sissons also suggested that the mean

January temperature on the high ground was no higher than -17° C. In association with these low temperatures permafrost extended once again down to sea level, its existence being indicated by fossil frost-wedges (Sissons, 1974a, 1980). At the same time the firn-line rose markedly from west to east, from below 300m in Mull to about 1,000m in the northern Cairngorms.

It was also inferred from the equilibrium firn-line altitudes and relative dimensions of Loch Lomond glaciers in Scotland and the Lake District, that snowfall during that period was associated mainly with south to south-east air streams preceding warm or occluded fronts. The effect of south-west air streams was also considered, and these, in conjunction with south-east air streams, appear to have been responsible for the generation of the extensive ice-cap over the Moor of Rannoch. South-west winds were particularly important in transporting snow from high ground onto sheltered lee slopes. Sissons (1977a, 1980) has shown a steep rise in the altitude of the firn-line inland from the South-West Highlands and Sissons and Sutherland (1976) have calculated a regression surface for the South-East Grampian glacier firn-lines that shows a rise from about 500m near the Highland edge to 850m north of Lochnagar. This rise is attributed to the dominance of south and south-east winds in the provision of snowfall in this part of the Grampians. The same method was also applied to the Gaick Plateau area of the central Grampians

(Sissons, 1980) and it has been suggested that the firn-line mean July temperature of that area during the Loch Lomond Stadial was around 1.5° C. Palaeoclimatic inferences from the former glaciers in the north-western Cairngorms (Sissons, 1979a, 1980) and in the Creag Meagaidh areas (Sissons, 1979b) reveal that during the stadial these areas were starved of precipitation. Birks and Mathewes (1978) also inferred very low precipitation in the Spey Valley and adjacent areas from the abundance of _Artemisia_.

2.3 _Postglacial climate_

There is ample evidence that the Loch Lomond cold episode was followed by a dramatic recovery of climate (e.g. Coope _et al_. 1971; Pennington _et al_., 1972; Walker, 1975a, 1975b, 1975c, 1977; Pennington, 1975a, 1977, Gray and Lowe, 1977; Walker and Lowe, 1977, 1979a). This further change in the Scottish environment is evidenced by lithostratigraphy and biostratigraphy in many parts of the country. The sudden termination of the harsh stadial climate is normally recorded by an abrupt change from minerogenic to organic sediment accumulation and by a sharp fall in the percentage of deteriorated pollen (Pennington, 1975b, 1977). This climatic change has been linked with changes in the prevailing wind circulation pattern over the continent of Europe (Lamb, 1977a, 1977b) and with the retreat of polar water (Ruddiman *et al*., 1977).

The coleopteran assemblage from peat from Brighouse Bay dated 9,640 ± 180 yr B.P. (Coope *et al*., 1971) shows that the climatic recovery, following the Loch Lomond Stadial, was very rapid, mean July temperature in South-West Scotland quickly rising to the level of the present day or even slightly higher. From the study of the Scottish Lake-deposits Pennington (1977) concluded that the deposition of mineral sediment ceased by 10,400 years B.P.. A similar radiocarbon date recently obtained from Mull led Walker (pers. comm.) to infer a time around 10,200 years B.P. for deglaciation in that area.

Pollen data demonstrate a transition to closed plant communities in Scotland resembling those of the Interstadial. The early Flandrian pollen record for Loch Etteridge (Walker, 1975a 1975c) shows fairly rapid colonization by temperate flora including *Juniperus* and later *Empetrum* in the central Grampian area. Walker considered this *Empetrum* maximum to be the characteristic indicator of progressive climatic warming. From palynological studies of three sites in Rannoch Moor in the western Grampians Walker and Lowe (1977) reached a similar conclusion, namely that after the complete disappearance of ice from that area *Empetrum* and *Juniperus* became firmly colonized. Pollen microfossil stratigraphy from Abernethy Forest (Birks and Mathewes, 1978) and several other parts of the central and southern Grampians (Lowe and Walker, 1979) also demonstrate the Flandrian climatic amelioration.

Four subdivisions, namely Boreal, Atlantic, Sub-Boreal and Sub-Atlantic, are recognized in the Flandrian. Iversen (1954) deduced that the Atlantic period was 3.5° F (2° C) warmer in summer, 0.8° F (0.5° C) warmer in the winter than now; the Sub-Boreal was as warm as the Atlantic period in summer but 0.8° F (0.5° C) colder in winter than now; in the Sub-Atlantic summer and winter averages were similar to those of today. These findings receive partial support from the evidence that in Scotland trees grew at higher altitudes than today. In the Cairngorms the maximum Post-glacial tree-line was possibly 30m (a hundred or so feet) higher (Pears, 1968).

Palynological work indicates that, following the initial rapid rise of temperature, recovery continued more slowly until it reached a level about 2° C higher than that of the present day around 7,500 years B.P. (late Boreal period) (Birks and Mathewes, 1978). Durno (1959) showed that in the eastern Grampians the Boreal-Atlantic Transition marks a change from the relatively warm and dry late Boreal period to the wetter Atlantic period. The Sub-Atlantic recession was marked by a fall of about 3.5°F (2° C) in mean summer temperature, and the uplands began to acquire most of their extensive peat cover under wet conditions (Durno, 1959, Conway, 1954).

The latest phase of the climatic deterioration that the Scottish Highlands have experienced was the Little Ice Age (approximately between 1550 and 1850). Using botanical indicators Lamb (1977b) showed that at the height of the Little Ice Age (around 1700 A.D.) the mean annual temperature was about 1.4° C lower than at present. As a result the annual depth of freezing on the high ground must have been slightly greater.

2.4 Conclusions

From the above summary of climatic changes in Scotland during the Lateglacial and Flandrian it is apparent that periglaciation in the Scottish Highlands largely corresponded with the severe climatic conditions of the Lateglacial and abated afterwards as the Flandrian progressed. Two phases in the Lateglacial probably provided an ideal periglacial climate : (i) the early phase when the hills projected for some time as nunataks above the slowly sinking ice-sheet surface and (ii) the late phase or the Loch Lomond Stadial when, owing to the return of a severe climate, glacier ice once again developed on some of the high ground, in corries and valley heads and on plateaux. Hence 'it was the fall in temperature that constituted the primary mechanism of periglacial phases in Scotland and incidentally of the glacial phases' (Galloway, 1958, p. 240). Periglacial activity during the Loch Lomond Stadial must have been severe as the temperature was sufficiently low (with a greater temperature range) and permafrost was extensive. The associated large-scale frost shattering produced extensive mountain-top detritus that subsequently moved downslope to produce major gelifluction features.

During much of the early and mid Flandrian mean temperatures in the Scottish Highlands were higher (by as much as 2^{o} C) than at present and during the Little Ice Age they may have sunk down possibly c 1.4^{o} C lower than now. This suggests that periglacial activity in the Scottish Highlands was less pronounced during much of the Flandrian than at present and that even the Little Ice Age was not harsh enough to give rise to any remarkable periglacial activity. The development of vegetation through the Flandrian influenced periglacial activity in various ways. The colonization of vegetation on sheltered risers of large gelifluction lobes inhibited mass movement and also helped the development of peat in areas of restricted drainage. Where vegetation cover is incomplete or sparse ground surfaces have remained exposed to the operation of frost creep, frost sorting, wash and deflation.

The evidence of biostratigraphic, lithostratigraphic and geomorphic changes demonstrates that severe conditions favoured periglacial erosion and deposition in ice-free areas of the Scottish Highlands up to the end of the

Lateglacial and much less severe conditions have continued to prevail on high ground ever since.

CHAPTER 3

The Study Areas

3.1 Introduction

Periglacial landforms are the product of exogenic processes under a predominantly cold climate, related mainly to temperature fluctuation and resultant frost formation, wind and rain. The scale to which these processes respond in a unit area depends on the character of its physical conditions. The aim of this chapter is to present a brief outline of these physical conditions consisting of relief, geology, glacial history, soil and regolith, natural vegetation and climate.

3.2 Relief

The three study areas are situated on a curved transect that stretches from the Creag Meagaidh hills near Loch Laggan in the west, through the Pass of Drumochter to the Cairngorms in the east. A major portion of the areas under study lies above 600m with the summits above 900m (Figs. 3.1, 3.2 and 3.3). All these three areas include pronounced plateau along with a great range of slopes from nearly flat ground to corrie head-walls at angles of 30°-70°.

The Pass of Drumochter is a spectacularly deep glacial trough in the central part of the Grampians stretching in a north-south direction. In the hills west of the pass the land rises towards the twin summits of Geal-charn (917m) and A' Mharconaich (975m) with, between, the stream valley of the Allt Coire Fhar which joins the north-flowing Truim river. Both of these summits have rolling topography descending symmetrically on all sides except for the northeast-facing corrie head-walls. The part of the study area lying east of the pass is the westernmost extension of the Gaick Plateau : here a maximum height of 916m is attained at the flat-topped summit of Meall a' Chaorainn.

The plateau surface in the Creag Meagaidh hills is rather dissected and a considerable portion rises higher than the Drumochter hills. The main Creag Meagaidh summit (1130m) falls just outside the western boundary of the study area. Within the study area a substantial part of the plateau curves round the corrie of Lochan a' Choire, the maximum altitude of 1112m being attained by an unnamed summit contiguously east of Creag Meagaidh summit. Coire Ardair, facing north-east, and Coire Choille-rais, facing south-east, both with lochs in them, provide the main drainage outlets from the plateau southwards to Loch Laggan.

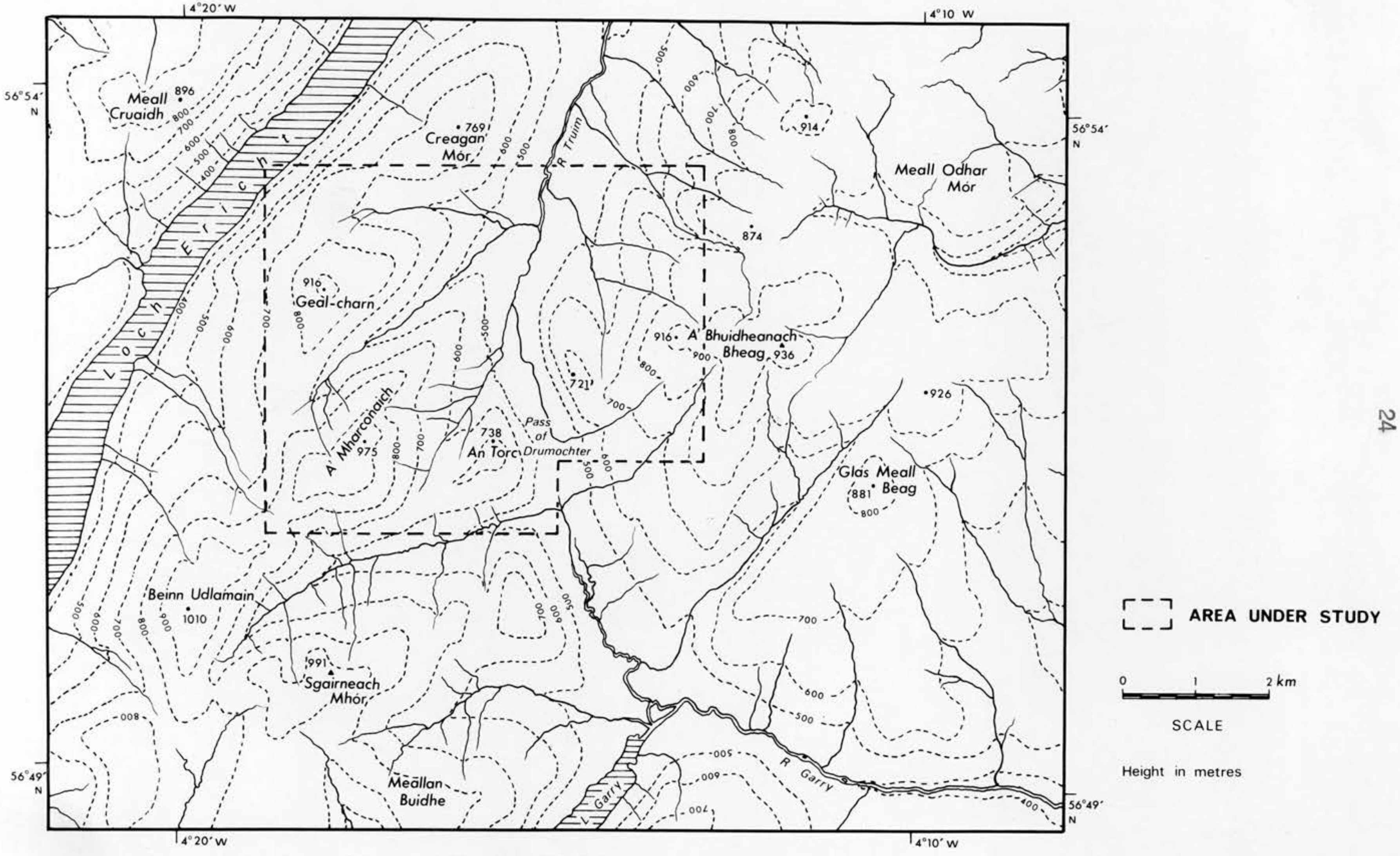


Fig. 3.1 Physiography of the Drumochter area.

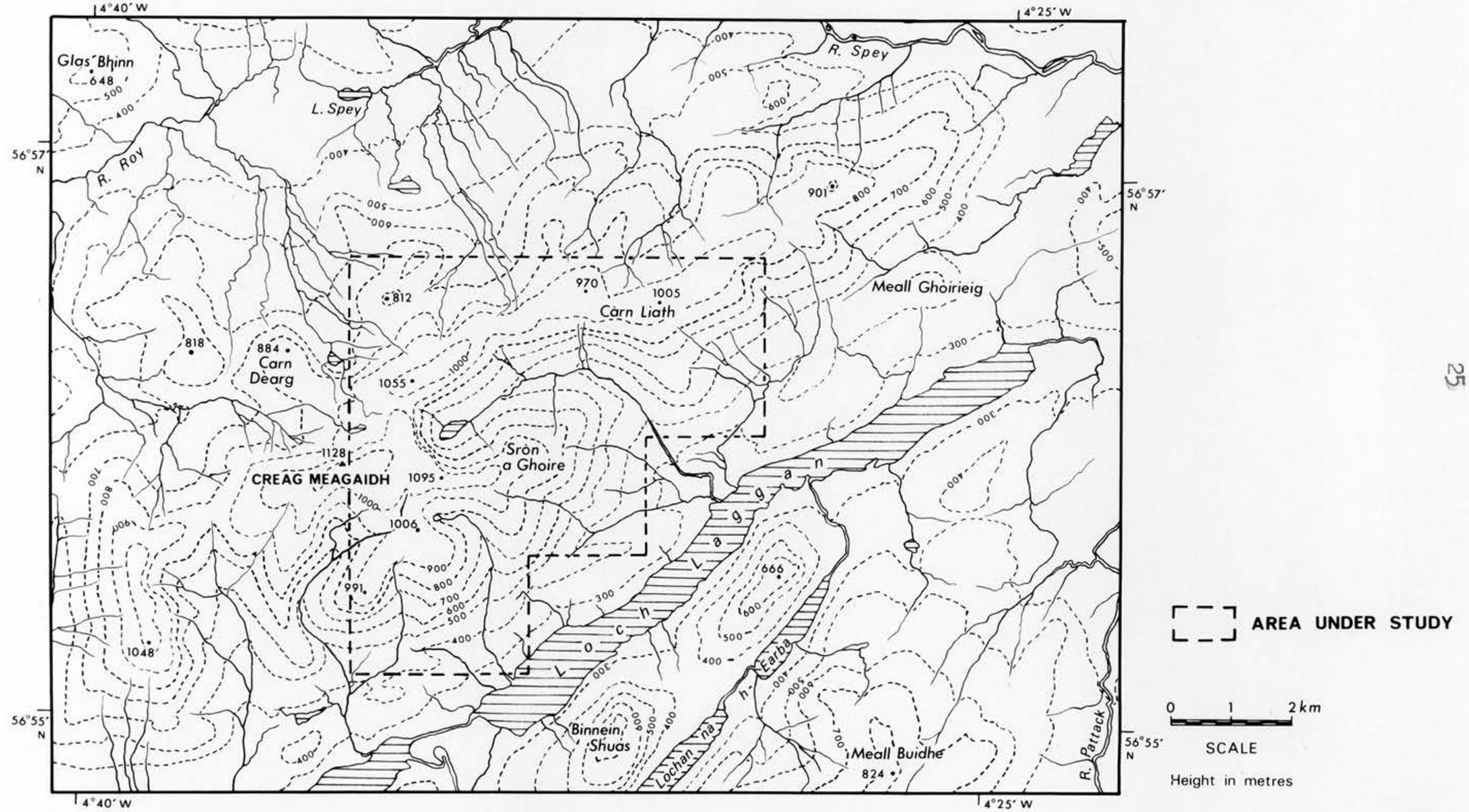


Fig. 3.2 Physiography of the Creag Meagaidh area.

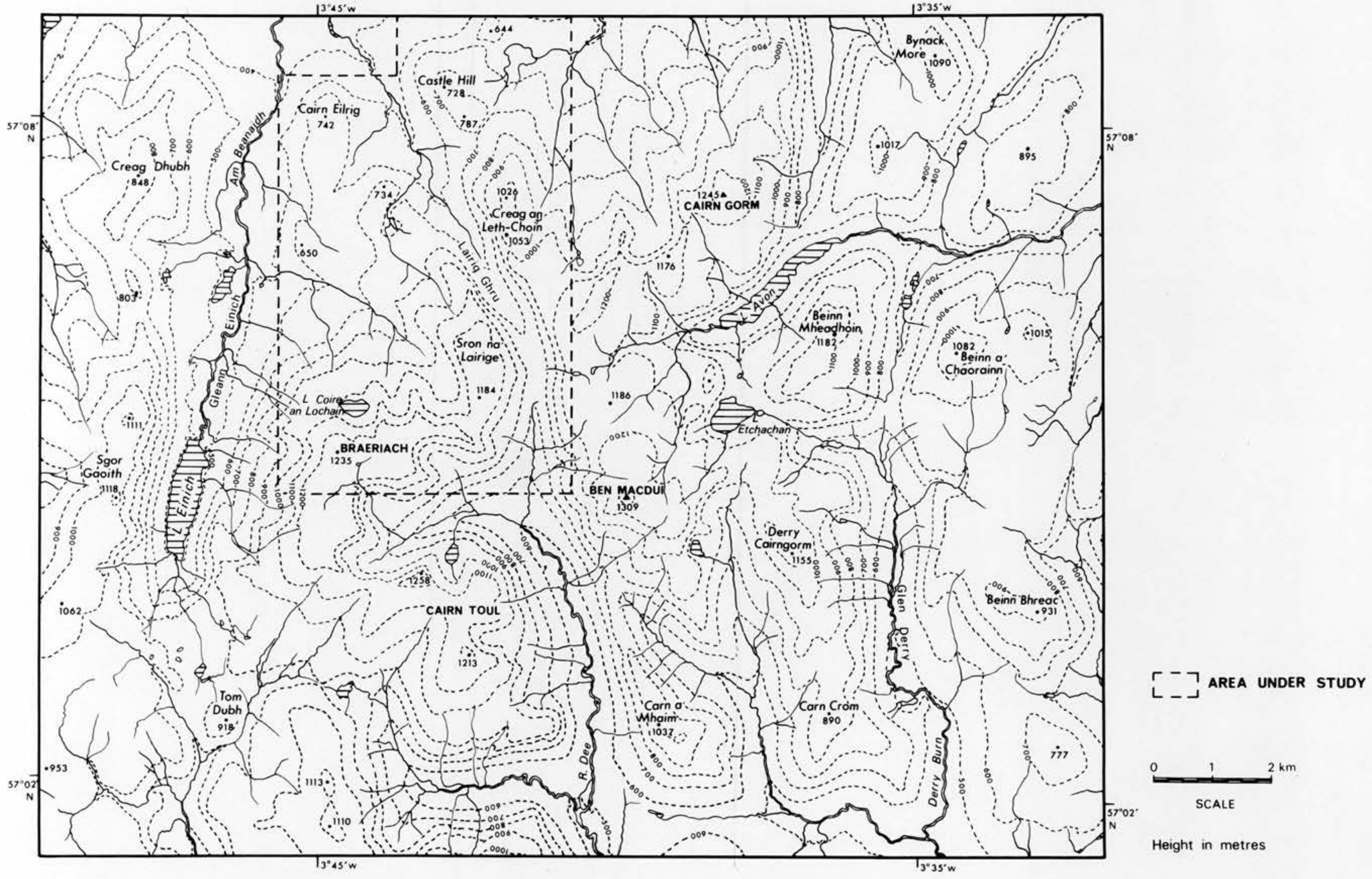


Fig. 3.3 Physiography of the Cairngorm area.

In the Cairngorms the study area includes a major part of the great massif on either side of the Lairig Ghru, a remarkably deep, narrow trough (summit of col : 823m) stretching roughly in a north-south direction. West of the Lairig Ghru the plateau rises to its maximum elevation around Braeriach (1296m) and Einich Cairn (1237m). From there rolling topography descends northwards towards the Spey valley except where interrupted by Cairn Eilrig (742m), a uniform and distinct hill. The northern face of the Braeriach massif consists of three striking corries. East of the Lairig Ghru is an extensive plateau around Cairngorm (1260m) and Ben Macdui (1309m). This plateau declines gradually northwards as far as Castle Hill (728m) and Airgoid-Meall (644m).

3.3 Geology

The Grampian Highlands, lying between the Highland Boundary Fault in the south-east and the Great Glen Fault in the north-west, are remains of the ancient Caledonian Mountain mass, formed mostly of Precambrian rocks (Fig. 3.4). Severe folding and faulting in association with periodical igneous intrusions were responsible for the present geological and structural complexity. The metamorphic Dalradian and Moinian groups (Early Orogenic) are in places intruded by massive granites (Late Orogenic). One of the remarkable characteristics of the structural pattern is substantial horizontal displacement along successive parallel faults.

The official geological map of the central-western Grampians (Sheet : 63) is yet to be published, this being a major drawback in the geological interpretation of both the Drumochter and Creag Meagaidh areas. Moreover, in the geological literature, these areas have never had more than a passing mention. For a basic geological understanding of the Drumochter area draft maps were made available by the Institute of Geological Sciences, Edinburgh.

(i) The Drumochter hills

One of Scotland's major fracture lines, the Ericht-Laidon Fault, runs along the length of Loch Ericht on the north-west of the Drumochter hills. The rocks north-west of the fault have been relatively displaced 6-8 km south-westwards (Read, 1948). South-east of this fault the geology is fairly uniform, being mainly siliceous schists and flags of Moinian origin. Quartz-biotite in the form of veins is exposed in places on the ground surface on either side of the Pass of Drumochter. They are well marked across the stream lines and crop out spectacularly in successive bands across the north-easterly spur of A' Mharconaich. Muscovite and pegmatite veins are frequent across the stream line of Allt Coire Fhàr, while quartz-

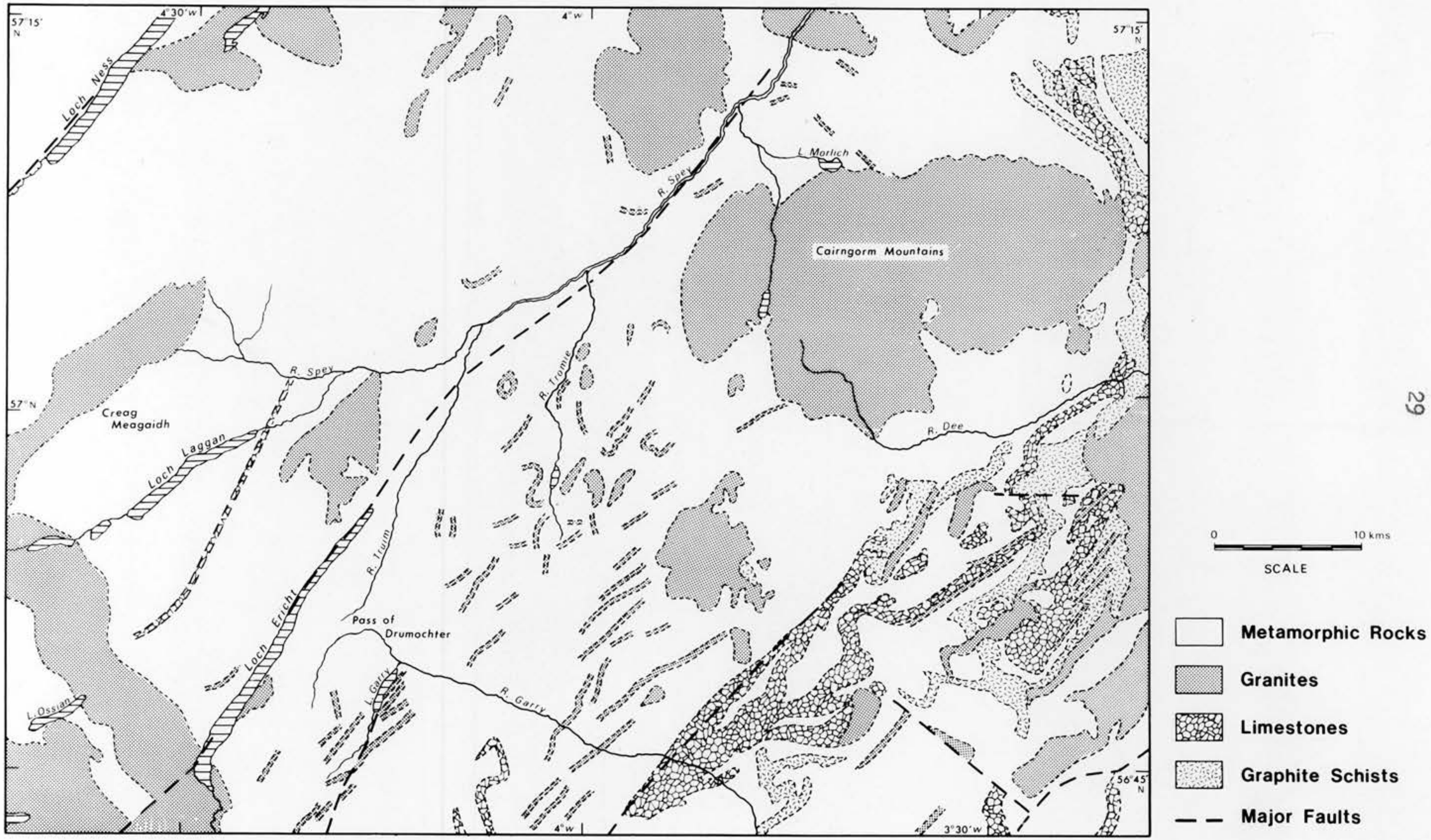


Fig. 3.4 Geology of the central Grampians.

biotite veins are scattered on the Gaick Plateau.

The excavation by the Grampian Electric Supply Company of the Garry-Ericht water tunnel through the hills about 1.5km south-west of the field area uncovered some structural details of the region (Robertson, 1939). The rocks were found to be both folded and crushed. The pattern of folding, observed from the disposition of the places of foliation in the tunnel, is apparently the result of a regional fold with a pitch of some 20^{o} in a slighly east and north-east direction. On the whole the direction of lineation is more nearly eastwards at an angle of about 10^{o} as measured by the tunnel excavation group.

(ii) The Creag Meagaidh hills

The Creag Meagaidh hills lie between the Laggan Fault and the Great Glen Fault, an area structurally close to the north-western part of the Kinlochlaggan Syncline. This forms a major fold in the Grampian Highlands traceable in a north-northeasterly direction for 30 km (Anderson, 1947). West of the Kinlochlaggan Syncline the Loch Laggan Anticline of Eilde Flags forms a broad upfold that includes Creag Meagaidh. As a part of the greater Grampian metamorphic complex the rocks have an overall similarity to those of the Drumochter area, being psammitic schists and flags (locally known as Eilde Flags) of Moinian age with occasional outcrops of quartz, felsite and lamprophyre. Exposures of igneous intrusions are conspicuous in places as, for example, on the summit of Meal an t-Snaim at the east end of the plateau where a superficially weathered quartz vein is markedly exposed (Plate 3.1). On the eastern part of the plateau the uniformity of the psammitic rocks is generally interrupted by the widespread occurrence of pegmatites. Structural inclinations have a wide range of variation (between 20^{o} and 58^{o}); on the whole the direction of inclination is nearly north-northwest in the western half and, by contrast, south-southwest in the eastern half of the area.

(iii) The Cairngorms

The Cairngorms have been surveyed by the Geological Survey (Sheets 64, 65, 74, 75) and have an adequate geological literature. The main mass of the plateau is formed of granite. This granite massif rises abruptly from the Moine Schist terrain in which it was intruded. The granite is medium to coarse grained having quartz and feldspar (orthoclase and oligoclase) as its principle constituents, together with biotite in varying quantity (Barrow et al., 1913). Two types of granite are common within the western Cairngorms, namely the Main Granite and the Porphyritic Granite (Harry, 1965). The main Granite covers nearly ninety percent of the study area and is

Plate 3.1 Exposure of a superficially weathered quartz vein on the Creag Meagaidh hills.

Plate 3.2 Hummocky moraines in the Pass of Drumochter.

formed chiefly of oligoclase (in abundance) and quartz. Muscovite occurs in rugged, apparently secondary, areas in feldspar. A small area of the west-facing slope of the Braeriach Plateau by Loch Einich is formed of Porphyritic Granite. This is distinguishable from the Main Granite by its darker colour and scattered feldspar phenocrysts on weathered rock faces. East of Loch Einich the contrast of this granite with the Main Granite is clearly displayed at a waterfall in Coire Bogha-Cloiche. Several fault lines extend from the Moinian Schist south-westwards through the Cairngorm granite mass. Secondary and discontinuous fractures have also been found within the area, but they do not create any disturbance in its structural uniformity.

(iv) Summary of geology

The selected study areas consist of two entirely different rock groups, namely foliated Moine Schists in the Drumochter and The Creag Meagaidh hills and massive granites in the Cairngorms. Diversity also exists amongst the Moine Schists which is not displayed in the simple geological map : for example, the strongly foliated schists of Drumochter contrast with the less foliated massive psammitic schists of many places in Creag Meagaidh. Hence it is conceivable that the rocks of the study areas exhibit a widely varied response to periglacial weathering and produce different types of superficial deposits. This discussion will be illustrated in the following section on soil and regolith.

3.4 Glacial History

The landscape of the Grampian Highlands came under the influence of successive glaciations during the Quaternary period. The distribution of glacial and fluvioglacial deposits, erratics and striations indicate the former existence of ice in the various areas under study.

(i) Geological Survey interpretation

The officers of the Geological Survey proposed a three-stage sequence comprising ice-sheet, valley glaciation and corrie glaciation (Hinxman *et al.*, 1923; Read, 1935). They showed that during the earliest phase of the glaciation the Moor of Rannoch formed a great ice-reservoir with radial dispersal. The Rannoch erratics, which rests on the high summits between Loch Ericht and Loch Garry, in Glen Truim and on the western part of the Gaick Plateau, led Hinxman *et al.*, (1923) to conclude that the Moor of Rannoch ice extended north-eastwards over the western part of the Gaick Plateau. They also described the path of Rannoch ice as extending in a north-east direction into the upper Spey valley and along the northern side of the Cairngorms, where it joined with the ice of the Cairngorm Mountains.

During the second period of glaciation dispersal of ice took place under strong physiographic control. In the central part of the Grampians, the valleys now occupied by Loch Garry and Loch Ericht, played an important role. Barrow *et al*. (1913, p. 93) said "... a branch of western ice, pouring from the great *mer-de-glace* of the Moor of Rannoch through the hollow of Loch Ericht, moved northwards from Dalwhinnie into the valley of the Upper Spey". It is also mentioned that this glacier was reinforced by two tributary glaciers from the west : one came from the head of the Spey and the other through the Calder valley (at the south-eastern flank of the Monadhliath). Hinxman *et al*. (1896, 1915) and Barrow *et al*. (1913) suggested that, in the Cairngorms, following the maximum of the last glaciation, valley glaciers existed in the glens and corries, these depositing enormous amounts of drift in the foot-hill areas.

In the final stage of the glaciation ice shrank into the high corries and eventually disappeared.

(ii) Recent interpretation

Quaternary studies in recent years have provided more precise understanding of the character of past glaciation in the Scottish Highlands. Penny et al. (1969) considered that during the period that the Late Devensian ice-sheet reached its maximal extent, the Grampian Highlands were submerged beneath thick ice that extended as far south as Holderness. The concept of this maximum ice-stage is in general accordance with the view of the officers of the Geological Survey who based their interpretation on the distribution of erratics and on the direction of striations. A consequence of this interpretation is that any previously generated periglacial landforms would have been removed or obliterated by the ice.

The lateglacial downwasting of ice in the Grampian Highlands has been explained by various workers (e.g. Charlesworth, 1926, 1955; Linton, 1949a, 1949b, 1951; Synge, 1952, 1956; Donner, 1957, 1962). Charlesworth described the character of glacial downwasting in the Scottish Highlands based on his own field work and that of Geological Survey. He said that, following the period of ice-sheet maximum, outlet glaciers moved through the glens and the valleys. He mentioned the existence of an extensive glacier in the Spey Valley and described it as an outlet glacier of the Rannoch ice-mass : "... it was about 100 miles (160km) long - had its root far to the west : ice poured through the upper Spey, Loch Ericht, Loch Garry and Loch Laggan, and from nearer sources of the Cairngorms and the hills about the upper Spey" (Charlesworth, 1955, p. 813). If such was the case both the Drumochter and the Creag Meagaidh hills would have been surrounded by confluent glaciers at that time.

Fluvioglacial deposits and meltwater channels are, by far, the most important indicator of the downwastage of former ice. Many valleys in the central and the eastern Grampians are flanked by fluvioglacial deposits. Strathspey exhibits the most extensive deposits of this type, including terraced outwash plains, esker systems and lake-filled kettle holes (Sissons, 1976a; Young, 1974). The study of the Cairngorm drift deposits led Bremner (1929), Linton (1949, 1951), Charlesworth (1955) and Sugden (1965, 1970b) to put forward the explanation that, following the maximum of the last glaciation, valley glaciers existed in the glens and corries and deposited enormous amounts of drift in the foot-hill areas. Sugden suggested that, following an early stage of radial dispersal of ice from the Cairngorms, outlet glaciers developed in the major valleys. He considered that these glaciers ultimately decayed by stagnation. Whatever the details of the glacial sequence, successive glaciations have resulted in impressive erosion of the plateau, producing the classic glacial breaches of the Lairig Ghru and Glen Avon - Glen Derry, the U-shaped troughs of Glen Einich and Avon and a number of spectacular corries like Coire an Lochain (NH 942001) and Coire Raud (NH 950002) on Braeriach.

Fluvioglacial deposits and meltwater channels in

Strathspey and in some other areas in the Grampian Highlands indicate that, as ice downwasting went on, mountains and hills gradually emerged out of the ice-surface and ice became increasingly restricted to the low ground of valleys and basins. Hence it seems likely that this was the time when, under a severely cold climate, periglacial erosion began to take place on the high ground.

During the last sixty years various workers have suggested that glacial readvances interrupted the retreat of the last Scottish ice-sheet. Charlesworth (1926) described the Lammermuir-Stranraer kame moraine associated with a presumed readvance of Highland ice. Later Simpson (1933) and Synge (1956, 1963) postulated readvance limits in the Grampians and vicinity but their views have been challenged (e.g. Paterson, 1974). The recently proposed Ardersier readvance in north-eastern Scotland (Smith, 1977) has not yet been disputed. The best morphological evidence for an ice-sheet readvance is in Wester Ross where a well developed end moraine often records the former ice limit (Robinson and Ballantyne, 1979). There is no published evidence of any equivalent of the Wester Ross Readvance in the Grampian Highlands.

Loch Lomond Advance

During the Loch Lomond Stadial (11,000 to 10,000 years

B.P.) glacier-ice once again accumulated on the high ground, in the corries and valley-heads and on plateaux. In the Western Highlands the ice surface attained an altitude of 850 to 900m (Sissons, 1974a, 1979d). Sissons also estimated that over the Moor of Rannoch, the ice thikness exceeded 400m. The question of whether or not the last ice-sheet completely disappeared before this advance has been raised by several workers. Peacock (1970) argued that without the aid of pre-existing ice a large volume of glacier ice in western Inverness-shire could not possibly have been developed during the assumed limited period of the Loch Lomond Stadial. Sugden (1970b) suggested that in the Cairngorms and adjacent parts of Strathspey the ice-sheet survived throughout lateglacial times. Sissons (1974-79), in reply, attempted to establish the understanding of Loch Lomond glacier regeneration with subsequent detailed maps of former glaciers.

In the central Grampians, around the Drumochter hills, a single large ice-mass developed with a total area of about 360km^2, the greater part of it on the Gaick Plateau (Sissons, 1974b, 1980). From this ice-cap outet glaciers descended to lower ground, one of them providing a north-flowing glacier all the way through the Pass of Drumochter along the Truim valley (Sissons, 1974b, 1976b, 1979c, 1979d and 1980). Some of the ice in the Pass and in the Truim valley came from high ground to the west and south-west. Hummocky moraines are excellently developed in the central part of the valley around the foot of An Torc (700m) (Plate 3.2). Low outwash terraces occur farther north in the Truim valley about a kilometre away from the study area.

In the Creag Meagaidh hills local glaciers were generated in the corries, the largest of which existed in the valley of the Allt Coire Ardair (Sissons, 1979b). This valley begins in several corries and a large area of its foot is occupied by morainic hummocks. Three other small glaciers identified by Sissons were in the corries of Coire Choille-rais, Garbh Choire and in an unnamed corrie immediately north of the Creag Meagaidh summit.

The extent to which Loch Lomond Advance glaciers affected the Cairngorms has given rise to controversy. Sugden (1965, 1970b, 1972; Clapperton and Sugden, 1972) hypothesised that deglaciation in the Cairngorms was a slow and a continuous process. The essence of this idea is that, in the glens and corries ice survived throughout the Lateglacial period and that during the Loch Lomond Stadial 'there was possibly a slight readvance for which there is some slight morainic evidence' (Sugden, 1972, p.22). Sugden also postulated that there was a possible ice occupation in some of the corries as recently as the 1740's. These interpretations contrast with those of Sissons (1974a, 1979a). He mapped seventeen former glaciers, several of which have well-defined end moraines, and argued that they developed exclusively during the Loch Lomond Stadial. The seventeen glaciers, described in detail by Sissons, were all nourished in high ground, mostly in the corries. In Coire an Lochain, north-west of the Braeriach plateau, boulders are heaped up into end moraines. South of Braeriach adjoining corries produced a fairly large glacier that extended down to the southern exit of the Lairig Ghru and formed a spectacular end moraine at its terminus. An extensive area covered by this glacier exhibits remarkable fluted moraines.

The evidence of successive periods of glaciation indicates that in all three study areas much ground that was covered by the last ice-sheet was exposed to periglacial activity during subsequent downwastage of the confluent glaciers and during the Loch Lomond Advance (see also Chapter 2). In the Scottish Highlands the very cold climate of the Loch Lomond Stadial resulted in widespread and varied periglacial activity (Sissons, 1976a, 1979d). In the Grampian Highlands powerful frost wedging produced enormous amounts of detritus that mantle many summits and plateaux. The absence of periglacial features from ground then occupied by glaciers demonstrates that, although periglaciation probably began during ice-sheet decay, the major gelifluction lobes and sheets, as now preserved largely in fossil form, were produced during the stadial.

3.5 Soil and regolith

The hillslopes in the study areas are often mantled with soil-forming material rather than with soil itself. Insufficient time, slow biological activity and excessive gradients are largely responsible for this. The chief climatic controls, related to water and temperature, have different impacts on schists and granites for regolith formation.

In the Moine schist areas of the Drumochter and Creag Meagaidh hills, where weathering of schistose rocks is moderately easy, frost action has readily broken down surface rocks to produce a considerable amount of fine material. Mature zonal soils, like podsols, are found in several places with leached micaceous A horizons and organic B_1 horizons of about 15-20cm thickness. Rocks of these areas result in soils of finer texture, 10-15% of the fine fraction being composed of silt and clay. Immature podsols or rankers are also found on psammitic schists in the areas of shallow regolith. Acid peat is common in the areas of restricted drainage, particularly on the moist hill tops and on gentle to moderate slopes (e.g. the Gaick Plateau in the Drumochter hills).

In the Cairngorms the granite rocks weather along vertical and horizontal joint planes to form boulders of varying size. Gentle slopes and summit plateaux are thickly covered with loose weathered blocks or coarse gritty sand, the latter often reaching a thickness of about 2m. On steep slopes debris is unstable and is often carried down by the melting of snow, delaying soil formation. Coarseness and excessive permeability of the soil prevent the retention of much water. Such physical weathering is dominant and the soil shows only superficial chemical alteration (Hendrick and Ogg, 1916). In general widespread erosion by wind and water tend to maintain the soil in an immature stage, especially on the slopes at the higher elevations (Watt and Jones, 1948).

Pears (1965) described three main soil types in the Cairngorms : 1) forest podsol up to 450m, 2) nanopodsol (dwarf podsol) at 450-900m and 3) podsol ranker (a horizon on granite) above 900m. In addition, there are skeletal, solifluction and organic (peat) soils.

3.6 Natural vegetation

Natural vegetation of the three study areas is, to a considerable degree, controlled by the lithology. The mineral soils, derived from the calcareous schists, are neutral or occasionally alkaline in reaction (as the Drumochter and the Creag Meagaidh hills) and on this type of soil the number of species comprising the vegetation is very large (Ferreira, 1955).

In the Drumochter hills around the actual pass (460m) the *Trichophoreto-Eriophoretum* assemblage has characteristic species (e.g. *Myrica gale*, *Sphagnum imbricatum*). The lower and drier hillslopes are blanketed with extensive Callunatum, carrying a good stock of grouse. Above 600m the vegetation community grades into bilberry-crowberry heath (*Vaccinium myrtillus* and *Empetrum nigrum*) with grasses and sedges. On wind-swept spurs above 760m dwarf Callunetum with abundant *Loiseleuria procumbens* is usual and often shows wave patterns with bare stripes. The large flat summits of A' Mharconaich and the eastern hills supports Rhacomitrium moss heaths. The schist, being the softest of the metamorphic rocks of the Highlands, results in widespread montane springs, flushes and soligenus mires with species such as *Alopecurus alpinus*, *Carex rariflora* etc. on the high ground.

On the southern slopes of the Creag Meagaidh hills patchy birch wood and some plantations of Scots pine occur with limited distribution of heather communities. On well-drained slopes a considerable extent of submontane grassland such as *Agrostics-Festuca* is present. *Saxifraga aizoides* occurs in many places, particularly where the influence of base-rich flush-water is apparent. As in the Drumochter hills bilberry-crowberry heath (*Vaccinium myrtillus* and *Vaccinium-Empetrum*) is extensive on the upper slopes. The area surrounding Creag Meagaidh summit, above 970m is covered mainly with *Descheampsia cespitosa* grassland and dwarf Callunetum is represented on wind swept-spurs in the east. The corries, cliffs and slopes of base-rich rocks have widespread calcicolous communities.

The flora in the Cairngorms is characterized by its acidic base-poor granite soil of extremely low fertility. The lower drift-covered hillsides have largely heather moor but support in places extensive forests of Scots pine. The heather moor passes on wetter ground into *Calluna-Trichophorum* communities. Callunetum extends up to about 1,000m, a high elevation than anywhere else in Britain, but changes with altitude to the prostrate montane form. Where snow-cover is greater than average vegetation like *Vaccinium myrtillus*, *Vaccinium-Empetrum hermaphroditum* and *Nardus stricta* - *Trichophorum cespitosum* are well developed. The porous gravelly soils of above 1,100m support a discontinuous vegetation-cover of ranging from *Juncus trifidus* co-dominant with *Rhacomitrium lanuginosum* to an open tussocky growth in which lichens are the main associates.

Watt and Jones (1948) and McVean (1958) described the following main vegetation zones in the Cairngorms : (i) pine forest of below 520m, (ii) Calluna zone, from 500m to 980m, (iii) *Empetrum vaccinium* zone on the higher ground, except for the areas covered by late-lying and semipermanent snow patches and (iv) damp-loving mosses, like *Dicranum starkai* and *Ploytrichum norvegicum*, characteristic of snow cover lasting till July or August.

3.7 Climate

The climate of the Grampians is determined largely by the procession of cyclonic disturbances moving eastwards from the North Atlantic. In its ultimate form the climate is expressed in a combination of low temperatures, persistent winter frost and snowcover, excessive precipitation, severe wind exposure, frequent cloud cover, high humidity, deficiency of sunshine, poor visibility, continuous ground wetness and low evaporation. The variety of relief creates sharp changes in local mesoclimates in both space and time. Information on the climates of upland Britain is extremely scarce. The location and distribution of meteorological stations show concentrations at low altitudes. Hence crude extrapolation for Highland climate from lowland stations is unavoidable. The following description is based largely on the Climatological Atlas of the British Isles. Climatological data for the nearby weather stations were made available from the Edinburgh Meteorological Office.

The variation of relief within the study areas manifests itself in the climate. A large proportion of land in each area lies above 600m and ground above this limit was shown by Pearsall (1965) to have a subarctic climate with a mean monthly temperature for July not higher than 10° C. Hence the 600m contour, which roughly marks the lower limit of the major periglacial features, approximately corresponds with the lower limit of tundra climate. At Dalnaspidal (412m), near the summit of the Pass of Drumochter, mean January temperature is 0.4° C while the mean July temperature is 12.5° C. At the Glenmore Lodge (341m), immediately north of the Cairngorms, January and July means are 0.65° C and 12.1° C respectively.

Mean monthly air temperatures for Dalwhinnie and Glenmore Lodge are given below :

Dalwhinnie (359m) : 1941-61

Maximum temperature (in °C)

J	F	M	A	M	J	J	A	S	O	N	D
2.6	2.9	5.9	9.1	12.6	15.5	16.2	16.0	13.6	10.2	5.9	3.7

Minimum temperature (in °C)

J	F	M	A	M	J	J	A	S	O	N	D
-2.3	-2.7	-0.6	0.8	3.1	6.2	7.6	7.8	6.4	6.4	0.6	-0.7

Glenmore Lodge (341m) : 1941-70

Maximum temperature (°C)

J	F	M	A	M	J	J	A	S	O	N	D
4.1	4.4	7.1	9.9	13.3	16.3	16.5	16.5	14.6	11.4	6.5	4.6

Minimum temperature (°C)

J	F	M	A	M	J	J	A	S	O	N	D
-2.8	-3.1	-0.9	0.8	3.1	6.3	7.7	7.7	6.4	4.1	-0.2	-1.3

Precipitation values are high throught the Grampian

Highlands and a considerable amount of this falls as snow. The most parts of the upland plateau in the Grampians receive over 180cm precipitation per year. At Dalnaspidal (412m) the value is 156cm, this decreasing to 121cm at Dalwhinnie (359m) only 10km to the north. At Ardverikie (260m), near Creag Meagaidh and at Glenmore Lodge (341m) near the Cairngorms average annual precipitation are 140cm and 99cm respectively.

The figures of mean monthly precipitation and number of days with ground snow for Dalwhinnie and Glenmore Lodge are given below.

Dalwhinnie (359m)

Precipitation (in cm) : 1941-70

J	F	M	A	M	J	J	A	S	O	N	D
11.4	10.2	7.9	8.0	7.7	7.2	8.1	10.0	11.1	13.1	11.2	14.7

Total = 120.6cm

Ground snow (in no. of days) : 1931-61

15	15	10	2	<1	0	0	0	<1	<1	3	9

Glenmore Lodge (341m)

Precipitation (in cm) : 1952-71

J	F	M	A	M	J	J	A	S	O	N	D
7.5	6.8	6.5	5.8	7.1	7.7	8.5	11.5	7.9	9.9	9.2	10.7

Total = 99.1cm

Ground snow (in no. of days) : 1956-71

14.6	15.3	10.0	3.8	-	-	-	-	-	-	5.5	10.7

There is an obvious relationship between snow cover and altitude. A number of estimates (Gloyne, 1968; Manley, 1971) gave the rate of increase of snowcover with altitude as about 15 days per 100m in the Central Highlands. Plateaux exposed to east and south-east winds receive the heaviest snowfall (e.g. the Cairngorms). The solar radiation available for melting of snow is greater on the south-facing slopes than on the north-facing slopes. Very steep north-facing slopes almost lack direct radient energy even on summer days, although low intensities are received in the early morning and late afternoon. At the height of the winter, no direct solar radiation is received on the north-facing slopes. Hence it is probable that the freeze-thaw cycles are greater in number on the south facing slopes.

CHAPTER 4

Periglacial processes and periglacial studies in Scotland

4.1 Introduction

The periglacial domain consists of a number of climatic environments in which frost processes dominate. Boundary conditions for the periglacial zone are rather arbitrary. The presence or absence of permanently frozen ground has often been used to delimit periglacial zones. However, most of the features classified as periglacial do not require permanently frozen ground. Hence temperature oscillations about the freezing point are considered more important. Sharp (1942) defined the periglacial zone as 'characterized by low temperatures, strong winds and many fluctuations across freezing point at certain seasons'. This definition conforms to the climatic conditions of the study areas in the Grampian Highlands.

Two dominant factors are involved in landscape evolution in periglacial environments. They are frost action, the chief process preparing bedrock for erosion, and mass wasting, the principal method of transport.

4.2 Frost action (gelifraction) processes

Frost action or gelifluction implies a number of distinct processes which result from freezing and thawing such as frost wedging, frost cracking, frost heaving and frost thrusting, along with mass displacement.

The freezing process and freeze-thaw cycles : The freezing of soil is a complex thermodynamic process since it involves several factors including soil properties, moisture conditions and duration and intensity of temperature below 0^{o} C. Studies in a number of periglacial environments (e.g. Cook and Raiche, 1962; Chambers, 1966a, 1966b; Washburn, 1967; Fahey, 1973) throw some light on the nature of present-day frost action. Chambers proposed a transitional zone of $\pm$ 0.5^{o} C as the freezing boundary indicator. Washburn (1969) observed in the Mesters Vig district of Northeast Greenland that only the annual freeze-thaw cycle is effective below a few centimetres depth. The restriction of short-term temperature fluctuations to the surface layer implies that the possibility of mechanical weathering at depth is less and the freezing boundary conditions, which are related to the annual cycle, are probably more relevant at depths in excess of 10-15cm (French, 1976).

Large differences between air and ground surface temperature can prevail. Washburn (1969) recorded a difference of over 30° C in Northeast Greenland. Freeze-thaw cycles in bedrock joints during negative air temperatures have been reported from the Antarctic (Andersen, 1963). On the contrary outgoing radiation was also found to have caused ground freezing at positive air temperatures in Iceland (Steche, 1933). However, it has been recognized that the freeze-thaw cycle is an important control in the operation of frost action, including frost wedging.

The nature and the rate of the spring thaw and the autumn freezing are given much importance in the study of geomorphic processes. The spring thaw influences the nature of spring run-off and the autumn freezing controls ice segregation and the nature of frost heaving of the soil. Owing to the higher thermal conductivity and easy percolation coarse sediments are particularly suited to rapid thaw. Usually the spring thaw occurs very rapidly as a result of the percolation of the meltwater through the soil transferring heat to the frozen material beneath. In contrast the autumn freeze-up is more complicated. Normally the soil freezes from the surface downwards but there is also a certain amount of upfreezing from the perennially frozen ground beneath. The annual cycle as described here may not be effective in the areas of many subarctic and Alpine environments where diurnal rather than seasonal conditions are more obvious.

Frost wedging : Frost wedging is synonymous with congelifraction (Bryan, 1946), gelifluction, frost riving and frost shattering. This process in general can be defined as the disintegration and mechanical breakdown of rock by the freezing of water within the joints, bedding planes and pore spaces. The disruptive force results from the 9 per cent volume expansion accompanying the freezing of water and in porous material may also be due to ice segregation and the directional growth of ice crystals (Taber, 1930a, 1930b).

The occurrence of extensive upland surfaces of angular frost-shattered rocks in periglacial environments is the most characteristic morphological result of intense frost wedging. Such surfaces are often referred to as 'block fields' or 'felsenmeer'. Some authors have considered frost wedging to be capable of cutting erosion terraces or altiplanation terraces by contributing to the back wasting of low cliffs (Guilcher, 1950; Te Punga, 1956; Waters, 1962, 1964; Demek, 1968) and producing tors (Palmer and Radley, 1961; Waters, 1962, 1964). Frost wedging is also responsible for the weathering of cliffs and rock outcrops, causing rockfalls (Rapp, 1960, 1962; Prior *et al*., 1971) and producing screes (A. Young, 1972).

The most important control over the effectiveness of frost wedging is the presence of moisture as revealed by laboratory experiments (cf. Tricart, 1956; Potts, 1970; Martini, 1967, 1973). Frost action was found to be particularly intense in areas adjacent to thawing snow patches and on shores where rocks are frequently wetted (Mackay, 1963a; Taber, 1950). Given adequate moisture a very important factor determining the susceptibility of frost wedging is the nature of the rock. Various workers (Tricart, 1956; Wiman, 1963; Potts, 1970) experimented with frost shattering processes on samples of different rocks. Potts found that shales break down more readily than igneous rocks. The varying resistances of rocks to shatter were attributed to the lithological and structural controls of the rocks. Sedimentary rocks, such as silt and shale containing mica, display planes of fissility through which water migrates preferentially and respond with high rates of shatter (Wiman, 1963). Crystalline rocks, rich in biotite or other mica, may also be vulnerable to frost wedging (Washburn, 1979).

Freeze-thaw cycles are another important factor in frost wedging. Laboratory experiments by Tricart (1956) showed that intensity of freezing as well as the number and length of cycles is important. Potts (1970) maintained that the number of freeze-thaw cycles is more important than the intensity of such cycles. It has also been suggested that slow freezing may cause frost wedging of fine-grained uncracked rocks on wet soil by permitting flow of water to the freezing front to build up disruptive ice crystals, whereas rapid freezing would inhibit the flow of water (Taber, 1950).

The characteristic products of frost wedging are angular rocks and boulders of widely varying size. Hopkins and Sigafoos (1951) argued that parent rock can exert a critical influence on the size of its products during disintegration. Experiments by Potts (1950) showed the absence of material finer than 0.06mm produced by frost action in any of his samples. This finding has further been substantiated by Guillien and Lautridou (1974) who stressed that very fine-grained limestones furnished little sediment as small as silt or fine or medium grained sand. This implies that processes other than frost action are responsible for the production of silt and clay particles in periglacial regions.

Frost cracking : 'Frost cracking is fracturing by thermal contraction at subfreezing temperatures' (Washburn, 1979, p. 103). Cracks develop following the rapid lowering of the temperature of ice-rich frozen soil. In the literature these are often called frost fissures or frost cacks (e.g. Dylik, 1966; Dylik and Maarlveld, 1967).

Thermal contraction cracks tend to occur as polygonal networks. The severity of the climate is indicated by the size of the polygons; the smaller the polygons the greater is the temperature range (Dostovalov, 1960). This implies that frost cracks may be of different orders or generations reflecting different temperature ranges. As proposed by Lachenbruch (1966) frost cracking is more dependent on the rate of temperature drop than on the actual subfreezing temperature at the time of cracking and the crack spacing may be of the order of two to three times the crack depth. Washburn (1979, p. 104) proposed that fine-grained, moisture-rich soils are probably highly susceptible to frost cracking.

In permafrost environments the direct result of frost cracking is the development of ice wedges or sand wedges. The infilling of the cracks with water results in the development of ice wedges. When the ground thaws and the ice melts infilling of the wedge takes place by material slumping in from the sides and from the surface. Such ice-wedge casts are widely recognized in Pleistocene periglacial environments (e.g. Johnsson, 1959; Black, 1969b). Certain temperature conditions are required for the growth and preservation of ice wedges. In Alaska the southern limit of presently active wedges roughly coincides with a mean annual air temperature of -6° to -8° (Péwé, 1966a, 1966b, 1975). A second type of frost crack that develops from the thermal contraction of the ground is the sand wedge. In this case, due to extreme aridity, the moisture that normally fills the crack is replaced by wind blown sediments or other materials. Péwé (1959) first described sand wedges in Antarctica which he termed 'tesselons' and subsequently similar features have been described from other polar regions (e.g. Nichols, 1966; Ugolini *et al.*, 1973; Pissart, 1968). Fossil sand wedges indicate primarily frozen ground associated with a very dry climate.

Frost cracks that develop primarily in the seasonally frozen layer have been described by many workers (e.g. Dylik, 1966; Pissart, 1968; Friedman *et al*., 1971 and a number of Russian investigators). This type of crack infilled with mineral soil is generally called a 'soil wedge'. Soil wedges are particularly well developed in parts of Yakutia, U.S.S.R (French, 1976, p. 25) and in various parts of Iceland where they are associated with broad polygonal trough patterns at the ground surface (Friedman *et al*., 1971).

Frost heaving and frost thrusting : The migration of water to the freezing plane and its subsequent expansion upon freezing cause upward movement of mineral soil during freezing. This is known as frost heaving. Eakin (1916, p. 76) proposed that 'the pressures generated by freezing water are exerted in all directions, but they are expressed in soil movements only upward and horizontally. The vertical expression has been termed heave; the horizontal, thrust' This idea has been contested by many workers. Taber (1929, 1930a, 1930b) demonstrated that the growth of ice crystals generates pressure at right angles to the freezing isotherm and not necessarily in all directions; and because freezing extends downward from the ground surface he stressed the role of frost heaving as opposed to frost thrusting. According to the explanation given by Washburn (1979, p. 79) frost heaving is the predominantly upward and frost thrusting the predominantly lateral movement of mineral soil during freezing.

Attempts to measure frost heave in the field usually involve stakes, rods or other objects resting on the surface or buried in the ground to varying depths. Washburn (1979) concluded that the critical variables that influence the amount of heave measured are (1) the moisture content of the mineral soil, and (2) the depth of insertion. He also stated that the amount of heave increases with depth at least in the upper 30cm of the ground and is directly proportional to the 'effective height' of the object being heaved. Taber found that the chief factors controlling ice segregation and heaving are the size of soil particles, the size and percentage of voids, the amount of water available and the rate of cooling. The size of the soil particles was found to be the most important factor as it controls segregation of water during freezing. Below a certain temperatures samples of clays underwent excessive heaving while clean sands were little affected. The height to which water may be lifted above the water table by surface tension is determined by the size of the capillary spaces in the soil. The amount of water content in the soil controls the heaving that is possible. A slow rate of cooling favours the formation of segregated ice layers and a slow lowering of the freezing isotherm occurs most commonly close to the surface and near the lower limit of frost penetration (Taber, 1929, p. 443).

The progressive upward movement of stones and other objects by upfreezing is characteristic of frost heaving. Two different hypotheses, namely 'frost-pull' and 'frost-push', have been suggested. The 'frost-pull' hypothesis assumes that, as the ground freezes from the surface downwards, the top of a pebble is gripped by the advancing freezing plane and raised in association with the overall heave of the underlying material upon freezing. When thawing occurs, the pebble fails to return to its initial position because the hollow created by the upfilling of the pebble is (a) compressed by lateral frost heaving (frost thrusting) during the freezing process and (b) infilled by material during thawing. Partial support for this mechanism was provided by Chambers (1967) from field experiments. The second or the 'frost-push' hypothesis involves the assumption that upfreezing is caused by the greater thermal conductivity of stones than fines resulting in the formation of ice around and beneath the stones. This would force the pebble up and, as in the frost-pull hypothesis, the infill of fines beneath the pebble would prevent it returning to its original position. Laboratory experiments (cf. Corte, 1966b) have shown that this process is visible particularly in the cases of numerous freeze-thaw cycles, when there is a rapid upfreezing. Washburn (1969) provided field support for he observed very rapid upfreezing of stones, which sometimes broke the overlying vegetation cover. It is not yet clear, therefore, which process is responsible for the upfreezing of stones. It seems probable that both the frost-pull and frost-push hypotheses may be valid but under slightly different conditions.

Needle ice or 'pipkrake' 'is an accumulation of slender, bristle-like ice crystals (needles) particularly at or immediately beneath the surface of the ground' (Washburn, 1979, pp.91-92). Direct cooling of the ground surface produces ice crystals that grow upward in the direction of heat loss and as a consequence pebbles and soil particles are lifted up. The needles can range in length from a few millimetres to as much as 35-40cm (Krumme, 1935) depending on the moisture, temperature and soil conditions. These generally produce a nearly vertical structure on a horizontal surface although long needles tend to curve.

The growth of needle ice is commonly associated with diurnal freezing and thawing (Outcalt, 1970) and the greatest frequency of freeze-thaw cycles. The development of needle ice is associated with several processes in periglacial environments. It has a sorting action through small-scale differential heaving as in miniature polygonal features and may also give rise to microhummocks (Troll, 1958; Fahey, 1973). On thawing and collapse it plays an important role in creep and downslope movement of the surface material.

Needle ice is characteristic of Arctic, temperate and alpine environments wherever temperature fluctuates near the freezing point.

Mass displacements and cryostatic pressures : Washburn (1969a, p. 90) defined the term mass displacement '... as the *en-masse* local transfer of mobile mineral soil from one place to another within the soil as the result of frost action'. The possible causes of mass displacements are artesian pressure, changes in density and interangular pressure, cryostatic pressure, differential volume changes in frozen soil, thawing pressure, and irregular upward freezing from the permafrost table. These pressures are essentially hydraulic since they develop in localized units of unfrozen material trapped between the downward moving freezing layer and the perennially frozen ground below (Washburn, 1979, p. 96).

4.3 Mass wasting (gelifluction) process

Mass wasting is the process of downslope movement of debris under the influence or gravity 'without the aid of a stream, a glacier of wind' (Flint and Skinner, 1977). A number of processes that operate separately or jointly are usually included in the term mass wasting. The most common types are frost creep, solifluction, avalanching and slumping.

Frost creep : Frost creep is a process which 'is the ratchet-like downslope movement of particles as the result of frost heaving of the ground and subsequent settling more nearly to the normal' (Washburn, 1967, p. 10). Frost is considered by most investigators (e.g. Iveronova; 1964; Kaplina, 1965; Jahn, 1975) as a process separate from gelifluction although when operating together it is difficult to distinguish between their contributions to the total movement. Carson and Kirkby (1972) considered solifluction in periglacial environments to be a rapid form of seasonal frost creep.

The heaving and settling of particles may extend through the entire thickness of the mantle affected by frost action. Upon freezing the ground tends to heave at right-angles to the slope proportional to the total thickness of segregated ice layers in the freezing soil. The horizontal distance involved in this movement of a particle represents the potential frost creep. The potential frost creep would be the true frost creep if the particle dropped vertically upon thawing (or depressing) of the ground. However, there is a tendency for the thawed material to settle back against the slope as the result of a retrograde component that is possibly related to capillary pressures (Washburn, 1967) and 'the slope tends to settle back against itself reducing the amount of frost creep that would otherwise be present' (Washburn, 1979, p. 200).

The actual amount of frost creep decreases with depth and depends upon the frequency of freeze-thaw cycles, the angle of slope, the moisture available for heaving and the frost susceptibility of the soil (French, 1976). This is a dominant process operating for much of the year in an alpine region with strong diurnal and seasonal rhythms, as in the Colorado Front Range (Benedict, 1970b).

Solifluction : J. G. Anderson (1906, p. 95) defined solifluction as 'slow flowing from higher ground to lower ground of masses of waste saturated with water'. The term 'gelifluction' has been proposed to describe the process under periglacial environments (cf. Washburn, 1973, 1979). Gelifluction was defined by Baulig (1956) as solifluction associated with frozen ground.

Availablity of sufficient moisture is a prerequisite for gelifluction. Favourable conditions occur in areas where (1) the frost table prevents downward movement of water and thereby promotes soil saturation and (2) the thawing of segregated ice-lenses provides excess water which reduces internal friction and cohesion in the soil. Observations by Washburn (1967) and C. Harris (1972) showed that significant gelifluction occurs usually when moisture values nearly reach or exceed the Atterberg liquid limits. Another important factor is the gradient, since the component of gravity in flow acting parallel to a slope increases as the sine of the gradient (Washburn, 1979, p. 204). Gelifluction is possible on slopes as low as 1° (St-Onge, 1965) or 1° - 2° (Schunke, 1975).

Grain size has a strong influence on gelifluction. Fine grain sizes tend to remain wet longer than coarse grain sizes and silt is particularly susceptible to flow (Washburn, 1967). The Atterberg liquid limit is lower in silt than clay and as a result less moisture is required for flow. Gelifluction will cease where an active layer is depleted of fines; moreover a slope lacking permafrost would permit deeper percolation of water and presumably less effective downslope eluviation of fines (Washburn, 1979, pp. 204-205).

Considering the above factors S. A. Harris (1973) attributed gelifluction to a function of depth, sine of the gradient (force parallel to the slope), amount of liquid moisture and grain size of the soil. It remains to be ascertained whether gelifluction is caused by flow as in a viscous liquid or sliding along discrete shear planes or both. Hutchinson (1974) suggested that gelifluction of clayey soils occurs by sliding. Washburn (1979, p. 205) considered sliding primarily on a microscale, along thawing ice lenses and by settling of soil in to voids left by thawing. He concluded that the overall effect is flow.

Frost creep and gelifluction deposits are widespread periglacial features that include sheets (a smooth surface with in places, a bench-like or lobate lower margin), benches (pronounced terrace form), lobes (long tongue-like form) and streams (pronounced linear form at right angles to the contour) with long axes of the component stones oriented up and down the slope. A tendency for stones to lie parallel to the surface has been attributed by many workers (e.g. Embleton and King, 1975; P. J. Williams, 1957a) to frost creep but this can equally result from gelifluction (Washburn, 1969, 1970).

4.4 Periglaciation in Scotland

It has been well established that a harsh periglacial climate formerly persisted in Scotland and periglacial processes are still operating on the high ground on a limited scale. During and before the development of the last ice-sheet periglacial processes must have operated extensively but apart from few fossil frost wedges most of the records failed to survive obliteration and removal by the glaciers. Many workers (e.g. Galloway, 1961a; King, 1968; Sissons, 1974a) have proposed that the major periglacial activity in the Scottish Highlands had ceased by the end of the Lateglacial. Sissons (1976a) suggested that some of the fossil periglacial features may have begun to be formed during last ice-sheet decay when the lower ground was still covered by the downwasting ice. Since the end of the Loch Lomond Stadial periglacial processes have affected little more than the regolith and have produced only minor modifications of the landscape. Thus much of the upland landscape of Scotland, fashioned by periglacial features, is now largely in relict form. Studies in various parts of Scotland have shown that periglacial features of many kinds occur on hills above 550-600m (e.g. Simpson, 1932; Watt and Jones, 1948; Fitzpatrick, 1958; Galloway, 1961a, 1961b; Ragg and Bibby, 1966; King, 1968; Shaw, 1977), although instances of features at lower altitudes have been reported from several areas, particularly the islands (e.g. Spence, 1957; Ryder and McCann, 1971; Goodier and Ball, 1969; Ball and Goodier, 1974).

4.4.1 Frost action features

Frost action features have long been recognized on the Scottish Highlands. In the early part of this century Geological Survey officers (Peach *et al*., 1912, 1913; Crampton and Carruthers, 1914) first mentioned the coverings of disintegrated rock and suggested the possibility of their having been formed by intense frost shattering. It has been claimed that shattering was most effective and extensive in the part of the Buchan area of

North-East Scotland that was considered to have escaped the last glaciation (Charlesworth, 1955; Synge, 1956) and was thus exposed to intense and prolonged frost shattering. Galloway (1961b) mentioned deeply shattered rock under till in lowland areas extending from the Orkney Islands to central Scotland and suggested formation under severe periglacial conditions at the onset of the last glaciation. Extensive coverings of frost-shattered debris occur mainly on high interfluves, summits and gentle slopes. Large angular fragments of rock on low slope gradients have given rise to block fields as in various parts of Scotland (Galloway, 1958, 1961b), the Southern Uplands of Scotland (Ragg and Bibby, 1966), the Cairngorms (King, 1968; Sugden, 1970a, 1971) and the Isle of Rhum (Clark, 1962; Ryder and McCann, 1971). Galloway (1961a, 1961b) mentioned several kinds of rock that are sensitive to frost disintegration. Quartzite was found most favourable for the production of angular rock debris with little fines, while schists, shales, slates and phyllites produce smaller fragments in a silty matrix. In Aberdeenshire and Banffshire quartzite hills were found mantled with angular blocks. Ryder and McCann (1971) reported extensive blockfields on the granophyre of western Rhum. Other examples include the quartzite summit of Schichallion in the central Grampians and the granite uplands of the Cairngorms (Sissons, 1976a). Ryder and McCann also investigated the extensive screes in the Isle of Rhum and suggested a major period of scree development at the very end of lateglacial times.

Fossil frost wedges have been uncovered in many areas. A few wedges near Edinburgh and Glasgow were found in fluvioglacial deposits and buried underneath glacial till (Sissons, 1974a, 1976a) indicating that they were formed before the last ice-sheet finally covered the areas. Most of the wedges extend down 1.5 to 3m, but some attain 4 to 5m. Since many of the frost wedges have been found on low ground on both east and west sides of the country, it appears that permafrost in Scotland extended down to sea-level during and/or after the decay of the last ice-sheet (Sissons, 1974b).

Features produced by mass displacements (cryoturbation) in the form of patterned ground and involutions have been reported from many parts of Scotland. Both fossil and active patterned grounds are present particularly in the summit areas. Large vegetated stone polygons with a mean diameter of 1m and stone stripes with a spacing of 1.5m were studied in the Cairngorms by King (1968, 1971). The present author also found small active stone polygons in the same area. Ryder and McCann (1971) described stone polygons and stripes on high ground in Rhum and suggested that their sorting is a contemporary process. Previously Miller _et_ _al_. (1954) examined the activity of stone stripes on the Tinto Hills in Lanarkshire. These authors destroyed a small area of the stripes and when the area was revisited after two years it was found that the stripes had formed again. 'Sorted stone circles' were studied in detail on several summits in the islands of Orkney and Shetland by Chambers (1965, 1966a, 1966b, 1967). Cryoturbation features in the form of turf hummocks have been described on many mountains as a part of the high altitude vegetation study. Such hummocks ('soil hummocks') of about 1m (3-4ft) in diameter were found on An Sgulan in Perthshire (McVean and Ratcliffe, 1962, plate 20). Similar features were mentioned on flat and gently sloping areas on summit plateaux in the Isle of Skye (Birks, 1973) and on the high ground of Ben Wyvis (Galloway, 1961a).

4.4.2 Frost creep and gelifluction features

Gelifluction deposits are widespread periglacial features in the Scottish Highlands. Some workers attempted to classify them in terms of their regolith characteristics although as a whole they have been referred to as solifluction sheets and lobes. Solifluction sheets are common on higher ground with gentle to moderate slopes. Galloway (1961a) found a characteristic development of uniform sheets in two situations : on moderate slopes near the valley floors and on gently sloping high-level plateaux. The deposits of the former situation consisted of slightly reworked glacial drift now immobilized beneath a cover of peat, while in the latter instance the material was mountain-top detritus derived from the underlying bedrock by frost shattering with scanty vegetation and no peat cover. On the mountains solifluction sheets often terminate downslope in series of lobes. In other instances the lobes occur in small groups or in isolation. They are conspicuous when formed of boulders with fronts rising up to several metres. Galloway recognized stone-banked and turf-banked lobes. He found massive stone-banked lobes on Lochnagar with risers of about 4/5m (15 feet) high composed of granite boulders up to a metre or more (up to 4 feet) long. A similar type of lobe was studied by King (1968, 1972) in the Cairngorms and by Shaw (1977) in the Lochnagar area. On Lochnagar and Mt. Keen in the southeast Grampians such lobes descend to altitudes varying between 700 and 500m but are completely absent from the ground occupied by the Loch Lomond Advance glaciers (Sissons, 1976a). Galloway favoured the formation of such exposed stone-banked lobes, along with those found buried in peat at lower altitudes, in lateglacial or early postglacial times and, said that they are largely inactive under the present climatic conditions. In Galloway's classification the second type or turf-banked lobes are smaller than the stone-banked variety and occur on grassy slopes in damp sites and do not contain large boulders, examples being provided by the high ground of Ben Wyvis. The disturbance of debris around such lobes led Galloway to assume that they are currently active. Turf-banked terraces in the same area were found to occur on well drained vegetated slopes that steepen at the edge of the summit plateau. From the study on Ben Wyvis Galloway (1961a, p. 82) concluded that 'Gentle slopes favour uniform solifluction sheets; moderate slopes are associated with turf-banked lobes and terraces and block fields. Steep slopes go with large stone-banked lobes, now immobile, and the contemporary movement of individual boulders' (ploughing blocks).

Ploughing blocks or gliding boulders are widespread on high ground in Scotland. These blocks are identified by depressions at the rear, typically 1-3m long but occasionally much longer, and bow-waves of debris and vegetation pushed up at the front. The present rate of movement of such blocks in the southeast Grampians has been studied by Shaw (1977).

4.4.3 Other landforms

Large scale landslips and analoguous features, largely preserved in relict form, have also been reported from different parts of the country, particularly in the corries and valley-floors adjacent to rockwalls that escaped glaciation during the Loch Lomond Stadial. The most striking features are protalus ramparts and fossil rock glaciers.

The most striking example of a protalus rampart occurs in

Wester Ross at the foot of Baosbheinn near Gairloch (Sissons, 1976a). It is up to 8m high on its inside and up to 55m on its steep outer side. This feature is fossil and it was most probably formed by frost-wedged blocks that slid down a snow slope during the Loch Lomond Stadial. A number of protalus ramparts have been mapped during the present study along both sides of the Lairig Ghru trough in the Cairngorms. Evidence of former landslides is also common in the Highlands and some of the islands, the most remarkable examples being in northern Skye (Anderson and Dunham, 1966). Some landslides, entirely in rigid rocks, descended to valley floors. One such that blocked a small valley by Glen Coe was reported by Bailey et al. (1916). Although many major landslides have been associated with periglacial conditions this has yet to be demonstrated.

Fossil rock glaciers are perhaps the best indicators of former permafrost. Examples described in Scotland are in Wester Ross (Sissons, 1975), the Isle of Jura (Dawson, 1977) and the Cairngorms (Sissons, 1979a). The period of their development has been assumed to have been in the Loch Lomond Stadial or immediately after.

4.5 Conclusions

The above survey summarizes the dominant periglacial processes in cold environments as well as the literature relating to periglacial features in Scotland. In Chapter 2 it was concluded from the discussion of the published literature on environmental changes that severe periglacial conditions persisted in the Scottish Highlands until the end of the Lateglacial to be followed by less severe conditions that are still continuing. The following chapters present the results of a study of a number of periglacial landforms on the basis of a systematic classification and assess the nature of past and present periglacial processes in the Grampian Highlands.

SECTION II PERIGLACIAL LANDFORMS AND DEPOSITS

CHAPTER 5

Classification and mapping of periglacial features

5.1 Introduction

In the periglacial environment mountain and hillslopes are often mantled with frost-shattered bedrock for which the descriptive term mountain-top detritus is usually used. Downslope movement of this detritus owing to freeze-thaw action is a characteristic feature that produces different types of landform. Over the last twenty-five years or so periglacial studies in Britain, particularly in Scotland, have given rise to an increasing number of new concepts derived from a growing knowledge of the range of processes and deposits. The wide range of periglacial phenomena so far recognized requires adequate definitions and terms. In this chapter a systematic classification and definitions of the high ground morphological features of the Scottish Highlands are presented. The classification aims to encompass all recognizable types of phenomena including some that are not strictly 'periglacial' (e.g. gullies, slump features, debris chutes).

5.2 Problems of classification

Individual periglacial features in upland Britain have been recognized and described by many workers. Gelifraction and gelifluction, the two major formative processes involved, have already been discussed in Chapter 4. Although some features are apparently the result of one of these processes, in a number of cases both are involved. In such cases an entirely genetic classification would be unsatisfactory (Benedict, 1970b). A classification based on the period of formation (fossil and active), which would often involve the size of features, is not acceptable because small older surface features would be less likely to be preserved than large ones (Ball and Goodier, 1970b). Most landforms found in periglacial environments are related to a combination of factors and the intensity of the process involved is likely to have varied as climate changed with the passage of time.

Washburn (1973, 1979) classified the forms of frost creep and gelifluction deposits as follows :

1) Gelifluction Sheets : smooth surfaces with in places a bench-like or lobate lower margin.

2) Gelifluction Benches : pronounced terraced forms, with the longest dimension tending to be parallel to the

contour of the slope, but in places at angles up to 45°.

3) Gelifluction Lobes : tongue-like forms, with the longest dimension tending to be at right-angles to the contours.

4) Gelifluction Streams : features with a pronounced linear form extending at right-angles to the contours.

5.3 Present classification

Periglacial features in upland Britain have often been classified in general terms and are likely to be confused owing to the ambiguity of some of the terms employed. In some instances features of a similar origin have been described by several different terms. In other instances markedly different features have been classed into one group. A systematic classification of features on the basis of a standard terminology was, therefore, felt essential at the beginning of this study.

The present classification and the terminology have been devised following the general principles of Washburn and other specialists. As the structure and underlying processes were largely unknown at the start of the study the derived classification had necessarily to be generic, being based on morphological and other surficial characteristics. The scheme proposed by C. K. Ballantyne (pers. comm.) has been maintained, although some additions and alterations had to be made to allow further subdivision.

Table 5.1 presents the classification. The first step of this classification separates 1) Primary Features from 2) Secondary Features. This division is rather subjective and is intended to distinguish features that result generally in considerable relief amplitudes and dominate in unit areas from those that are less dominant in unit areas or, if dominant, exhibit low relief amplitudes.

1. Primary Features

The primary features have two subdivisions : a) Plateau Surface Features and b) Slope Features.

1. a) Plateau Surface Features

Debris Surface : A considerable area, usually level or of gentle gradient (less than 10°), covered with shattered debris consisting of small to moderate size angular blocks with some fines.

Block Field : A considerable area, usually level or of gentle gradient (less than 10°), covered with moderate to large size angular blocks (cf. Sharpe, 1938).

- PERIGLACIAL FEATURES
  - PRIMARY FEATURES
    - PLATEAU SURFACE FEATURES (Debris surface, block fields, stone pavements, deflation surfaces, tors, rock outcrops)
    - SLOPE FEATURES (Free faces, talus slopes, block slopes, debris slopes)
  - SECONDARY FEATURES
    - MASS MOVEMENT FEATURES
      - DETRITUS SHEET FORMS (Rock glaciers, boulder sheets and lobes, debris sheets and lobes, vegetation-covered sheets and lobes (fossil and active types), terraces, terracettes, steps)
      - STREAM FORMS (Block streams, debris streams)
      - RAPID MASS MOVEMENT FORMS (Debris chutes, debris cones, slumps)
      - OTHERS (Ploughing blocks)
    - PATTERNED GROUNDS (Stripes, polygons, circles, garlands, turf hummocks, hummock stripes, wind stripes, wind crescents)
    - MISCELLANEOUS (Aeolian sand, sand scarps, nivation hollows, protalus ramparts, gullies, alluvial cones)

Table 5.1 Classification of periglacial features.

Stone Pavement : A veneer of coarse particles in which the surface stones lie with a flat side up and are fitted together like a mosaic.

Deflation Surface : A plateau surface resulting from the removal of vegetation and fine material by wind action. Deflation surfaces commonly exhibit wind-scoured bare patches with a concentration of coarse material (Plate 5.31).

Tor : A hillock or a residual mass or bedrock projecting abruptly from a gently undulating land surface. In periglacial environments tors are produced chiefly by frost wedging and mass wasting.

1. b) Slope Features

Free Face : A vertical or near vertical rock wall with a talus or scree slope below.

Talus Slope : An apron-like accumulation of angular blocks on a hillslope backed by a bedrock cliff or free face.

Block Slope : A considerable area of hill slope (usually steeper than 10^{o}) covered with moderate to large size angular blocks (Plate 5.2).

Debris Slope : A relatively small area of hillslope with a continuous or near continuous veneer of frost-shattered debris consisting of small to moderate size angular blocks with some fines (Plate 5.3 & 5.4).

Commonly block slopes and debris slopes have no bedrock cliff or free face at their heads as occurs with a talus slope.

2. Secondary Features

The secondary features include three categories : a) Mass Movement Features, b) Patterned Ground Features and c) Miscellaneous.

The category of Mass Movement Features is further subdivided into : (i) Detritus Sheets Forms, (ii) Stream Forms, (iii) Rapid Mass Movement Forms and (iv) Others.

2. a) Mass Movement Features

2. a) (i) Detritus Sheet Forms

Rock Glacier : A massive, often tongue-like body of angular boulders that usually occurs at the base of a steep slope (cf. Potter, 1969) (Plate 5.34).

Lobes and Terraces

Galloway (1961a, p. 75) described lobes and terraces as 'comprising a mixture of large and small stones in a scanty fine-grained matrix. They form steps on slopes with 'risers' from a few inches to several feet high, usually aligned along the contour and consisting of bands of dense vegetation ("turf-banked") or large stones ("stone-banked")'. According to the definition given by King (1968, p. 93) 'lobes are U-shaped in plan with the open end of the 'U' on the upslope side : terraces and benches have an approximately straight plan'. Galloway classed lobes into two main types : stone-banked and turf-banked. According to his description stone-banked lobes have a stone garland and turf-banked lobes are garlanded by a turf levée.

Gelifluction sheets and lobes in the three study areas have been grossly divided into three main categories. The first comprises stones and fines with either turf or stones at the riser (debris sheet and lobe); the second type is formed predominantly of large boulders and cobbles with very little and no fines (boulder sheet and lobe); and the third type is almost entirely coverd with vegetation (vegetation-covered sheet and lobe). The vegetation-covered type includes both a miniature type, formed of fine material on the higher slopes and massive features of the first two types (boulder type and debris type) occurring particularly on the lower slopes under a thick cover of vegetation.

Debris Sheets and Lobes : A debris sheet is a veneer of small to medium size (cobble size) stones with some fines on moderate slopes (Plate 5.9). Debris lobes are the individual lobate feature commonly occurring at the front of debris sheets or debris slopes (Plates 5.9 & 5.10). They can also occur separately on hillslopes (Plate 5.11).

Boulder Sheets and Lobes : A boulder sheet is a veneer of medium to large size boulders on moderate slopes (Plate 5.5 & 5.6). Individual boulder lobes commonly occur at the front of boulder sheets or block slopes. Like debris lobes they can also occur separately on hillslopes (Plates 5.7, 5.8 & 5.12).

Vegetation-covered Sheets and Lobes : A vegetation-covered sheet can be formed of cobbles and boulders or of small stones and fines and is morphologically identical to the boulder sheet and the debris sheet. Vegetation-covered sheets of cobbles and boulders are usually of massive dimensions, covered with a thick layer of vegetation and thus classed in the fossil type (Sheets, Plate 5.13; Lobes, Plate 5.14) while those formed of small stones and fines exhibit miniature landforms covered with a relatively thin layer of vegtation and are thus classified as active (Sheets, Plates 5.15 & 5.16; Lobes, Plates 5.7 & 5.18).

With the increase in hillslope gradient detritus shows a downslope gradation from horizontal sheet to lobate sheet to lobes. The compositional difference between debris lobes and boulder lobes appears to reflect lithological control. Rock type affects frost action (gelifraction) and thus exerts a strong influence on the nature of the debris available for lobe formation. From the findings of a number of workers (e.g. Watson, 1961, p. 12; Dutkeiwicz, 1961, p 288; Galloway, 1961a, p.82) the following ascending order of frost susceptibility can be devised : volcanics, mudstones and greywacke, schists, dolomite. The Drumochter and the Creag Meagaidh hills, where most of the debris lobes were mapped, are fomed mainly of siliceous schists and flags (see Chapter 3). Owing to marked fissility along the schistosity weathering in these types of rock is moderately easy (Ollier, 1969). Consequently frost weathering can rapidly break down surface rocks to produce small stones and cobbles with considerable amounts of fine material. A typical granite, as in the Cairngorms, where boulder lobes are common, is coarse grained and well jointed. Frost action splits granite into blocks and these frequently exhibit granular disintegration. The debris lobes in the Drumochter and the Creag Meagaidh areas have further been grouped into turf-banked type and stone-banked type in recognition of their riser pattern. Where strongly foliated schists grade into less foliated massive psammitic schists or are interrupted by pegmatite and other harder rocks, as in many places in the Creag Meagaidh area, boulder lobes occur. An example of such locally developed boulder lobes is shown in Plate 5.8.

The crude definition of lobes as 'turf-banked' or 'stone-banked' seems incomplete and unsatisfactory because these terms can only describe the frontal character of a lobe, not the entire feature. The material that accumulates at the lobe-front to form the bank (often covered with turf) is apparently the result of a rapid and continuous frost shattering of suitable rocks, in the present instances schists. Once the bank is developed any washing of finer material produced afterwards, is prevented and the lobe exhibits a deposit of stones and fines (i.e. the debris). Hence a turf-bank is common for most of the well developed debris lobes on schistose rocks. The process is different for the boulder lobes. In this case the rate of washing of fine material exceeds the rate of its production (on granite and other local igneous and less foliated rocks in these instances) leaving the lobe front free of any accumulation of debris. These bare risers are obvious features of boulder lobes when seen from a distance.

Terraces : Bench-like landforms of debris generally parallel to the contours. Terraces can be of different types depending upon their response to the slope gradient or to the regolith upon which they occur. The types recognized are normal terraces (Plates 5.19 & 5.21), inter-connecting terraces (Plate 5.20), oblique terraces (Plates 5.23 & 5.24) and lobate terraces (Plate 5.22).

Terracettes : Closely spaced, narrow and small terraced features formed parallel to the contours on steep slopes.

Steps : Bench-like features with a downslope border of vegetation or stones embanking an area of relatively bare ground upslope.

2. a) (ii) Stream Forms

Block Stream : Accumulation of moderate to large size angular blocks of rock as a narrow linear deposit extending down the steepest available slope.

Debris Stream : Accumulation of small to moderate size angular blocks with some fines as a narrow linear deposit extending down the steepest available slope.

2. a) (iii) Rapid Mass movement Forms

Debris Chute : A long steeply-sloping linear accumulation of debris (finer material in abundance) on a hillslope resulting from rapid flow of material (Plate 5.33)

Debris Cone : Debris with a semi-circular or semi-elliptical base accumulated at the bottom of a slope.

Slump : A feature resulting from the downward sliding of a mass of rock or consolidated slope material, commonly moving as unit. This leaves a small cliff or steep slope from which it has descended.

2. a) (iv) Others

Ploughing Block : A boulder that moves downslope faster than the regolith in which it rests. Ploughing blocks are commonly recognized by a linear depression (the former course of movement) to the rear end and by a small heap of debris forced up at the front (Plates 5.25 & 5.26).

2. b) Patterned Ground Features

Sorted and Non-sorted Stripes : Sorted stripes are patterned ground with a striped pattern and a sorted appearance due to parallel lines of stones and fines oriented down the steepest available slope (Plate 5.3). For the sorted fossil stripes the bands of fines are often covered with vegetation (Plate 5.27). Nonsorted stripes are striped patterned ground with a nonsorted appearance due to parallel lines of vegetation-covered ground and intervening stripes of relatively bare ground (cf. Washburn, 1956).

Sorted and Nonsorted Polygons : Sorted polygons are patterned ground whose mesh is dominantly polygonal with a concentration of stones at the border and fines in the centre. Nonsorted polygons lack a border of stones (cf. Washburn, 1956). Sorted fossil polygons exhibit a cover of vegetation at the centre (Plate 5.28).

Sorted Circles : 'Sorted circles are patterned ground whose mesh is dominantly circular and has a sorted appearance commonly due to a border of stones surrounding finer material' (Washburn, 1956, p. 827) (Plate 5.29).

Garlands : A garland-like arrangement of stones with the convex side oriented downslope.

Turf Hummocks and Hummock Stripes : Turf hummocks are vegetation-covered small mounds with a core of soil regolith (Plate 5.32). Hummock stripes consist of bands of elongate turf hummocks aligned downslope.

Wind Stripes : Stripes formed by wind action on vegetation covered surfaces exhibiting parallel bands of vegetation and deflation surface.

Wind Crescents : Crescentic troughs on plateau surfaces created by wind action.

2. c) Miscellaneous

Aeolian Sand : Extensive deposit of fine-grained sediments laid down by wind on the sheltered parts of hills.

Nivation Hollows : A localized hollow on a hillside created by the erosive activities of frost action, mass wasting and sheet flow or rill erosion by meltwater at the edge of and beneath lingering snow drifts (cf. Washburn, 1979). The downslope part of the hollow is generally flat or gently inclined, whilst the upper part is steeper.

Protalus Rampart : A ridge of debris that commonly occurs at the foot of a talus owing to rockfall or debris fall accompanied by sliding across a perennial snowbank (cf. Bryan, 1934) (Plate 5.33).

Gulley : A steep- often vertical-walled channel developed on a hillslope when rills or sheetflow of water become concentrated into distinct channel.

Alluvial Cone : A cone of material deposited by a stream where it debouches from high ground onto flat or gently-sloping ground.

5.4 Method of Mapping

The three study areas, comprising the Drumochter hills, the Creag Meagaidh hills and the selected part of the Cairngorms, were first studied stereoscopically using high and low magnification on aerial photographs at approximately c 1:25,000 scale. All identifiable glacial and periglacial features on the higher ground were marked on the photographs, although particular attention was paid to the periglacial features, and in the valleys only major glacial landforms and drift limits were marked using published maps and literature (e.g. Sissons, 1974b, 1979a, 1979b, 1980). The features marked on the photographs were subsequently checked in the field. Many miniature features unidentified on the photographs were mapped during this checking. The complete field maps were then transferred to Ordnance Survey 1:10,000 scale maps with the aid of a Grant Projector. Special care was taken to reduce the effect of distortion.

Selected symbols for individual features following the classification given above are shown in Fig.5.1. Fig. 5.2, 5.3, 5.4 and 5.5 (in the folder) present the geomorphological maps of the study areas.

Plate 5.1 Frost riving, the corrie back wall of Coire-Ruadh, Cairngorms.

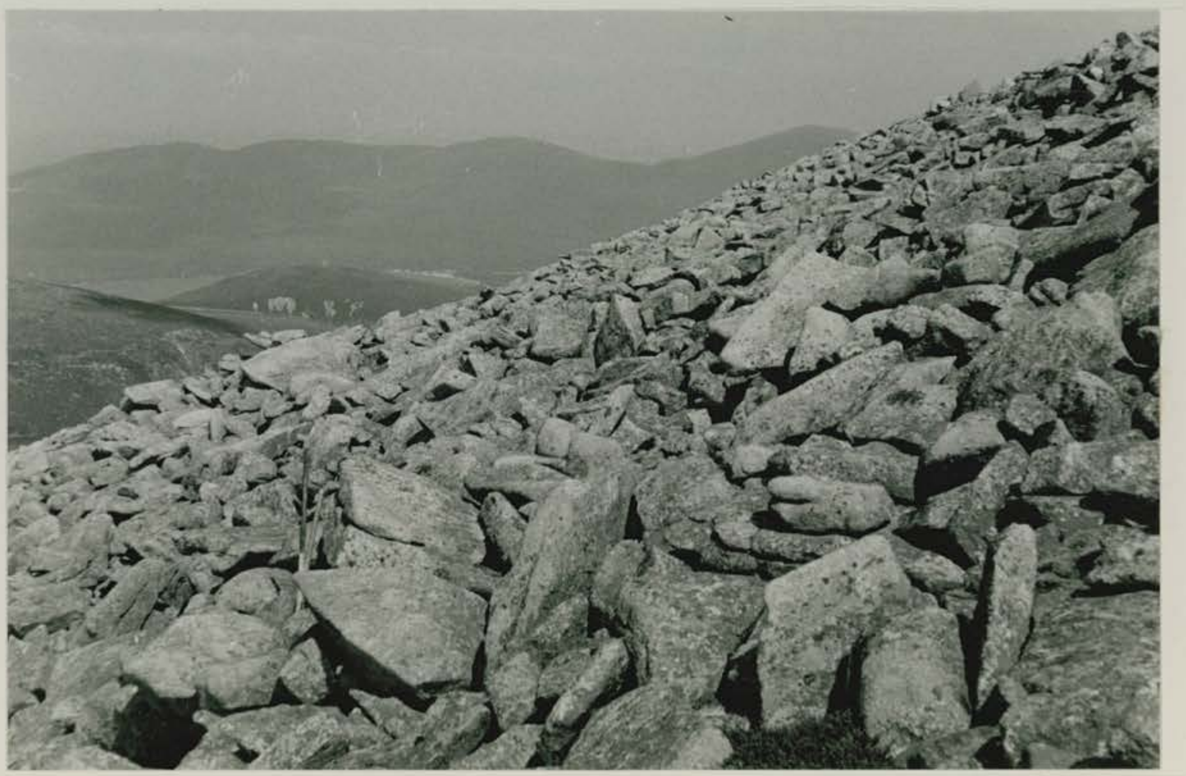


Plate 5.2 Block slope, Creag an Leth-choin, Cairngorms.

Plate 5.3 Debris slope (a distant view), Creag Meagaidh hills.

Plate 5.4 Debris slope, Geal-charn, Drumochter hills.

Plate 5.5 Lobate boulder sheets, Creag an Leth-choin, Cairngorms.

Plate 5.6 Lobate boulder sheets, Coire gorm, Cairngorms.

Plate 5.7 Large boulder lobes, Coire Cas, Cairngorms.

Plate 5.8 A large boulder lobe, Carn Liath, Creag Meagaidh hills.

Plate 5.9 Lobate debris sheets, Geal-charn, Drumochter hills.

Plate 5.10 Turf-banked debris lobes, Geal-charn, Drumochter hills.

Plate 5.11 Stone-banked debris lobes, Geal-charn, Drumochter hills.

Plate 5.12 A thin boulder lobe, A' Mharconaich, Drumochter hills.

Plate 5.13 Large vegetation-covered lobate sheets (fossil type), Miadan Creag an Leth-choin, Cairngorms.

Plate 5.14 Large vegetation-covered lobes (fossil type), Coire Gorm, Cairngorms.

Plate 5.15 Vegetation-covered (solifluction) sheet (active type), Meall a' Chaorainn, Drumochter hills.

Plate 5.16 Vegetation-covered lobate (solifluction) sheets (active type), A' Mharconaich, Drumochter hills.

Plate 5.17 Vegetation-covered (solifluction) small lobes (active type), Meall a' Chaorainn, Drumochter hills.

Plate 5.18 Partly vegetation-covered lobes (active type), Creag Meagaidh hills.

Plate 5.19 Large turf-banked terraces, Coire Gorm, Cairngorms.

Plate 5.20 Turf-banked interconnecting terraces, A' Mharconaich, Drumochter hills.

Plate 5.21 Vegetation-covered normal terraces, Meall a' Chaorainn, Drumochter hills.

Plate 5.22 Lobate terraces, Meall a' Chaorainn, Drumochter hills.

Plate 5.23 Large oblique terraces, Coire Gorm, Cairngorms.

Plate 5.24 Small oblique terraces (a distant view), Coire Gorm, Cairngorms.

Plate 5.25 Ploughing blocks, A' Mharconaich, Drumochter hills.

Plate 5.26 A ploughing block, Meall a' Chaorainn, Drumochter hills.

Plate 5.27 Large sorted stripes (fossil type) on the summit to the north of Coire Ardair, Creag Meagaidh hills.

Plate 5.28 Large sorted polygons, Braeriach Plateau Cairngorms.

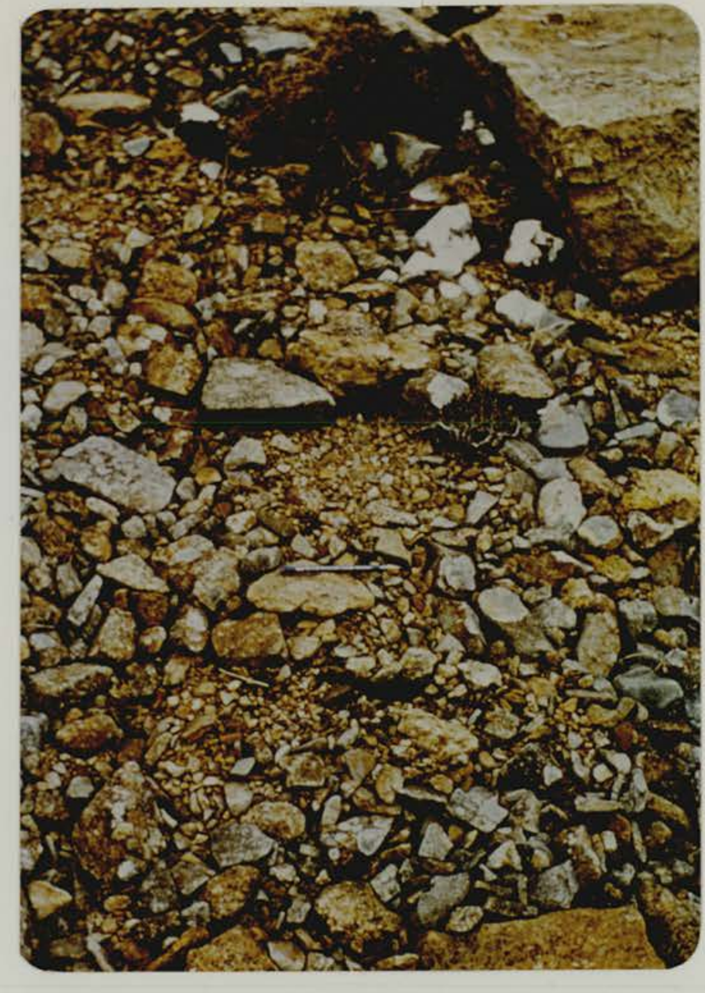


Plate 5.29 Small sorted circles, western plateau, Isle of Rhum.

Plate 5.30 Poorly developed small sorted stripes (active type), A' Mharconaich, Drumochter hills.

Plate 5.31 A deflation surface, An Torc, Drumochter hills.

Plate 5.32 Turf hummocks, Meall a' Chaorainn, Drumochter hills.

Plate 5.33 A protalus rampart and fresh debris chutes, Lairig Ghru, Cairngorms.

Plate 5.34 A fossil rock glacier, Coire Beanaidh, Cairngorms.

CHAPTER 6

Gelifluction lobes and sheets

6.1 Literature

The history of the recognition of lobate features in the Scottish Highlands dates back to the beginning of this century when Geological Survey Officers (Peach *et al.*, 1912, 1913; Crampton and Carruthers, 1914) mentioned the coverings of disintegrated rock and suggested the possibility of their having been formed by intense frost-shattering. But it was not until the publication of the work of Galloway (1958) that mass movement features in Scotland received proper attention. In his extensive work on the periglacial environment in Scotland Galloway described several types of associated landform in many upland areas. He identified three different types of lobe ('stone-banked', 'turf-banked' and 'vegetation-covered') on Ben Wyvis and presented a brief indication of their size and preferred slope angles. On Lochnagar he found 'stone-fronted' lobes of larger type for which later he used the term 'stone-banked lobe' (1961a, 1961b). Ragg and Bibby (1966), working in the Southern Uplands, described patterns of 'solifluction lobes' upon the highest summits. Afterwards King (1968, 1972) made considerable progress in the understanding of Scottish periglacial landforms, particularly of lobes, on a quantitative basis. He studied 'stone-banked', 'turf-banked' and 'vegetation-covered' lobes in the Cairngorms, collecting data on their size, angle of facets, and the nature of their structure and boulder size.

Since King's work identification of lobes and other periglacial landforms started to gather momentum. Goodier and Ball (1969) and Ball and Goodier (1970) discussed stone-banked lobes and terraces in the Rhinog Mountains of North Wales. Sugden (1970a, 1971), on the basis of his study in the Cairngorm mountains, discussed the distribution, general size-range and possible age of lobes and terraces. Kelletat (1970a, 1970b) published a detailed study of fossil and contemporary solifluction forms (described as lobate, garlanded and terraced features) of the Central Grampians. Ryder and McCann (1971) described lobes on the high ground in the island of Rhum. White and Mottershead (1972) produced a contour map of a turf-banked terrace (which is of lobate type) on Ben Arkle, Sutherland. They studied vegetation, soils, stone orientations, particle-size distribution and the pollen content of a buried organic horizon. The most recent work on gelifluction lobes is that of Shaw (1977), who studied the boulder lobes of the Lochnagar area and produced some valuable quantitative information.

6.2 Present Study

The aim of the present study was to analyse more precisely the lobes in the three parts of the Grampian Highlands : the Drumochter hills, the Creag Meagaidh hills and a selected part of the Cairngorms. The gelifluction lobes in these areas were classified into three main types : debris type, boulder type and vegetation-covered type as described in Chapter 5. It has also been discussed in that chapter that frost shattered rocks in the predominantly mica-schist areas tend to produce lobes and sheets characterized by stones and fines; hence the terms debris lobe and sheet are adopted. These feature are widespread in the Drumochter and the Creag Meagaidh hills where mica schist is the basic rock. Lobes of massive boulders are characteristic of the Cairngorm granite area. Some of this type of lobe are also seen on higher slopes of the two other areas where strongly foliated schists grade into less foliated psammitic schists or are interrupted by pegmatite and other harder rocks. The three types of lobe were studied separately in terms of their distribution, morphology, structural characteristics and, where applicable, present-day mass movement pattern.

6.3 Distribution

Gelifluction lobes and sheets are the most extensive feature in the Grampian Highlands. One of the main objects of this study was to attempt to understand the altitudinal distribution, aspect and preferred slope angle of all types of lobe and to assess the factors that limit their occurrence in the study areas. These three parameters were first measured during the sample survey of each type of lobe. One of the drawbacks of this procedure was that the number of measurements was restricted. Hence additional data were obtained by map sampling. This involved measuring the altitude, aspect and slope angle of lobe-covered ground on the geomorphological maps. Sampling was done for each of the study areas using the Ordnance Survey 100m grid on the photogrammetrically surveyed maps (1:10,000 scale) with 10m contour interval.

6.3.1 Altitude

Debris lobes in the Drumochter and the Creag Meagaidh hills The lowest lobe in the Drumochter area was mapped at about 640m altitude on a north-facing hillslope to the east of the Pass of Drumochter (NN 664791). The hills east of the pass, in fact, exhibit a very limited number of this type of lobe, a fairly large area of the higher ground being occupied by the vegetation-covered small type. Debris lobes are abundant on the hills to the west of the pass, particularly on the slopes of all aspects of Geal-charn and the range is between 700m on the north-northwestern slope (NN 592786) and about 900m near the summit (NN 598782). The frequency of lobes is greater on the slopes declining northwards than on any other side. A' Mharconaich, the other hill in this area, has far fewer debris lobes, the only remarkable area being the northern slope above the col between the two hills (NN 594764).

In the Creag Meagaidh area relief is much higher and the lobes exhibit a wide range of distribution. The lowest lobe was observed on the south-facing slope of A' Bhudheanach at about 650m (NN 430881). Debris lobes were present on almost all hillslopes except some steeper parts of the valley-wall on either side of the Allt Coire Ardair where detritus take the form of debris chutes. Lobes are particularly abundant on the south-facing slopes of Meall Coire Choille-rais (NN 433857), the south and south-eastern slopes of Sròn a' Ghoire (NN 452875) and the south, south-east and south-western slopes of A' Bhudheanach (NN 470900). On the upper slopes of A' Bhudheanach series of boulder lobes are found which coincide with the widespread occurrence of pegmatites.

The sample study of altitude from the geomorphological maps of these two areas by grid method using 50m class intervals reveals certain features of debris lobe and

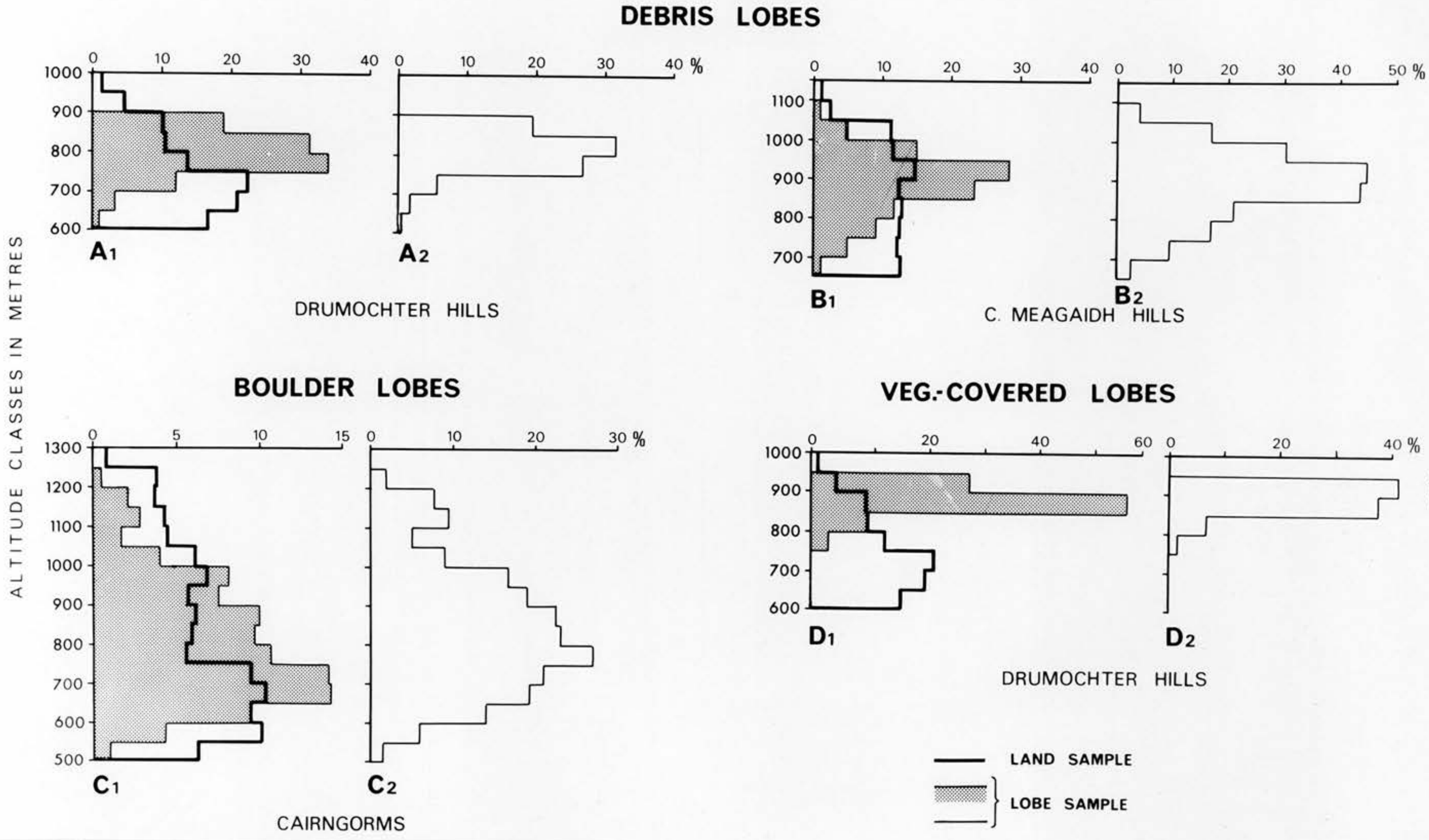


Fig. 6.1.1

The altitudinal distributions of gelifluction lobes in the three study areas based on data derived from the geomorphological maps. The diagrams A1, B1, C1 and D1 show the percentage distributions of land and lobes and A2, B2, C2, and D2 represent the percentage of ground surface occupied by lobes in different altitudinal zones above the lowest lobe limit.

lobate sheet distribution. Diagrams A1 and B1 in Fig. 6.1.1 demonstrate the percentage distributions of land and lobes at different altitudes. Lobe sample is represented by the shaded area and land sample by the solid line. In the Drumochter hills, although the lobes occur from below 650m, a major portion of the sample lies above 750m with a mean altitude of 802m (standard deviation : 53m). In the Creag Meagaidh hills, where relief is higher , the altitudinal range extends to 670-1,070m, the mean being 888m (standard deviation : 80m). A preferred zone of debris lobes in each area is seen in the diagrams where lobe sample exceeds land sample. In the Drumochter area this zone is between 750 and 900m and in the Creag Meagaidh between 850 and 1,000m. It is also interesting to note that in both cases lobe concentration is greater on higher ground. The diagrams A2 and B2 represent the percentage of ground surface covered by debris lobes and sheets. There is a distinct variation in the lobe occupation of the ground in the two areas. A maximum of about 45% of ground covered with lobes at 900-950m altitude obtained for the Creag Meagaidh area is considerably higher than that found for the Drumochter area at any altitudinal zone (maximum being about 32% at 800-850m). This suggests a wider spread of lobes and lobate sheets in the Creag Meagaidh area than in the Drumochter area.

<u>Boulder lobes in the Cairngorms</u> In the Cairngorms

boulder lobes occur over a very wide range of altitude. On the western slopes of Castle Hill (NH 952058) the lowest lobe was mapped at about 540m altitude and the highest examples were found at 1,210m on the eastern side of the Braeriach massif (NH 962000).

Lobes and lobate sheets are distributed over the hillslopes on either side of the Lairig Ghru. The northern, north-eastern and north-western slopes of Creag an Leth-choin exhibit spectacular manifestations of lobes and lobate sheets with frequent boulder streams in them. The large boulder sheets that occur in this area and elsewhere on concave slopes (as on Coire Gorm, NH 960022) were named 'lobate scree' by King (1968, p. 102). Vegetation-covered boulder lobes and lobate sheets are extensively developed on the moist gentler slopes of Miadan Creag an Leth-choin (NH 972035) and Sròn na Lairige (NH 961018).

Analysis of the Cairngorm boulder lobe distribution using the geomorphological map shows a mean altitude of 809m (standard deviation : 148m). Diagram Cl in Fig. 6.1.1 demonstrates the altitudinal distribution of boulder lobes in 50m class intervals. A preferred zone is present in the diagram between 650 and 1,000m where the lobe sample exceeds land sample. It is interesting to note that boulder lobes prefer lower ground shown by negative skewness in the histogram. Diagram C2 represents the percentage of ground surface covered with lobes. The most characteristic feature obtained from the two diagrams is the gradual decline of occupation of ground by lobes as the altitude increases, a feature in contrast with that of the debris lobes in the two other areas. The most likely reason for this is the typical plateau character of the Cairngorms with very low slope gradients at the higher altitudes. This factor will be discussed later. From diagram C2 it appears that the altitude 750-800m is particularly favoured for boulder lobes. The occurrence of a peak in the histograms at this altitude is probably accidental rather than of general significance because slopes in the Cairngorm study area, which as a whole faces north, tend to become steeper with altitude until the gently sloping plateau is reached.

Vegetation-covered small lobes Vegetation-covered lobes of miniature type, mainly composed of fine material, were found largely in the Drumochter hills. Limited areas in the Creag Meagaidh hills and Cairngorms also exhibit a similar type of feature. In all these areas their distribution is restricted to the higher ground near the summit areas. In the Drumochter hills they descend from 950 to 750m with a mean altitude of 889m (standard deviation : 38m). The highest altitude for this type was near the north-eastern summit of A' Mharconaich (NN 600760) and the lowest on the western slope of the eastern hills (NN 644786). Small lobes of this kind are a predominant feature on the gently sloping surfaces around the summit of A' Mharconaich and on the eastern hills.

In the Creag Meagaidh area, north of the corrie of Lochan a' Choire, a similar type of vegetation-covered lobe occurs on the high plateau (950-1,000m) that declines northwards. A very limited number of them was found inside the study area in the Cairngorms, this being in the high-level col (980-1,000m) between Creag an Leth-choin and Miadan Creag an Leth-choin (NH 791029).

Diagram D1 in Fig. 6.1.1, showing the altitudinal distribution of land and vegetation-covered lobes in the Drumochter hills, indicates a fairly strong inverse relationship between the two variables, for the former decreases as the latter increases markedly at least up to the altitude of 850-900m. A preferred zone occurs between 850 and 950m where lobe sample exceeds land sample. Diagram D2 represents the percentage of ground surface occupied by vegetation-covered lobes. This demonstrates more clearly the nature of the increasing spread of this type of lobe with the increase in altitude.

Discussion

In the three areas where altitude of debris lobes and boulder lobes was analysed the lower limits in many cases correspond with the upper limit of valley-side peat, as on Geal-charn (NN 593787, NN 597776) in the Drumochter area, A' Bhuidheanach (NN 475896) in the Creag Meagaidh area and on the western slopes of Castle Hill (NH 953057) in the Cairngorms. On either side of the Pass of Drumochter, where the Loch Lomond drift limit is as high as 700m, the lobes and the lobate sheets terminate abruptly downhill at this limit, an excellent example being seen on the western slope of Creagan Doire Dhonaich (NN 631774). No boulder or debris lobe sample was found inside the ground occupied by Loch Lomond Advance glaciers. In other situations lobes terminate at the sudden change of gradient onto hillside benches or high valley-floors. The best examples were noticed in the Creag Meagaidh area on the north-eastern flanks of the main summit (NN 425884) and on the eastern slope of Sròn a' Ghoire (NN 454884). The third important factor seemed to be convexity of hillslope. Several hills in the Creag Meagaidh area have lobes only on their upper convex slopes suggesting that material was available only on those parts, e.g. an unnamed summit near Carn Liath (NN 470905). In the Drumochter hills a large number of lobes and lobate sheets occurs on the upper convex slopes of Geal-charn. Boulder lobes in the Cairngorms are markedly developed upon the convex slopes (e.g. NH 972040, NH 973040).

All vegetation-covered lobes of miniature type in the Drumochter and Creag Meagaidh hills occupy summit areas where ground remains moist throughout the year largely due to late-lying snow patches. Some of them were found well inside the Loch Lomond Advance Limit on the Gaick Plateau

(NN 648788) in the Drumochter area.

A noticeable feature of all types of lobe distribution as displayed by the diagrams in Fig. 6.1.1 is that lobes cease to occur on the ground of maximum altitude, i.e. near the summit areas. The reason is largely related to the slope conditions, a factor which will be discussed in Section 6.3.3 on slope angle.

6.3.2 Aspect

Along with the study of altitude it was considered necessary to study the slope aspects of lobes and lobate sheets in the respective areas. The basic purpose was to find out if lobes and lobate sheets prefer any particular aspects.

Several drawbacks were encountered in this study, as followes. a) The slope aspects are largely controlled by the overall topography; consequently the hillslopes of a certain area may not be equally distributed among all aspects. The proportion of land facing south in the Cairngorm study area is markedly limited. b) As has been discussed before, the distribution of lobes and lobate sheets largely depends upon the nature of the slope. Regardless of aspect convex slopes exhibit a greater number of all types of lobe than concave ones : concave slopes are often found lying below very steep rock slopes including cliffs. c) A further limiting factor is the nature of the surface topography. Cliff faces, very steep slopes (>$35^{o}/36^{o}$) or very gentle slopes (<6^{o}), particularly near the summits, may occupy a considerable area of any aspect, thus resulting in considerable areas without lobes or other mass movement features. d) The other important factor appears to be the peat that occupies some parts of the study areas.

Bearing all these limiting factors in mind a map study of aspects was carried out for the lobes in the Drumochter area. Only this area was studied since it is the only one that has a considerable area of ground facing all aspects. Samples of total land area and lobe-covered land area were collected for the eight major aspects and all types of lobe were taken into account. The diagram A of Fig. 6.1.2 represents the distribution of land and lobe-covered land of all aspects. This shows an overall similarity between the two variables. The significant lag of lobe percentage behind the land percentage for the eastern slopes is largely due to the occurrence of cliff faces or peat. For the south-western slopes turf-banked terraces associated with vegetation-covered sheets are found to be the dominant feature. Diagram B in the same figure illustrates the percentage of lobe-covered ground in terms of the total ground surface for all major aspects. It suggests a certain tendency for the lobes to prefer northern, north-western and south-eastern slopes. This

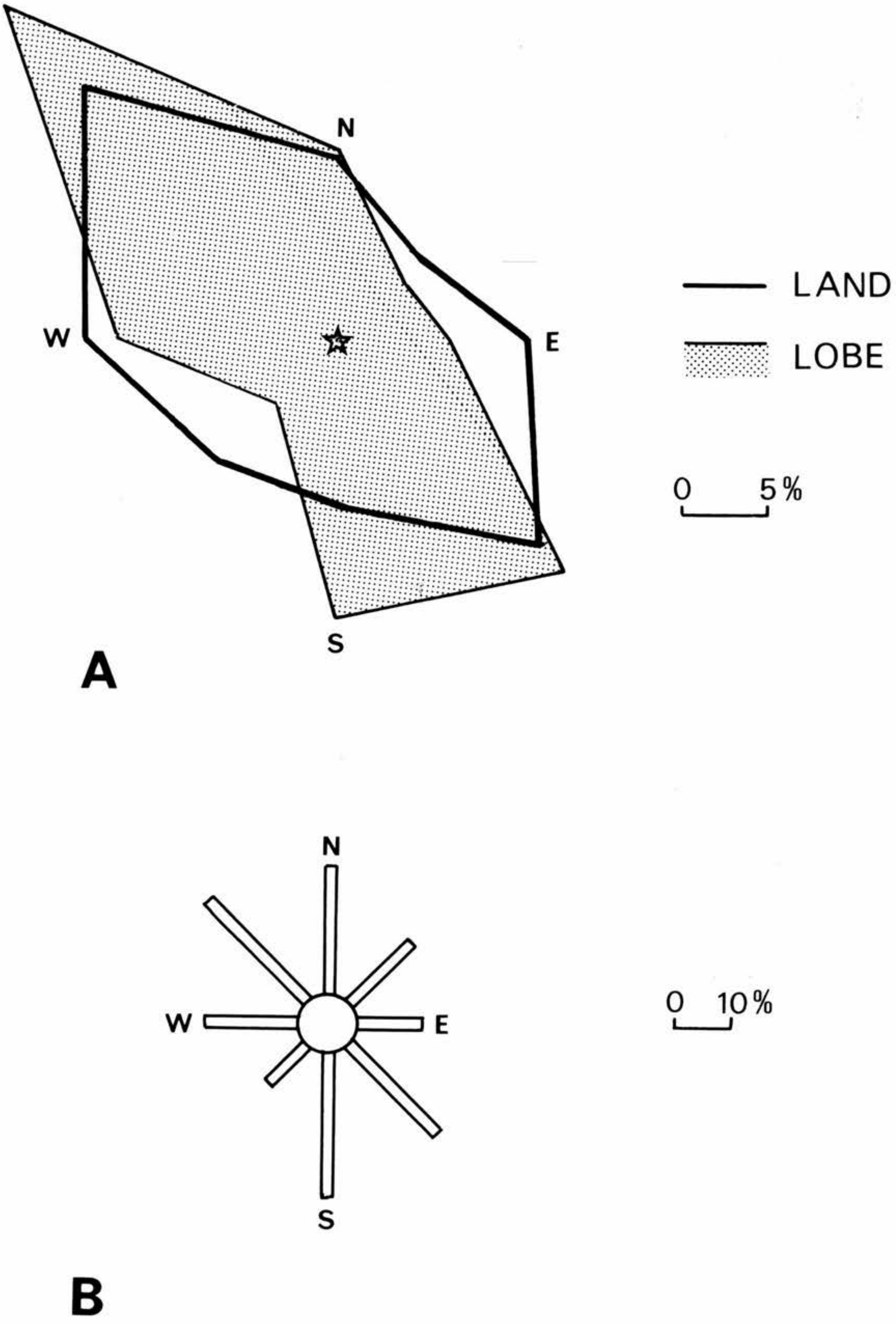


Fig. 6.1.2

The pattern of all types of lobe distribution on the hill slopes in the Drumochter area for the eight major aspects based on data derived from the geomorphological map. Diagram A shows the percentage distributions of land and lobes and B represents the percentage of ground surface occupied by lobes for different aspects.

largely coincides with the convex nature of hillslopes and, in turn, availablity of lobe and lobate sheet-forming material. The highest values for debris lobes were collected from the convex slopes of Geal-charn which decline north-westwards.

6.3.3 Slope angle

Map sampling for the slope angle of lobes and lobate sheets was done on the geomorphological maps of the study areas based on 100m grid and 5° classes.

Debris lobes in the Drumochter and the Creag Meagaidh hills In the Drumochter and the Creag Meagaidh hills all debris lobes are developed upon slopes between 8° and 35°. In the Drumochter area 53% of the sample occurred between 15° and 25° slope angle with a mean of 19° (standard deviation : 7°). This pattern can be compared with that of the Creag Meagaidh area where more than 64% of the sample lies in the same range with a mean angle of 20° (standard deviation : 6°).

The pattern of debris lobe distribution in the study areas in terms of hillslope gradients is illustrated in Fig. 6.1.3. Diagrams A1 and B1 show the distribution of debris lobes in the Drumochter and the Creag Meagaidh hills relative to the land surface from above the observed minimum. The favoured range of slope angle as obtained from these two diagrams (where lobe sample rises above land sample) differs slightly between the two areas. In the Drumochter hills this range is 15°-25°. In the Creag Meagaidh area this expands to 15°-30°. Diagrams A2 and B2 demonstrate the percentage of ground occupied by lobes in different slope gradient classes. There is a general similarity between the two diagrams, for the percentage of ground occupation by lobes increases up to the 20°-25° classes from where a decline begins. But the amount of lobe occupation in successive lobe gradient classes in the Creag Meagaidh area is greater than in the Drumochter hills. There are two possible reasons for this diversity, as follows. (i) A considerable portion of ground in the Drumochter area is covered with peat, thus restricting lobe occurrence in spite of favourable slope conditions. (ii) Vegetation-covered small lobes, which are more widespread in the Drumochter than the other area, occupy a considerable area of ground whose slope is ideal for all types of lobe.

<u>Boulder lobes in the Cairngorms</u> In the Cairngorm study area boulder lobes are developed on slopes with a range of 7°-35°, which is identical to that of the debris lobes in the two other areas. For the Cairngorm boulder lobes the mean slope angle is only marginally higher than that of the debris lobes, being 21° (standard deviation : 6°). Diagram C1 in Fig. 6.1.3 shows a favoured range of slope

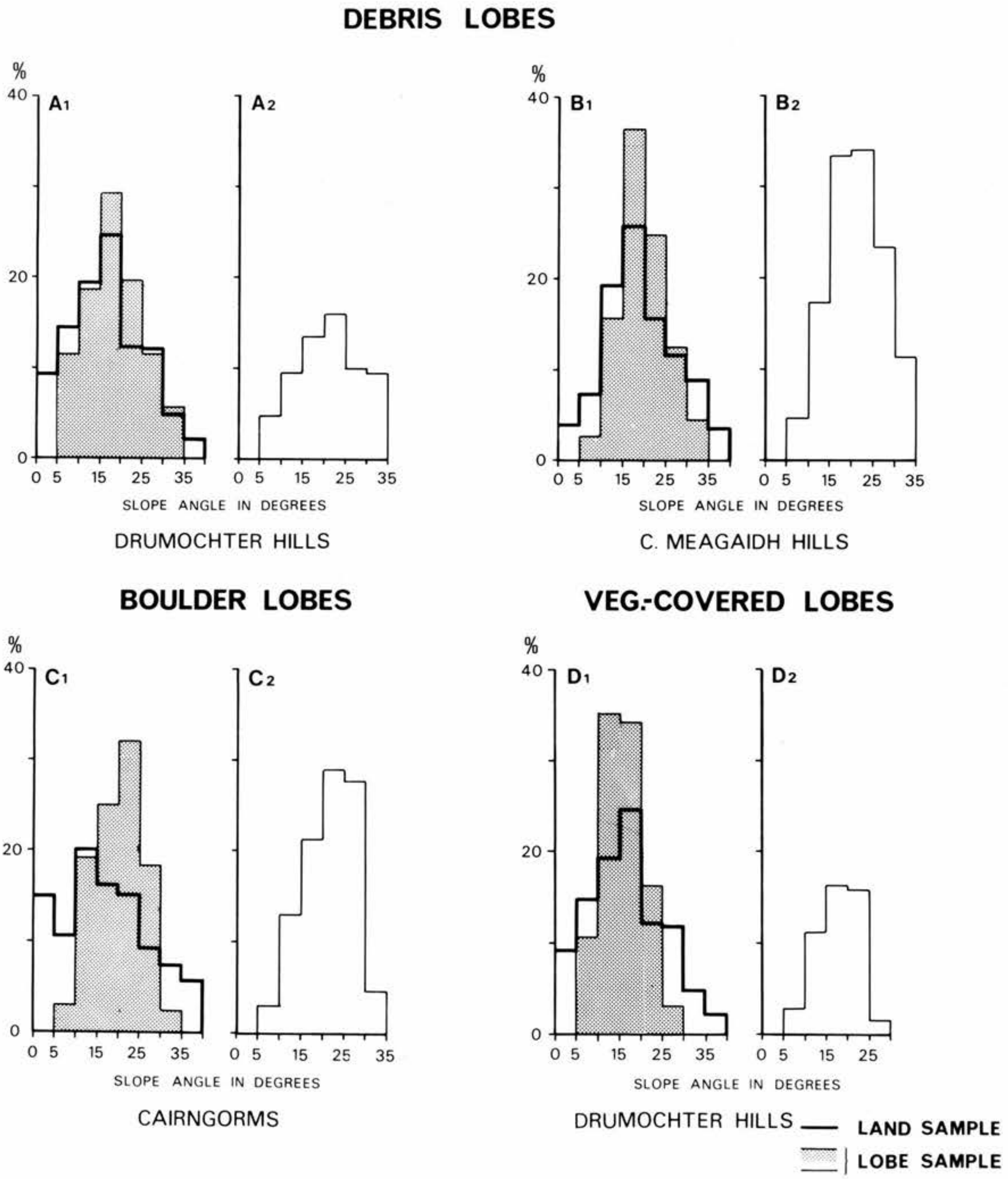


Fig. 6.1.3

Distribution of lobes in relation to hillslope gradient in the three study areas based on data derived from the geomorphological maps. The diagrams A1, B1, C1 and D1 show the percentage distributions of land and lobes, and A2, B2, C2 and D2 represent the percentage of ground surface occupied by lobes at different slope gradient classes above the favoured minimum.

angle between 15^{o} and 30^{o} as the lobe sample exceeds land sample. Diagram C2, representing the percentage of ground covered with lobes in different slope angle classes, indicates an increasing impact of boulder lobes on ground upto 15^{o}-20^{o} slope gradients.

Vegetation-covered small lobes in the Drumochter hills

Vegetation-covered small lobes were found to have developed, in all cases, upon gentler slopes. In the Drumochter area their range of slope angle is 6^{o}-27^{o}, the mean being 16^{o} (standard deviation : 5^{o}).

Diagram D1 suggests a preferred range of slope angle between 10^{o} and 25^{o}. The diagram also indicates that about 68% of the sample are inside the range 10^{o}-20^{o}. Diagram D2 reveals that this type of lobe has a lesser impact on the ground surface of any slope angle classes, which is consistent with their limited occurrence in the study area.

Discussion

There are relationships between ground slope and the three types of lobe, as follows. a) In all cases both land and lobe samples increase steadily towards the moderate slope thus showing a very similar relationship of these two variables with the slope angle, although this relationship is not symmetrical for the Cairngorm boulder lobes. A large proportion (>45%) of the ground surface in the Cairngorm study area is of fairly low gradient (<15°), which is typical for the plateau topography. b) The mean values of slope angle for the debris lobes and boulder lobes have a general similarity , being between 19° and 21°, whereas a considerably smaller value (16°) is obtained for the vegetation-covered small lobes. c) No lobe sample was obtained from slopes gentler than 6°. The maximum slope gradient obtained for the boulder and debris lobes is 35° and for the vegetation-covered lobes 27°.

The above results may be compared with those of other workers in Scotland. Many of the debris type of lobe that Galloway (1958, 1961a) reported as stone-banked lobes from Ben Wyvis have an estimated range of 8°-20°, which is considerably lower than the present findings by extensive sample study. King (1968, 1972), from a small sample, found that 'stone-banked lobes' (considered to be boulder lobes) in the Cairngorms are generally developed upon slopes of 20°-35°. Shaw (1977) measured 'granite lobes' between 10° and 34° and 'metamorphic lobes' between 18° and 33° slope angles. Sugden (1970a) suggested that 'stone-banked lobes' (boulder lobes) can develop upon slopes of 20°-35°.

Galloway (1961a) gave a slope range of 5°-12° for 'turf-banked lobes' (vegetation-covered small lobes in the present study) on Ben Wyvis, which can be compared with the range of $6^{o}-27^{o}$ for the similar features in the Drumochter hills.

Most of these reports on the lobe slope-gradients are based on either visual assessment or limited sample study and are not in entire agreement with the findings of the present study involving detailed measurement on extensive areas.

6.3.4 Summary

The above study of lobe distribution can be summarized as follows :

(i) Lobes of debris type and small vegetation-covered type tend to become more widespread as altitude increases. On the other hand, the boulder lobes in the Cairngorms are more widespread on the lower slopes. For the vegetation-covered small lobes the lowest limit of 750m was obtained in the Drumochter hills, which suggests that this type is particularly sensitive to altitude and its occurrence is restricted to the higher ground. No lobes occur on the highest ground or the summit areas chiefly because of very low slope gradients.

(ii) The study of lobe aspects for the Drumochter hills indicates that northerly, north-westerly, southerly and south-easterly slopes are preferred for all types of lobe. The convex nature of hillslopes with these aspects, providing abundant lobe and lobate-sheet forming material, is suggested as the explanation.

(iii) The mean slope angle for the vegetation-covered small lobes (16°) is distinctly lower than those of the two other types (between 19° and 21°). This value reflects the tendency of the former to prefer higher ground of lower slope gradients.

(iv) The absence of boulder and debris lobes inside the Loch Lomond Advance limit implies that no such lobe formation has taken place since final deglaciation; conversely the presence of some vegetation-covered small lobes inside this limit in the Drumochter area, although in very small numbers, suggests that they at least have formed and moved downslope in postglacial times. This view is supported by the mid and late Flandrian radiocarbon dates obtained by Mottershead (1978) from a buried organic layer beneath a solifluction feature on Ben Arkle.

6.4 Morphology

The morphological characteristics of the three types of lobe were studies by measuring a number of parameters. The survey was carried out in the field for the selected sample size of each type of lobe . The measured parameters are : (i) altitude, (ii) slope angle, (iii) surface angle, (iv) riser length, (v) riser height, (vi) riser angle, (vii) lobe length, (viii) lobe width, (ix) lobe area, (x) lobe thickness, (xi) spacing and (xii) vegetation cover.

Two main elements of lobes were considered. They are the riser and the tread. The riser is the downslope front of the bank where a lobe or lobate sheet terminates and the tread is the surface of the lobe. The ground below the riser is less steeply inclined than the riser itself and this break of slope was normally easily identified as the base of the riser. However, the top end of the riser was found, in most cases, to merge into the surface of the tread, for the riser profile is convex compared to the flat or slightly concave profile of the tread. A point, therefore, had to be selected where these two profiles joined together as representing the highest point of the riser.

The parameters used in the field for the lobes can be explained as follows :

(i) Altitude : the approximate altitude of the ground at which lobes and lobate sheets occurred. The Ordnance Survey (1:10,000 scale) maps with 10m contour intervals were used for this purpose.

(ii) Slope angle : the gradient of the slope upon which the sample lobe occurred. This was measured in the field by an Abney level. Two poles were placed on the hillslope, one at the ground below the riser and the other at the rear-end of the lobe upslope, the Abney level reading taken from the lower pole (Fig. 6.2, B : θ).

(iii) Surface angle : the gradient of the slope of the lobe-tread. This parameter was also measured by the Abney level and the reading was taken from the top of the riser to the rear end of the lobe (Fig. 6.2, B : ϕ).

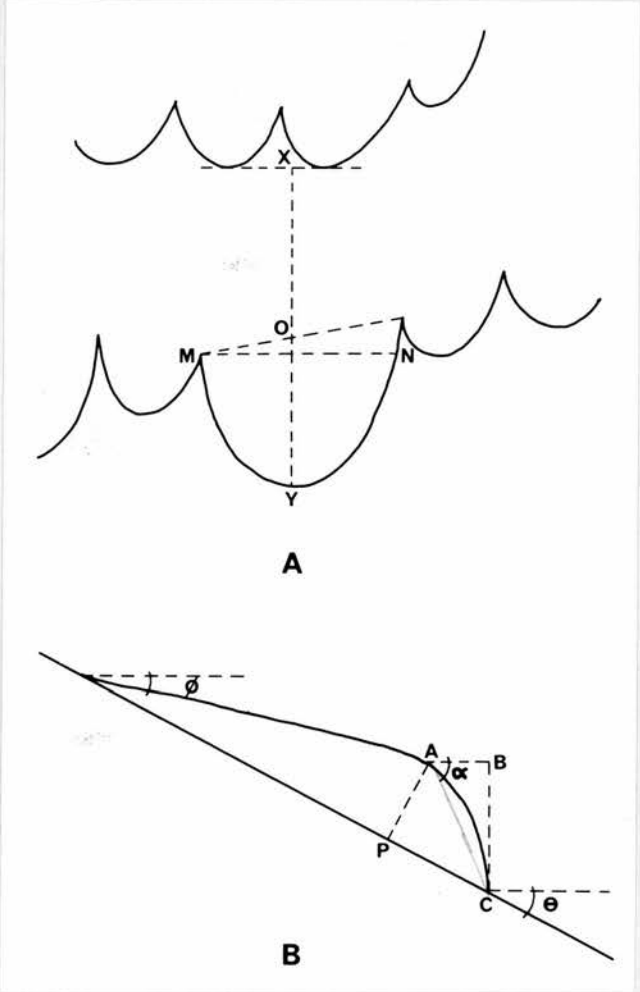


Fig. 6.2 Key to the measured parameters of lobe.

(iv) Riser length : the horizontal distance from the riser crest to the base of the riser (Fig. 6.2, B : AB).

(v) Riser height : the height of the crest of the riser above its base (Fig. 6.2, B : BC).

(vi) Riser angle : the gradient of the riser (from the horizontal plane). This was calculated from the riser height and the riser length using the equation *A tan (riser height/Riser length)* (Fig. 6.2, B : α).

(vii) Lobe length : the distance from the front to a line connecting the end points of the left-hand and the right-hand sides of the lobe (Fig. 6.2, A : OY). This is because the sides of a lobe are often unequal in length.

(viii) Lobe width : the horizontal distance between the upper end of the shorter side (left or right) and the other side (Fig. 6.2, A : MN).

(ix) Lobe area : the surface area obtained from lobe length and lobe width. As the lobes taper downslope, area was calculated as *2/3(Lobe length* X *Lobe width)*.

(x) Lobe thickness : the thickness of the lobe-forming detritus. Four variables were used to calculate the thickness : riser length, riser height, slope angle and riser angle. The equation is *Sin (Riser angle - Slope angle)* X *Sq. rt. (Riser length*^{2} + *Riser height*^{2}). The result is the maximum thickness or the thickness at the front of the lobe (Fig. 6.2, B : AP).

(xi) Spacing : the distance from the lobe front to the front of the nearest lobe upslope along a straight line (Fig. 6.2, A : XY).

(xii) Vegetation cover : the cover of vegetation on the tread and the riser of each lobe was estimated at 10% intervals.

The measurements were carried out in the field on a number of randomly selected lobes from each type. The study of the debris lobes is based on 400 sample lobes, 200 being selected from each of the Drumochter and Creag Meagaidh areas. The sample size for the boulder lobes is 200, all being selected from the Cairngorms. Vegetation-covered small lobes were found to have developed in relatively limited areas and 100 sample lobes were studied in the Drumochter area.

The result of the study of morphological characteristics of all types of lobe are illustrated in Fig. 6.3.

6.4.1 Lobe size (length, width and area)

Debris lobes Debris lobes in the Drumochter hills range in length from 1.2 to 18m and in width from 1.7 to 14m with mean length and width being 5.1m (standard deviation : 3.3m) and 5.3m (standard deviation : 2.5m) respectively. 70% of the sample lengths and greater than 85% of the sample widths are below 6m. This results in a high degree of positive skewness in the distribution. In the Creag Meagaidh area debris lobes have a mean length of 6.2m (standard deviation : 3.1m) and width 6.8m (standard deviation : 3.3m) indicating that lobes in this area are larger features. This difference in length and width is also reflected in the calculated lobe surface area obtained for these two areas. The mean area for the Drumochter lobes is $20.5m^2$ and for the Creag Meagaidh lobes is $32.2m^2$.

Boulder lobes Boulder lobes in the Cairngorms are distinctly larger features and their mean length and width as derived from the study are 9.1m (standard deviation : 3.9m) and 8.2m (standard deviation : 2.8m) respectively. A noticeable similarity exists between the debris lobes and the boulder lobes in the range of length. Boulder lobes range between 2.4 and 20.8m in length. A majority (70%) of the boulder lobes are less than 10m long. A mean of $54.1m^2$ was obtained for the area of this type of lobe.

Vegetation-covered small lobes Small vegetation-covered lobes in the Drumochter hills have a very limited individual extent compared to the two other types. The mean values for the length and width are 2.1m (standard deviation : 0.8m) and 3.4m (standard deviation : 1.1m) respectively. The ranges of length (0.8 to 4m) and width (1.9 to 6.7m) are also limited. The mean area calculated for this type of lobe is $5.1m^2$.

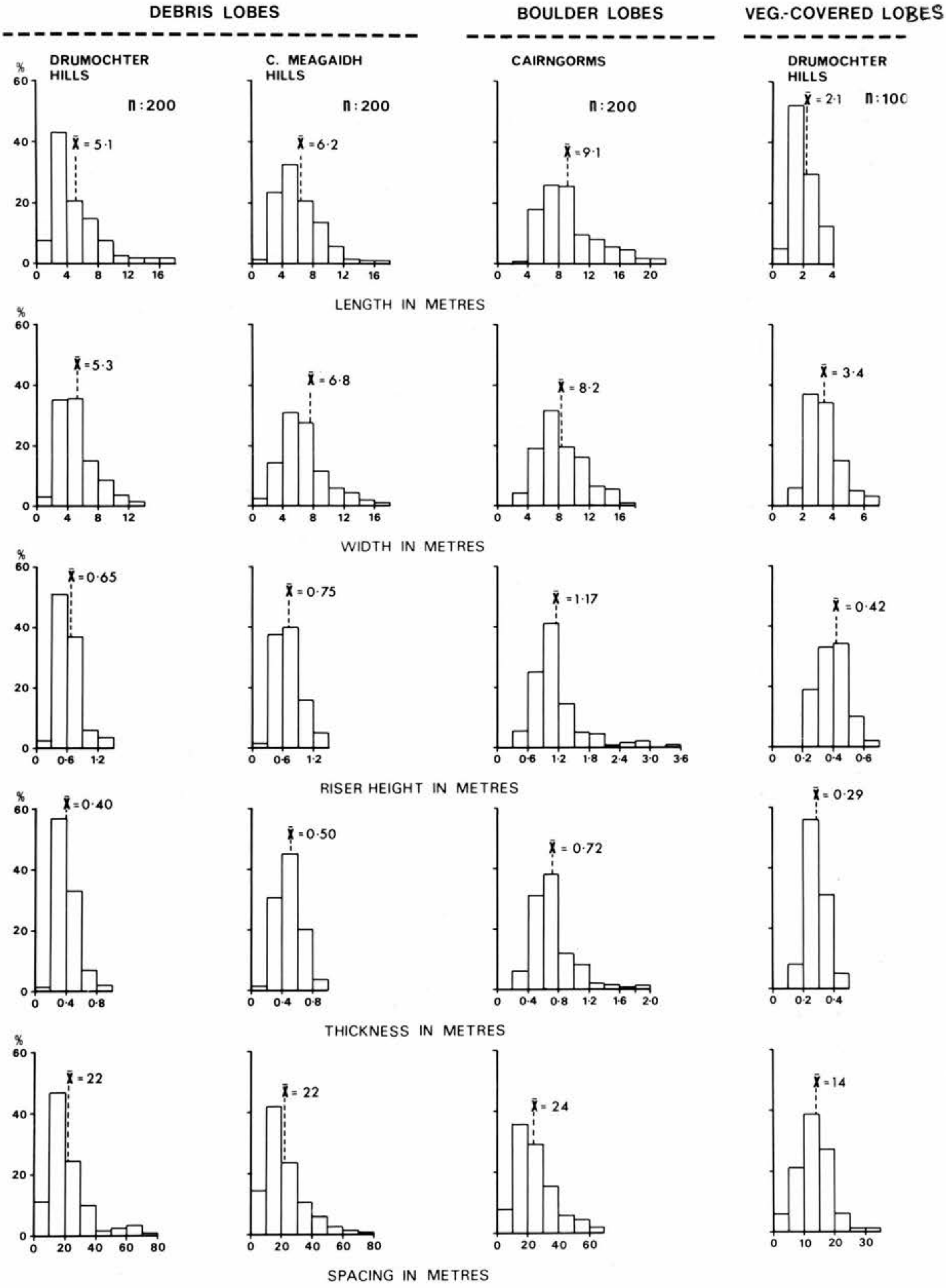


Fig. 6.3

Percentage frequency distributions summarizing some morphological characteristics of the three types of lobe surveyed in the field.

Discussion

The above study of the size of the lobes shows the following for the sample studied. (i) The three types vary markedly in size. The length and width of the two sample distributions, Drumochter debris lobes and the Cairngorm boulder lobes, were statistically compared (Kolmogorov-Smirnov test) and found to be significantly different at the 99% confidence level. The same degree of difference occurred when this statistical test was applied to the Drumochter debris lobes and the vegetation-coverd small lobes. This could suggest that these three types of lobe have not developed through the similar response of lithology to the weathering and mass movement processes. (ii) Debris lobes and boulder lobes have a very similar range in length although for the debris lobes the length values are largely concentrated to the negative side of the mean. (iii) Unlike boulder lobes the debris lobes and the vegetation-covered lobes are greater in width than in length. This feature is apparently associated with the pattern of mass movement processes which will be discussed in Section 6.5. Primarily this feature may be attributed to the nature of these lobes. It has been observed (Chapter 5) and demonstrated by the sample study (Section 6.4.4) that the majority of debris lobes are of turf-banked type. The progression of lobe development can be hypothesised as follows. As the turf bank develops at the front of a debris lobe the internal constitution of fines and stones tends to spread horizontally, i.e. along the width owing to restriction of downslope movement. This helps the debris lobe to expand along the width. For the development of vegetation-covered small lobes the process is largely controlled by the vegetation-covered sheets. These sheets occur largely on the higher slopes where incresingly low gradient of slope restricts any rapid downslope movement of surface material; consequently lobes of greater width develop. True boulder lobes are, on the contrary, exposed at their fronts (as described in Chapter 5) and it is proposed that unrestricted mass movement of material favours greater expansion of the feature downslope than along the width.

The size of gelifluction lobes has been reported by several workers. Individual lobate terraces in the Cairngorms have been reported up to 30 to 40m long and 30m wide (Metcalfe, 1950). 'Stone-banked lobes' (boulder lobes) in the western Cairngorms were found to be spaced at 9 to 180m with a mean spacing of 70m and mean width of 13.6m (King, 1968). 'Stone-fronted lobes' between 4 and 30m wide have been reported from Ben Wyvis (Galloway, 1958, 1961a). Lochnagar lobes have been described as up to 15m or more long (Fyffe, 1968). Mean length and width of the granite lobes in the same area were measured as 33.2m and 14.8m (Shaw, 1977). 'Stone-banked lobes' of some tens of metres in downslope length were reported from Snowdonia (Ball and Goodier, 1970). Very small features, up to only 0.3 or 0.6m wide were described from the Southern Uplands of Scotland (Tivy, 1962) and from northern England (Tufnell, 1969).

Any comparison of these findings with the result of the present study is difficult since, in most cases, data were derived from visual estimation. Also the length of lobes was often based on the spacing distance or the length of the longer side of the lobe, neither of which methods was followed in the present study.

6.4.2 Lobe thickness

The thickness of lobe is a difficult parameter to measure. Lobes and lobate sheets descend downslope to terminate abruptly as a bank formed either of turf (vegetation) or stone. The ground of the lobe surface (tread) is always gentler than the ground below. This is because the maximum accumulation of debris is concentrated near the front of the lobe and this gradually becomes thinner upslope. The equation (given earlier), using the slope angle, riser angle, riser length and riser height, approximates the maximum thickness or the thickness at the front of the lobe.

Debris lobes In the Drumochter hills mean thickness for the debris lobes was calculated to be 0.4m (standard deviation : 0.14m), which can be compared to a mean of 0.5m (standard deviation : 0.25m) found for the lobes in the Creag Meagaidh area. The thickness of debris lobes varies considerably, a maximum of 0.9m in the Drumochter and 0.91m in the Creag Meagaidh hills having been found.

Boulder lobes A mean value of 0.72m (standard deviation : 0.3m) for boulder lobe thickness was obtained from the Cairngorm area with 70% of the sample occurring to the negative side of the mean. The maximum thickness of 1.82m found for the boulder lobes in this area is considerably higher than the maximum thickness of the debris lobes of the two other areas.

Vegetation-covered small lobes The range of thickness for the vegetation-covered small lobes is noticeably limited being only from 0.16 to 0.42m with a mean of 0.29m (standard deviation : 0.06m).

Discussion

The study reveals distinct variations in thickness of the three types of lobe. This variation is obvious for the vegetation-covered small lobes. The difference between the debris lobes of the Drumochter and the Creag Meagaidh areas and the boulder lobes of the Cairngorms is significant at the 99% confidence level (Kolmogorov-Smirnov test). It has previously been propopsed (Chapter 5) that with the increase of hillslope gradient detritus shows a downslope gradation from horizontal sheets to lobate sheets to lobes. The thickness of lobes and lobate sheets is certainly a reflection of the type of detritus available. Individual granite boulders are larger in volume than schistose rocks; consequently boulder lobes and lobate sheets attain distinctly greater thickness than any other types. Vegetation-covered small lobes are restricted to the upper hillslopes and their considerably smaller thickness is largely related to the type of material (small stones and a substantial amount of fines) of which they are formed.

The riser height has often been quoted in the literature. Galloway (1958, 1961a) reported stone-fronted lobes from 1 to 5m high on Ben Wyvis. King (1968) examined risers of 'stoned-banked lobes' (boulder lobes) upto 4 and 5m high in the western Cairngorms. Metcalfe (1950), working in the same area, had previously observed 1 to 4m high risers for the lobate features. The heights of the risers of lobes in the Lochnagar area have been estimated as up to 6m (Galloway, 1958), up to 4.6m (15ft) (Fyffe, 1968) and at 2 to 5m (Grant, 1971). Shaw (1977) reported a calculated range of thickness for the granite lobes in the same areas between 0.3m and 5.9m.

Riser height is certainly the principal controlling factor the lobe thickness but a substantial degree of variation exists between the size of the two variables. Riser height is always much larger than thickness.

This can be seen in Fig. 6.2, B, where BC (riser height) is distinctly longer than AP (lobe thickness). In the Cairngorms a maximum riser height of 3.5m was obtained for the boulder lobes, which markedly exceeds the calculated maximum thickness of 1.82m.

6.4.3 Lobe spacing

Lobe sequences succeeding one another downslope were also investigated. The distance from the lobe front to the next lobe front upslope was measured in an attempt to understand the order in which the lobes and lobate sheets are arranged on the hillslope.

Debris lobes In the Drumochter hills debris lobes are spaced from 2.4 to about 72m with a mean of 22m (standard deviation : 13.4). The same type of lobe in the Creag Meagaidh area has a range of spacing between 2.1 and 82m with the same mean of 22m (standard deviation : 13.1m). 60% of the samples of both of these two areas are spaced at less than 20m.

Boulder lobes The spacing range for the Cairngorm boulder lobes (7.5 to 70m) has a broad resemblance with the debris lobes. The mean spacing distance is 24m (standard deviation : 13m) with greater than 70% spaced at less than 30m.

Vegetation-covered small lobes Vegetation-covered small lobes in the Drumochter area maintain a relatively close spacing having a range of 2 to 34m with a mean of 13.7m (standard deviation : 5.3m). 53% of the sample are spaced at less than 15m.

Discussion

It has already been mentioned in the preceding section that the patterned gradation of detritus upon hillslopes is the most important determining factor of lobe morphology. The size range for the lobes of debris type and boulder type is much longer than that for the vegetation-covered small lobes. Boulder lobes and debris lobes occupy hillslopes where frost-shattered blocks and debris are abundant. Hence lobes of larger size develop and the spacing distance is basically determined by their size. It was observed in the field that lobes and lobate sheets of all types are remarkably developed upon convex slopes (Section 6.3.1). Upon convex slopes lobes and lobate sheets were seen frequently overriding one another and thus exhibiting very close spacing. This pattern disappears as the slope gradient increases. Consequently individual lobes, which have often become separated from sheets, occur with longer spacing distances. The very positively skewed spacing distribution, as shown in the histograms of the two major lobe types is, in fact, due to the influence of a limited sample of lobes of very distant spacing from outside preferred hillslopes. Vegetation-covered small lobes, on the contrary, are restricted only to the upper convex slopes and exhibit a general uniformity in close spacing. Their shorter spacing distances are also consistent with their miniature size.

Very little work has been done on lobe spacing. Many of the workers previously mentioned confused lobe length and spacing in their field studies. However, King (1968) derived, from a very small sample in the Cairngorms, a mean spacing of 70m for the boulder lobes (range 9-180m). Shaw (1977) reported from the Lochnagar area, on the basis of his estimation from the longest lobe-side distance, a mean length (spacing) of 33.2m for the granite lobes and 13.8m for the metamorphic lobes.

6.4.4 Vegetation cover

Vegetation is characteristic of all types of lobe measured in the study areas. The higher slopes and summits of the hills are often carpeted with Rhacomitrium heath. Small lobes of finer material on the upper slopes are almost entirely covered with this type of vegetation. Vegetation is considered as an important component of the gelifluction process (e.g. Wilson, 1952; Sigafoos and Hopkins, 1952; Washburn, 1967, 1973, 1979), although it is not essential in boulder and debris lobe formation as these lobes were formed before widespread vegetation came to be established upon them. During the field study a visual estimate was made of the gross percentage of vegetation cover on the tread and riser of each sample lobe of debris type and boulder type.

Debris lobes Debris lobes were found to have a less amount of vegetation cover on the tread than on the riser. Only 10% of the lobes in these areas exhibit vegetation cover greater than 50% on the tread. The mean values for vegetation cover on the tread for the Drumochter and the Creag Meagaidh debris lobes are 35% and 30% respectively. By contrast the lobe risers are often thickly vegetated. Mean vegetation cover on the riser for the Drumochter lobes is 70% and for the Creag Meagaidh lobes 75%. Greater than 90% of the debris lobes in the Drumochter and the Creag Meagaidh hills are found to have more than 60% vegetation cover on the riser and can be termed turf-banked lobes (as opposed to stone-banked lobes).

Boulder lobes Boulder lobes in the Cairngorms are, however, less vegetated on their riser than on the tread.

Boulder lobe treads are characteristically covered with thick patches of lichens and often with a variety of plants. 60% of the sample lobes were found to have greater than 50% vegetation cover on the tread. Risers of the boulder lobes were found to be generally lacking in vegetation and these bare risers are obvious features when seen from a distance. Only occasional groups of plants were found in the niches between some boulders. 72% sample were found to be almost completely devoid of vegetation on the riser and the remaining 28% were only partly vegetated.

Discussion

The most interesting feature revealed by the study of vegetation is the distinct variation in vegetational distribution upon lobes of debris type and boulder type. Debris lobes in general, are exposed at the tread and banked by turf (vegetation) at the riser. This can be regarded as a major criterion for distinguishing the two types. The mechanism through which a turf-covered or an exposed riser develops remains to be discussed in detail in a later section (composition and mechanism). In general the growth of a turf-bank in front of the debris lobe appears to be related to the presence of a considerable amount of finer material, which is not common for the boulder lobes.

6.4.5 Factors controlling lobe morphology

The three types of lobe present in the study areas are varied in size, thickness, spacing and vegetation cover as revealed by the above study. An attempt has been made to understand the relationships between the lobe morphology and the most likely controlling factors : altitude and hillslope angle. Six important parameters (length, width, riser height, riser angle, thickness and spacing) of each lobe type, sampled from the study areas, were regressed on the corresponding altitudes and the hillslope angles. Table 6.1 illustrates the results of the study.

Debris lobes For the Drumochter debris lobes statistically significant inverse relationships are found between altitude and all tested parameters except width. This is highly significant (99%) for riser height, riser angle and thickness. The thickness of the lobe is largely influenced by the riser height and the riser angle. Hence a highly significant relationship of thickness with altiutude indicates a gradual thinning of debris lobes as altitude increases. Moderate statistical significance (95%) is obtained for spacing and length. These results are comparable with those obtained for the Creag Meagaidh debris lobes where all the tested parameters produced a statistically highly significant (99%) inverse relationship when regressed against altitude. The

Drumochter debris lobes
n : 200

	Alt.	Slp.ang.
Length	-0.036 - - - -	0.032 - - - -
Width	0.012	0.000
Riser height	-0.123 -------	0.348 -------
Thickness	-0.078 -------	0.212 -------
Riser angle	-0.116 -------	0.706 -------
Spacing	-0.040 - - - -	0.029 - - - -

Creag Meagaidh debris lobes
n : 200

	Alt.	Slp.ang.
Length	-0.096 -------	0.102 -------
Width	-0.185 -------	0.010
Riser height	-0.281 -------	0.303 -------
Thickness	-0.176 -------	0.073 -------
Riser angle	-0.109 -------	0.563 -------
Spacing	-0.240 -------	0.032 - - - -

Cairngorm boulder lobes
n : 200

	Alt.	Slp.ang.
Length	0.303 -------	0.000
Width	0.212 -------	0.014
Riser height	0.203 -------	0.048 - - - -
Thickness	0.303 -------	0.048 - - - -
Riser angle	0.000	0.010
Spacing	0.084 -------	0.008

Drumochter veg-covered lobes
n : 200

	Alt.	Slp.ang.
Length	-0.303 -------	0.001
Width	-0.032 - - - -	0.001
Riser height	-0.303 -------	0.176 -------
Thickness	-0.221 -------	0.053 - - - -
Riser angle	0.001	0.040 - - - -
Spacing	0.004	-0.006

r^2 values are plotted in the table.

-------	99% Significant diff.
- - - -	95% Significant diff.

Table 6.1 Correlations between selected lobe parameters and most likely controlling factors.

strongest relationship exists for the riser height as in the Drumochter hills.

The inverse relationships of the major debris lobe parameters with altitude suggests that lobes tend to become morphologically less important as altitude increases.

Correlation testing of the debris lobe parameters with hillslope angle shows a very high degree of significance in all cases except for lobe width where no significant statistical relationship exists. In the Drumochter hills riser height, riser angle and thickness have a statistically highly significant (99%) relationship with hillslope angle. In the Creag Meagaidh area lobe length also attains maximum statistical significance (99%) when correlated with slope angle. The strongest relationship was found in the case of riser angle for both areas (Drumochter hills, r^2 : 0.706; Creag Meagaidh hills, r^2 : 0.563). The regression equation for all 200 data values for riser angle and slope angle for the Drumochter hills is : $Y = 13.91 + 0.42X$.

Correlation values are larger for slope angle than for altitude. This can be attributed to the greater influence of slope angle than altitude on debris lobe development. From the above analysis it can also be inferred that hillslopes of lower altitude (above the lowest lobe limit) with higher gradients of slope favour the development of debris lobes of larger size.

Boulder lobes Boulder lobes in the Cairngorms have statistically highly significant (99%) positive relationships of all their tested parameters with altitude, except riser angle. The strongest relationship occurs for lobe length and lobe thickness. This indicates that boulder lobes tend to be longer and thicker. i.e. larger in extension and in volume as altitude increases.

Correlation tests of these lobe parameters with hillslope angle produced results that are not statistically significant except for the riser height and thickness where moderate statistical significance (95%) exists.

The results of the relationship test for the Cairngorm boulder lobe parameters strongly suggest that altitude is the most important factor for the occurrence of larger lobes whereas hillslope gradient plays a relatively minor role. The tests also reveal that, unlike debris lobes in the two other areas, boulder lobes tend to become morphologically dominating features as altitude increases. This feature extends to the two other areas as well; all boulder lobes in the Drumochter and the Creag Meagaidh hills were found restricted to the higher ground.

Vegetation-covered small lobes Selected parameters of sample lobes of vegetation-covered miniature type in the Drumochter hills were regressed on the corresponding altitude and hillslope angle values. The results demonstrate a statistically highly significant (99%) inverse relationship in the cases of length, riser height and thickness. A lesser statistical significance (95%) was obtained for the width and no significance was found for the riser angle and spacing.

Correlation testing of lobe parameters with slope angle produced a highly significant (99%) statistical relationship only for the riser height.

Hence the interpretation of the above analyses could be that hillslope gradient has less influence than altitude on the occurrence of the vegetation-covered small lobes in the Drumochter hills, a result that differs from that for the debris lobes found in the same area.

6.5 Structural characteristics and possible mechanisms

The structure of lobes was studied by the investigation of surficial and internal composition of selected lobes of all types.

6.5.1 Surface characteristics

The study of surface characteristics involved the investigation of six debris lobes, three boulder lobes and three vegetation-covered small lobes. The three debris lobes chosen in the Drumochter hills were on the slopes of Geal-charn facing east (NN 608787), north-northwest (NN 595785) and south (NN 597780). In the Creag Meagaidh hills the sites were on the northwest-facing slope to the north of the corrie of Allt Coire Ardair (NN 435894), on the east-northeast-facing slope of Sròn a' Ghoire (NN 453877) and on the south-southwest-facing slope of Meall an t-Snaim (NN 460902). The three boulder lobes in the Cairngorms were selected from the slopes of Creag an Leth-choin facing east (NH 952033) and north-west (NH 968041), and the northwest-facing slope of Coire Gorm (NH 961021). Of the three vegetation-covered small lobes in the Drumochter hills one was on the north-northwest-facing slope of Geal-charn (NN 596785) and the other two were on the west-facing hillslope to the east of the pass (NN 644777, NN 644778). The purpose of this study was two-fold : to obtain the average clast size and to determine the pattern of fabric orientation for the three different types.

The characteristics of the mean clast diameter ((a+b+c)/3) of the selected lobes are displayed in Fig. 6.4 and in Table 6.2. A direct impression of clast-size variation for the three types of lobe can be obtained from Fig. 6.4 showing the distribution of mean clast size (n:50) for the front, sides and centre of the sample lobes of each type.

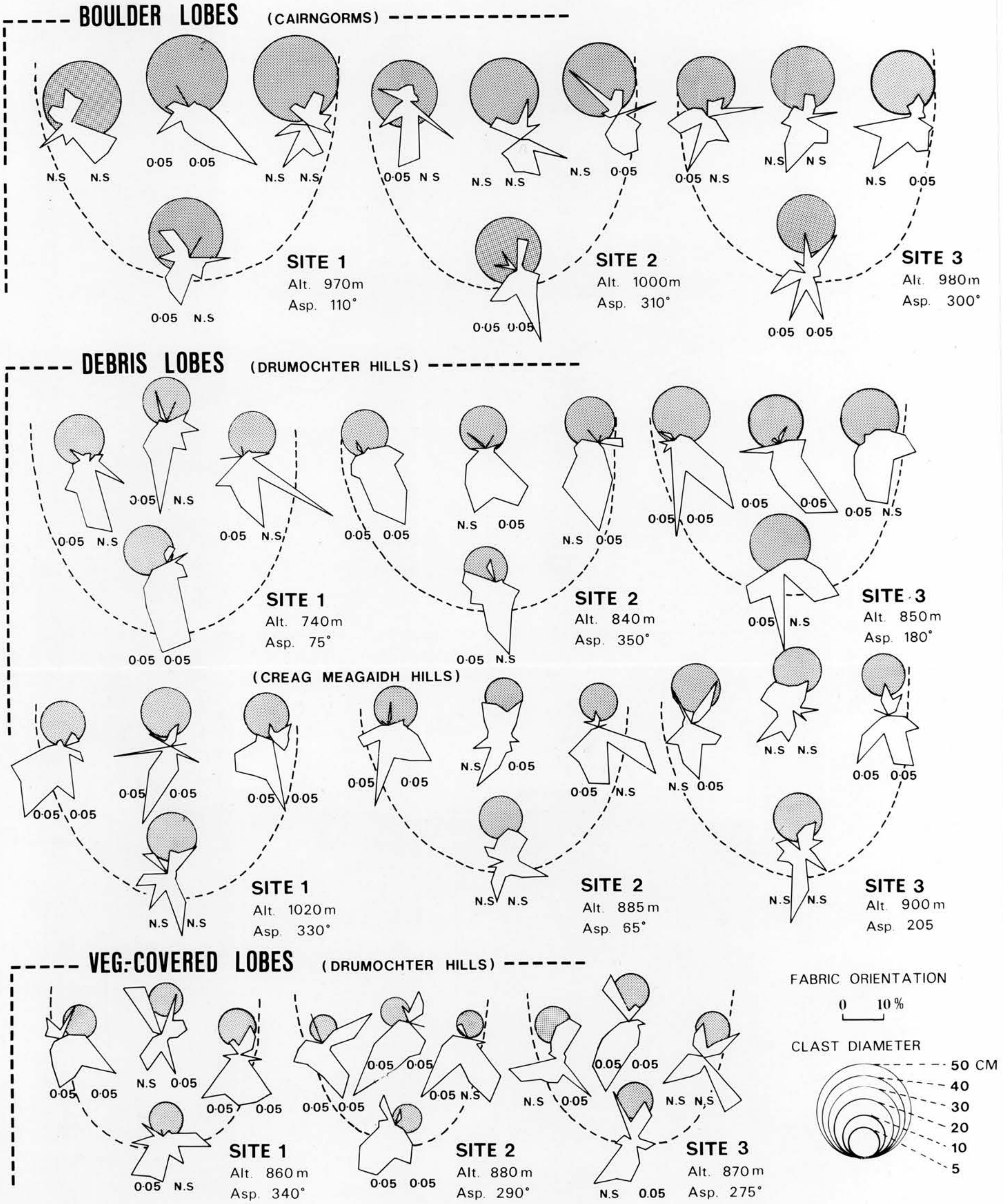


Fig. 6.4

Surface plan for three boulder lobes, six debris lobes and three vegetation-covered small lobes surveyed in the field, showing clast diameter (circles) and fabric orientation (fabric diagrams) at different locations on samples of 50 clasts in each case The figures represent significance level under the null hypothesis of circular uniformity in terms of inclination (A_n 360 statistic, left-hand figure) and orientation (A_n 180 statistic, right-hand figure). N. S. denotes no statistical significance.

The lengths of the three axes (a, b and c) of each clast for debris lobes and boulder lobes were measured to the nearest centimetre and for the vegetation-covered small lobes these were measured to the nearest millimetre.

The boulder lobes of the Cairngorms contain noticeably larger clasts in almost all locations on the surface than the debris lobes of the two other areas. The only exception is the Site 3 debris lobe of the Drumochter area where clast diameter is markedly greater than those of the average lobes in the same family. Such examples in the debris lobe category are very limited in number and are apparently transitional between debris lobes and boulder lobes. Table 6.2 shows that mean clast diameter for the boulder lobes extends from a minimum of 20.4cm to a maximum of 45.5cm considering all the locations on the surface. For the debris lobes a clast range of 7.9-22.5cm is found and if the example of the extreme case (i.e. Site 3 in the Drumochter hills) is excluded this range becomes restricted to 7.9-14.7cm, showing a distinct difference from those of the boulder lobes. For the vegetation-covered lobes, where the surface profile is dominated by a substantial amount of finer material, the average clasts are considerably smaller than both the other types, a range of 3.6-7.9cm for the clast diameter having been obtained from the study of the three samples.

There is no distinct pattern of surface sorting for the clasts in the three types of lobe studied except a slight

		<u>Mean clast diameter</u>					<u>Mean clast sphericity</u>
		((a+b+c)/3) incm					$(bc/a^2)^{1/3}$
	Site	L.side	R.side	Front	Centre	All sides	All sides
Cairngorm boulder lobes	1	45.5	35.2	31.5	40.1	38.1	0.65
	2	28.9	23.6	24.0	25.3	25.5	0.66
	3	24.9	20.6	20.4	22.2	22.0	0.62
Drumochter debris lobes	1	12.5	13.5	13.3	12.0	12.8	0.56
	2	14.3	11.2	10.3	12.4	12.1	0.52
	3	18.4	18.9	22.5	16.5	19.1	0.59
C.Meagaidh debris lobes	1	11.4	13.3	13.3	13.2	12.8	0.56
	2	8.9	9.5	9.6	7.9	9.0	0.52
	3	11.5	14.2	14.7	14.0	13.6	0.57
Drumochter veg-covered lobes	1	7.9	7.4	7.0	6.6	7.2	0.58
	2	3.6	4.1	4.4	3.7	4.0	0.58
	3	5.5	6.6	6.5	6.1	6.2	0.54

Table 6.2 Mean values of the surface clast diameter and sphericity for the three types of lobe measured in the field.

tendency for the larger clasts to be concentrated at the left-hand side of the boulder lobes which can be explained as accidental. For the boulder lobes at Site 1 and 3 the mean diameters of clasts at the front fall below those of the other locations. All the six debris lobes exhibit an irregular pattern in the surface clast sorting in terms of diameter. This pattern applies to the vegetation-covered small lobes as well.

Mean clast sphericity ($(bc/a^2)^{1/3}$) was also calculated for each of the sample lobes. Table 6.2 shows that sphericity values vary between 0.52 and 0.59 for the debris lobes and between 0.54 and 0.58 for the vegetation-covered lobes. The values for the boulder lobes are distinctly higher, being between 0.62 and 0.66. This is partly due to geological control, for the granite boulders tend to be more spherical than those predominantly of mica schist origin. However, the length of the period of exposure to weathering may also be relevant : it is suspected that surface clasts of the Cairngorm boulder lobes have experienced a longer period of superficial weathering and thus show greater sphericity of their component material. This can have been possible owing to stagnation since their formation. It has been suggested above that the debris lobe at Site 3 in the Drumochter hills is transitional between the debris type and the boulder type : a greater sphericity value for the clasts of this lobe than for those of the other lobes of the same family supports this view.

Investigations of periglacial slope deposits, in the form of gelifluction sheets and lobes and other head deposits, have shown that long axes of the contained clasts generally tend to be oriented parallel to the direction of movement (Lundqvist, 1949, 1962; Fitzpatrick, 1958, 1975; Rapp and Rudberg, 1960; Tivy, 1962; Ragg and Bibby, 1966; Benedict, 1966; 1970, 1976; Washburn, 1973, 1979). On the cessation of movement of the surface layer the clasts are often oriented to a position almost transverse to the previous direction of movement (Lundqvist, 1949, 1962a; Benedict, 1966, 1970, 1976). Previous studies on periglacial slope deposits have largely been concerned with fine-grained deposits like small stone-banked lobes and terraces. The present study attempts to establish the pattern of fabric orientation for the three different types of lobe.

Figure 6.4 illustrates the fabric orientation pattern of the sample lobes of the three types. The direction of alignment of the clast long axis (n:50) was measured using a Suunto compass. The orientation results are plotted in 15° classes and a radial scale of 360° was used. A_n 360 and A_n 180 Statistics (Dale and Ballantyne, 1980) were used to determine significance levels under the null hypothesis of circular uniformity in terms of inclination and orientation.

Fabric diagrams for the three boulder lobes can be interpreted as not representing a very distinct orientation pattern of clasts. Only five of the twelve samples are significantly different from a uniform distribution at the 0.05 level (A_n 360). However, the clasts at the front of the lobes of Site 2 and Site 3 show a significant difference at this level. The three lobe samples also exhibit no definite trend in downslope inclination of their clast long axes. Only five of the twelve samples are significant at the 0.05 level (A_n 360). This evidence indicates that the features have not resulted from a single movement *en masse* but that they have been subject to flow.

The application of the same statistical analysis to the six debris lobes presented relatively less random fabric orientations than those found for the boulder lobes. Thirteen of the twenty-four samples show a significant difference from a uniform distribution at the 0.05 level (A_n 180). The samples also exhibit a general trend in downslope inclination having sixteen of the twenty four samples significant at the 0.05 level (A_n 360). Such a tendency of the fabrics to be aligned generally parallel and downslope to the direction of movement approximates the findings of previous workers.

The three lobes of vegetation-covered type present a picture in fabric orientation. Nine of the twelve samples are significantly different from a uniform distribution at the 0.05 level (A_n 180) and eight samples are significant in downslope inclination at the 0.05 level (A_n 360).

The reasons for the diversity of fabric orientation among the three types of lobe largely involve the nature of their internal composition and the related mechanism of downslope movement, which will be discussed in detail in the following subsection.

6.5.2 Composition

Debris lobes in the Drumochter and the Creag Meagaidh hills The study of the internal structure and composition of debris lobes was carried out following trenching at four sites, two being in the Drumochter area and two in the Creag Meagaidh area. The stratigraphy of the individual lobes was recorded by drawing sections to scale, collecting material for textural analysis and measuring the size and shape of clasts.

Figure 6.5 illustrates the soil profiles for the four lobes. Sites 1 and 2 are in the Drumochter area, Site 1 being located on a 16° north-facing slope at an altitude of 830m and Site 2 on a 10° south-facing slope at 820m. Sites 3 and 4 are in the Creag Meagaidh hills at 870 and 850m respectively. The gradient in both cases is 15° and the slopes face east.

The lobe sections exhibit four main units from the surface downwards. These are (1) a surface layer of stones and pebbles with some fines (debris), (2) a relatively less stony layer of fine-textured soil, (3) a thin horizon of very dark brown soil and (4) a regolith of small stones and pebbles mixed with a fine-grained subsoil.

The surface layer of stones and pebbles is 30-40cm in thickness in all cases. Unlike Sites 1 and 3, which are classed as stone-banked type, Sites 2 and 4 have their surface debris layer banked at the front by a unit of turf-covered finer material. A cohesive network of surface vegetation holds this friable and structureless sandy loam tightly. The material beneath the debris is a dark brown sandy loam with occasional stones embedded in it. The presence of this layer of varying thickness in all four excavated lobes suggests the operation of vertical frost sorting in the upper zone at different scales. For the lobe of Site 1 (Fig. 6.5 and Plate 6.1) this layer is well defined. A very distinctive feature of the lobes is the presence of a thin layer of very dark brown sandy loam that extends the length of the features. A maximum thickness of about 15cm for this layer was found for the Site 4 lobe. Chemical analysis revealed a concentration of organic carbon, ranging between 7% and 9%. The very dark colour of this layer is probably owing to the combined effect of the carbonization of leached organic material and minerogenic inwash. A structural

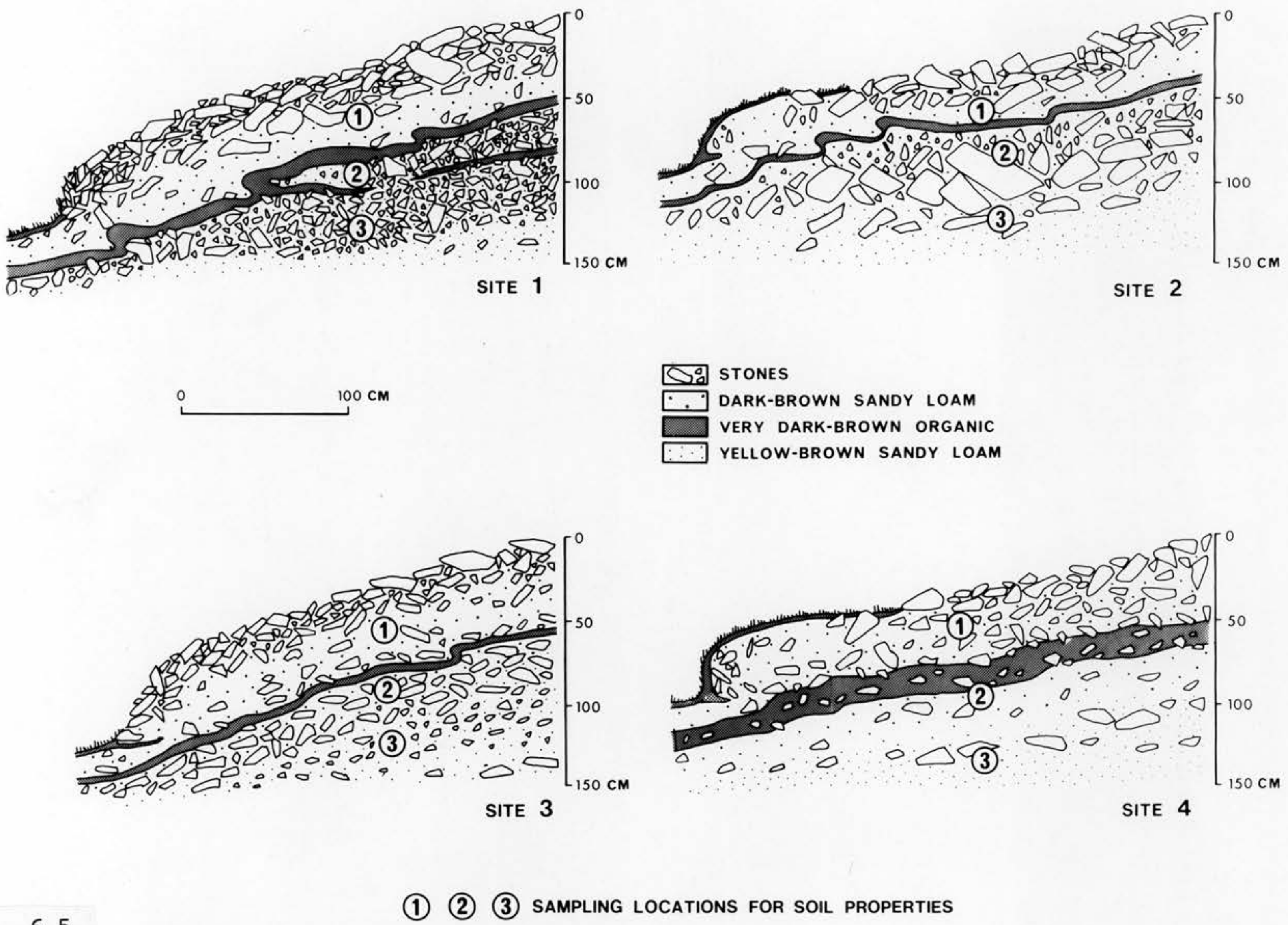


Fig. 6.5

Sections through the four debris lobes studied in detail. Sites 1 and 2 are located in the Drumochter and Sites 3 and 4 in the Creag Meagaidh area.

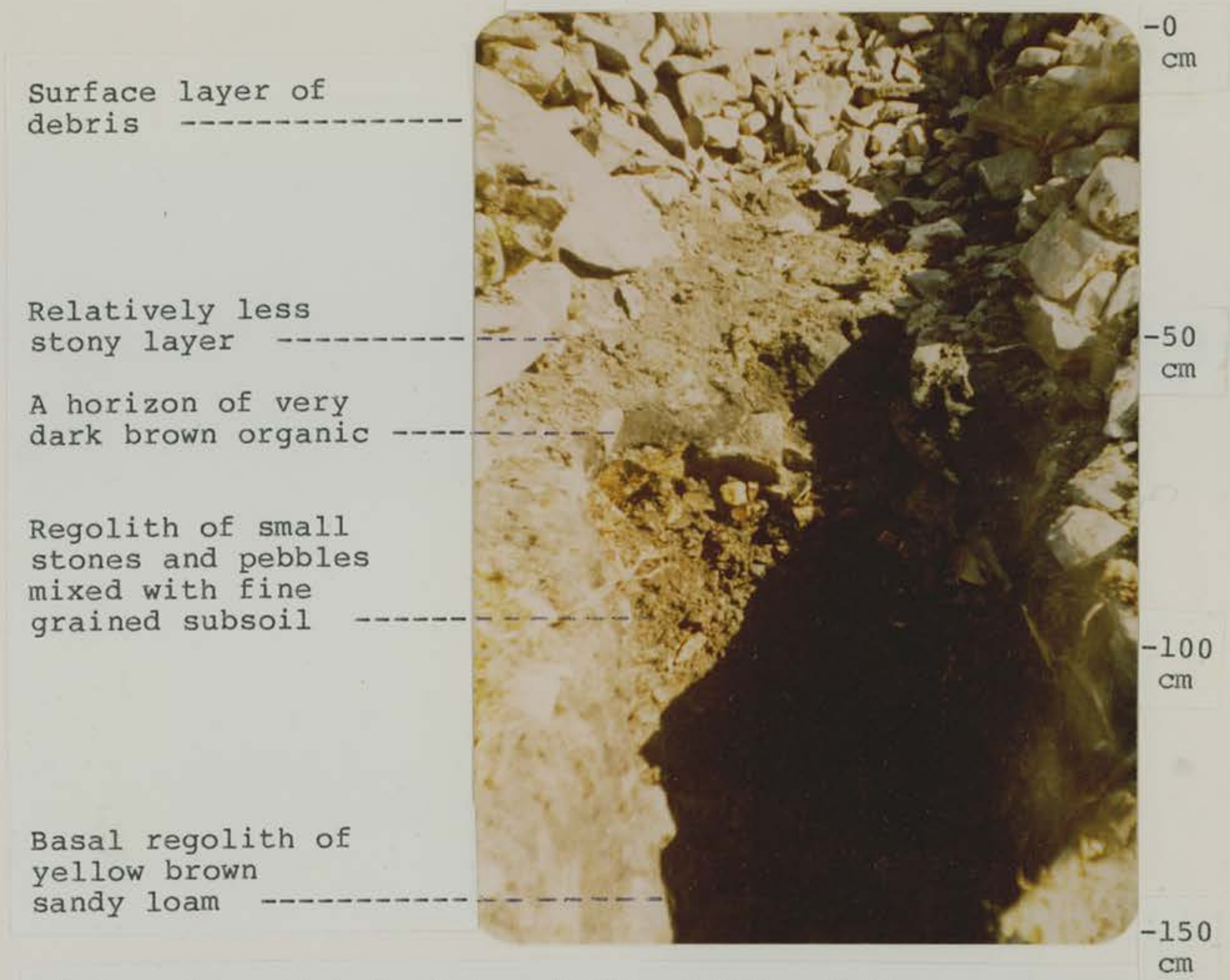


Plate 6.1 Debris lobe of Site 1 (Fig. 6.5) : an excavation along the tread.

Plate 6.2 A thin stone-banked debris lobe in the Drumochter hills : an excavation across the tread.

diversity occurs below this layer. In the cases of Site 1 and Site 3 the lower zone (unit 3) consists of small stones and pebbles mixed with a brown sandy matrix that grades into the basal regolith of yellow-brown sandy loam at an approximate depth of 120cm. For Site 2 a large number of cobbles and boulders occupy this zone. A very different picture is obtained for the lobe at Site 4, where this zone is dominated by finer material with occasional small stones. For Sites 2 and 4 the basal regolith of yellowish-brown sandy loam begins at about 100cm depth.

For size and shape analyses clasts were sampled from selected surface and subsurface locations of the four debris lobes. A sample size of 50 was used in each case. On the surface clasts were sampled from the front, the centre and the rear, and the subsurface clast sampling was done from the centre and the rear. The results are plotted in Table 6.3 and in Fig. 6.6. In all cases except one (Site 1) slightly lower mean values of diameter ((a+b+c)/3) were obtained for the clasts at the front. The size variation between surface and subsurface clasts is evident for all the sample lobes. The lobe of Site 2 shows a concentration of markedly larger clasts at the subsurface centre. A systematic pattern in mean clast sphericity ($(bc/a^2)^{1/3}$) is also apparent for the lobes. Table 6.3 shows greater sphericity values for the subsurface clasts compared with those of the surface.

Debris lobes	Mean clast diameter $((a+b+c)/3)$ cm	Mean clast sphericity $((bc/a^2)^{1/3})$
<u>Site 1</u>		
Surface	9.4	0.59
Subsurface	5.8	0.67
<u>Site 2</u>		
Surface	9.7	0.58
Subsurface	12.8	0.59
<u>Site 3</u>		
Surface	9.1	0.58
Subsurface	7.5	0.59
<u>Site 4</u>		
Surface	9.2	0.54
Subsurface	7.2	0.57

Table 6.3 Mean values of the surface and subsurface clast diameters and sphericities for the four excavated debris lobes.

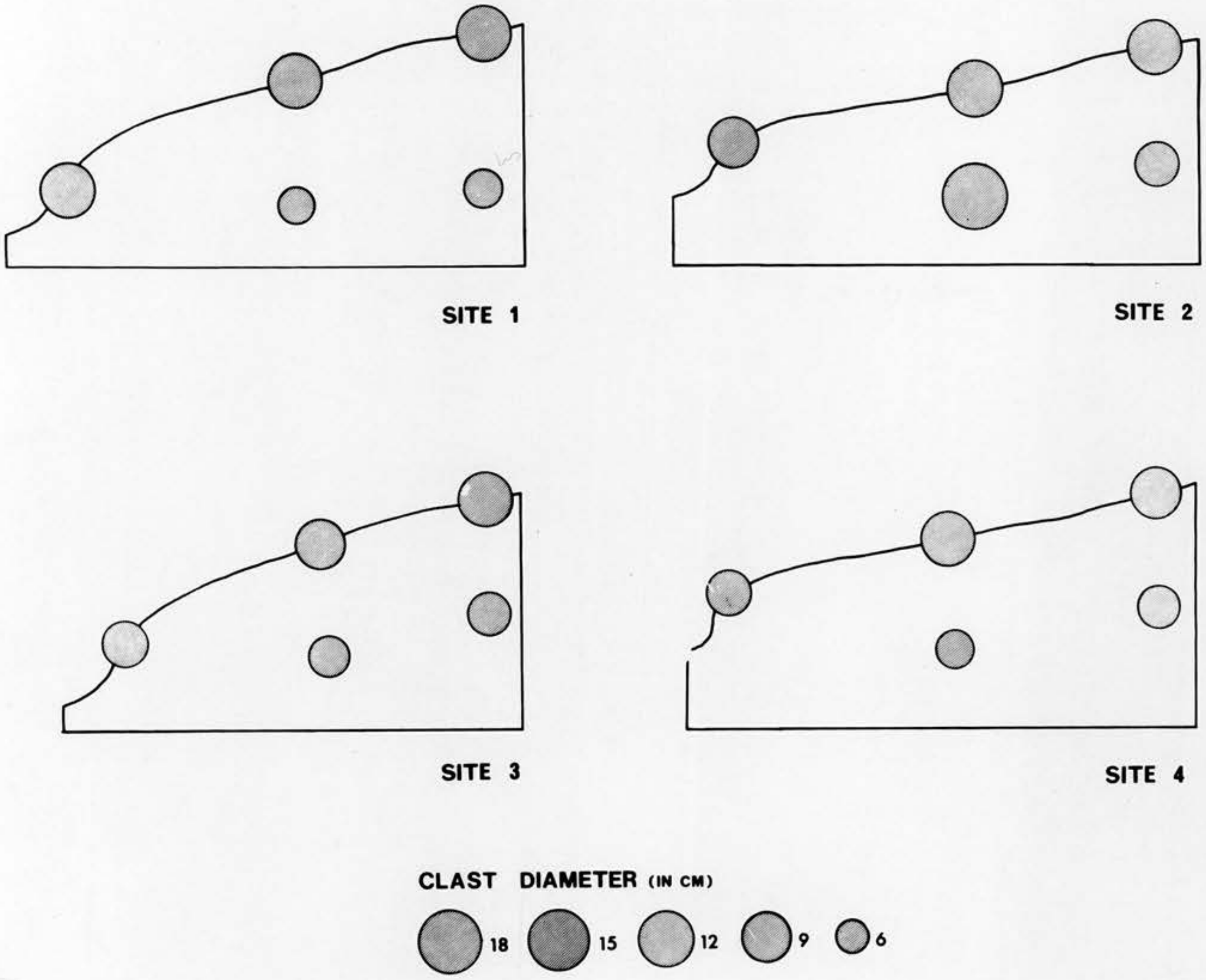


Fig. 6.6

Profiles of the four debris lobes (Fig. 6.5) showing mean clast diameters in the surface and subsurface locations.

This feature indicates the absence of any vertical exchange of components within the lobes. This can also be inferred from the finding that the subsurface clasts have been subjected to a longer period of weathering.

The pattern of grain-size distribution was studied using material collected from varying depths in the sample lobes. The material was first air dried in the laboratory and then analysed mechanically using standard sieves. The results are shown in Fig. 6.7. A fairly uniform picture is apparent for the samples collected from the surface at the first two locations. The samples from depths of 20 and 50cm contain a considerable proportion of material classed as clay and silt (18%-22% <0.063mm) and in all cases except one (Site 1) the proportion of silt and clay at 100cm depth falls below those of the upper two. For Site 1 the sample collected from the lowest level (100cm) exhibits the largest concentration (24%) of silt and clay.

The relatively high clay-silt composition in the debris lobes developed in these areas of micaceous rocks suggests the susceptibility of the features to freeze-thaw action. The required proportion of fine-grained particles (e.g. Washburn, 1979, pp. 67-68) present in the studied lobes substantiates the suggestion of large-scale frost penetration in the features in the form of ice-lenses. This would cause the material to be frost-heaved and the segregated ice-lenses would generate solifluction activity upon thawing. The concentration of relatively larger

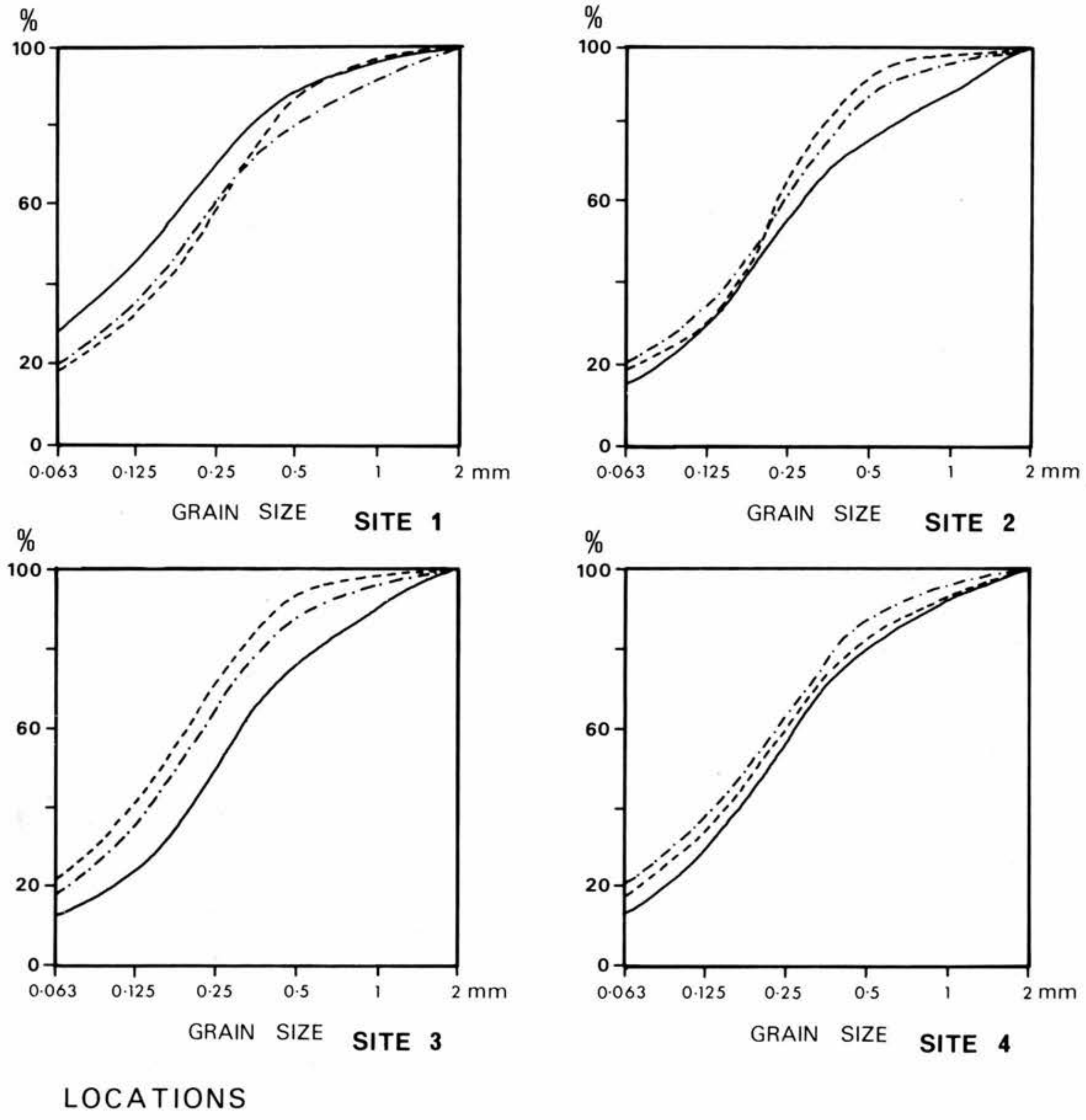


Fig. 6.7

Grain-size distributions of samples of fine material collected from the four debris lobes from varying depths. Sampling locations are shown in Fig. 6.5.

clasts in the lobe surface appears to allow predominantly frost creep activity for downslope movement of the surface material.

Vegetation-covered small lobes in the Drumochter hills

Structural investigation was carried out on two vegetation-covered small lobes in the Drumochter area. Fig. 6.8 demonstrates the characteristics of the two lobes. Site 1 is located on the Gaick Plateau to the east of the pass on a 10° west-facing slope at an altitude of 900m and Site 2 is on A' Mharconaich, to the west of the pass, on a 12° south-facing slope at 930m. The former falls inside the presumed Loch Lomond Advance limit and the latter is outside it.

The two lobes were studied in detail by digging trenches about 3m long from the front. Fig. 6.8 and Plates 6.3 and 6.4 illustrate the composition of the lobes as revealed by the excavations. A fairly similar type of soil profile was found in both cases. The surface layer is about 45cm thick and consists of small angular stones set in a matrix of dark brown sandy loam under an almost complete cover of vegetation dominated by Rhacomitrium heath association. The lobe of Site 1 has a thinner vegetation cover. Beneath the upper zone a thin layer (10-12cm) of very dark-coloured soil, composed predominantly of organic material, continues upslope along the lobe length. This layer, although often interrupted, clearly marks a

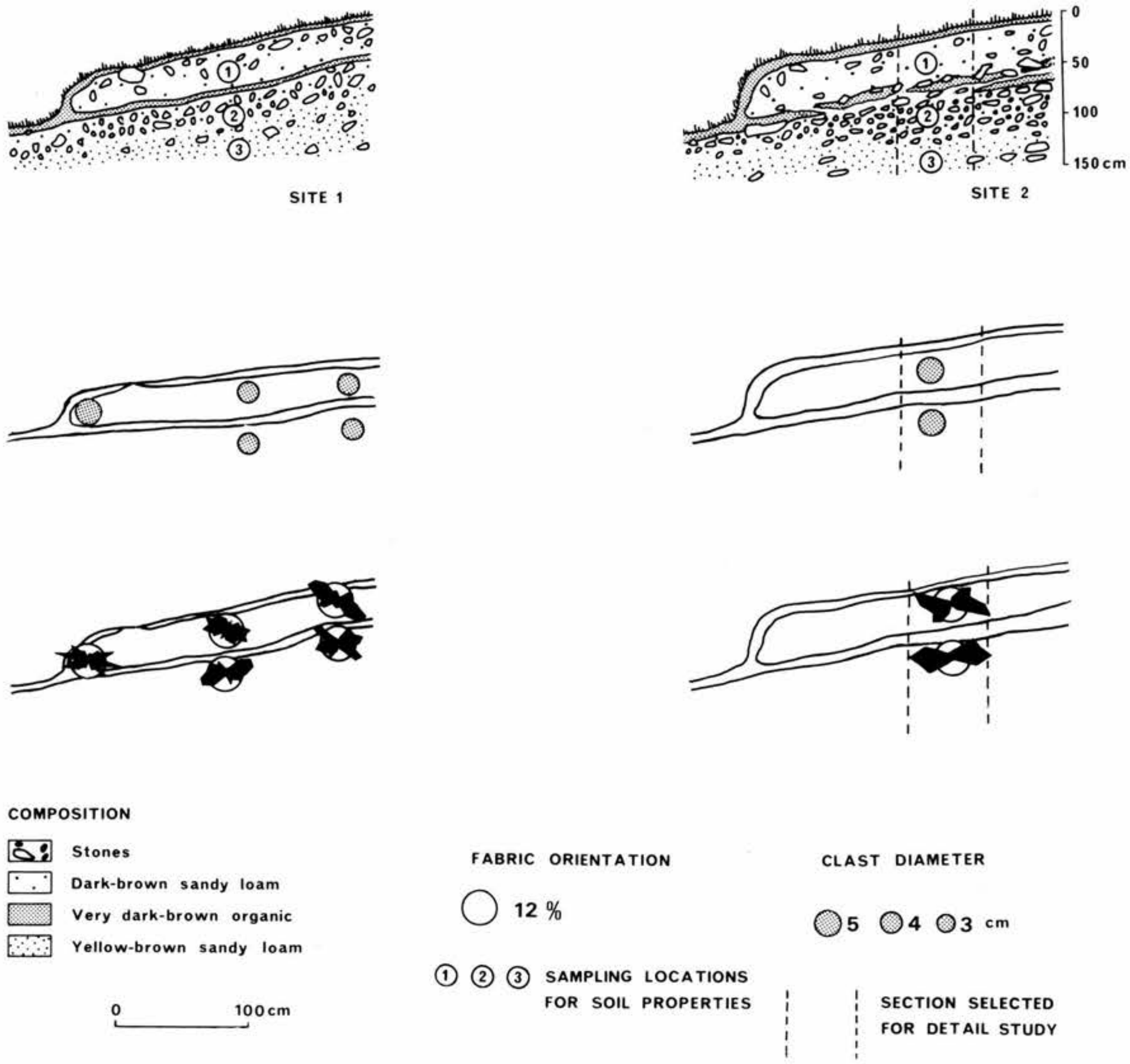


Fig. 6.8

Sections through two vegetation-covered small lobes showing soil profiles, mean clast diameters and fabric orientations within the features.

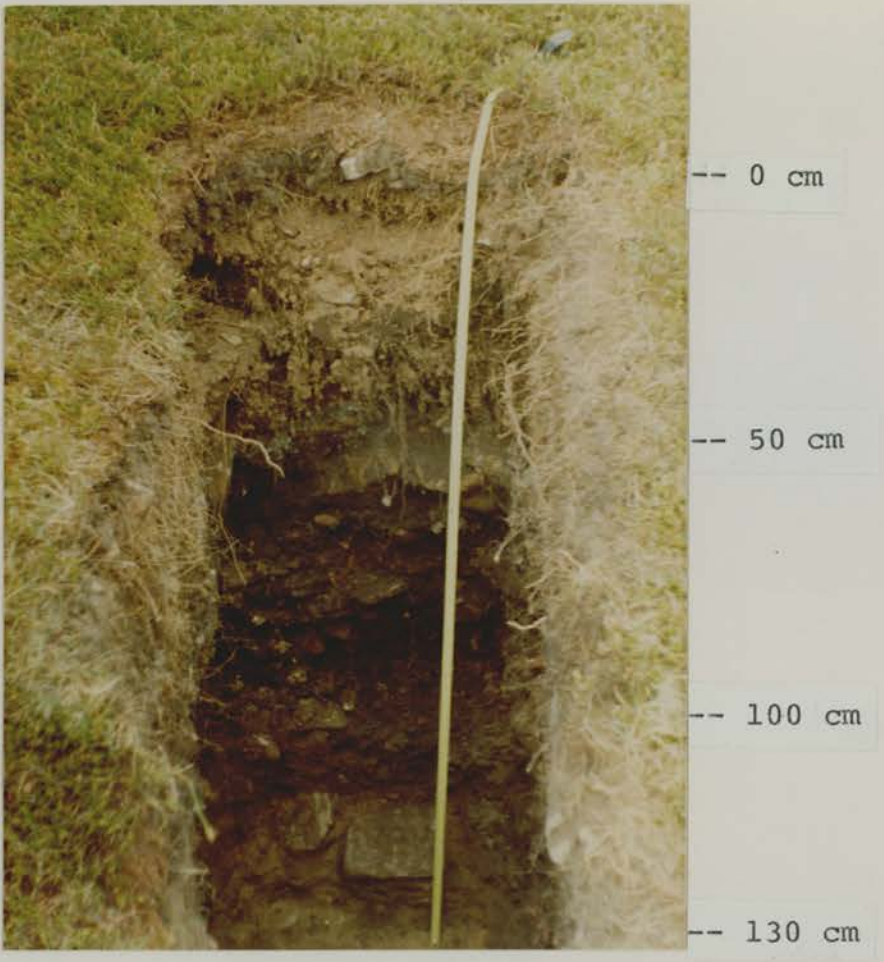


Plate 6.3 Vegetation-covered small lobe of Site 2 (Fig. 6.8) : an excavation along the tread.

Plate 6.4 Vegetation-covered small lobe of Site 1 (Fig. 6.8) : an excavation across the tread.

division between the upper and the lower units of regolith. It appears that the upper unit buried surface vegetation and soil as it moved downslope. The material below is a mixture of small stones and pebbles with dark brown sandy loam that grades into the basal regolith of yellow-brown sandy loam.

The analyses of clast size and sphericity were carried out on 50 clasts from the selected locations through the two sample lobes (Fig. 6.8) and the results are plotted in Table 6.4. The study of clast diameter ((a+b+c)/3) revealed two noticeable features : (i) clasts at the front of the Site 1 lobe are distinctly larger than at any other locations and (ii) no distinct variation exists in clast size between surface and subsurface layers for the centre and the rear of the two lobes. The absence of any pattern in clast sphericity $((bc/a^2)^{1/3})$ for the surface and subsurface layers is another characteristic feature of this type of lobe.

Fabric analysis showed that clast orientation conforms with the pattern (up and down the slope) typical for solifluction components. All surface and subsurface clasts are significantly different from a uniform distribution at the 0.05 level in terms of inclination (A_n 360 statistic) and orientation (A_n 180 statistic).

Samples from the two vegetation-covered lobes exhibit a fairly similar pattern in grain-size distribution (Fig.

Veg.-covered small lobes	Mean clast diameter $((a+b+c)/3)$ cm	Mean clast sphericity $((bc/a^2)^{1/3})$
<u>Site 1</u>		
Surface, front	5.1	0.57
Surface, centre	3.9	0.57
Surface, rear	3.8	0.59
Subsurface, centre	3.8	0.57
Subsurface, rear	3.7	0.57
<u>Site 2</u>		
Surface, centre	5.1	0.65
Subsurface, centre	5.0	0.63

Table 6.4 Mean values of the surface and subsurface clast diameters and sphericities for the two excavated vegetation-covered small lobes.

6.9). Both contain a considerable proportion (10%-17%) of sand-silt (<0.063mm). This suggests that they are

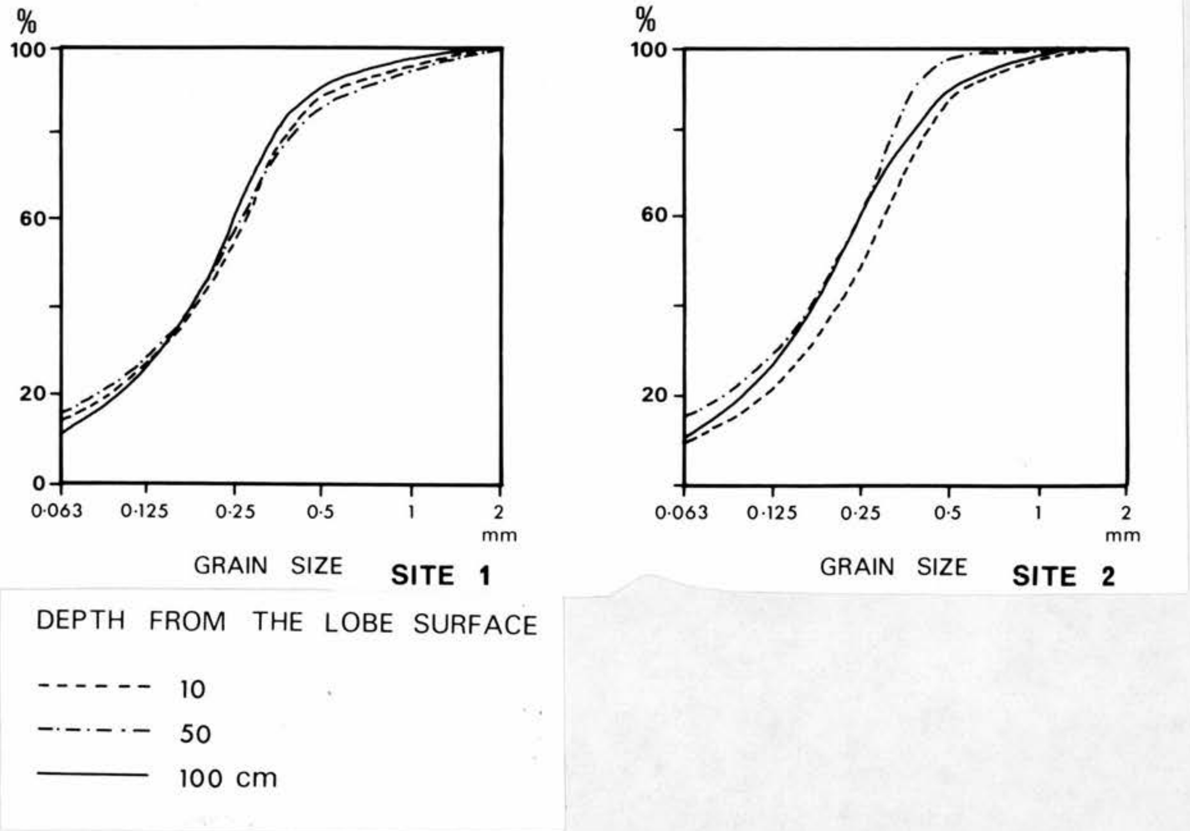


Fig. 6.9 Grain-size distributions for samples of fine material collected from two vegetation-covered small lobes from varying depths. Sampling locations are shown in Fig. 6.8.

susceptible to the segregation of ice lenses in winter. Therefore solifluction activity during spring thaw and summer saturation is highly likely.

The lobe at Site 2 was studied along the section marked in Fig. 6.8. Fig. 6.10 illustrates the section in detail in association with some of the salient features of material collected from varying depths. From each location about 1kg of material was collected for analysis. The upper unit of the regolith is dark yellowish-brown in colour with surface vegetation roots penetrating down to a depth of about 20cm. The colour strongly reflects the presence of organic material which increases to 11% at the buried organic layer at a depth of 50cm. The organic layer was wet and very dark brown in colour and remains of grass and other vegetation were found in places. The profile of the buried soil beneath the organic layer is broadly similar in composition to the upper unit with the percentage of organic carbon decreasing steadily downwards, a minimum of 0.6% being found at a depth of 130cm near the basal regolith of yellow-brown sand and silt.

The grain-size distributions of the samples collected from varying depths in the profile reveal other characteristic features. For the silt-clay component a value of 9% from near the surface (at 10cm depth) increases to 16.5% at the base of the upper unit (at 50cm depth). Following an abrupt fall to 5% at 70cm this rises to a maximum of 18% at 130cm depth. The distribution of stones follows a pattern of increase and decrease broadly similar to that of silt and clay down to the 90%cm level : it shows an increase from 43% near the top (at 10cm depth) to 72% at the base of the upper unit, whereafter there is a sudden increase to 94% at 90cm depth followed by a decrease to 10% at 130cm in the basal regolith.

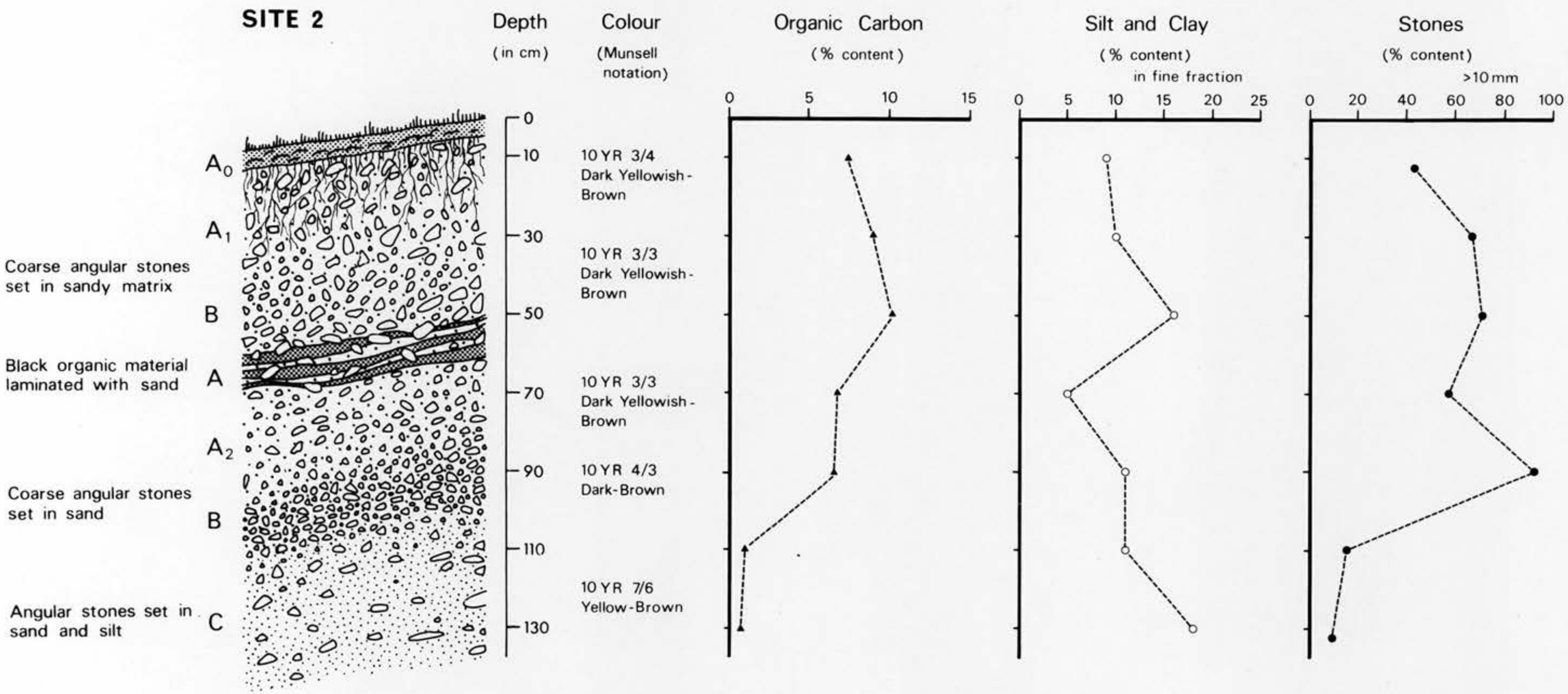


Fig. 6.10

The selected section of the vegetation-covered small lobe at Site 2 (Fig. 6.8) and some characteristics of its soil properties indicated by samples collected from varying depths.

It is interesting to note that the distributions of organic carbon, silt-clay component and stones have a distinct turn at 50cm depth, thus showing a contrast between the upper and the lower units of the regolith. The increase of organic carbon and silt-clay properties down to the level of the buried organic horizon reflects the result of leaching and downward eluviation. A limited amount of leaching and eluviation is apparent in the lobe at Site 1 (Fig. 6.10).

<u>Boulder lobes in the Cairngorms</u> For these assemblages of massive clasts any detailed study of internal composition is very difficult. However, an unvegetated lobe in the Cairngorms was studied by removing clasts at the front across the tread. The lobe has a riser height of 2m and is on a 20° slope of Coire Gorm at an altitude of 980m facing north-west. Plate 6.5 shows the section.

The section demonstrates the assemblage of large blocky clasts lacking any interstitial fines typical of the boulder lobes. The mass of clasts apparently rests upon a lower layer of bouldery debris. Almost all surface clasts are well rounded, suggesting that they have been subjected to a considerable period of superficial mechanical weathering following stagnation of the lobe. The absence of interstitial fines discounts any possibility of saturated flow being involved in former movement. The lobe tread was partly covered by a thick layer of peat

Plate 6.5 A boulder lobe in the Cairngorms : an excavation across the tread.

supporting typical moorland vegetation. Apart from slight imbrication in the near-surface part of the section the clasts appeared to be assembled in a chaotic and unstable condition, a feature which reflects former flow as was inferred from the study of the surface clast orientations and inclinations (Section 6.5.1).

Clast widths (B axis) were measured at the front, sides and centre of the three boulder lobes to find if any variation exists. Samples of 50 were collected from each of the front, left side, right side and centre of each lobe. Only clasts not shorter than 10cm in A axis were considered. The combined distributions for the three lobes plotted in Fig. 6.11 show that the frequency for the

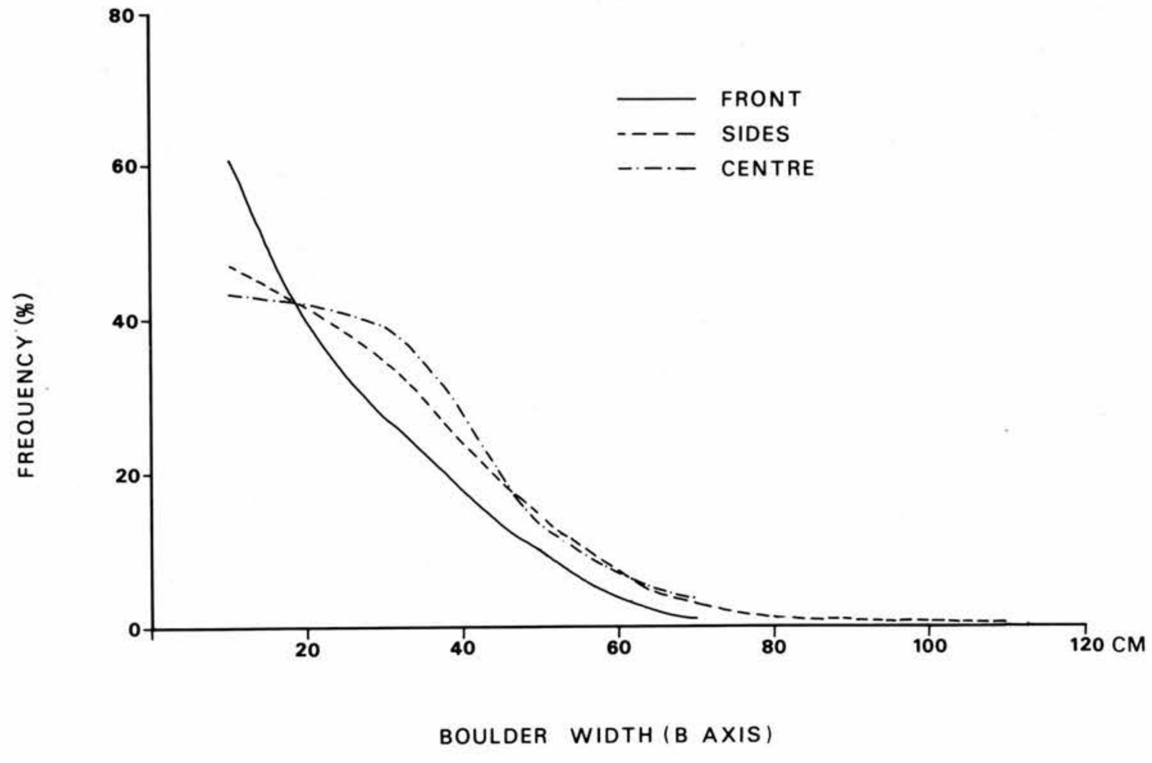


Fig. 6.11 Frequency distribution curves for clast sizes at the front, sides and centre of the three boulder lobes surveyed in the Cairngorms.

side clasts extends up to a maximum of 110cm. This suggests that the largest clasts are more likely to be in the sides than in the other parts of a boulder lobe, although the number of clasts involved is very small.

Discussion

From the above study it appears that the three types of lobe, classified in terms of composition, resulted from different processes. It was demonstrated in Chapter 5 that the nature of lobes generally reflects lithological control or that the rock type responds to frost action (gelifraction) and in turn exerts an influence on the nature of the detritus available for lobe formation. Hence debris lobes and sheets are found on the Drumochter and the Creag Meagaidh hills where frost action on micaceous rocks resulted in stones and cobbles with significant amounts of fines. For this type of lobe the surface layer of predominantly coarse material was found to rest upon a subsurface layer of finer material. Benedict (1970b) suggested that features like debris lobes can form only where coarse debris is moving more rapidly than fines. Studies in Northeast Greenland by Washburn (1969) also indicated that stones can be expected to move faster than fines where movement is determined by frost creep. However, a combined activity of gelifluction and frost-creep can be suggested as the most likely mechanism for the debris lobes. For the boulder lobes movement of large clasts by saturated flow and true solifluction is highly unlikely. Many workers (e.g. Galloway, 1961b; Caine, 1968; Embleton and King, 1975) have proposed that such lobes and block fields are inactive at the present-day because of the washing out of interstitial fines. This proposition appears unsatisfactory in the present instances since no such washed-out material was found in front of the lobes. It is suspected that the coarse-grained and well jointed granite blocks never produced adequate amounts of fines to permit any gelifluction activity through saturation. The most likely mechanism is perhaps similar to that of rock glacier movement, in which interstitial ice plays the major role (cf. Wahrhaftig and Cox, 1959; P.G. White, 1976; S.E. White, 1976). In such case frozen ground (permafrost) is required to provide the shear plane upon which accumulated boulders can creep downslope.

All vegetation-covered small lobes occur on slopes where fine material is readily available and the ground remains saturated through a greater part of the year owing to the late-lying snow patches. Studies of contemporary gelifluction lobes (e.g. Williams, 1957a; Washburn, 1967; Benedict, 1970b) have suggested the importance of water-saturated fines to support movement, the water usually being derived from melting snow. Freshness of form of the lobes in the present instances indicates that their development is more of a contemporary process. The movement of this type of lobe has been revealed by the presence of a buried organic horizon. The characteristic bulging front with steep riser suggests contemporary activity involving downslope movement of material on the tread. The steepness of the riser apparently resulted from the onward pressure of the lobe material. The operative process probably relates largely to the activity of solifluction or localized liquefaction resulting from the thawing of segregated ice-lenses.

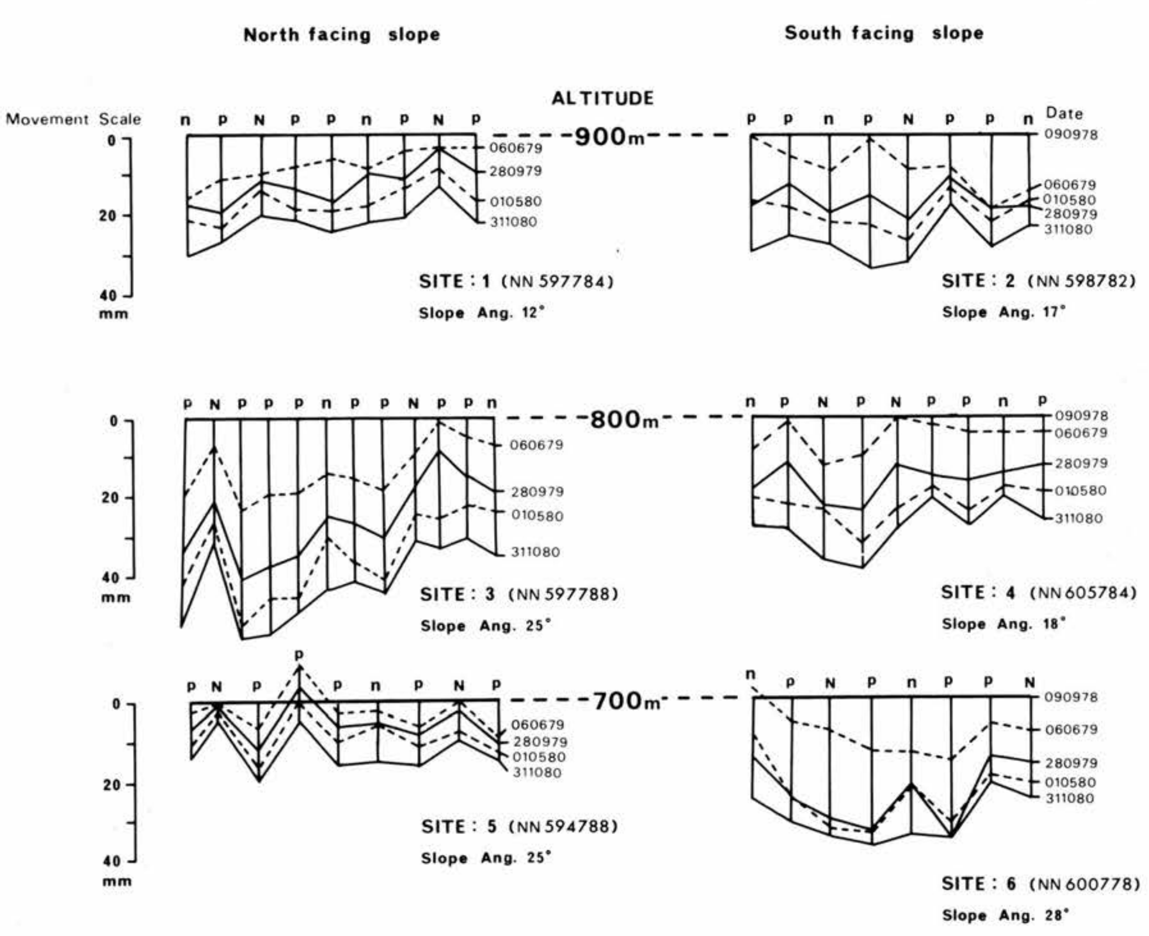
6.6 Present-day activity

Present-day activity of lobes was assessed by installing measurement sites on a number of debris lobes and on a vegetation-covered small lobe in the Drumochter area.

For the study of downslope displacement of surface material mass movement sites were installed across the treads of six small stone-banked debris lobes. The sample lobes were selected on Geal-charn on the north-facing and the south-facing slopes at 900, 800 and 700m altitudes. This was to allow a comparative study of lobe activity between the aspects and the altitudes. The sites were installed in September 1978 and a two-year (1978-79 and

1979-80) investigation was carried out. The measurements were taken twice a year, in early summer (May-June) and late summer (September-October). Two iron poles 1.5m long were inserted into the ground, one on each side of the lobe and the movement indicators were placed across the lobe tread from pole to pole. More than half of the pole length was driven into the ground to avoid any chance of displacement due to frost heave and mass movement. Three types of indicators were employed : drawing pins, 3" nails and 6" nails. Drawing pins were set on the surface clasts with the help of strong adhesive with their points facing up and the nails were inserted into the fine material. The measurements of indicator movements were made using a small plumb bob suspended from the string joining the side poles across the lobe. The results are illustrated in Fig. 6.12.

The diagram shows that all the six lobes experienced downslope movements of their material although a considerable variation exists between the lobes and between indicators on the same lobe. The maximum movement of indicators was found for the lobe at Site 2 and the minimum for Site 5, both being on the north-facing slope. The three lobes on the south-facing slope exhibit a fairly uniform movement pattern. A retrograde component was found for a number of indicators, particularly in Sites 5 and 6. The other noticeable feature is the irregularity in movement over the period of measurement. The results also show that movement between the same type of indicators varied markedly with individual ones moving



p : Drawing pin (on surface clast) n : 3" nail N : 6" nail

Fig. 6.12 Downslope displacements of movement indicators across the treads of six small debris lobes on the Drumochter hills.

upto 40mm in one year while adjacent indicators moved only a few mm during the same time period (Site 3, 1978-79).

The following table gives mean annual displacements of the indicators in the two-year period.

Year	Drawing pins	3" nails	6" nails
1978-79	17.9	16.5	14.2
1979-80	10.9	10.8	10.1
Total	28.8	27.3	24.3

Table 6.5 Mean annual displacements (in mm) of movement indicators on the treads of six small debris lobes on the hillslopes in the Drumochter area.

The table shows that among the indicators, drawing pins (surface clasts) moved farthest in the two-year period although the differences between the three types of indicator are not very large, ranging between 28.8 and 24.3mm. This suggests that frost-creep-gelifluction activity operates at least down to 6" or about 15cm with diminishing effectiveness. The other noticeable feature is that all indicators moved much greater distances during 1978-79, the year of severe winter and very wet summer.

The activity of lobes for the two time periods in each year have been assessed by calculating percentages of indicator displacements and the results are shown in the following table.

	Period	% displacements of all indicators
I	9.9.'78-6.6.'79	43
II	7.6.'79-28.9.'79	57
		100
I	29.9.'79-1.5.'80	40
II	2.5.'80-31.10.'80	60
		100

Table 6.6 Percentage displacements of movement indicators in two time periods during 1978-80.

In the table Period I represents predominantly the winter and spring months whilst Period II is the summer months. It is interesting to note that in both the years summer movements exceeded the movements of winter and spring. It seems probable that a greater part of the movement occurred in late spring and early summer. Thus spring thaw and summer saturation (solifluction) appear to have a dominant control on the present-day lobe activity.

Movements of surface and subsurface material of a lobe were studied using iron tubes inserted vertically into the tread of a vegetation-covered small lobe in a saturated area on the eastern hills. Ten pieces of iron tube, each 3cm long, were inserted vertically through the lobe in September, 1978 and excavated in June, 1981. Fig. 6.13 shows the downslope displacement profile of the pieces of tube. The profile illustrates an approximate exponential decline in displacement with depth. A maximum of 50mm at the surface diminished almost to nil at the depth of 200mm. This type of lobe, formed largely of finer material, allowed the formation of ice lenses within the feature which was found by excavation during the winter and spring field investigations. Hence thawing of ice-lenses probably provided momentum for the downslope movement of the surface and subsurface material (solifluction) and thus caused the displacements of the iron tubes.

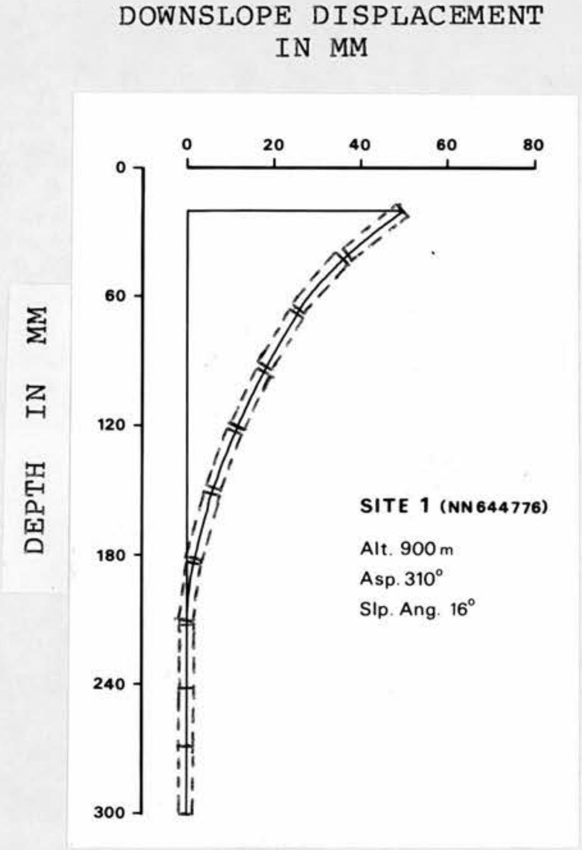


Fig. 6.13 Downslope displacement profile of iron tubes inserted vertically into the tread of a vegetation-covered small lobe on the Drumochter hills in September, 1978 and excavated in June, 1981.

6.7 Conclusions

The proposed classification of lobes as boulder lobes, debris lobes and vegetation-covered small lobes is based on their component material. Boulder lobes and debris lobes are common where large-scale frost shattering poduced larger clasts as the basic ingredients. Boulder lobes comprise medium to large blocky clasts with very little fines whereas debris lobes exhibit a mixture of coarse and fine materials. Many Scandinavian workers (e.g. Lundqvist, 1960; Rapp and Rudberg, 1964) recognized a general altitudinal subdivision for periglacial mass movement features : this comprises a high-altitude frost-shatter zone dominated by blockfields and boulder lobe features as a result of large-scale frost heave and frost creep and a relatively low-altitude zone with landforms produced mainly by solifluction. This division of features has a similarity with that found in the Grampian Highlands. It was observed in the field and revealed by the correlation analysis (Section, 6.4.5) that boulder lobes tend to become morphologically dominating features as altitude increases and, in contrast, the hillslopes of lower altitude with higher gradient of slope favour the development of debris lobes (composed of stones and fines) of larger size.

It is probable that most of the large boulder lobes on the higher ground of lower slope gradients were formed during the lateglacial (Loch Lomond Stadial) following severe frost shattering and subsequent frost heave and frost-creep activities. These lobes formed and moved downslope during much of the stadial under permafrost conditions and became stagnant when the severe climate ended. In this severe climate solifluction was presumably effective in the Drumochter and the Creag Meagaidh hills on micaceous rock-debris. It is probable that the regolith in these areas remained active from the lateglacial through to the early part of the Flandrian under the combined processes of frost creep and solifluction, thus forming major debris lobes and lobate sheets at altitudes lower than those found for the boulder lobes and the lobate sheets. Most of the debris lobes presumably stagnated later in the early Flandrian as a result of the climatic amelioration. The development of vegetation fairly early in the Flandrian largely controlled periglacial activity; vegetation colonized sheltered risers of the debris lobes inhibiting mass movement.

Stone-banked debris lobes are not as widespread as the turf-banked lobes. Some of them are thinner, relatively small and contain greater amounts of fines with clasts smaller than the turf-banked lobes. They also exhibit a certain amount of present-day activity as revealed by the present study. Hence in terms of origin they are closer to the vegetation-covered small lobes than to the turf-banked debris lobes.

Vegetation-covered small lobes are in many respects different from the turf-banked debris lobes and the boulder lobes. They are restricted to the moist ground in the summit areas and are associated with vegetation-covered sheets. Their unsorted structure of fine material suggests that they are more likely to be the result of solifluction than frost creep. The present-day downslope movement studied by iron tubes showed they are still active under the present climatic conditions. A number of them are found well inside the presumed Loch Lomond Advance limit in the Drumochter hills. This implies that, unlike boulder lobes and large turf-banked debris lobes, these lobes and lobate sheets have formed and moved downslope during much of the Flandrian. This view receives support from the radiocarbon dates obtained by Mottershead (1978) from the organic material of a similar feature on Ben Arkle. On the basis of the component material and structural characteristics these lobes can be termed solifluction lobes.

CHAPTER 7

Turf-banked terraces

7.1 Literature

The history of the recognition of terraced forms on the Scottish mountains is contemporary with that of the lobate features as the Geological Survey officers (Peach *et al*., 1912, 1913; Crampton and Carruthers, 1914; Baily, 1916) mentioned frost-shattered debris and related features on the high ground in the early part of this century. Peach *et al*. identified high ground terraced features saying : 'The materials are frequently arranged in parallel lines or terraces due to soil creep aided by the movement of snow' (1913, p. 99). It was perhaps Hollingworth (1934) who, from Lake District examples, first explained elaborately the characteristics and preferred slope angles of different terraced features. He mentioned 'turf-banked' and 'turf-covered' terraces in the Lake District and attempted to explain their mode of origin. Several workers reported terraced features on the Scottish mountains (particularly the Cairngorms) in high ground vegetational studies (e.g. Watt and Jones, 1948; Metcalfe, 1950; Burges, 1951).

During the last two decades the study of turf-banked terraces has been inseparable from the study of gelifluction lobes. Galloway (1961a, 1961b) reported turf-banked terraces on Ben Wyvis and the other parts of the Scottish Highlands. King (1968, 1972), from his study of turf-banked terraces in the Cairngorms, attempted to explain their formation. Goodier and Ball (1969, 1975) and Ball and Goodier (1970, 1974) discussed stone-banked and turf-banked terraces from different parts of Great Britain (e.g. Rhinog Mountains in Wales, Ward Hill in Orkney, Ronas Hill in Shetland). Stone-banked and turf-banked terraces were also reported from the hills of Sutherland by Mottershead and White (1969). White and Mottershead (1972) afterwards studied a lobate type of turf-banked terrace on Ben Arkle, Sutherland, in terms of vegetation, soils, stone orientations, particle-size distribution and pollen content of a buried organic horizon. Sugden (1970a, 1971) discussed the distribution, general size-range and possible age of lobes and terraces in the Cairngorms. Kelletat's (1970a, 1970b) publication produced a study of lobate, garlanded and terraced features of the central Grampian Highlands.

7.2 Present study

The aim of the present study was to analyse turf-banked terraces in detail in the three study areas of the

Grampians. These features, recognized as terraced forms, are composed predominantly of finer material and banked by turf or dwarf type of vegetation. The generic classification devised in Chapter 5 (Fig. 5.1) recognizes three main types of turf-banked terraces : normal, lobate and oblique. The first two types can be broadly classed as horizontal type. A fourth type, recognized as an interconnecting type, can be described as transitional between the horizontal and the oblique types. All types of terrace were studied as a whole for their distribution. For the study of the morphological characteristics, composition and mechanism of formation, the three main types were considered separately.

7.3 Distribution

Turf-banked terraces are distinctive feature on the hillslopes of the three study areas. They occur in the same altitudinal zones as the gelifluction lobes. The primary object of this study was to attempt to understand the altitudinal distribution, aspect and preferred slope angle of turf-banked terraces and to assess their limiting factors. The study of distribution is entirely based on the data collected from the periglacial maps using the same procedure as applied for the gelifluction lobes in Chapter 6. The map sampling was done for each of the areas using the Ordnance Survey 100m grid on the photogrammetrically surveyed maps (1:10,000 scale) with 10m contour intervals. The six-figure grid lines were placed on the maps and each grid intersection above the lowest terrace was sampled.

7.3.1 Altitude

The lowest terrace in the Drumochter hills was mapped at about 665m altitude on a west-facing hillslope to the east of the pass (NN 640791). Terraces in this part extend up to 900m (NN 665778). On the lower slopes of these hills the terraces are mostly of vegetation-covered normal type and, as the altitude increases their treads become free of vegetation. With the decrease in slope near the summit areas terraces gradually take the form of vegetation-covered hummock-terracettes (see Chapter 9), examples of such transitional features being seen near the summit of Meall a' Chaorainn (NN 646777).

Of the two hills of the west of the pass, A' Mharconaich exhibits a widespread occurrence of various types of terraces. They descend from about 970m near the summit (NN 265764) to about 680m on the slope of the spur that extends to the north-east. Lobate terraces of this hill are remarkably developed around the extensive summit areas of gradual slopes. These features are often seen associated with vegetation-covered small lobes. The shoulder of A' Mharconaich, that declines from the summit northwards, has a spectacular manifestation of a series of oblique terraces. Normal terraces are characteristic on the wind-swept spur of this hill extending north-eastwards. The greater part of Geal-charn, the other hill in this area, is occupied by gelifluction lobes and sheets and only limited areas near the summit (e.g. NN 602783, NN 605784) are characterized by normal terraces. A small area on the eastern part of this hill, below the lobe limit (NN 610789), exhibits some vegetation-covered terraces.

Terraces are widely distributed in the Creag Meagaidh area. The lowest terrace was found on the north-facing slope of Sròn a' Ghoire, at about 725m (NN 456884). Normal terraces are common on the eastern slopes on this hill, extending almost to the summit areas of about 970m altitude. Lobate and normal terraces are widespread on the higher moist ground to the south-west of Lochan a' Choire, around the slope of the unnamed summit (NN 424785) immediately east of the main Creag Meagaidh summit, on the western and north-western slopes of Meall Coir Choille-rais (NN 430863), and on the higher ground in the north (NN 436895) that slopes gradually northwards. Oblique terraces are best developed on the steeper hillslopes facing north-west to the south of the high-level col of Uinneag Coire Ardair (NN 427884). Very limited areas of terraces were observed on the eastern hills.

In the Cairngorm area turf-banked terraces are developed on the high ground on either side of the Lairig Ghru. On the western slope of Carn Odhar (NH 843038) the lowest example was found at about 640m altitude and the highest was mapped at 1,250m on the eastern flank of the Braeriach massif (NH 949001). An extensive area of Coire Gorm, west of the Lairig Ghru, is covered with terraces of normal type. They are developed upon vegetation-covered sheets. Oblique terraces of larger type are characteristic of the hillslope north of Allt a' Choire Gorm (NH 957028). The ground to the west of Coire an Lochain, that descends from the Braeriach massif north-northwestwards manifests widespread small normal terraces. Below 950m on this slope there are much larger features of similar type. Terraces, chiefly of normal type, are also distributed on the high plateau to the east of the Lairig Ghru. Examples are found on the north-western slopes of Miadan Creag an Leth-choin (e.g. NH 975030, NH 973040), in limited areas on the western slopes of Creag an Leth-choin (e.g. NH 967039, NH 966044) and on the northern flank of Castle Hill (NH 957061).

Diagrams A1, B1 and C1 in Fig. 7.1.1 demonstrate the altitudinal distribution of land and terraces in 50m class intervals. It is obvious from the diagrams that terraces prefered higher ground in all three areas. A preferred zone is apparent in each diagram where terrace sample exceeds land sample. In the Drumochter and Creag Meagaidh

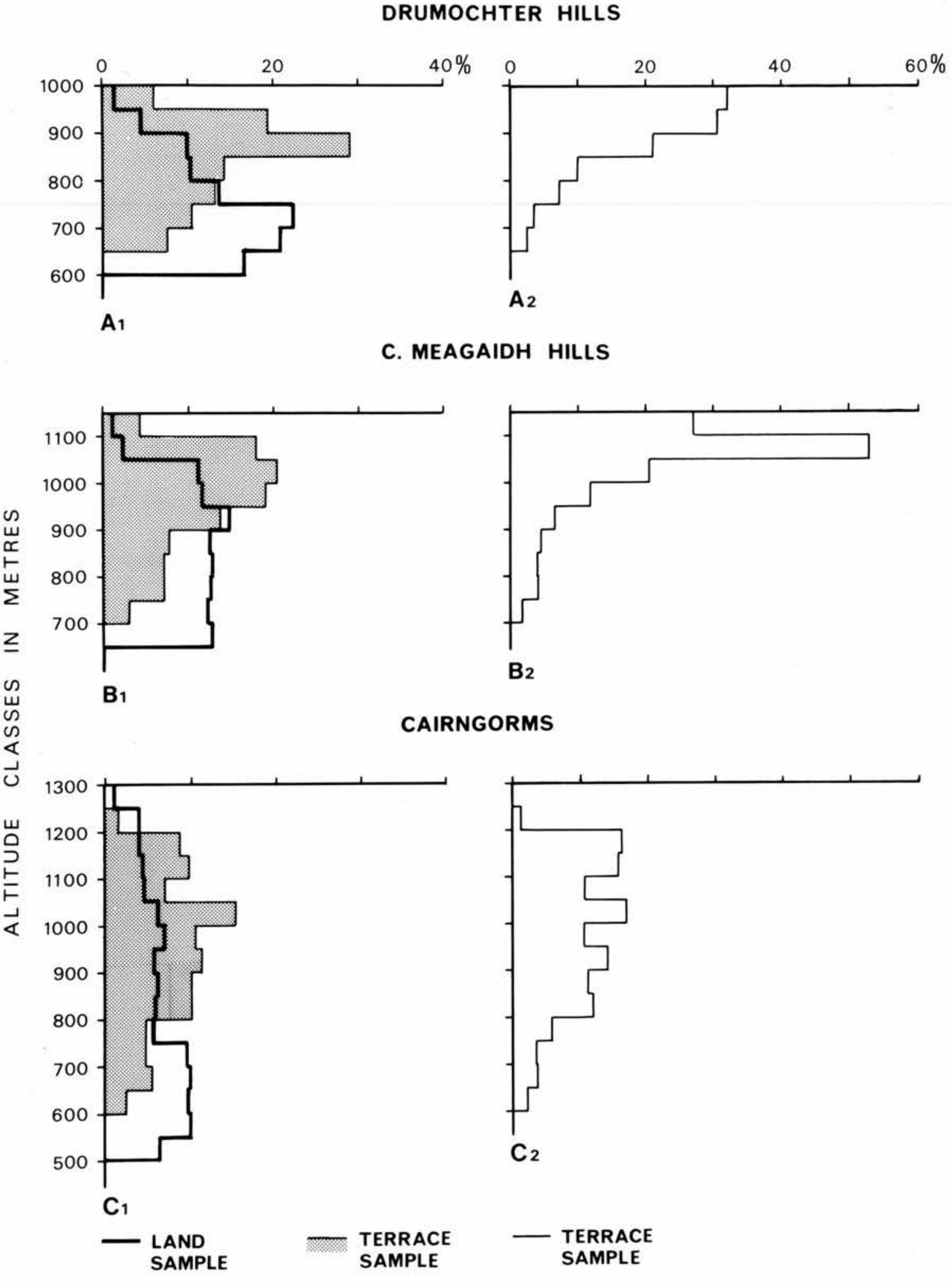


Fig. 7.1.1

The altitudinal distributions of turf-banked terraces in the three study areas based on data derived from the geomorphological maps. The diagrams A1, B1, and C1 show the percentage distributions of land and terraces, and A2, B2 and C2 represent the percentage of ground surface occupied by terraces in different altitudinal zones above the lowest terrace limit.

hills this zone extends from 800m and 950m respectively upwards to the maximum altitude. For the Cairngorms the preferred zone begins at 800m altitude, which is similar to that of the Drumochter hills, but terminates at 1,200m. The maximum ground height attained in this area is 1,296m. The fall of terrace sample below land sample above 1,200m and the complete absence above 1,250m can be attributed to the unfavourable ground conditions owing to the very bouldery nature of the plateau summits with very little amounts of fines to allow the formation of terraces and also very low slope angles. The diagrams A2, B2 and C2 in the same figure demonstrate the percentage of ground surface occupied by terraces. The most characteristic feature obtained from these diagrams is the steady increase of terrace occupation with increase of altitude. In diagram B2 (Creag Meagaidh hills) the altitudinal zone of 1,050-1,100m shows a sudden peak exceeding the 50% level. Two possible reasons can be suggested to explain this feature : (i) the ground surface at that altitude may have the maximum spread of finer materials which, in turn, favoured widespread terrace formation, (ii) favourable ground slope condition. The latter factor will be discussed in the section on slope angle (Section 7.3.3).

Discussion

Several factors determine the altitudinal distribution of terraces in the three study areas. As with the gelifluction lobes, in various places valley-side peat delimits the lowest altitudes of turf-banked terrace, as on the eastern hills (NN 640799) and Geal-charn (NN 610488) in the Drumochter area; on Bealach a' Ghoire (NN 457880) in the Creag Meagaidh area and on Coire Gorm (NH 925055) and Coire Odhar (NH 943039) in the Cairngorms. In several instances, above the lower limit, the terrace occurrence was seen to be restricted by the widespresd distribution of debris and boulder lobes and lobate sheets. Where frost-shattered debris and blocks are abundant debris and boulder lobes are most likely to form. Terraces are commonly related to vegetation-covered sheets. Series of them have developed remarkably upon the extensive treads of the sheets that are common on the moist ground of the upper slopes. Examples can be seen on the eastern hills and on A' Mharconaich in the Drumochter area, on Puist Coire Ardair and on the slopes of an unnamed summit (NN 424871) in the Creag Meagaidh area, and on the higher slopes to the east of the Lairig Ghru in the Cairngorms. These high summit areas remain moist throughout the year largely due to late-lying snow patches. Like debris and boulder lobes large turf-banked terraces do not occur inside the Loch Lomond Advance limit. On the other hand, some miniature terrace features on the eastern hills in the Drumochter area were found inside this limit. In the Creag Meagaidh and the Cairngorm areas no terrace was found inside the ground occupied by Loch Lomond Advance corrie glaciers.

7.3.2 Aspect

As with the study of lobe aspects, the study of terrace aspects encountered difficulties. These were as follows. a) The unequal distribution of hillslopes among the aspects has a direct influence on the percentages of terrace distribution for different aspects. b) The occurrence of terraces is largely coincident with the occurrence of vegetation-covered sheets and these sheets, in turn, are found to be distributed largely on moist convex slopes regardless of aspect. c) The nature of the surface topography is a further limiting factor. Excessively steep slopes (>35°) and ground of very low gradient (<6°), particularly near the summits, result in considerable areas devoid of terraces. It has also been pointed out in the previous section that turf-banked terraces are very few in number on the hillslopes where, owing to the widespread occurrence of coarse debris and boulders, associated gelifluction lobes dominate. d) Peat may also restrict terrace distribution in certain aspects.

Despite these limiting factors a map study was carried out in the Drumochter hills. This area alone was selected since it is the only one having considerable areas of ground facing all aspects. Samples of total land area and terrace-covered land area were collected from the geomorphological map for the eight major aspects. Diagram A in Fig. 7.1.2 shows the percentage distribution of total land by solid line and and terrace-covered land by shaded area. The disparity between land and terrace areas for almost all major aspects is largely related to the topographical conditions and the dominance of debris lobes. The significant lag of terrace percentage behind land percentage, particularly for the eastern and north-eastern slopes can be attributed to the presence of cliff faces. For the northern and north-western slopes, particularly on Geal-charn, the ground surface is extensively mantled with frost-shattered debris resulting in the presence of debris lobes. However, terrace percentage greatly exceeds land percentage for the southern and south-western slopes where vegetation-covered sheets are common features. The characteristics of terrace aspects are more appropriately illustrated by diagram B in the same figure, showing the percentage of ground surface occupied by terraces for all major aspects. This suggests a certain tendency for the terraces to prefer southern and south-western slopes. As discussed in the previous section, the development of turf-banked terraces largely coincides with the presence of vegetation-covered sheets of finer material. Southern and south-western slopes in this area are extensively covered with this type of sheet. The development of vegetation-

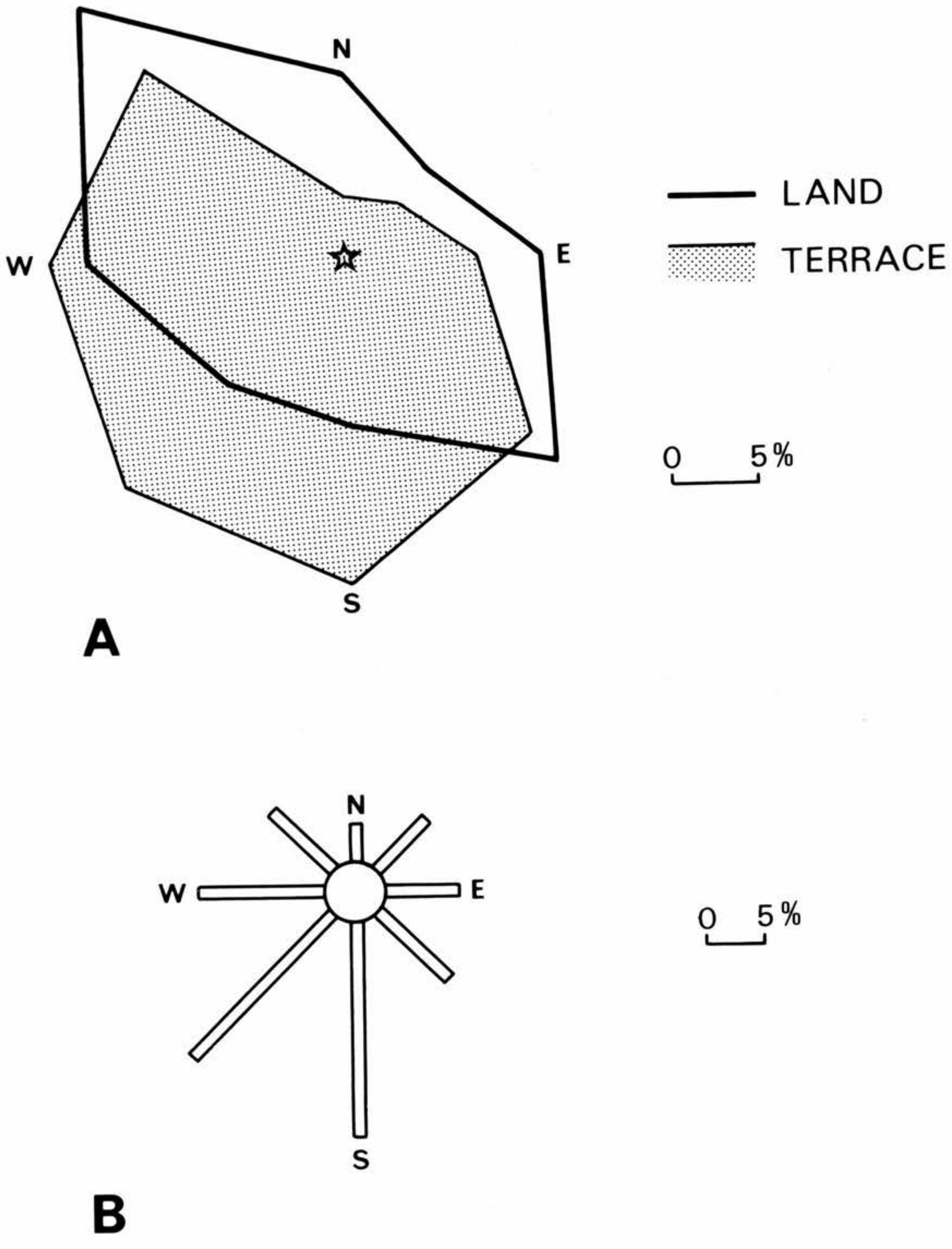


Fig. 7.1.2

The pattern of turf-banked terrace distribution on hillslopes in the Drumochter area for the eight major aspects based on data derived from the geomorphological map. Diagram A shows the percentage distributions of land and terraces and B represents the percentage of ground surface occupied by terraces for different aspects.

covered sheets in combination with saturated ground conditions associated with late-lying snow patches (favoured by slopes of low and moderate gradient) appears to have favoured the maximum spread of terraces on the slopes of southern and south-western aspects of this area.

7.3.3 Slope angle

Map sampling for the slope angle of turf-banked terraces on the geomorphological maps (1:10,000 scale) of the respective areas was based on the 100m grid and 5° classes.

In the Drumochter hills terraces are developed upon slopes between 7° and 35°. 81% of the sample occurred between 7° and 20° with a mean angle of 18° (standard deviation : 6.5°). This pattern may be compared with that of the Creag Meagaidh area where the features occurred between 6° and 35°. Here 86% of the sample exist in the range of 6°-20° with a mean angle of 17° (standard deviation : 6°). In the Cairngorms terraces were found to have developed between 5° and 34° having a mean of 19° (standard deviation : 5°).

The pattern of terrace distribution in the study areas in terms of hillslope gradients is illustrated in Fig. 7.1.3. Diagrams A1, B1 and C1 demonstrate the percentage

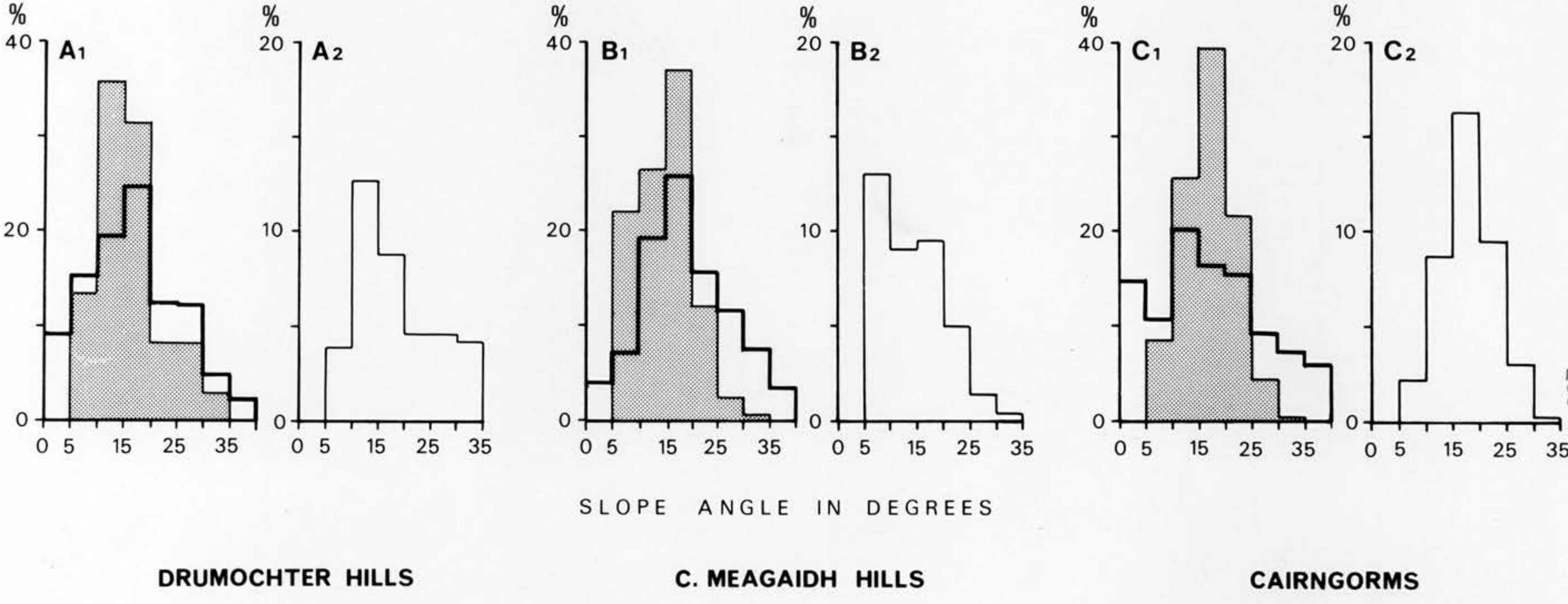


Fig. 7.1.3

Distribution of turf-banked terraces in relation to hillslope gradient in the three study areas based on data derived from the geomorphological maps. The diagrams A1, B1 and C1 show the percentage distributions of land and terraces and A2, B2 and C2 represent the percentage of ground surface occupied by terraces at different slope gradient classes above the favoured minimum.

distribution of land and terraces at every 5° slope angle class from above the favoured minimum. The preferred range of slope gradient, as obtained from the diagrams, where terrace sample exceeds land sample, varies from area to area. In the Drumochter hills this range is 10°-20°. In the Creag Meagaidh area this extends to 5°-20° and in the Cairngorms it is 10°-25°. Maximum ground occupation in the 10°-15° class for the Drumochter hills, at 5°-10° for the Creag Meagaidh area and at 15°-20° for the Cairngorms presents a degree of diversity but as a whole suggests a range between 5° and 20°, which may be regarded as ideal for turf-banked terrace formation.

Discussion

The characteristic features obtained from the study of the slope-terrace relationships are as follows. a) In all cases both land and terrace samples tend to increase towards moderate slopes (approximately 10°-25°) and decrease with the steepening of the slope angle, and b) no terrace sample was obtained from slopes steeper than 35° and gentler than 6°.

The results of the slope angle study for the terraces in the three parts of the Grampians can be compared with other studies. Hollingworth (1934) reported from the Lake

District a range of slope gradient from 6° to 27° (1 in 10 to 1 in 2) for turf-banked terraces and a maximum of 14° (1 in 4) for the 'turf-covered' (vegetation-covered) terraces. Galloway (1961a, 1961b) estimated slope angles of 5°-12° for the turf-banked lobes and terraces in the Scottish Highlands. From the Cairngorms Metcalfe (1950) reported a range for 'oval terraces' between 15° and 20°. In the Northern Highlands of Scotland Mottershead and White (1969) found stone-banked and turf-banked terraces on slopes of 4°-11° and 8°-25° respectively. Ball and Goodier (1974) reported from Ronas Hill in Shetland a maximum of 21° slope angle for turf-banked terraces. Later Goodier and Ball (1975) found turf-banked terraces upon slopes as high as 35° on Ward Hill in Orkney.

A general disadvantage in comparing these findings with the present work is that most of these reports are based on either visual assessment or a very limited sample study. As a consequence they are not necessarily similar to the findings of the present work involving measurements over an extensive area.

Summary

The above study of terrace distribution can be summarized as follows :

(i) Turf-banked terraces tend to occupy a larger area of the ground surface as the altitude increases. This feature is largely associated with the increasing occurrence of vegetation-covered sheets composed predominantly of finer materials which offer an ideal base for terrace formation.

(ii) Lobate terrace areas often coincide with the vegetation-covered lobe areas, both occurring on the higher ground near the summits.

(iii) A study of terrace aspects for the Drumochter hills indicates that the southerly and south-westerly aspects are favoured for the terraces.

(iv) The means of slope angle (18°, 17° and 19°), obtained for the three areas suggest that this feature prefers hillslopes gentler than those preferred for the debris and the boulder lobes. Altitude has an inverse relationship with slope angle, for the former increases as the latter decreases. Thus the preferred lower slope angle for the terraces appears consistent with their increasing tendency to prefer higher ground. Turf-banked terraces also do not occur on slopes steeper than 35° and gentler than 6°.

(v) Some small turf-banked terraces are found within the limits of Loch Lomond Advance glaciers. This implies that they at least have formed and remained active since final deglaciation.

7.4 Morphology

The morphological characteristics of the three types of terrace and their possible controls (altitude and hilslope angle) were investigated. The measured parameters are : (i) altitude, (ii) slope angle, (iii) surface angle, (iv) riser height, (v) riser angle, (vi) terrace length, (vii) terrace width, (viii) terrace thickness and (ix) vegetation cover. Except for terrace length and terrace width, all other parameters were measured in the way explained for gelifluction lobes (Section 6.4). Terrace length and terrace width parameters are illustrated in Figure 7.2. The length for the horizontal terraces (normal and lobate type) was measured across the tread AB at right angles to the hillslope and the width was measured as the distance between the riser-crest and the base of the riser of the next terrace upslope (CD). For oblique terraces length was measured along the inclination of the long profile of the terrace.

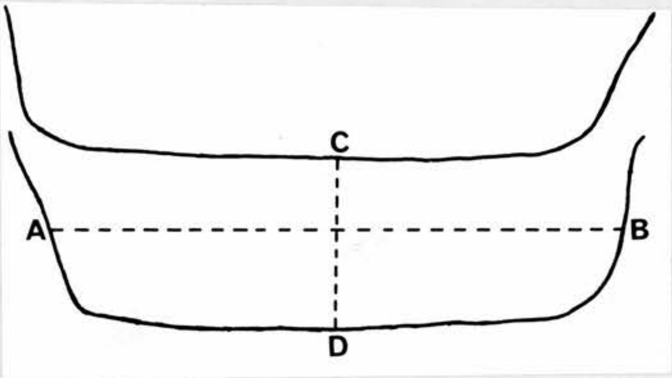


Fig. 7.2 Terrace length and width as measured in the field; AB = length and CD = width.

The terrace morphology was measured on 246 of normal type, 135 of lobate type and 119 of oblique type at different sites in the three areas. Fig. 7.3 and Table 7.1 demonstrate some of the results of the terrace survey.

7.4.1 Terrace size (length and width)

The three types of terrace display distinct variations in size among themselves. The greatest variation is found for the oblique terraces with lengths ranging from 2.7 to 25.2m and tread widths from 0.5 to 4.5m. The shortest oblique terrace was surveyed in the Drumochter area and the longest in the Cairngorms. Lengths of normal terraces range from 2.5 to 18.3m and lobate terraces from 2.0 to 12.2m. This reveals that the lobate terraces are the shortest features among the three types. In the three areas 68% to about 80% of the normal terraces are less than 8m long, whereas in all areas more than 90% of lobate terraces are found to have lengths shorter than 8m. Before field investigation the lobate terraces were thought to have the widest tread of the three types. But the sample survey shows that in three instances (normal and oblique terraces of Creag Meagaidh and oblique terraces of the Cairngorms) the means for the two other types exceed the highest calculated mean (found in the Creag Meagaidh area) of the lobate terraces (Table 7.1).

It was mentioned earlier that turf-banked terraces were

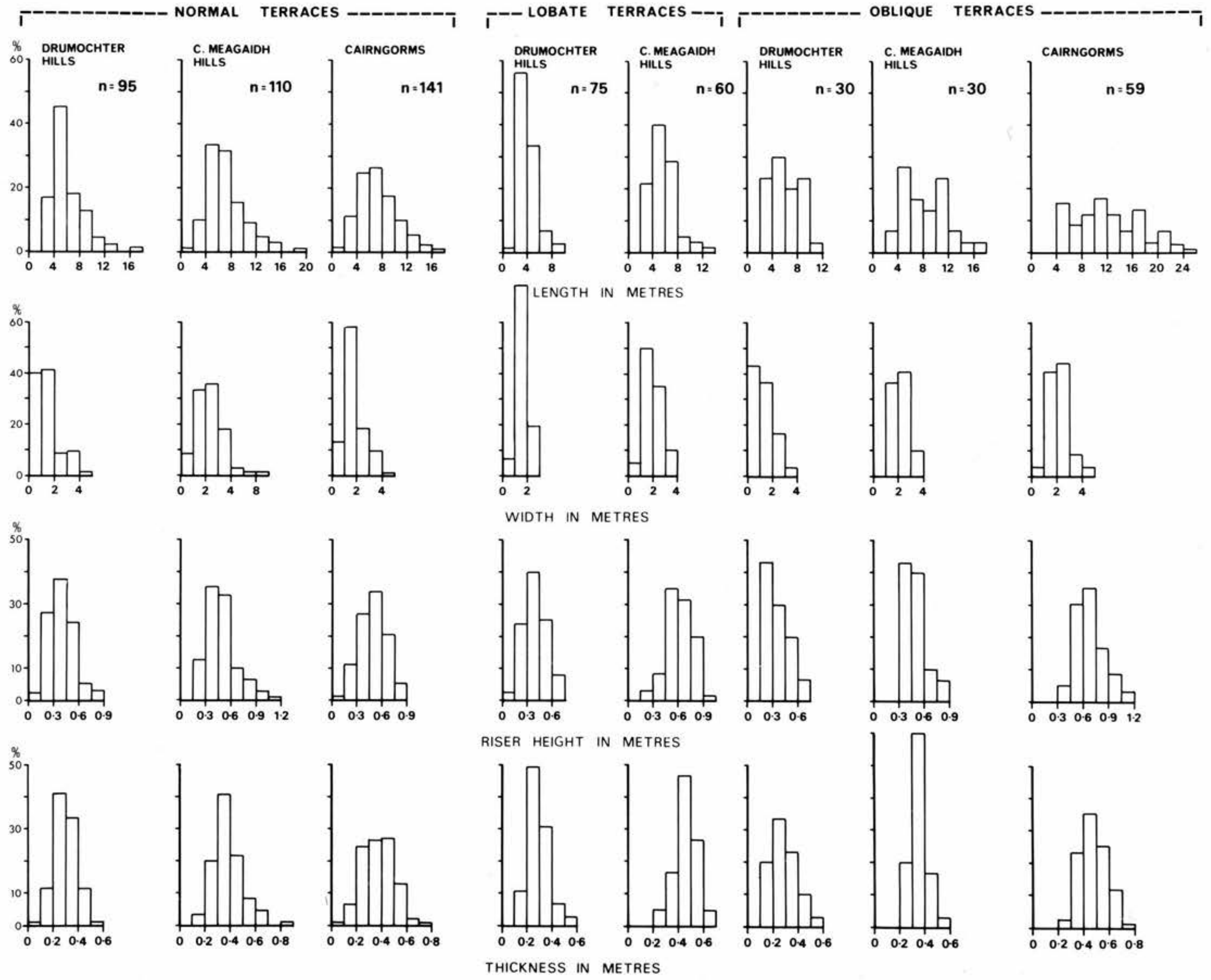


Fig. 7.3

Percentage frequency distributions summarizing some morphological characteristics of the three types of turf-banked terrace surveyed in the field.

Site	Terrace type	n	Length	Width	Riser height	Thick- ness	Riser angle
			<---------(in m)---------			--------->	(deg.)
Drumochter hills	Normal	95	6.12	1.54	0.42	0.31	47°
C.Meagaidh hills	,,	110	7.28	2.34	0.51	0.38	59°
Cairngorm area	,,	141	7.24	1.81	0.52	0.38	50°
Drumochter hills	Lobate	75	4.11	1.67	0.41	0.30	45°
C.Meagaidh hills	,,	60	5.65	2.06	0.65	0.46	58°
Drumochter hills	Oblique	30	6.08	1.45	0.40	0.28	45°
C.Meagaidh hills	,,	30	10.33	2.25	0.52	0.35	59°
Cairngorm area	,,	59	12.39	2.18	0.70	0.48	51°

Table 7.1 Mean values of some selected parameters of the three types of turf-banked terrace surveyed in the field.

found in abundance where vegetation-covered sheets were well developed, as the former usually form upon the tread of the latter. These two types of feature were distinguished in the field on the basis of their downslope inclination of tread. Vegetation-covered sheets consequently incline with the slope but the terrace tread has an inverse relationship with the slope angle, i.e. unlike sheets, terraces become increasingly flat at their tread with the increase of slope angle. One of the consequences of this feature is that near the upper hillslopes, where gradient is low, terraces frequently merge with sheets. Hence lobate terraces of shorter length and width, often difficult to distinguish from vegetation-covered lobes, occur. In almost all cases, as described in Section 7.3.1 and shown in the geomorphological maps, lobate terraces were found in the summit areas.

The size of terraces has been reported from different parts of the country. Stone-banked terraces of about 10m (32ft) long were found in Sutherland (Mottershead, 1969). Turf-banked terraces in the Lake district were described as a few metres (several yards) long (Tufnell, 1969). Widths of the same type of terrace were earlier reported to be between 1 and 3 metres (1 to 3 yards) (Hollingworth, 1934). On Ben Wyvis turf-banked terraces from smaller than 1m to about 6m in width were described (Galloway, 1961a). Some terraces of up to 15m long were found in the

Cairngorms (King, 1968). Terraces of turf-banked type 2 to 3m in width have been studied on Ward Hill, Orkney (Goodier and Ball, 1975).

7.4.2 Riser height and thickness

Riser height and calculated thickness for the three types of terrace have been analysed. As with length the largest variation has been found for the oblique terraces. A minimum height of 0.2m for oblique terraces was found in the Drumochter area and a maximum of 1.2m in the Cairngorms. Terraces of normal type and lobate type ranged between 0.1m and 1m. Table 7.1 demonstrates that, except for the Creag Meagaidh lobate terraces and the Cairngorm oblique terraces, in all cases the mean values for riser height and thickness are fairly uniform.

The riser height and the thickness of individual terraces are chiefly determined by the nature of the vegetation-covered sheets to which they are generally related. Where a large turf-banked terrace merges with this type of sheet the terrace riser was measured from the riser of the sheet. Hence for the horizontal (normal and lobate) terraces some markedly high (as much as 1m) risers were encountered. The other important determining factor appears to be the nature of the terrace-forming material.

Oblique terraces in the Cairngorms contain a considerable amounts of stones and pebbles in the fines, resulting in the largest mean value of riser height, as well as of thickness.

Riser heights have received more thorough attention than any other variables from previous workers who have studied turf-banked terraces. Peach *et al*. (1912) described riser heights of terraces up to 1 metre (1-3ft) on the Scottish mountains. From the Lake District Hollingworth (1934) reported turf-banked terrace riser heights of about 0.6m (2ft). Tufnell (1969) suggested a range of 0.3-0.6m for the riser heights of terraces of the same area. Galloway (1961a, 1961b) from his study of terraces on Ben Wyvis and other Scottish mountains produced reports of riser height between 0.3m and around 1m. King (1968), in his study of the Cairngorms, described risers of terraces about 1m and often 2m high. In the Isle of Rhum Ryder and McCann (1971) found turf-banked terraces up to 0.45m (18 inches) in height.

7.4.3 Vegetation cover

The most characteristic feature of turf-banked terraces is the contrast in vegetation cover between the tread and the riser. Terrace treads are often sparsely vegetated compared to the almost completely vegetation-covered risers. In the Drumochter area 40 out of 95 normal terraces were studied in an area on the north-eastern slopes of Geal-charn where low altitude (about 700m) and abundant peat cover on the ground appeared to be the major controlling factor for vegetation distribution. All terraces surveyed on this slope were almost entirely covered with vegetation (Calluna vulgaris, grasses). The other 55 normal terraces, sampled from higher altitudes, showed about 32% vegetation-cover on treads. This can be compared with a mean of 42% found for the same type of terrace (n:110) in the Creag Meagaidh area. A striking contrast in vegetation cover was found for the Cairngorm normal terraces, where terrace treads are often extensively exposed, a mean of only 20% for vegetation cover being found. In contrast with the normal terraces, lobate terraces in all instances exhibited greater amounts of vegetation cover on their treads. Means of 47% in the Drumochter area (n:75) and 56% in the Creag Meagaidh area (n:60) were obtained. It has been mentioned that all lobate terraces were sampled from higher ground where slope gradient is low and terraces are difficult to distinguish from vegetation-covered sheets and small lobes. Thus greater amounts of vegetation cover found for this type of terrace can be related to their close association with these sheets and vegetation-covered small lobes. The largest variation in vegetation cover on treads was found for the oblique terraces, with a range of 10%-90%. A minimum mean of 21% was obtained for the

Drumochter sample (n:30). For the Creag Meagaidh area (n:30) and the Cairngorms (n:59) the means are larger, being 40% and 46% respectively.

7.4.4 Factors controlling terrace morphology

Like gelifluction lobes turf-banked terraces were also presumed to have responded to the two main controlling factors: altitude and hillslope angle. Possible relationships between terrace morphology and these two controlling factors were tested by regression analysis. For the three areas only horizontal (normal and lobate) terraces were considered as the sample measurements for the oblique type were obtained from a very limited range of altitudes and hillslopes. Five important morphological variables (length, width, riser height, riser angle and thickness) of horizontal terraces of the respective study areas were regressed on the corresponding altitudes and hillslope angles. The results are shown in Table 7.2.

For the Drumochter and the Creag Meagaidh hills inverse relationships are found between altitude and all tested parameters except width, although high statistical significance (99%) exists only in the cases of length for the Drumochter and riser height for the Creag Meagaidh samples. In all other cases, except for terrace length in the Creag Meagaidh area (95% significant difference), correlation values are too small to reveal any meaningful relationships. In contrast, for the Cairngorm terraces positive relationships of moderate to high statistical significance (95%-99%) suggest a strong influence of altitude on terrace morphology. Thus unlike those of the two other areas terraces in the Cairngorms appear to become increasingly well developed with increase in altitude.

Correlation testing of terrace parameters with hillslope angle for the three areas produced very similar results at least in the cases of riser height, riser angle and thickness. Large correlation values of high statistical significance (99%) for these three terrace parameters suggest that hillslope angle is a major control of terrace morphology regardless of lithological variations : riser height, riser angle and thickness of terraces tend to increase significantly as the hillslope steepens.

The morphological variables of the three types of terrace were each studied in relation to slope angle. This was to ascertain if the terrace types show any significant differences in response to hillslope angle. The samples of the three types of terrace obtained from the Drumochter area are plotted on the two sets of scattergram in Fig. 7.4, one comprising values for terrace length and the other terrace riser height. In the scattergram where length is considered, none of the three types shows any

Drumochter terraces

n : 170

	Alt.	Slp.ang.
Length	-0.230 -------	0.008
Width	0.032 - - - -	0.032 - - - -
Riser height	-0.001	0.423 -------
Thick-ness	-0.001	0.212 -------
Riser angle	-0.012	0.518 -------

Creag Meagaidh terraces

n : 170

	Alt.	Slp.ang.
Length	-0.036 - - - -	-0.010
Width	0.008	-0.014
Riser height	-0.176 -------	0.372 -------
Thick-ness	-0.006	0.176 -------
Riser angle	-0.001	0.476 -------

Cairngorm terraces

n : 141

	Alt.	Slp.ang.
Length	0.032 - - - -	0.040 - - - -
Width	0.230 -------	0.096 -------
Riser height	0.160 -------	0.436 -------
Thick-ness	0.152 -------	0.325 -------
Riser angle	0.548 -------	0.656 -------

r^2 values are plotted in the table.

----- 99% Significant diff.

\- - - 95% Significant diff.

Table 7.2 Correlations between selected parameters of horizontal terraces and most likely controlling factors.

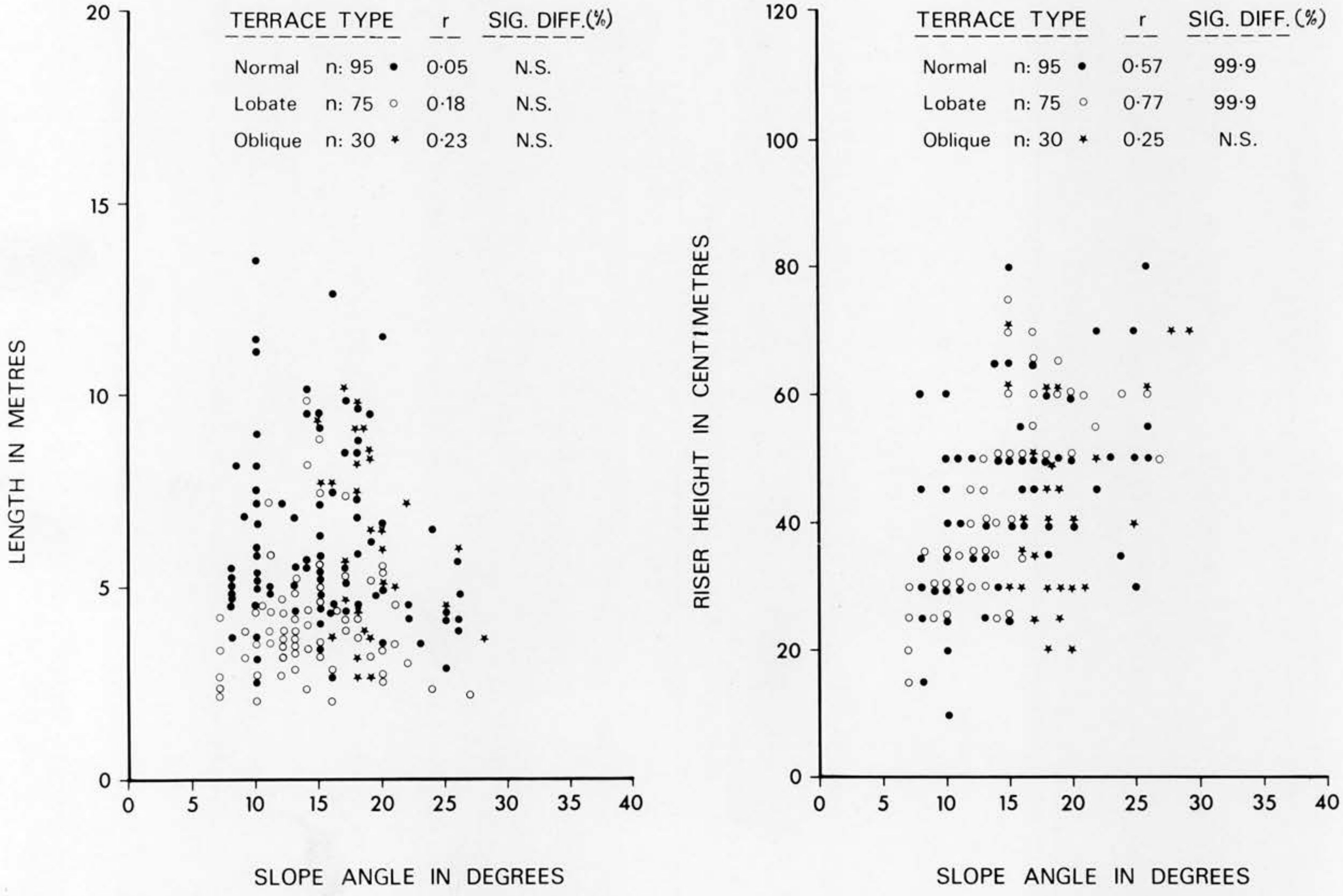


Fig. 7.4

Scattergrams showing relationships between two selected parameters of the three types of turf-banked terrace and hillslope angle in the Drumochter area.

statistically significant relationship to slope angle. But the regression of riser height values on the hillslopes, as shown in the other scattergram, produced markedly strong correlations and high statistical significance (99%) for the normal and the lobate terraces. For the oblique terraces the absence of any acceptable statistical significance and correlation value appears to be consistent with their smaller range of slopes (confined to steeper gradients). Oblique terraces in the three areas occur within the range of 15°- 32° slope gradient compared to 6°-35° for the two other types.

7.5 Structural characteristics and possible mechanisms

Structural characteristics of turf-banked terraces were studied by excavating four normal terraces selected in different parts of the three study areas. The investigation of stratigraphy for each site involved drawing sections to scale, measurements of size and shape of surface and subsurface clasts and analysis of material collected from varying depths.

The sections in the four terraces are illustrated in Fig. 7.5. The terraces of Sites 1 and 2 are in the Drumochter area, the former on a 20° east-facing slope on Geal-charn at 780m and the latter on a 12° west-facing slope on Meall a' Chaorainn (to the east of the pass) at 870m. The terrace of Site 3 is located in the Creag Meagaidh area at

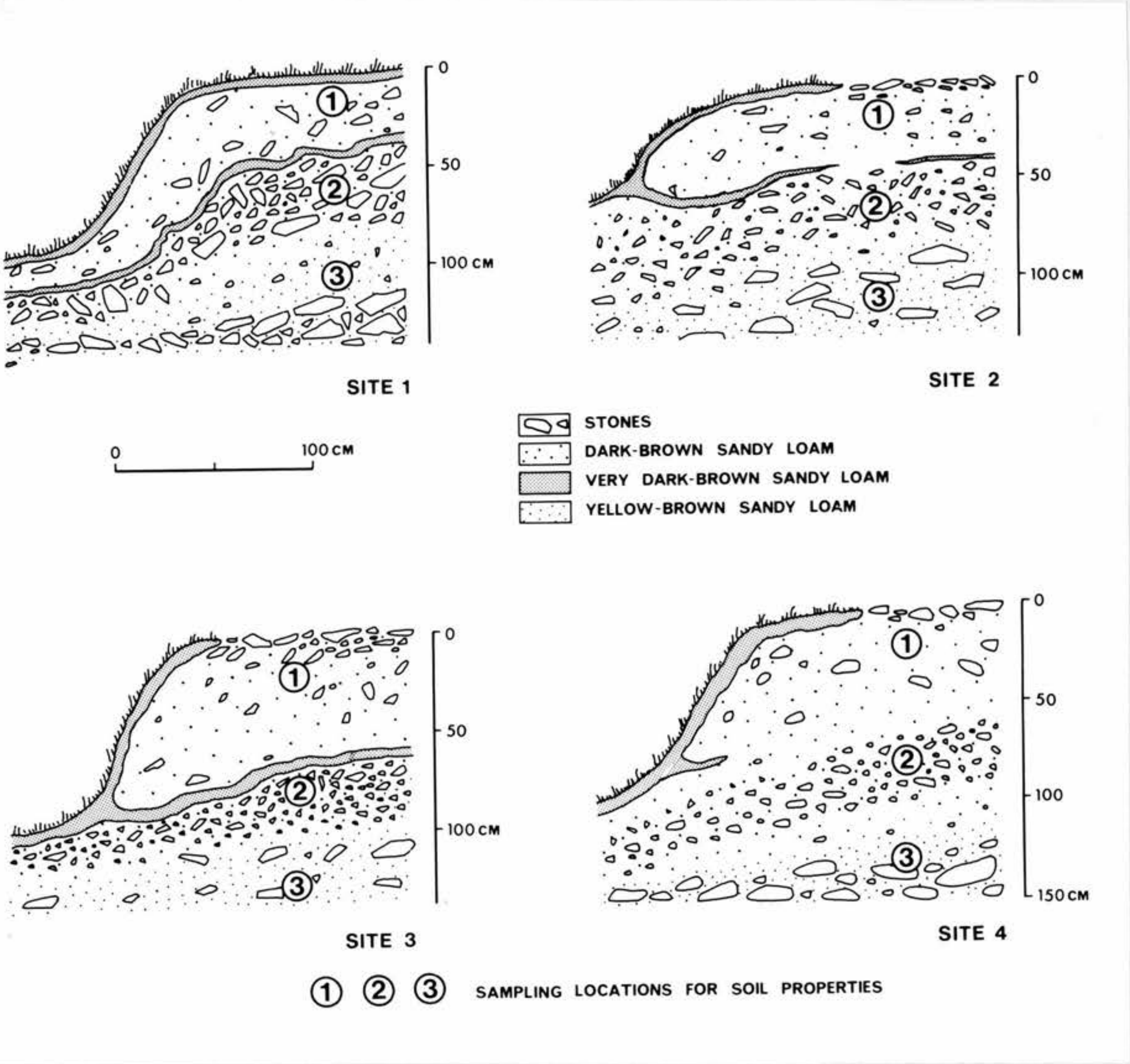


Fig. 7.5 Sections through four turf-banked terraces studied in detail. Sites 1 and 2 are located in the Drumochter area, Site 3 in the Creag Meagaidh area and Site 4 in the Cairngorm area.

1030m altitude on a 15^o southwest-facing slope of Puist Coire Ardair, and Site 4 is in the Cairngorms on a 20^o north-facing slope of Coire Gorm.

The structure revealed by the excavations differs from terrace to terrace with a general similarity that all are developed upon a basal regolith of angular blocks mixed with yellow-brown sandy loam. Except Site 1, which is a vegetation-covered relict type, all terraces have a thin layer at the surface with very little fines. This suggests that the fines have been removed by wind. The upper unit of all the terraces is 30-60cm thick and comprises a regolith of dark brown sandy loam with occasional small stones. A thin (3-8cm), very dark brown horizon rich in organic material was found in Sites 1, 2 and 3. For Sites 2 and 3 this layer connects with the surface soil at the front and is apparently the result of overriding by the upper unit. This feature is similar to the two vegetation-covered small lobes (Chapter 6, Section 6.5.2) trenched in the Drumochter area. For Site 1 this horizon probably marks the downward limit of humic and minerogenic materials that leached through the upper layer of sandy loam. An intermediate layer, composed of dark brown sandy loam with abundant small stones, was found in each terrace.

The size and shape of clasts were studied on samples of 50 from selected surface and subsurface locations of the four terraces and the results are shown in Fig. 7.6 and Table 7.3. No marked variation exists in mean diameter ((a+b+c)/3) for surface and subsurface clasts, except for Site 2 where a slightly lower value for the subsurface

Turf-banked terraces	Mean clast diameter $((a+b+c)/3)$ cm	Mean clast sphericity $((bc/a^2)^{1/3})$
<u>Site 1</u>		
Surface, front	4.1	0.59
Surface, centre	3.5	0.61
Subsurface, centre	3.4	0.65
<u>Site 2</u>		
Surface, front	2.9	0.63
Surface, centre	3.0	0.62
Subsurface, centre	2.8	0.65
<u>Site 3</u>		
Surface, front	2.3	0.58
Surface, centre	3.4	0.59
Subsurface, centre	2.2	0.62
<u>Site 4</u>		
Surface, front	5.1	0.66
Surface, centre	3.0	0.66
Subsurface, centre	2.8	0.67

Table 7.3 Mean values of the surface and subsurface clast diameters and sphericities for four excavated terraces.

clasts was found. In Sites 1 and 4 markedly larger clasts are concentrated at the front. The study of mean clast sphericity ($(bc/a^2)^{1/3}$) reveals greater values for the subsurface clasts for all sites. The other interesting feature obtained is that the sphericity values differ

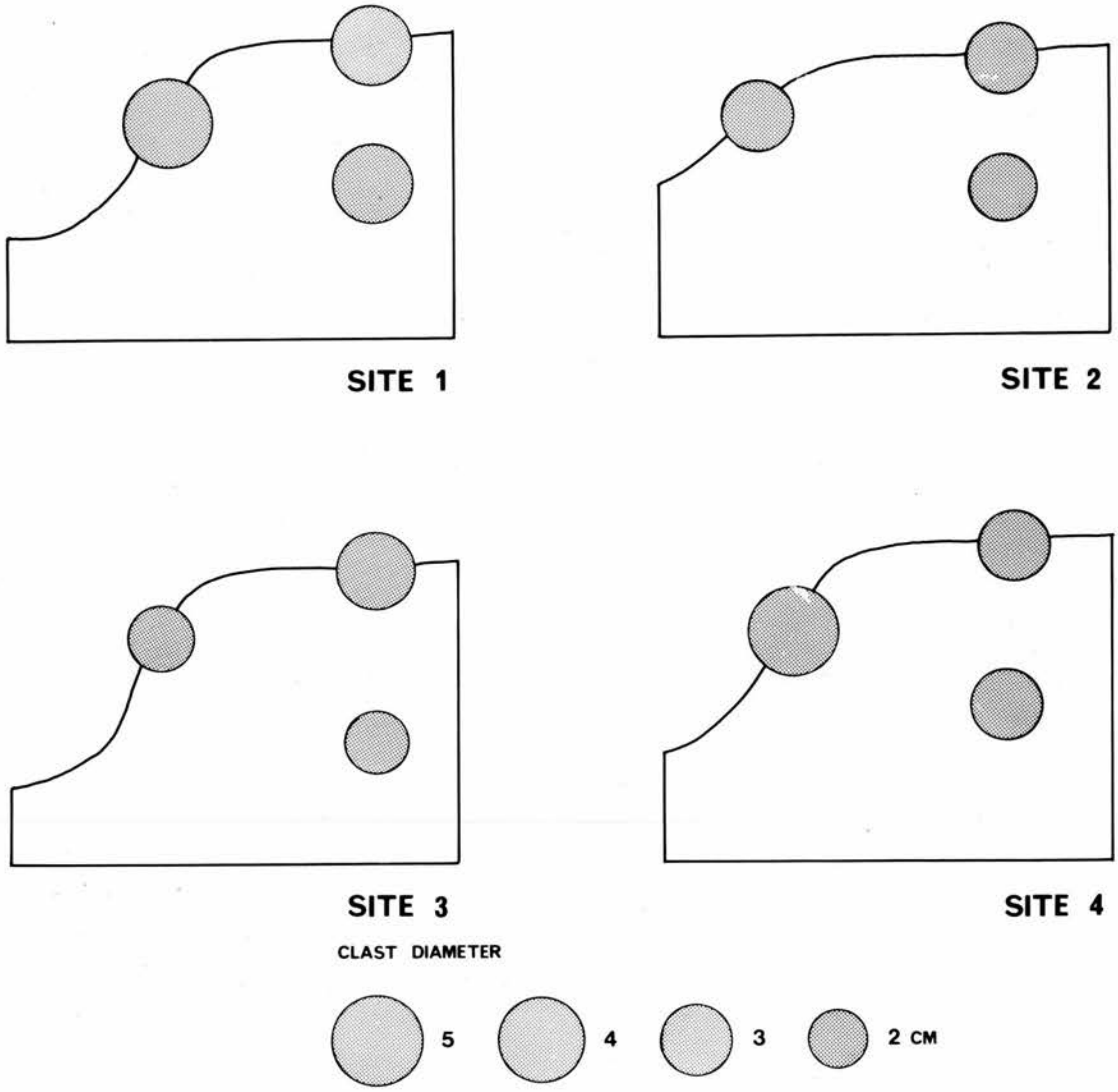


Fig. 7.6

Profiles of the four turf-banked terraces (Fig. 7.5) showing mean clast diameters at the surface and subsurface locations.

distinctly between terraces under the two different lithological controls. The clasts of all the terraces on micaceous rocks of the Drumochter and the Creag Meagaidh hills (Sites 1, 2 and 3) produced sphericity values distinctly lower than those for the terrace developed on granites in the Cairngorm area. The clast orientation and inclination were studied on samples of the surface (front and centre) locations using A_n 360 and A_n 180 statistics as explained in the previous chapter (Section 6.5.1). With one exception (Site 1; surface, centre) all samples showed a significant difference from a uniform distribution in orientation (A_n 180 statistic) at the 0.05 level. Downslope inclination (A_n 360 statistic) is not significant at the 0.05 level for the samples of any of the locations.

The pattern of grain-size distribution was studied on samples collected from varying depths shown in Fig. 7.5 and the results are displayed in Fig. 7.7. The terraces developed on Moine Schists in the Drumochter and the Creag Meagaidh areas and on granites in the Cairngorms do not present any marked contrast. In all cases the clay-silt component (<0.063mm) for the surface and the subsurface horizons exceeds 9% with a maximum of 20% for the terrace of Site 1. The dominant fraction in each sample is, however, coarse and medium sand (0.063-2mm).

The relatively high percentage of the clay-silt component in the studied turf-banked terrace samples is very similar

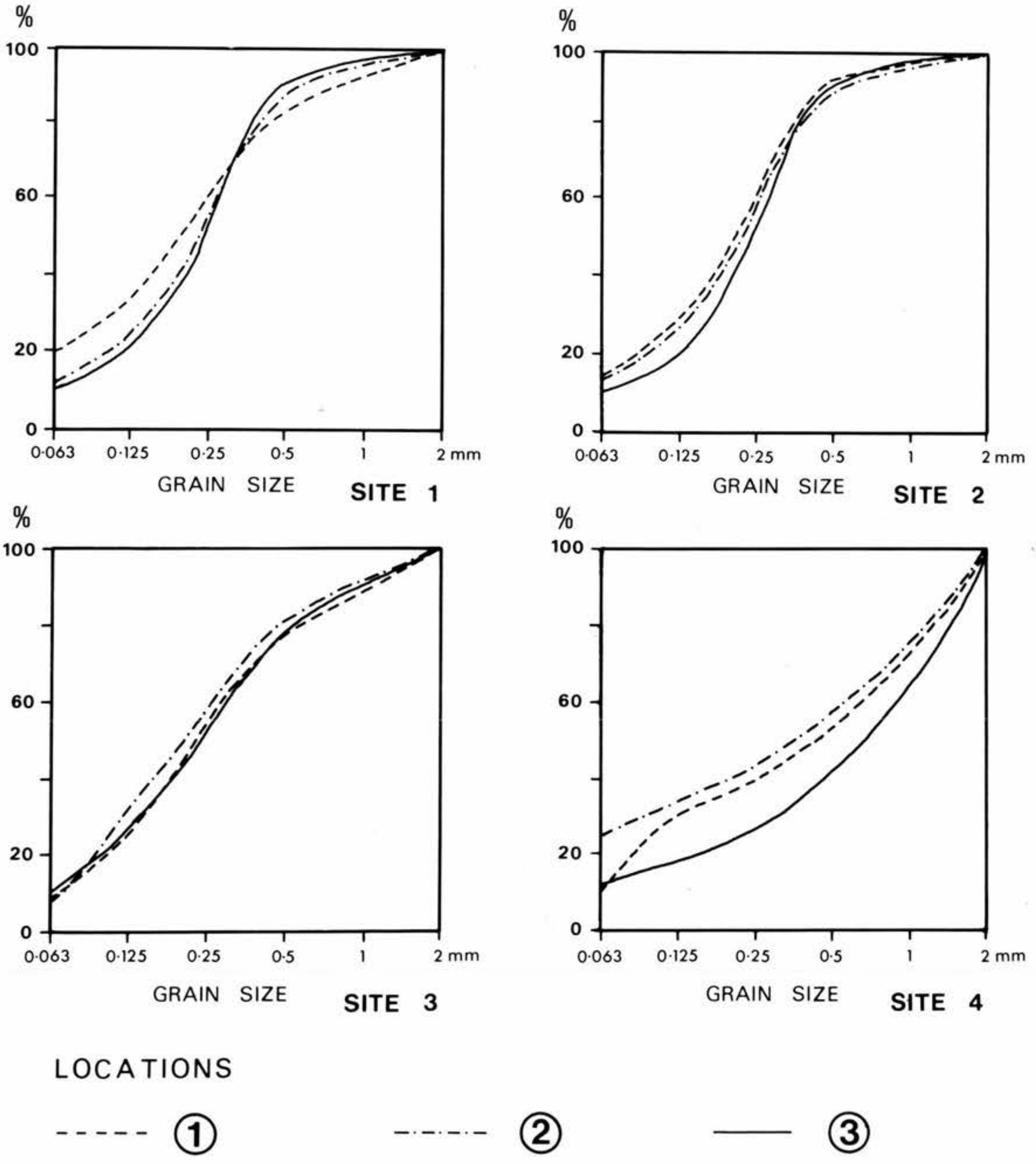


Fig. 7.7

Grain-size distributions of samples of fine material collected from the four turf-banked terraces from varying depths. sampling locations are shown in Fig. 7.5.

to that of the vegetation-covered small (solifluction) lobes and, as with the latter, suggests susceptibility to frost heave upon formation of ice-lenses and related solifluction activity during spring thaw and summer saturation. Segregated ice-lenses were found in an excavated terrace on the Drumochter hills (760m) in the winter of 1979 when ground freezing extended to a depth of about 65cm.

Discussion

Many suggestions have been put forward for the formation and activity of turf-banked terraces. Peach *et al*. (1912) proposed 'earth creep' as the main controlling factor. Hollingworth (1934), expressed a similar view, saying that frost creep helped the movement of such features. Later Galloway (1958, 1961a) and Ryder and McCann (1971) attributed the development of turf-banked terraces to the activity of solifluction. King (1968) inferred from his study in the Cairngorms that the distribution of such features is largely controlled by the deflation activity of wind. Deflation at varying scales has also been suggested by many workers who have studied in upland Britain (e.g. Kelletat, 1970a; Ball and Goodier, 1974; Goodier and Ball, 1975) and abroad (e.g. Taylor, 1955; Benedict, 1970b).

The formation of the turf-banked terraces of the present study is rather problematic. The terrace treads are exposed and normally exhibit the effect of deflation in contrast to their vegetation-protected risers. This indicates that wind has flattened the treads. But there is little evidence that turf-banked terraces develop only on lee slopes with an alignment across the direction of dominant wind. The dominant wind in the central Grampians is from the south-west. The grid-study of terrace aspect in the Drumochter area (Section 7.3.2) revealed that turf-banked terraces are widespread on southern, south-western, western and north-western slopes. However, in this study all large and small terraces were considered and in the field large horizontal (normal) terraces, with relatively high (>40cm) risers protected by characteristic Calluna stems, were found on the north and north-east facing (lee) slopes. On exposed southerly and south-westerly slopes terraces are shorter in length with riser vegetation often scoured by strong wind action. Small horizontal (lobate) terraces are widespread on these slopes. In other instances horizontal (normal) terraces were found aligned approximately parallel with the wind, as on the north-easterly extended spur of A' Mharconaich in the Drumochter area and on Carn Odhar in the Cairngorms. These terraces have low risers and appear transitional between wind stripes and terraces.

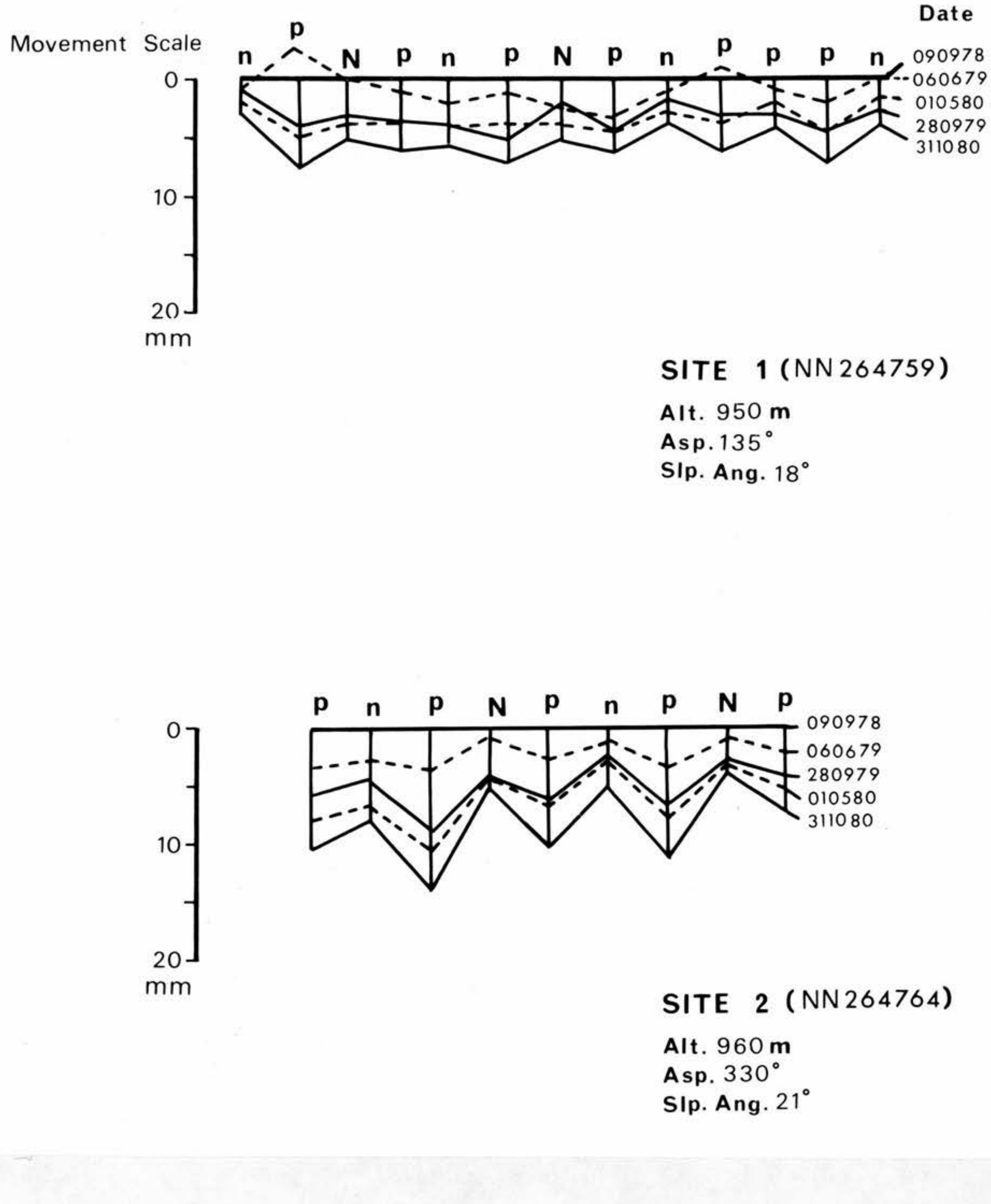
Oblique terraces were found on steeper slopes, particularly by cols, where the dominant wind is controlled by the local relief, as on the northerly-sloping shoulder of A' Mharconaich, in the Drumochter area, on the slope south of Uinneag Coire Ardair in the Creag Meagaidh area, and on the north-westerly slope of Coire Gorm by the Lairig Ghru in the Cairngorms. The horizontal (normal and lobate) terraces on both sheltered and exposed slopes largely occur on higher ground in association with vegetation-covered (solifluction) sheets. Hence they should respond to frost-creep and gelifluction activities proposed for the formation of these sheets. All these terraces are virtually wind-modified vegetation-covered (solifluction) sheets.

Oblique terraces are generally inclined down towards the west from the contours. The possible influence of a locally dominant wind has already been proposed. If this is the case, an initial vegetation-free surface is required to permit free movement of the slope regolith in the form of oblique lines. The other reason for the inclined growth of these terraces is probably related to the effect of frost along the riser. As suggested by Rapp and Clark (1971) both vegetation and frost remaining during the period of thaw can stabilize the terrace front, causing the downward movement of the material along the sloping terrace.

For the normal terraces, which occur parallel to the dominant wind and have low risers, gelifluction activity seems insignificant. Once the surface vegetation is stripped off in forming parallel lines of alternating exposed surface and vegetation, exposed areas are likely to come under the process of superficial frost creep chiefly by needle-ice activity. The continuation of this process can supply material along the line of vegetation on the downslope edge of the stripe, thus helping the development of a low but distinct riser for the stripe.

7.6 Present-day activity

Present-day activity of turf-banked terraces was assessed by measuring indicator displacements on the terrace surfaces in the Drumochter area. Mass movement sites were installed on two horizontal terraces on the slopes of A' Mharconaich at 950-960m, one facing south-east and the other facing north-west. As for the lobes two iron poles, each 1.5m in length, were inserted into the ground, one on each side of a terrace and three types of movement indicator (drawing pins, 3" nails and 6" nails) were placed across each terrace from pole to pole. The movement sites were installed in September 1978 and measurement of displacements was made twice a year, in early summer (May-June) and late summer (September-October) during 1978-79 and 1979-80. The results are plotted in Fig. 7.8.



p : Drawing pin (on surface clast) n : 3" nail N : 6" nail

Fig. 7.8 Downslope displacements of movement indicators across the treads of two turf-banked terraces on the Drumochter hills. Site 1 is a normal terrace and Site 2 is a lobate terrace.

Site 1 is a normal terrace with the characteristic long bare tread surface along the hillslope contour and Site 2 is a lobate terrace. The diagram shows that all indicators were displaced downslope in the two-year period by different amounts. For the normal terrace (Site 1) the displacement is fairly uniform from end to end and a retrograde component is apparent for a number of movement indicators. The retrogradation was found mostly at the time of the first summer measurement in 1979 when a dry-day ground contraction apparently drew the indicators backward from their possible advanced positions. For the lobate terrace (Site 2) the movement of all indicators has a regular pattern with the drawing pins, set on surface clasts, moving the longest distances. In general the indicator movements are much less pronounced on the turf-banked terraces than on the lobes.

The following table gives details of the mean annual indicator displacements on the two turf-banked terraces.

Year	Drawing pins	3" nails	6" nails
1978-79	9.7	5.0	5.8
1979-80	6.3	4.5	3.8
Total	16.0	9.5	9.6

Table 7.4 Mean annual displacements (in mm) of movement indicators on the treads of two horizontal terraces on the Drumochter hills.

The table shows a distinct variation in displacement between the drawing pins (on surface clasts) and the other indicators, and between the two years studied. The greater amounts of displacements in 1978-79 can be correlated with the very severe winter and the following exceptionally wet summer. In common with the lobes indicator movements appear to be the result of the combined effect of frost creep and gelifluction, with frost creep dominating at least for the surface clasts. In the late summer and spring individual clasts were found heaved up from their original positions largely by needle-ice activity. This coincides with the fact that drawing pins on the surface clasts moved markedly longer distances than the two other types of indicator.

7.7 Conclusions

The most characteristic feature of turf-banked terraces is their contrast in vegetation cover between the riser and the tread : the former exhibits a thick cover of vegetation and the latter is relatively sparsely vegetated and shows the result of wind action. The three main types recognized : normal, lobate and oblique terraces - respond primarily to slope regolith - predominantly of fine material, and slope gradient. Correlation analyses revealed that slope angle is a significant control at least for riser height, thickness and riser angle of the horizontal (normal and lobate) terraces. Lobate terrace areas often coincide with the vegetation-covered (solifluction) lobe and lobate sheet areas, both occurring on higher ground near the summits. These two features can be distinguished on the basis of their pattern of downslope inclination of tread and vegetation cover. Vegetation-covered sheets consequently incline with the slope but the terrace treads become increasingly flat and sparsely vegetated with the increase of slope gradient. The occurrence of normal terraces is rather problematic. The sample of 481 surveyed in the three areas include both those developed on vegetation-covered (solifluction) sheets across the dominant wind and those on deflation surfaces parallel with the dominant wind, although the former predominate. The terraces on deflation surfaces are largely the result of wind action and can be termed deflation terraces. Wind action appears to be responsible also for the downslope inclination of the oblique terraces. The internal composition of many normal terraces (e.g. Sites 1, 4) is similar to that found for the debris lobes. It appears that, like debris lobes, some of these terraces were formed during late glacial times and moved through the Flandrian. The presence of a number of small turf-banked (lobate) terraces inside the presumed Loch Lomond Advance limit in the Drumochter hills suggests that some of them have formed and remained active in postglacial times. The recorded present-day activity shows that many of the turf-banked terraces in the high altitude areas are still active under the present climatic conditions.

CHAPTER 8

Ploughing blocks

8.1 Literature

Ploughing blocks or individual boulders that glide down hillslopes in a mild periglacial environment were initially referred to in the literature on British examples by Hay (1937, 1942). He observed 'gliding blocks' in the Lake District on moist hillslopes of about 8^{o} gradient (1 in 7) and attributed them to solifluction and frost action. He concluded that their downhill movement must have been going on 'ever since the ice left the tops of these fells'. After Hay's introductory work no observation on ploughing blocks was done until the study of Galloway (1958). He recognized downhill moving boulders on the Scottish mountains in his study of periglacial phenomena. He described two types of block : one which moved downslope more slowly than the fine material upon which it rested (brake block) and the other moving faster than the surrounding finer material (ploughing block). Galloway proposed no name for these features apart from mentioning these blocks of the second type as 'individual block creep' in his later work (1961b). This type was reported from Ben Wyvis, the lower slopes of Ben Macdui (Cairngorms), the hills in the Southern Uplands and the Tinto Hills, with a range of hillslopes from 6° to about 24°. Afterwards Tivy (1962) found large blocks and stones on the Lowther Hills showing evidence of contemporary downslope movement. The first systematic study of ploughing blocks was attempted by King (1968) based on the Cairngorm mountain examples. He reported the widespread occurrence of 'gliding boulders' on convex slopes of 5°-30° gradient and between 850 and 1,200m altitude. He also pointed out that this feature frequently occurred on the grassy areas, particularly on the east-facing hill slopes where snow persists longer in the year. Afterwards Sugden (1970b) also expressed a similar view on the ploughing block distribution in the Cairngorms saying that they occurred above 830m elevation and almost exclusively on east-facing slopes. He maintained that this feature was influenced by aspect more than any other periglacial landform.

Goodier and Ball recognized 'gliding blocks' on the Rhinog Mountains of North Wales at 700m on a slope of 27°. The largest block they found was 1.6m long with a furrow length of 13m. Other good examples were seen in North Wales on several hills above 610m. From further observations these authors (Ball and Goodier, 1970b) concluded that the mechanism was basically associated with gelifluction processes occurring during seasonal thaw. This implies sliding of blocks upon unstable water-saturated or loosely frozen ground. It was also suggested from the observation of the accumulated soil (bow-wave) in front that after a 'substantial movement the ploughing blocks were slowed down or completely stopped'.

The most detailed study on ploughing blocks in the British Isles so far is that of Tufnell (1972), who studied a number of characteristics of ploughing blocks in northern England and in the Alps. He measured the rate of downslope movement over the period 1965-75 and gave the rate of annual and seasonal downslope movements (Tufnell, 1976).

A recent study of ploughing blocks by Shaw (1977) involved the size relationships, distribution, general characteristics and movement rates of 'gliding boulders' in granite and quartzite areas in the south-east Grampians.

8.2 Present study

From the above summary of the literature it is evident that studies on ploughing blocks in Great Britain have not yet provided a thorough understanding of these features. The number of detailed studies on the Scottish mountains is limited. The aim of the present study is, therefore, to produce some quantitative information and related analysis of the distribution, size characteristics and present-day activity of ploughing blocks based on an extensive study of geomorphological maps and measurements made in the field.

8.3 Distribution

In an attempt to determine the distributional pattern (altitude, aspect and slope angle) of ploughing blocks and their limiting factors in the study areas the same sampling procedure was followed as for the gelifluction lobes and the turf-banked terraces (Chapter 6 and 7). The map sampling was done for each of the areas using the Ordnance Survey 100m grid on the photogrammetrically surveyed maps (1:10,000 scale) with 10m contour intervals. The six-figure grid lines were placed on the geomorphological maps and each grid intersection above the lowest ploughing block was sampled.

8.3.1 Altitude

Ploughing blocks are abundant on many parts of the hillslopes in the three areas of the Grampians. In the Drumochter hills the lowest sample was found at about 650m on the south-east-facing slope of an unnamed hill to the north of Geal-charn (NN 620759). Ploughing blocks are characteristic on the slopes where vegetation-covered sheets are well developed and the ground remains moist almost throughout the year owing to late-lying snow patches. These favourable conditions occur on A' Mharconaich, which exhibits widespread ploughing blocks on slopes of all aspects. Some ploughing blocks on this hill were found near the summit areas at an altitude of about 970m (NN 603763) on very low slope gradients. On Geal-charn ploughing blocks are distributed mostly on the north-eastern and the north-western slopes. On the hills to the east of the pass they descend from near the summit to about the altitude where vegetation-covered sheets terminate.

In the Creag Meagaidh area ploughing blocks are markedly developed on the hillslopes north and west of the corrie of Allt Coire Ardair. The highest block was mapped at an altitude of about 1,100m on the south-facing slope of an unnamed summit in the west (NN 425875) and the lowest example was found on a hillslope in the east at about 680m (NN 479897). Ploughing blocks are well developed on the vegetation-covered sheets on the slopes by the main corrie. In contrast on the hills to the south, where these sheets are of limited occurrence, ploughing blocks are sparsely distributed.

Ploughing blocks in the Cairngorm area were found mostly on the high ground on either side of the Lairig Ghru. Unlike the two other areas the Cairngorms do not exhibit ploughing blocks down to the lowest altitude to which gelifluction lobes and terraces descend. To the west of the Lairig Ghru, on the slopes of Coire Gorm, they are most abundant. The lowest example of this feature was mapped on the east-facing slope of Castle Hill (NH 980021) at about 700m. Compared to the two other areas ploughing blocks in the Cairngorms are sparsely distributed and restricted to patchy areas. This accords with the limited occurrence of vegetation-covered sheets in this area.

The altitudinal distribution of ploughing blocks given by the grid reference study is summarized in Fig. 8.1.1. Diagrams A1, B1 and C1 demonstrate the altitudinal distribution of land and ploughing blocks in 50m class intervals. The ploughing block sample is represented by the shaded area and the land sample by the solid line. For each area the diagram of ploughing block sample has been superimposed on the diagram of the land sample obtained for the lobes and terraces. In the Drumochter and the Creag Meagaidh hills, although ploughing blocks occurred from below 700m, a major portion of the sample was collected from the higher ground. A preferred zone obtained from the diagrams where ploughing block sample exceeds land sample is between 750 and 950m in the Drumochter area and from 850m to the highest altitude in the Creag Meagaidh area. In the Cairngorms this zone

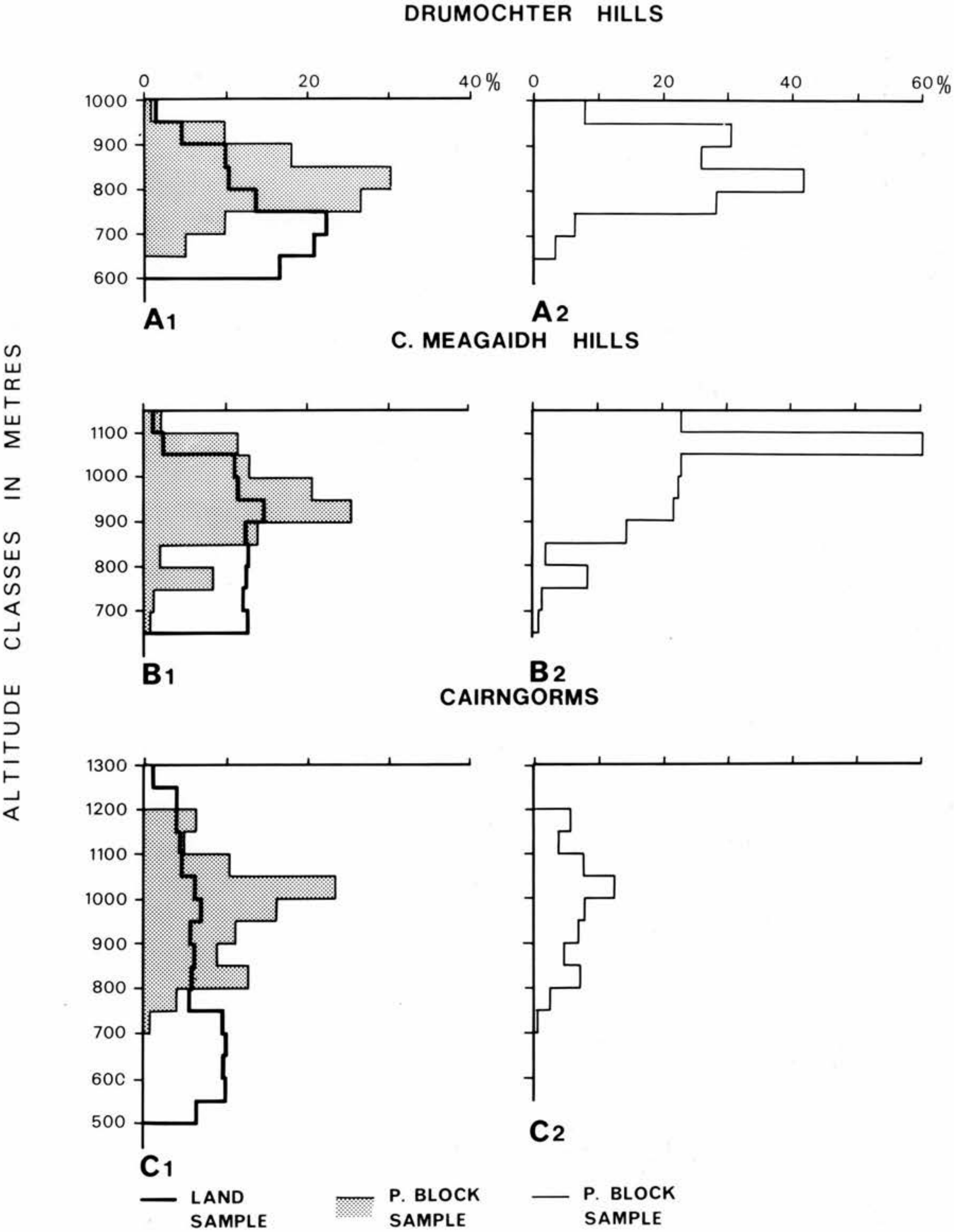


Fig. 8.1.1

The altitudinal distributions of ploughing blocks in the three study areas based on data derived from the geomorphological maps. The diagrams A1, B1 and C1 show the percentage distributions of land and ploughing blocks and A2, B2 and C2 represent the percentage of ground surface occupied by ploughing blocks in different altitudinal zones above the lowest ploughing block limit.

extends from 800 to 1,200m. Diagrams A2, B2 and C2 illustrate the percentage of ground surface occupied by ploughing blocks in different altitude classes. Two distinct features appear in the diagrams : (i) in the Cairngorms there is a complete absence of ploughing blocks above 1,200m (diagram C1) and (ii) in the Creag Meagaidh area there is a sudden rise in ground occupation by ploughing blocks at 1,050-1,100m (diagram B2). This trend can be compared to the similar picture obtained for the turf-banked terrace distribution. It was observed in the field that both turf-banked terraces and ploughing blocks are closely associated with vegetation-covered lobes and sheets developed on moist ground. In the Cairngorms the very bouldery nature of the ground surface above 1,200m elevation appears to be the main reason for the absence of ploughing blocks. Conversely the extensive distribution of vegetation-covered sheets associated with moist ground conditions in the Creag Meagaidh area at 1,050-1,100m altitude seems to have provided an ideal base for their widespread distribution.

Ploughing blocks in the study areas have apparently responded to several controlling factors. The influence of moist ground and the presence of vegetation-covered sheets have already been mentioned. The lowest altitude of ploughing block developement approximately corresponds with the lowest altitude of vegetation-covered sheets. On the lower slopes the blocks were often seen to have been completely retarded by peat. Unlike large gelifluction lobes and terraces, ploughing blocks occur both inside and outside the areas occupied by Loch Lomond Advance glaciers. For example, on the eastern hills in the Drumochter area and on the steeper slopes declining southwards into the corrie of Allt Coire Ardair in the Creag Meagaidh area a number of ploughing blocks were mapped well inside this limit.

8.3.2 Aspect

Ploughing blocks were studied on slopes of all aspects in the three areas. But since the hillslopes in the Creag Meagaidh and the Cairngorm areas are unequally distributed among the aspects, as discussed in the previous chapters (Chapter 6 and 7), the sample study for the aspects of ploughing blocks has been carried out only in the Drumochter area, as for the lobes and the terraces.

Samples of the total land area and of the area covered by ploughing blocks were collected from the geomorphological map for the eight major aspects and are illustrated in Fig. 8.1.2. The solid line in diagram A represents the land sample and the shaded area demonstrates the ploughing block sample. The ploughing block sample noticeably exceeded the land sample for the northern and north-

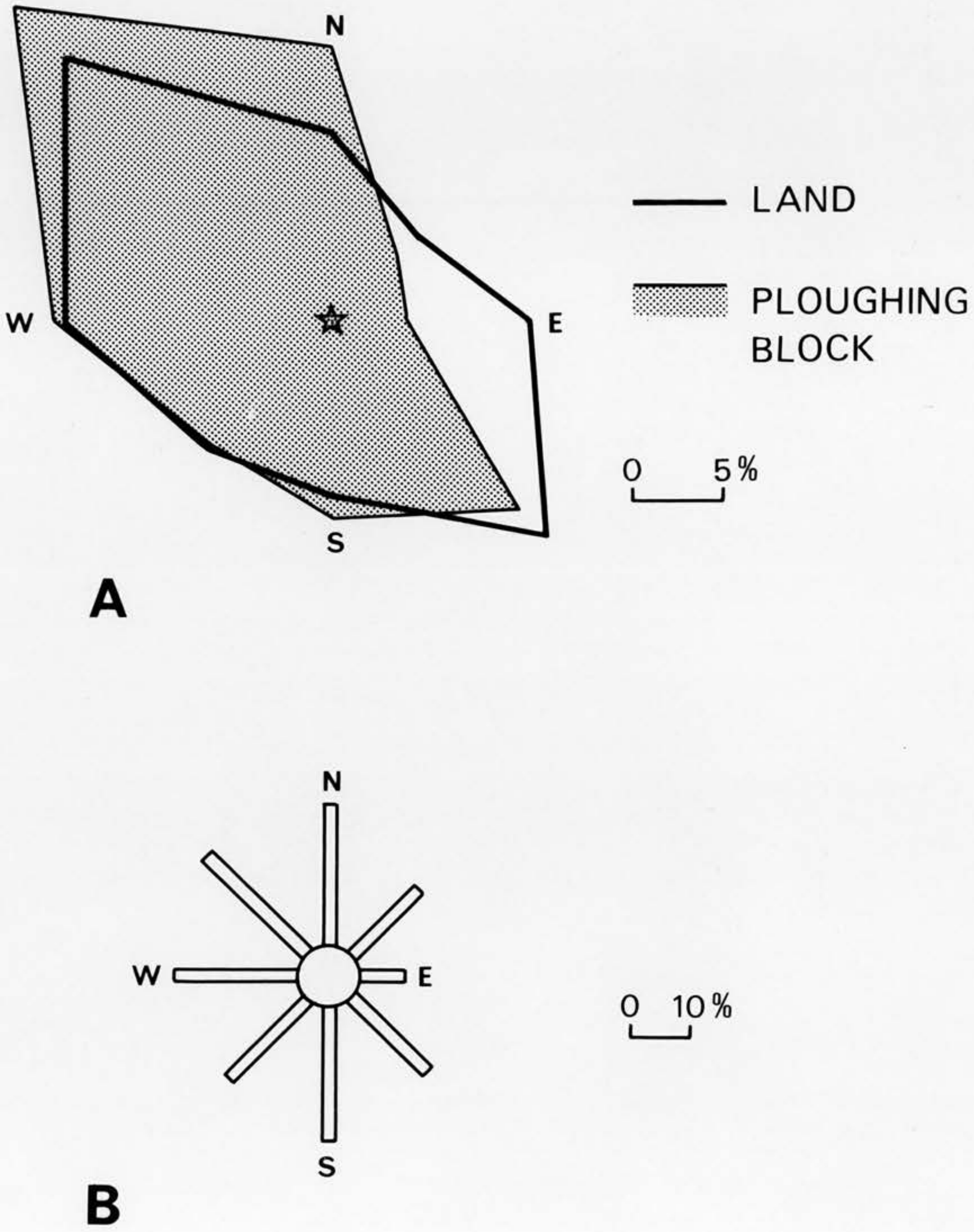


Fig. 8.1.2

The pattern of ploughing block distribution on hillslopes in the Drumochter area for the eight major aspects based on data derived from the geomorphological map. Diagram A shows the percentage distributions of land and ploughing blocks and B represents the percentage of ground surface occupied by ploughing blocks for different aspects.

western slopes and fell well below it for the eastern slopes. Another illustration of ploughing block aspect is provided by diagram B in the same figure showing the percentage of ground surface occupied by ploughing blocks for all major aspects. This suggests a fairly even distribution of this feature on slopes of all aspects except the east where adverse physiographic conditions (very steep slopes and cliff faces) restrict ploughing block distribution. On the northern and north-western slopes, although debris lobes and sheets dominate, ploughing blocks were seen to be well developed on the moist grassy slopes between lobes and sheets. For the western, south-western and southern slopes the spread of ploughing blocks appears mainly associated with the vegetation-covered sheets and related lobes.

These findings differ from those of King (1968) and Sugden (1970a). They considered from their observational studies in the Cairngorms that ploughing blocks are strongly influenced by aspect, occurring most extensively upon east-facing slopes. Shaw, however, (1977) concluded from his sample study in the Lochnagar area that 'gliding boulders' do not favour any particular aspect.

8.3.3 Slope angle

Map sampling for the slope angle of ploughing blocks was done on the geomorphological maps based on the 100m grid and 5° classes.

Ploughing blocks in the three areas were sampled from slopes as low as 4° although the maximum gradient differ for each area, this being 34° for the Drumochter area, 37° for the Creag Meagaidh area and 28° for the Cairngorms. The mean slope gradients for these three areas are 16° (standard deviation : 8°), 15° (standard deviation : 8°) and 18° (standard deviation : 7°) respectively. This suggests that this feature, in general, favours a moderate hillslope gradient despite the fact that a portion of the sample occurred on slopes as steep as 37°.

The pattern of ploughing block distribution in terms of hillslope gradients in the three areas is illustrated in Fig. 8.1.3, where diagrams A1, B1 and C1 represent the ploughing block distribution relative to the land surface above the favoured minimum. The preferred range of slope angles as obtained from the diagrams, where ploughing block sample exceeds land sample, are 10°-20° for the Drumochter and the Creag Meagaidh areas and 10°-25° for the Cairngorms. Diagrams A2, B2 and C2 demonstrate the percentage of ground with ploughing blocks in different slope gradient classes. Maximum ground occupation in the 10°-25° class for the Drumochter area, at 5°-20° for the Creag Meagaidh area and at 15°-25° for the Cairngorms presents a certain degree of difference but, summarizing the three areas as a whole, it can be inferred that a

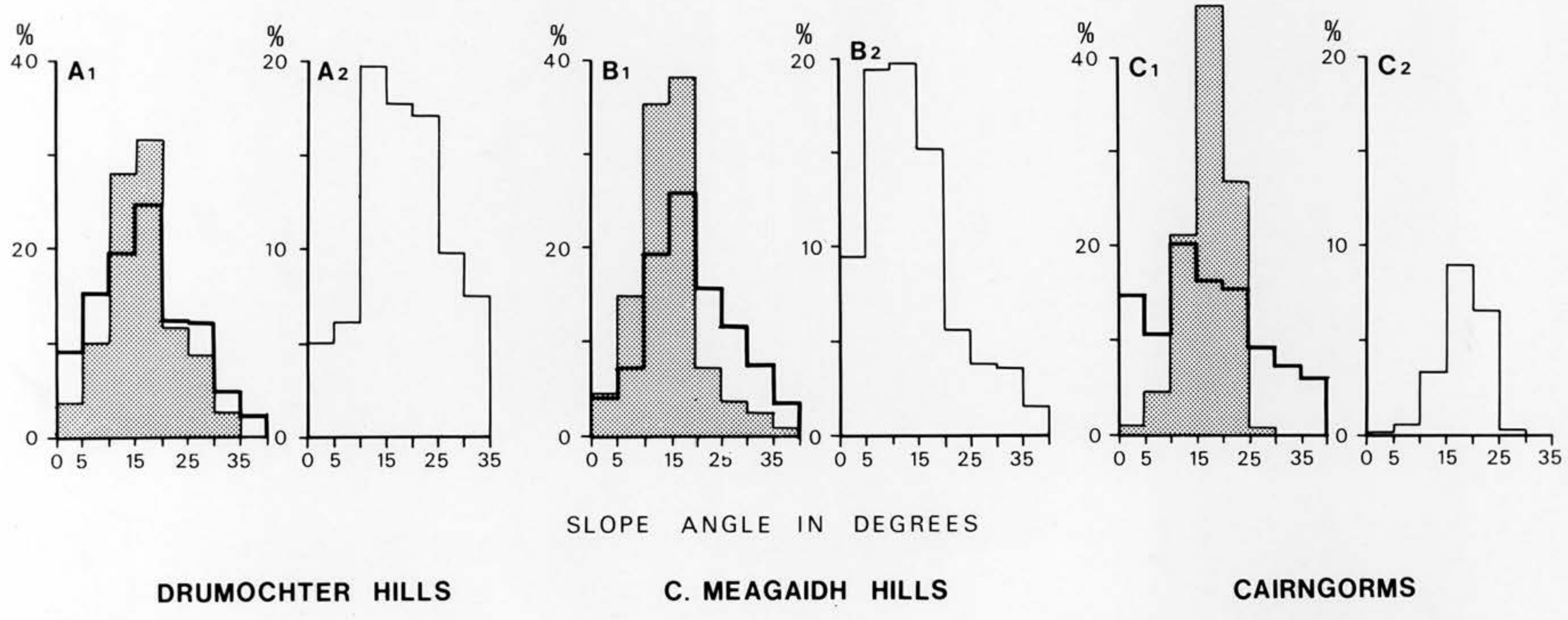


Fig. 8.1.3

Distribution of ploughing blocks in relation to hillslope gradient in the three study areas based on data derived from the geomorphological maps. The diagrams A1, B1 and C1 show the percentage distributions of land and ploughing blocks, and A2, B2 and C2 represent the percentage of ground surface occupied by ploughing blocks at different slope gradient classes above the favoured minimum.

range of slope gradient between 15^{o}-20^{o} is most favourable for ploughing block development.

At least two important features can be obtained from the study of the slope-ploughing block relationships. (a) Like gelifluction and turf-banked teraces ploughing block samples tend to increase with the land samples towards the moderate slopes and decrease thereafter as the slope gradient increases. (b) Ploughing blocks can occur on slopes steeper than 35^{o} and as gentle as 4^{o}. This reveals a range of slope angle for this feature greater than those of the two other gelifluction features examined in the same areas.

Ploughing blocks in the western Cairngorms were found upon slopes of 5^{o} to 30^{o} (King, 1968) and in the Southern Uplands of about 24^{o} (Galloway, 1958). Previously this feature was noticed in the Lake District to be best developed upon a slope gradient of about 8^{o} (Hay, 1942). From the Moor House Reserve in England a sample study of 500 ploughing blocks showed that about 85% developed upon slopes of 10^{o} to 29^{o}, with a mean of 18.1^{o} (Tufnell, 1972). In the Lochnagar area ploughing blocks were sampled between gradient limits of 9^{o} and 38^{o} (Shaw, 1977) with 95% occurring on slopes between 11^{o} and 29^{o}. The mean slope for the ploughing blocks in this area was calculated as 19.9^{o}. It is interesting to note that these findings by visual estimation and sample study agree closely with the results of the present study.

Summary

The above study of ploughing block distribution can be summarized as follows :

(i) Ploughing blocks are present throughout the slopes where gelifluction lobes and terraces occur, although this feature was not found to have descended to the lowest altitude for the lobes in the Cairngorms.

(ii) Vegetation-covered sheets on moist hillslopes exhibit large numbers of ploughing blocks with well defined furrows at the rear.

(iii) Aspect study in the Drumochter area suggests that, unlike gelifluction lobes and terraces, ploughing blocks have a fairly even distribution on slopes of almost all aspects (except the east).

(iv) The wide range of slope angle (4^{o}-37^{o}) found for the ploughing blocks indicates that this feature can develop on slopes gentler and steeper than those for lobes and the terraces.

(v) The preferred range of slope angle for the ploughing blocks considering the three areas together is 10^{o}-25^{o}.

(vi) The presence of ploughing blocks inside the Loch Lomond Advance limit (in the Drumochter and the Creag Meagaidh areas) implies that they have moved downslope during Postglacial times.

8.4 Morphology

The three main parameters (altitude, aspect and slope angle) discussed in Section 8.3 suggested the possible hillslopes upon which ploughing can occur. The study of ploughing block characteristics is based on the measurement of the following morphological elements : (i) block length, (ii) block width, (iii) block height, (iv) block orientation, (v) furrow length, (vi) furrow depth, (vii) bow-wave height and (viii) lithology.

Two physiographic micro-features are directly related to the ploughing blocks. They are the furrow and the bow-wave. From the ploughing block upslope there exists a well defined linear depression showing the former course of the block movement. The term 'furrow' for this depression has been accepted in the present study following Hay (1937) and Galloway (1961a). The debris that is pushed up at the front of the moving block was termed the 'bow-wave' by Galloway (1961a) and Ragg and Bibby (1966). Hence this term is used here.

The morphological elements measured in the field for the ploughing blocks can be explained as follows :

(i) Block length : long axis or the longest dimension of the block parallel to the ground surface.

(ii) Block width : the shortest dimension of the block parallel to the ground surface.

(iii) Block height : the maximum height to which the block projects above the ground surface.

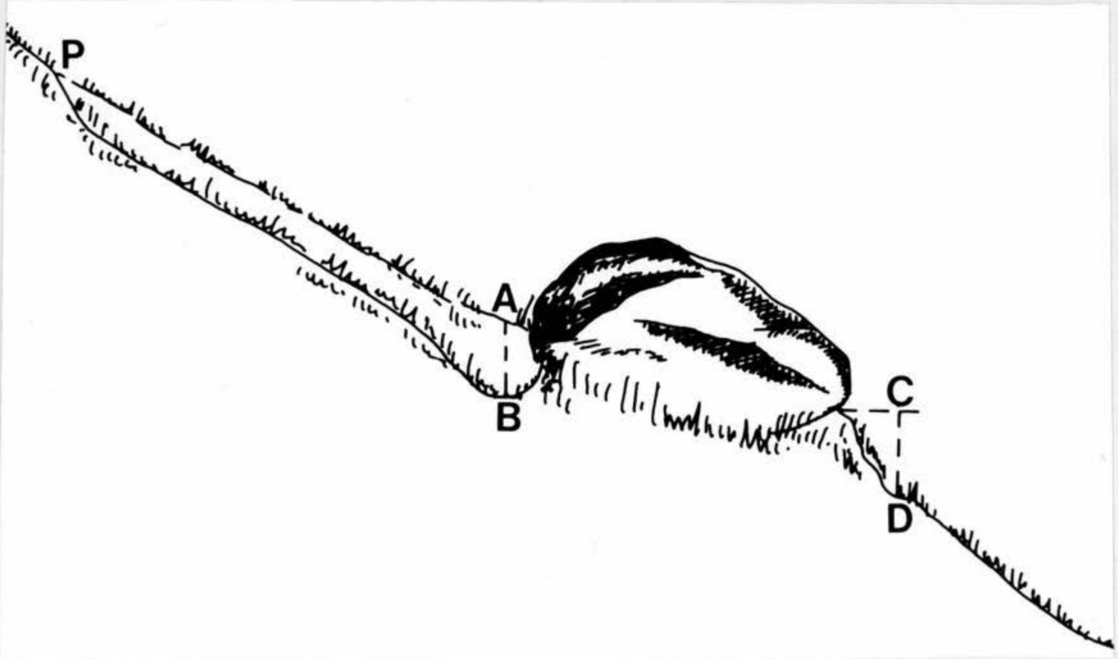


Fig. 8.2 Micro-features associated with ploughing blocks described in the text.

(iv) Block alignment : the deviation in degrees of the long axis of the block from the direction of the maximum slope.

(v) Furrow length : the length of the depression recognizable from the upslope edge of the block (Fig. 8.2, AP).

(vi) Furrow depth : the depth of the furrow immediately behind the block from the surrounding ground surface (Fig. 8.2, AB).

(vii) Bow-wave height : the height of the bow-wave from the surrounding ground surface (Fig. 8.2, CD).

(viii) Lithology : the type of rock of which the block is formed.

The study of the characteristics of ploughing blocks and their associated micro-features is based on the sample of one hundred randomly selected in the Drumochter area.

8.4.1 Nature of blocks

Blocks move downslope by sliding and ploughing. This movement is relevant to the size of the block as recorded by its A, B and C axes. Since the movement causes some amount of sinking into the ground the measurement of the three axes becomes difficult. The alternative technique employed to measure block size is the measurement of its largest and shortest dimensions parallel to the ground surface and the maximum height to which the block stands above the ground surface.

Block Size : The sampled ploughing blocks have a considerable range of size. Figure 8.3.1 illustrates the size range of the one hundred surveyed blocks. They range in length from 30 to 230cm, in width from 20 to 190cm and in height from 20 to 142cm. A large proportion of the sampled blocks are of moderate size, 80% being less than 120cm long, 73% less than 90cm wide and 63% less than 60cm high. The longest block has a length of 230cm, a width of 190cm and a height of 142cm above the ground surface.

The mean size of all sample blocks was calculated to be 102.8 X 77.5 X 55.4cm with standard deviations of 39.6cm, 32.8cm and 24.7cm respectively. This suggests that the average ploughing blocks in this area are larger than those surveyed in the Moor House Reserve (northern England) by Tufnell (1972), which averaged 65 X 49.5 X 16.3cm, and those in the south-east Grampians examined by Shaw (1977), which were 82.5 X 51.7 X 28.3cm in the metamorphic area and 113.5 X 70 X 38.3cm in the granite area. In the Swiss Alps much larger ploughing blocks were found by Tufnell (1972) which averaged 146cm long and 116cm wide, no heights being mentioned. Previously Höllermann (1964) and Furrer (1965a) observed ploughing

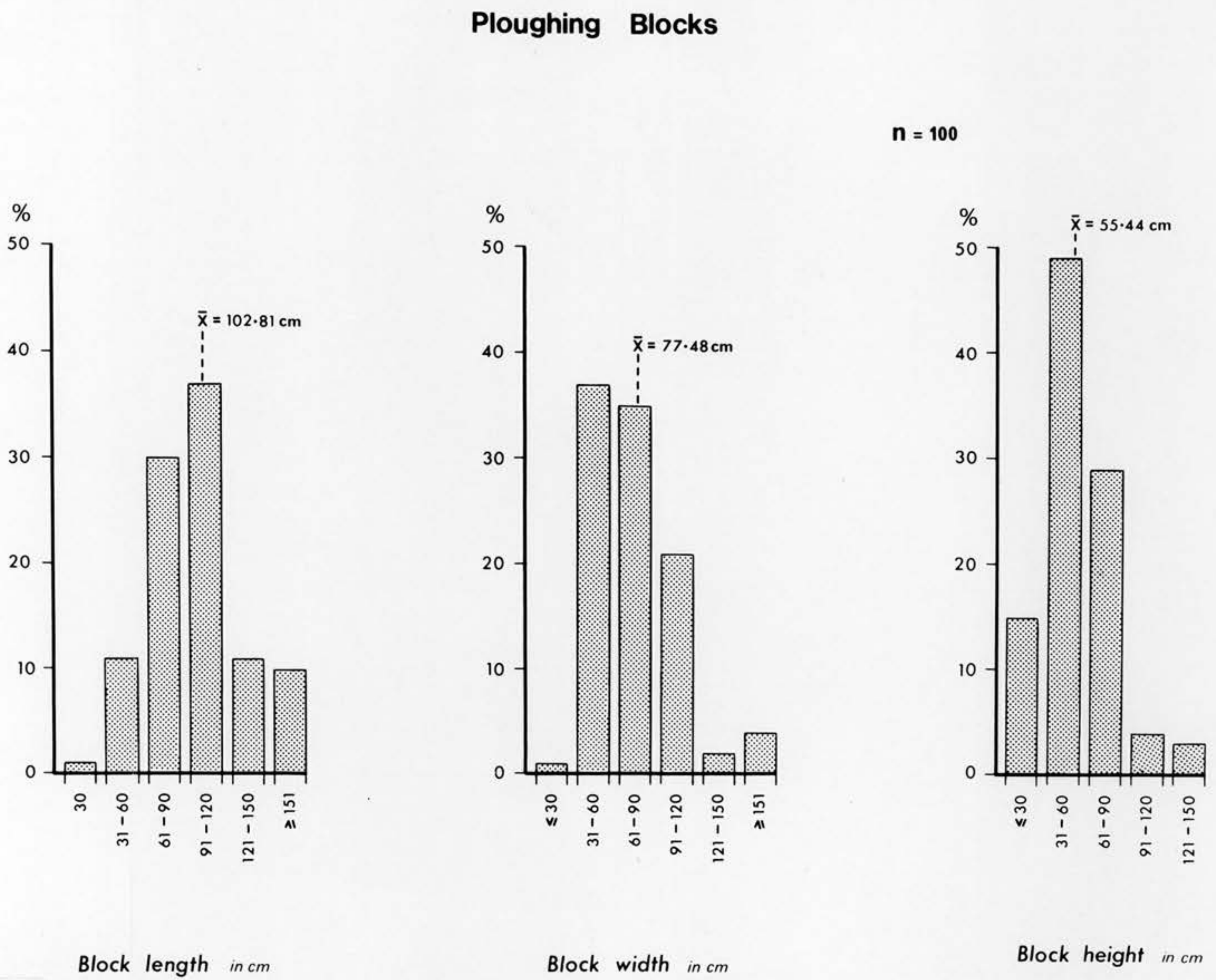


Fig. 8.3.1

Percentage frequency distributions of selected morphological elements of the ploughing blocks surveyed in the field.

blocks in the Alps whose long axes measured around 5m.

Block Alignment : Another aim of the ploughing block study was to determine the orientation of the long axis of each block in relation to hillslope aspect. A Suunto compass was used to measure the deviation of the block long axis from the direction of maximum slope. The results are plotted in Fig. 8.3.2 in 15° class intervals from 0° to 90°.

The diagram demonstrates that 52% of the sample blocks are aligned with their long axes almost parallel (within 15° deviation) with the direction of maximum slope. The remaining 48% range from 16° to 90° alignment, suggesting that a considerable proportion of ploughing blocks can have their long axes orientated at any angle to the direction of maximum slope. However, a major portion of the sample (72%) lies below 30°.

Gelifluction deposits are generally expected to have their clast long axes orientated with the direction of movement. Isolated surface stones like ploughing blocks are also supposed to respond to this trend. Since some of the sample blocks do not show this trend, it was initially suspected that the development of a bow-wave in front could have caused the rotation of the long axis of the block. Therefore the orientation values of the one hundred blocks were regressed against the bow-wave height values to find if any relationship exists. The equation produced a very low correlation value (r^2 : 0.026) indicating no statistically significant relationship. This suggests that bow-wave height and orientation are independent variables or the blocks aligned themselves before the movement become retarded by the development of the bow-waves. It can, however, be suggested that the limited number of ploughing blocks whose long axes are aligned at a large angle to the slope aspect (e.g about 16% greater than 45° alignment), were influenced by factors other than gelifluction. This could be the result of a boulder being affected by any obstacle in its course of movement.

In northern England Tufnell (1972), from his study of 500 ploughing blocks, found 83% of the samples orientated parallel to the direction of steepest available slope and 17% perpendicular to this direction. However, his classification was generalized for he assumed that each category lay within 45° of the downslope or cross-slope direction. Shaw (1977) found from his study in the north-east Grampians that 79.4% of the samples were orientated within 45° of the downslope direction. These findings have a general similarity to the results of the present study, which showed 84% of the sample blocks orientated within the same limit.

8.4.2 Nature of related micro-features

As a block moves downslope faster than the surrounding ground two types of micro-feature can be produced by its action. They are the furrow and the bow-wave.

The Furrow : The furrow or elongated depression upslope from the block is the most characteristic feature of the ploughing block. This helps a boulder to be recognized as a ploughing block at first glance. The length and depth of the furrow have been investigated in the present study.

The minimum distance over which a ploughing block has moved downslope is displayed by the length of its furrow. The length of the furrow is determined not only by how actively the block is travelling but also by how actively gelifluction and frost creep are obliterating it. The older the furrow the greater is the chance of its having been filled up by the encroachment of material and the development of vegetation extending from the surrounding ground. These processes tend to obliterate the furrow from the upper edge and to progress downwards reducing its length. On the lower slopes coarse stems of *Vaccinium myrtillus* and *Empetrum nigrum* were often seen to obscure the furrow profile, whose existence can be revealed by removing the vegetation. On the upper slopes, where dwarf types of vegetation (mainly Rhacomitrium heath association) dominate, the furrow is obvious.

The length of furrow ranged from 50 to 560cm with a mean of 238.5cm (standard deviation : 129.4cm) (Fig. 8.3.2). 67% of the sample furrows are under 250cm long and 11% are longer than 400cm.

Short furrows of less than 90cm long are very common for ploughing blocks in northern England, being 75% from a sample size of 500 (Tufnell, 1972). Tufnell called these 'niche furrows'. Some furrows in this area were found by the same author to exceed 300cm. In the northern Cairngorms King (1968) examined furrows up to 350cm long. Furrow length in the south-East Grampians ranged from 15 to 317cm in the metamorphic area and from 13 to 888cm in the granite area as measured by Shaw (1977).

The variation in furrow length can generally be attributed to the difference in rates of downslope movement of a block relative to the ground upon which it rests. The long profile of furrows is usually straight, following the direction of maximum slope, although in some places they show slight changes in direction to comply with the micro-topography. Tufnell (1972) observed four types of furrow in northern England : straight, angular, curved and winding. In the Drumochter area 'straight' and 'curved' furrows were identified. The cross profile of a furrow is grossly related to the shape of the block associated with it. Among the six types : trough-shaped, parabolic, U-shaped, V-shaped, complex and levee as recognized by

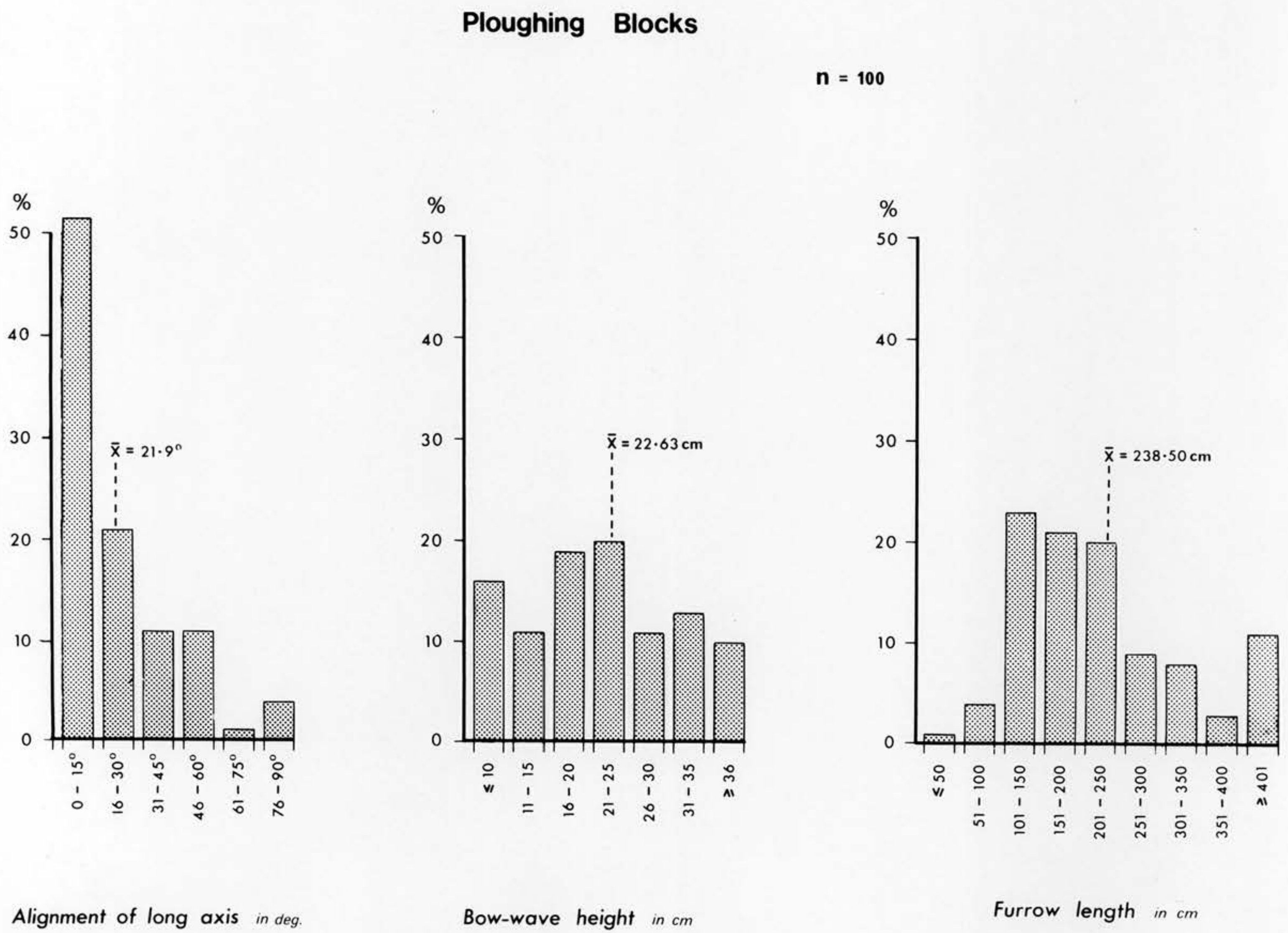


Fig. 8.3.2

Percentage frequency distributions of selected morphological elements of the ploughing blocks surveyed in the field.

Tufnell, trough-shaped furrows were found to be most common. This type of furrow is characterized by a flat floor with low but steeply rising sides. With the increase in distance from the block upslope, trough-shaped furrows often grade into the shallow V-shaped type.

Another characteristic furrow feature is a depression immediately behind the block. Its existence often remains obscured owing to the growth of plants but is visible when they are pushed aside. The presence of a well defined trough strongly suggests that the block has moved downslope very recently. The extent of the trough approximates the block width and the bottom of the depression probably lies very near to the base of the block. A block that has a considerable orientation of its long axis from the direction of maximum slope can produce an even wider furrow. Maximum furrow depth for the surveyed blocks ranged from 10 to 45cm with a mean of 24.9cm (standard deviation : 9.1cm).

In summary the furrow is the major indication of the movement of a ploughing block. Its form is largely related to the shape, orientation and trend of downslope progression of the block. Mobility of the slope deposits and vegetation can also influence its extent and long-term existence.

The Bow-wave : Another diagnostic micro-feature associated with ploughing blocks is the bow-wave or ridge that develops immediately in front of them. This develops chiefly by the typical ploughing movement of the block. The bow-wave is the most complex feature associated with the ploughing block.

Since the form of bow-waves in the Drumochter hills is variable a generic classification has been adopted. Fig. 8.4 illustrates the three major types identified. The simplest type is a single ridge developed on the downhill side of the block (type A). This can be termed a 'frontal crescentic bow-wave'. Digging around three blocks with this type of bow-wave revealed that the blocks were only slightly embedded in the regolith. Thus the combined effect of sliding and ploughing of the block could have led to the formation of this type. The second and most common type occurs when the bow-wave extends upslope along both sides of a block (type B, Fig. 8.4 & Plate 8.1). This can be called a 'frontal-lateral bow-wave' following Tufnell (1972). Blocks of this type are deeply embedded in the regolith and are often almost completely sunk into the ground. The existence of the block in extreme cases was ascertained by removing the surface vegetation. Progressive sinking with predominant ploughing activity of the block are proposed for the formation of this type. Frontal-lateral bow-waves are commonly associated with the longer furrows and with a continuous ridge on either side of the furrow upslope from the block. The third type (type C, Fig. 8.4 & Plate 8.2) is probably the most

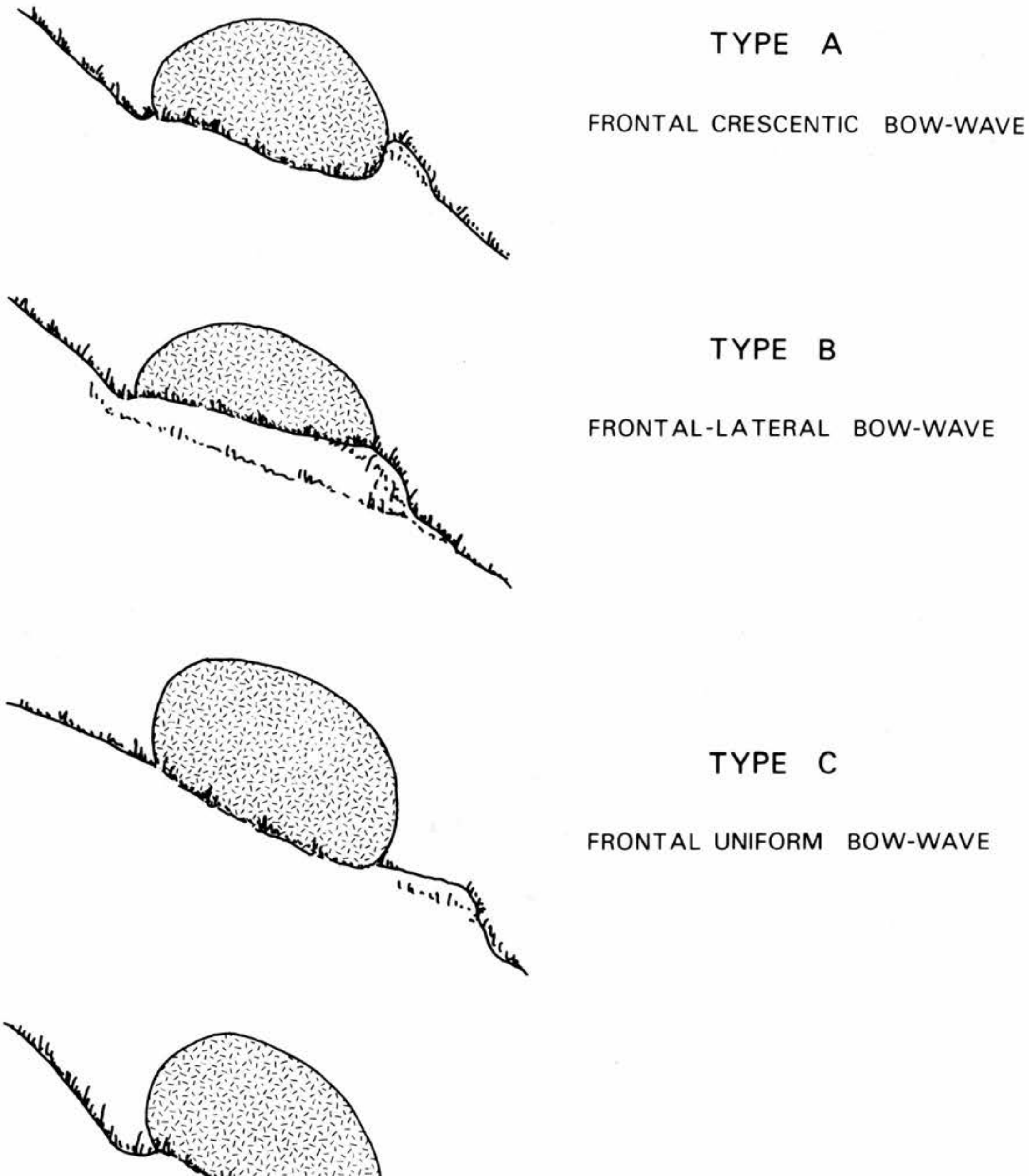


Fig. 8.4

Types of ploughing block bow-wave on the hills in the Drumochter area.

Plate 8.1 A ploughing block on the hillslope to the west of the Pass of Drumochter (840m). The bow-wave is characteristic of Type B shown in Fig. 8.4.

Plate 8.2 A stagnated ploughing block on the hillslope to the east of the Pass of Drumochter (710m). The bow-wave is characteristic of Type C shown in Fig. 8.4.

complex one found. The term 'frontal uniform bow-wave' is suggested for this type. This bow-wave extends almost horizontally from the downslope edge of the block like a platform. Large ploughing blocks on lower gradients were seen to be associated with bow-waves of this kind. It is difficult to explain precisely under what conditions they develop. The most likely factor could be related to the flattening of a frontal-crescentic bow-wave by erosion following the stagnation of block movement. This view is supported by the fact that in most cases the bow-wave surface is almost completely devoid of vegetation. Another important factor worthy of consideration is that these bow-waves were not found above 850m, where a higher degree of ground saturation due to late lying snow patches facilitates downslope movement of the blocks.

Bow-waves are generally composed of small clasts and fines with surface vegetation-roots penetrating to a considerable depth. No definite structure was found in excavating a number of bow-waves. Hence it is suspected that roots have disturbed any structures that formerly existed.

The measured bow-waves ranged from 9 to 55cm in height with a mean of 22.6cm (standard deviation : 9cm) (Fig. 8.3.2). 65% of the samples are under 25cm in height.

A number of ploughing blocks, however, were seen without any identifiable bow-waves, this being common for blocks that followed the course (furrow) of a preceding one. Twelve out of the one hundred samples were completely devoid of such micro-relief. Thus, although the bow-wave is a major criterion for recognizing ploughing blocks it is not a prerequisite as is the furrow.

Lithology : Boulders that are susceptible to downslope movement by predominant ploughing activity range from cobbles to massive boulders depending on the response of rocks to weathering processes. For the study of ploughing block characteristics all samples were collected from the Drumochter hills where the basic rock is mica-schist. Therefore any comparative study in terms of block size variation under different geological settings is not possible.

In the Drumochter hills a large number of ploughing blocks are of medium size as they are formed of schistose rocks of fairly low resistance to frost disintegration. On the slopes where more resistant rocks such as quartz-biotite and granulite occur, ploughing blocks of larger size were found. In other instances glacially transported, massive, granite erratic blocks were seen to show marks of downslope movement by ploughing. Several examples of this type were found on the south-western slopes of A' Mharconaich where Moor of Rannoch granite erratic blocks are common.

8.4.3 Factors controlling ploughing blocks and associated micro-features

Ploughing blocks in the Drumochter hills are varied in size and associated micro-relief features as revealed by the above study. An attempt has been made to understand the relationships between ploughing block morphology and the most likely controlling factors : altitude and hillslope angle. Six important parameters (length, width, height, furrow length, furrow depth and bow-wave height) of the one hundred sample blocks were regressed on the corresponding altitudes and hillslope angles. Regression analysis was also applied between the ploughing block parameters to understand the interrelationship pattern. Table 8.1 illustrates the resuts of regression analysis.

The analysis reveals very low and statistically non-significant correlations with altitude for block size (length, width and height) but shows significant (99%) relationships for the associated micro-features, i.e. furrow length, furrow depth and bow-wave height. Since the correlation with furrow length is positive it appears that the higher the altitude the longer is the trail of the ploughing blocks. The two other associated features (furrow depth and bow-wave height), however, show significant (99%) inverse relationships with altitude. Correlation testing of the ploughing block parameters with hillslope angle shows no meaningful relationships. Thus

	Altitude	Slope angle	Length	Width	Height	Furrow length	Furrow depth
Slope angle	-0.001						
Length	0.010	-0.029					
Width	0.014	-0.014	0.828* -----				
Height	0.000	-0.004	0.533* -----	0.640* -----			
Furrow length	0.116 -----	0.008	0.240 -----	0.292 -----	0.130 -----		
Furrow depth	-0.123 -----	0.001	0.160 -----	0.168 -----	0.230 -----	0.012	
Bow-wave height	-0.123 -----	0.017	0.176 -----	0.221 -----	0.384 -----	0.010	0.203 -----

* Correlation between dependent variables.

r^2 values are plotted in the table.

------ 99% Significant diff.

Table 8.1 Correlations between tested parameters of the ploughing blocks (n : 100) of the Drumochter hills.

slope angle does not exercise any dominant control on the size of the ploughing blocks or upon thir furrows and bow-waves.

Correlation values between length, width and height of the blocks can be disregarded owing to their high dependence on each other. Among other parameters furrow length is strongly related (99% significant) to the length, width and height of blocks. Hence the variation of furrow length is largely associated with the changes in block size. This implies that the larger blocks have travelled greater distances downslope. Although furrow depth showed highly significant (99%) correlation with the length, width and height of the blocks, it showed no meaningful relationship with furrow length. The strongest relationship was obtained between the bow-wave height and the block height. Bow-wave height is also significantly (99%) related to block length, block width and furrow depth but lacks any relationship with furrow length.

From the above analyses it can be concluded that no single factor examined produces a dominant influence upon the movement of ploughing blocks. Furrow length, furrow depth and bow-wave height are directly influenced by the size of block. It has also been shown that furrow depth and bow-wave height are independent of the length of furrow. However, the most interesting feature that emerged from the analyses is that with increase in altitude furrows tend to be longer while furrow depths and bow-wave heights become less. This strongly suggests that the ploughing blocks on the higher slopes have been more active, i.e. they have moved more rapidly and more frequently under the present climatic conditions. The shallowest furrow in these instances may be correlated with the higher rate of infilling by gelifluction on the higher ground. This accords with the fact that type C bow-waves which appear to be related to the stagnation of ploughing blocks, as discussed earlier, are restricted to altitudes below 850m.

8.5 Present-day activity

There is general agreement that in upland Britain ploughing blocks show detectable contemporary movement under favourable ground conditions, although there are differences of opinion as to the rate at which the blocks move down slope. Tufnell (1972, 1976) measured the movements of five ploughing blocks at altitudes varying between 685 and 820m on slope angles between 5° and 22° on the Moor House Reserve in the period 1965-75. The total amount of annual movement for all five blocks combined ranged from 10.8 to 14.3cm. He also observed that the movement of individual blocks within a 12 month period ranged from nothing to almost 8cm. From his study Tufnell found that (i) blocks that moved fastest in any one year did so in other years and *vice versa*, (ii) movement rate was influenced by the block size; small blocks travelling faster than larger ones and (iii) rates of movement varied on slopes of approximately equal steepness. Shaw (1977) conducted a three-year movement study on twelve 'gliding boulders ' in the south-east Grampians at 680-920m and on 14^{o}-37^{o} slope gradients. He found that the average annual movement rate for individual blocks ranged from 0.03cm to 0.87cm. The maximum displacement for a block in one year was found to be 2.05cm.

In the present study a two-year investigation (1978-79 and 1979-80) of ploughing block movement was carried out on seven blocks in the Drumochter hills. The sample sites were selected on the north-northwesterly slope of A' Mharconaich where ploughing blocks are widespread upon a wide range of slope gradients. The equipment used for this purpose consisted of iron stakes, drawing pins and a tape. An iron stake of one metre length was driven into the ground approximately 25 to 50cm from the upslope edge of each boulder. The stake was emplaced in the ground for more than half of its length to avoid any chance of displacement due to frost heave and mass movement. Drawing pins were set on the upslope edge of the block with the help of strong adhesive with their points facing upslope. Measurements were taken of the distance between the back-edge of the stake and the points of the drawing pins on the block.

The following table gives details of the sample blocks and their movements :

Site	Alt. (m)	Slp.ang. (deg.)	Diameter (m)	Furrow (m)	Movements (cm) '78-'79	'79-'80	Total
1	850	8°	0.87	6.5	0.3	0.2	0.5
2	840	13°	0.73	1.5	0.3	0.3	0.6
3	790	15°	0.57	4.0	0.2	0.1	0.3
4	800	17°	0.78	3.5	0.3	0.2	0.5
5	860	22°	0.79	2.0	0.5	0.4	0.9
6	870	26°	0.83	9.5	0.6	0.5	1.1
7	880	32°	0.84	7.6	0.8	0.6	1.4

Table 8.2 Characteristics and movements (1978-80) of seven ploughing blocks on the Drumochter hills.

The table shows that the selected blocks are at altitudes ranging from 790 to 880m and on slope gradients from 8° to 32°. Block altitudes are random but blocks that had moved a considerable distance as indicated by a distinct furrow behind were selected. A range of slope gradients was selected in an attempt to determine the influence of slope on the rate of movement. The annual displacement of each block was determined from the increased distance between the stake and the points of the drawing pins on the block. Although a solitary pin would have been enough for measurement, as many as three pins were employed as a precaution : some pins in fact became dislodged during the study period. Initially it was attempted to record movements twice a year : in spring (the end of April) and in late summer (the end of September). But the spring displacements for both the years were negligible (maximum 0.2cm) and in most cases no movement was detected. Hence only the annual recording has been used.

From the findings of a limited two-year survey, as in the present instance, it is difficult to draw firm conclusions about the nature of ploughing block movement in any area. At least a five-year period is required. However, certain inferences relating to ploughing block movement can be made from the above table as follows :

1. Each of the seven ploughing blocks experienced downslope movement during the period 1978-80. The minimum of 0.3cm was found for Block 3 resting upon a 15° slope and the maximum of 1.4cm was observed for Block 7 upon a 30° slope. From these two-year measurements the calculation of the average annual rates would not be satisfactory. However, the trend indicates that the rates of ploughing block movement in the Drumochter area are distinctly lower than those in the Moor House Reserve in northern England (Tufnell, 1972, 1976) but not very different from those in the south-east Grampians (Shaw, 1977).

2. Blocks 6 and 7, which moved the maximum distances (1.1cm and 1.4cm respectively), are associated with higher

elevations, steeper slopes and longer furrows. The influence of altitude upon movement has already been established by the correlation analysis (Section 8.4.3). The present-day movement study also suggests that the blocks at the higher elevations move faster although they are on the steepest slopes.

3. The length of furrow does not always correspond with the present-day movement of the blocks. For example Block 2, which is associated with a furrow only 150cm long, travelled 0.6cm in two years whereas Block 3, with a furrow of 4.0m, travelled only 0.3cm during the same period. It would appear that for the present slow-moving Block 3 the relatively long furrow reflects former faster movement.

4. The present rate of movement shows no relation with slope gradient at and below 17°.

5. Block size has no direct relationship with movement rate. There is no indication that smaller blocks moved longer distances as revealed by the study of Tufnell (1972, 1976). In the present study the second largest block (Block 7) has moved the farthest distance and the smallest block (Block 3) travelled the minimum distance. Hence factors other than size appear to control ploughing block movement at the present day.

6. The movement was found to be virtually restricted to the summer months (May-September). This suggests that

ploughing block movement is largely affected by spring thaw and associated summer saturation.

7. A slightly higher rate of movement was detected in the period 1978-79, a year that had an exceptionally severe winter and wet summer.

CHAPTER 9

Miniature patterned ground features

(Small sorted circles and turf hummocks)

9.0 Introduction

The patterned ground features as defined in Chapter 5 include stripes, polygons, circles, garlands, vegetation-covered hummocks, wind stripes and wind crescents. It has generally been recognized that the smaller patterns develop in less severe climatic conditions. During the field study a number of miniature patterned features of different types were encountered of which (1) small circles of stones and fines and (2) small mounds covered by a mat of vegetation were common, particularly in the summit areas. Hence these two types were selected for study in detail. For the small circles the term 'sorted circle' and for the vegetation-covered small mounds the term 'turf hummock' have been adopted in the present study.

9.1 Sorted circles

9.1.1 Literature

Small sorted circles with fines in the centre have frequently been referred to as stone polygons in the literature relating the study of cold environments. Washburn (1956, p. 827) defined sorted circles as patterned ground whose mesh size is 'dominantly circular and has a sorted appearance commonly due to a border of stones surrounding fine material'. These features were first observed in Britain by Simpson (1932), who noticed 'stone polygons' near the summit of Ben Iadain in Argyllshire and speculated that they were produced by repeated freezing and thawing of soil 'saturated with moisture that can not escape'. Later Hollingworth (1934) described such features in the northern part of the English Lake District and called them 'stone polygons' and 'stone circles'. Caine (1961) maintained that such patterns develop less frequently than stone stripes in the Lake District. Tallis and Kershaw (1959) studied 'stone polygons' in Snowdonia and proposed that they can be 'extremely unstable' i.e. they are prone to disappear with a sudden change of weather conditions. Tufnell (1969) stated that active stone polygons occur most frequently above 600m in northern England. 'Sorted stone circles' were studied in detail on several summit areas in Orkney and Shetland by Chambers (1965, 1966a, 1966b, 1967). In the Isle of Rhum Ryder and McCann (1971) found similar 'stone polygons' in the high areas and suggested that their sorting is a contemporary process.

9.1.2 Present study

The present study was carried out on the small sorted circles on the high ground in the three areas. The principal aim was to investigate their structural characteristics and possible formative mechanisms.

9.1.3 Distributional pattern and size characteristics

Sorted circles are in all instances found on high ground largely around the summit areas. Small circles of 10-20cm in diameter were widespread upon the summit of A' Mharconaich in the Drumochter area at altitudes of 950-975m. In the Creag Meagaidh area the eastward-extending ridge of Puist Coir Ardair exhibits sorted circles of larger dimension (15-40cm) at altitudes of 900-920m (Plate 9.1.1). The summits of the Cairngorms are in most cases covered with large boulders and show very limited evidence of this feature. Small circles were found in the summit areas of Miadan Creag an Leth-choin at 1,000-1,080m.

Three types of ground surface were found to provide an

Plate 9.1.1 Typical sorted circles on the Creag Meagaidh hills.

Plate 9.1.2 Small sorted circles on the Drumochter hills during formation in spring (April) showing frost-heaved stones and developing centres of finer material.

ideal base for this type of feature. In the first place the features were found extensively on deflation surfaces where vegetation has been stripped off by wind action. The second important location was the tread of terraces particularly on the higher slopes. In the other instances small circles were found to have been superimposed upon the disintegrated stone-borders of large fossil polygons. Examples of the first two types are common in the Creag Meagaidh hills, while the circles of the third type were seen in the Cairngorms on the high ground to the east of the Lairig Ghru.

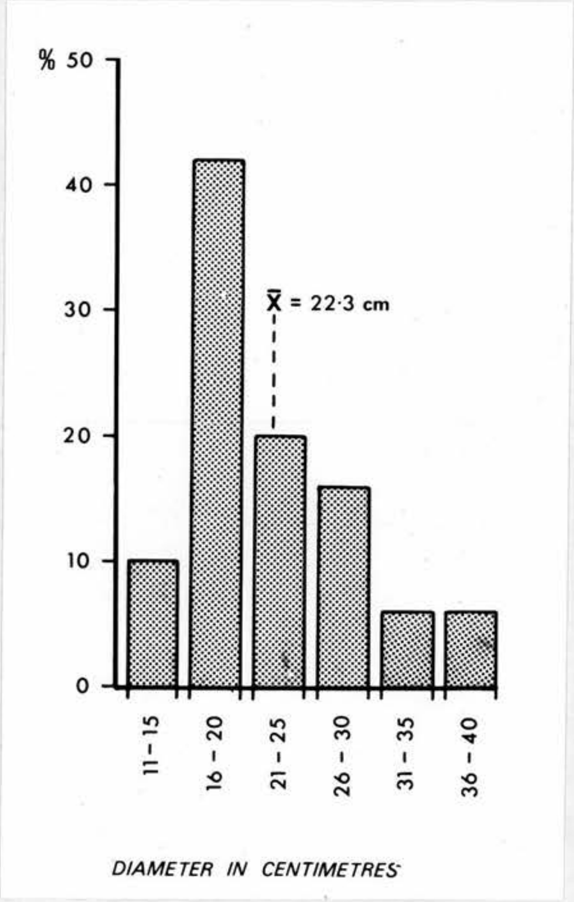


Fig. 9.1.1 Percentage frequency distribution of diameter of 50 sorted circles measured.

The study of the dimensions of the sorted circles is based on a sample of 50, selected randomly in the Creag Meagaidh area. The results of the measurements are summarized in Fig. 9.1.1. The histogram shows a range of dimensions from 11 to 40cm with a mean of 22.3cm (standard deviation : 6.4cm). 72% of the features are less than 25cm in diameter.

9.1.4 Surface form

In order to understand the surface from and related sorting pattern within the features three circles were examined by sampling material from the surface and subsurface locations. These samples were subjected to mechanical analysis using standard sieves. Two sample sites were in the Creag Meagaidh hills where the features are developed upon deflation surfaces. The other sample site was in the Drumochter hills on the tread of a large turf-banked terrace. The examined circles were 20-25cm in diameter.

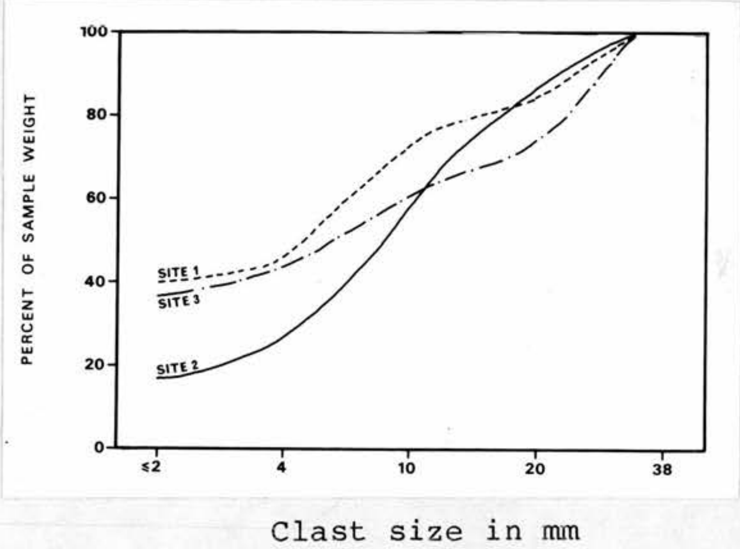


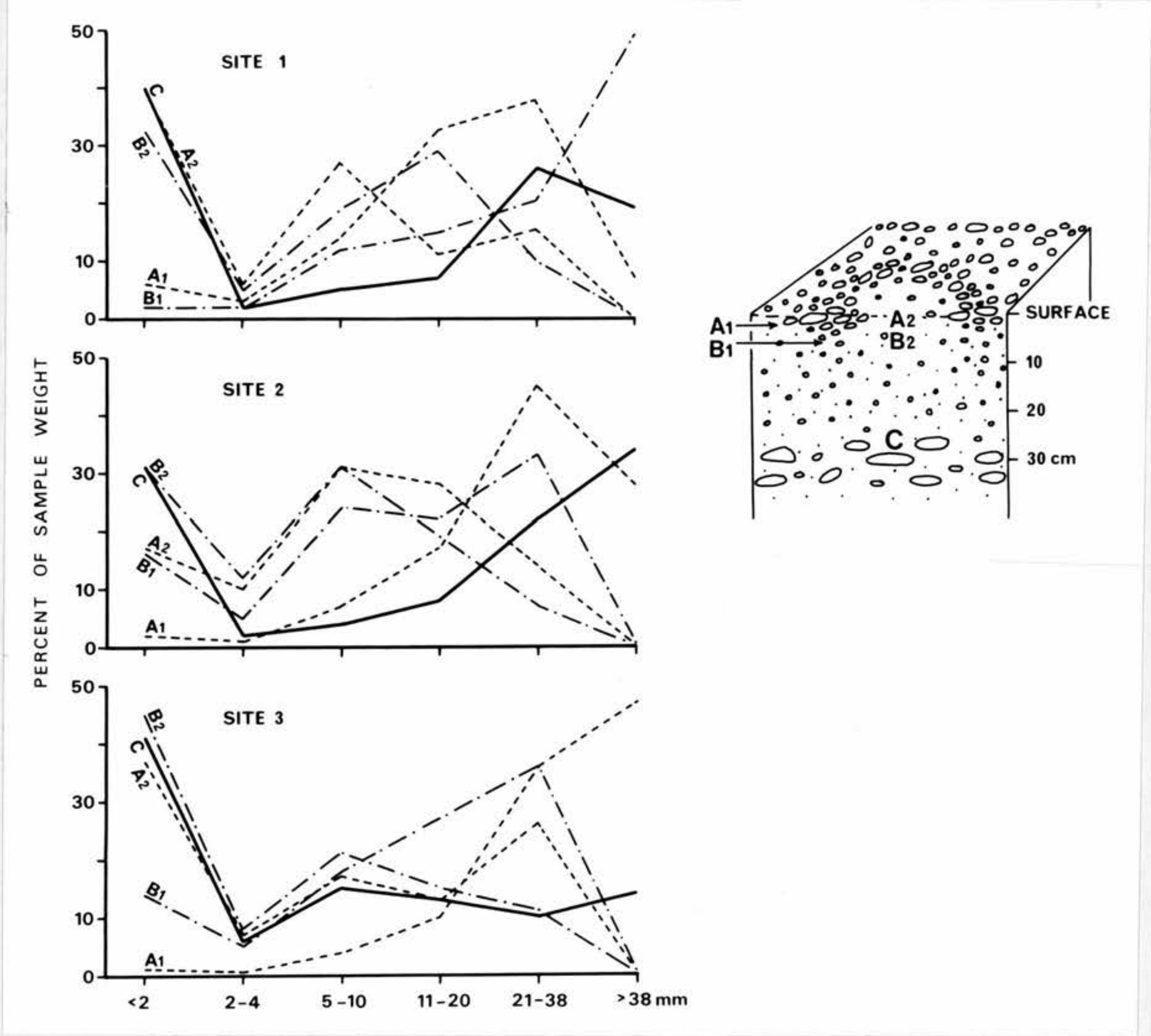
Fig. 9.1.2 Clast-size distribution of material of the centres at the surface of three sorted circles.

Figure 9.1.2 illustrates the cumulative percentage of sample weight of material in five classes for clasts from the centre at the surface. The circles of Site 1 and Site 3 show a general similarity in distribution from fine to coarse material having 37%-40% in the fine fraction (<2mm) although Site 2 shows only 17% in this category. It appears that for the circle of Site 2, either the surface sorting was not complete or the process operated in material coarser than the other two.

9.1.5 Structure and sorting

Excavation of the three circles revealed that in all cases the rim of stones was restricted to a surface layer of 5cm maximum thickness resting on a bed of clay-loam with occasional stones. The pattern almost disappears below 5cm where stones are randomly distributed through the layer. The underlying layer can have been derived from the decomposition of rock in situ. This layer is about 20cm thick and is underlain by a bed of rock debris.

For textural analysis sampling was done from the surface and from 5cm below the surface. Clast-size distribution was determined by screening down to <2mm (fine fraction) by standard sieves and the distribution of material in different classes shown in Fig. 9.1.3. From each of A1, A2, B1 and B2 sites about one kilogram of material was collected. In all three cases the surface material at the rim (A1) has a much smaller proportion of fines (<2mm) than the surface centre (A2). For the samples from the surface-centre clast diameter does not exceed 38mm for any of the sites. A marked difference, particularly in the proportion of the fine fraction, occurs when A1 and A2 (surface material) are compared while the difference is reduced considerably in the comparison between B1 and B2 (material from below 5cm). This suggests that the sorting is largely superficial and has very little effect below 5cm.



Clast-size class

Fig. 9.1.3

Clast-size distributions for samples of material collected from surface and subsurface locations of three sorted circles.

9.1.6 Formative mechanisms

It is well established that the origin of patterned ground features is related to freeze-thaw action, although opinions differ as to the method of differential sorting. Högbom (1910) considered sorting to be caused by upward thrust from a moist centre due to volume expansion on freezing. The process would lead to sorting by ejection of stones from the fine material, the subsequent contraction on thawing failing to move the larger fragments. Taber (1943) maintained that differential heaving of local origin in association with gravity brings about sorting to form most polygonal features. He also proposed that finer-grained soils may form a frost boil. Rock fragments rise to the surface by repeated freezing and thawing and then move gradually outwards and downward across the gently sloping surface to form a polygonal network. Washburn (1956, 1969, 1979) favoured local differential heaving and cryostatic movement by freeze-thaw action as the key factor for the sorting within patterned ground.

The present explanation of mechanisms of the sorted circles is put forward in the light of the recognized concepts. It has already been mentioned that in most cases the circles occur on deflation surfaces and turf-banked terrace treads, where the surface mantle is a mixture of small stones and fines. Considering frost penetration and subsequent expansion of finer material as the basic factor it appears that the depth of freezing is likely to be significant. For these miniature patterned ground features it is proposed that frost penetration is only slight, amounting to a few centimeters and the most effective cycle of freeze-thaw is diurnal. At the height of winter (mid-February, 1979) it was found by excavation in the Drumochter hills that ground freezing extended down to about 75cm at an altitude of about 850m, above which most sorted circles were recorded. It was also observed that circles did not exist at that time. In spring (April-May) on the same patches sorted circles were found to be in the process of development. This was the time when the top of the annual freezing layer had subsided to about 30cm from the ground surface leaving the upper layer susceptible to diurnal freeze-thaw action. Plate 9.1.2 shows the initial development of these circles on a deflation surface with stones showing signs of very recent heaving mainly by needle-ice activity. The centres of fines started to take shape in response to sorting activity which continued until the end of June. The complete form of circles emerged thereafter when previously upturned stones were found to have settled horizontally on the rim surface. The pattern of sorting, as was explained earlier and shown by Fig. 9.1.3, strongly supports the view that the amount of freezing (diurnal) responsible for such sorting hardly penetrated below 5cm. Downward movement of stones after rising at a domed centre, hypothesised by many workers (e.g. Taber, 1943) is not satisfactory in the present instances. This is because the central dome of finer material did not attain enough height (maximum observed 1cm for the circles of 30-40cm in diameter) to permit such movement of stones. Hence a horizontal-radial surface sorting of stones from centre to border on ejection from fines (predominantly by needle-ice activity) can be proposed for the sorted circles studied. These circles are prone to almost disappear with the cessation of needle-ice activity in the early summer.

9.2 Turf hummocks

9.2.1 Literature

Vegetation-covered small mounds forming in periglacial environments have often been referred to as earth hummocks or turf hummocks. The term 'earth hummock' was first used by Sharp (1942) and Washburn (1956, 1969) classified such features as a special type of non-sorted net. Raup (1965) applied the term 'turf hummock' to emphasise the dominating role of turf (vegetation) in their formation. In Great Britain little quantitative study has been devoted to turf hummocks. Their occurrence has been described on Dartmoor (Te Punga, 1957; Waters, 1962), Ben Wyvis (Galloway, 1961a), North Wales (Ball and Goodier, 1970a), Shetland (Ball and Goodier, 1970b), Isle of Skye (Birks, 1973) and on the northern Pennines (Tufnell, 1975). Pemberton (1980) found such features in northern England in valley areas as well as on high ground.

9.2.2 Present study

The present study describes the morphological and structural characteristics of turf hummocks on the mountain summits in the Drumochter area and discusses possible formative mechanisms.

9.2.3 Distribution and vegetation pattern

Like sorted circles turf hummocks occur on high ground in the summit areas particularly where the vegetation cover is complete. They are widespread upon the summit of A' Mharconaich to the west of the Pass of Drumochter (Plate 9.2.1) at altitudes of 950 to 970m. With increasing slope to the west-northwest the hummocks gradually take the form of hummock stripes, consisting of bands of elongate hummocks (Plate 9.2.2), and vegetation-covered terracettes (hummock-terracettes) (Plate 9.2.3). Similar features occur at 900-916m (the summit level) altitude on Meall a'

Plate 9.2.1 Typical turf hummocks on the level summit of A' Mharconaich.

Plate 9.2.2 Hummock-stripes on a gentle slope.

Plate 9.2.3 Hummock-terracettes on a sloping ground.

Plate 9.2.4 Disintegrated turf hummocks.

Chaorainn (western part of the Gaick Plateau) to the east of the pass, where irregular hummocks often grade into spectacular hummock-terracettes with increasing slope.

In the Creag Meagaidh hills hummocks are formed only on the summits to the north of Coire Ardair at altitudes of 1,030-1,050m. No hummocks were found in the Cairngorm study area.

Areas dominated by turf hummocks exhibit a characteristic vegetation cover. McVean and Ratcliffe (1962, Plate 20) described the vegetation pattern of similar features ('soil hummocks') in the central Grampian area where the hummocks were found to have developed in areas dominated by Rhacomitrium heath with a greater abundance of *Rhacomitrium lanuginosum* at the hummock mounds and *Carex bigelowii* in the depressions. During the field study other species found were *Calluna vulgaris*, *Cladonia spp.*, *Carex bigelowii* and moss (*Polytrichum*) on the mounds and *Vaccinium myrtillus* and grasses in the depressions.

9.2.4 Morphology

The surface pattern of hummocks can be circular or elongate depending on gradient. On slopes of less than 5° the hummocks are generally circular, but as the slope increases they tend to become elongate downslope. Hummock-stripes, consisting of bands of elongate hummocks

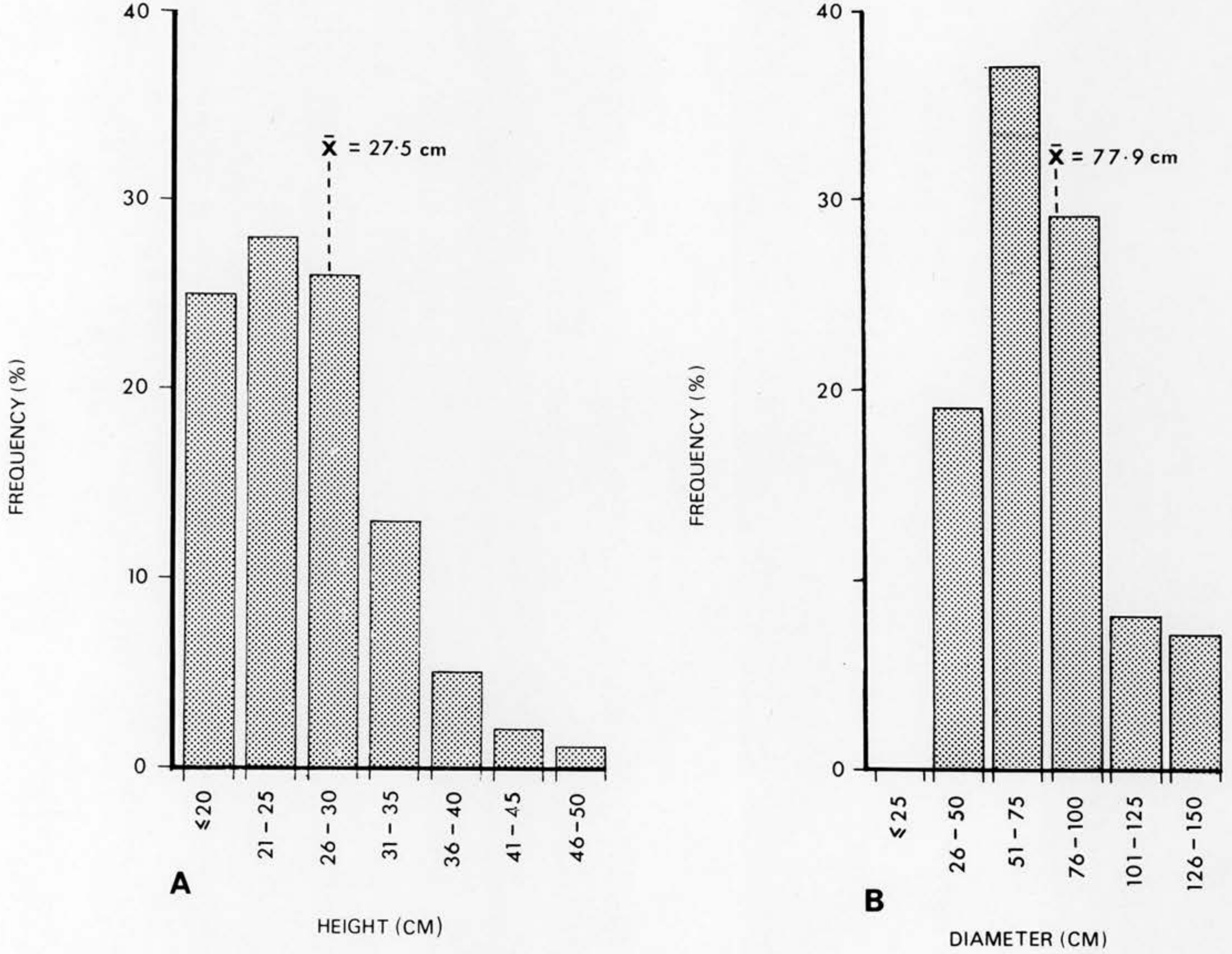


Fig. 9.2.1

Histograms summarizing the dimensions of one hundred turf hummocks surveyed on the Drumochter hills.

aligned downslope, occur on gradients of 5^{o} to 8^{o}; on steeper slopes they grade into hummock-terracettes. The distance between hummocks on relatively flat ground is usually less than their widths. In cross section the hummock sides rise steeply and flatten out gradually. A large degree of variation in size exists for the individual hummocks even at the same location. It is quite usual to find turf hummocks that are four or five times greater in size (both in height and width) than others.

To determine the dimensions of typical turf hummocks in the Drumochter area a sample of one hundred was selected randomly. The results of measurement of hummock height and diameter are illustrated in Fig. 9.2.1. The height of the hummocks range from 18 to 50cm (histogram A) with a mean of 27.5cm (median : 30cm). 79% of the hummocks are less than 30cm in height. Hummock diameters (histogram B) range from a minimum of 40cm to a maximum of 150cm, the mean being 77.9cm (median : 75cm). 80% of the sample have a diameter not exceeding 75cm.

9.2.5 Structure and composition

The structure and composition of turf hummocks were studied by digging cross-sections through three hummocks. Figure 9.2.2 illustrates the sections through the hummocks. The sites were selected on A' Mharconaich between 950 and 970m. As shown in the diagram the ground is covered with a mat of vegetation that increases in thickness at the hummock mounds, a maximum of 20cm being found for Site 3. The lower part of the vegetation mat was found to have partly decomposed. Excavation revealed a marked contrast in composition between the mound and depression immediately below the mat of vegetation for all the three sites. The top part of the mound exhibits a layer of fine grey sand while the depression shows a mixture of stones up to cobble size with a very small amount of fines. In the mound the sandy material exists as a cap layer anchored by vegetation roots extending from the surface. This layer displays a sharp distinction in colour and texture from the material below, which is composed of dark yellowish-brown sandy loam mixed with small stones. These stones are arranged in a layer that bulges up parallel to the surface of the hummock. The upper horizon of this layer has fewer stones and sand and silt dominate. Angular stones of larger dimension set in a yellowish-brown sandy matrix were found from 70-75cm below the mound surface.

Material was collected from varying depths in the three hummocks for particle-size analysis. The samples were first air-dried in the laboratory and then analysed mechanically using standard sieves. Materials were studied in two groups : fine (<2mm) and coarse (>2mm).

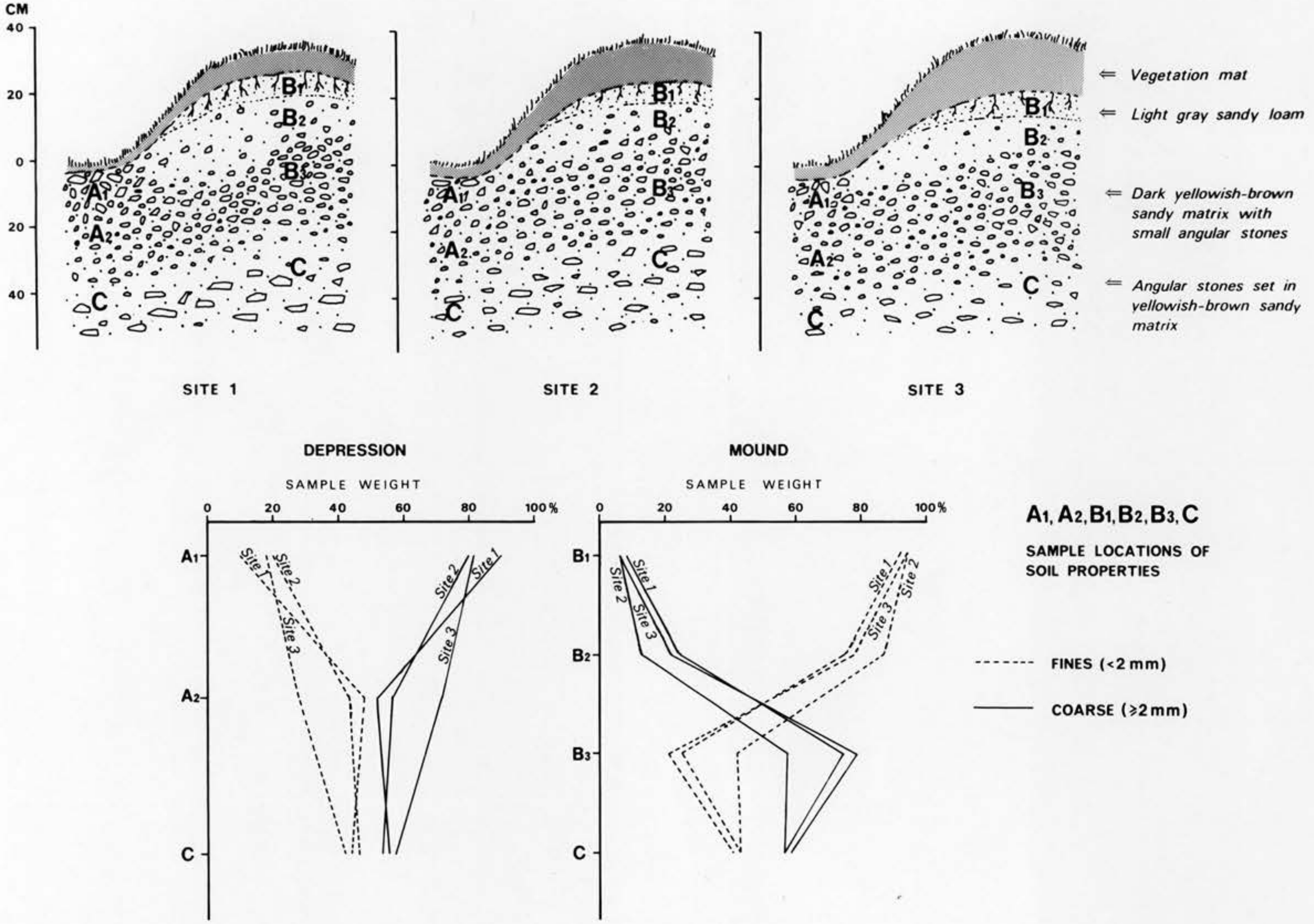


Fig. 9.2.2

Cross-sections of three turf hummocks and particle size distributions of samples.

The results are shown in Fig. 9.2.2 and 9.2.3. It was found (Fig. 9.2.2) that the material in the depression near the surface (A1) is predominantly coarse (>80%) with a very small proportion of fines. This difference is reduced markedly downwards for the samples of the two other locations (A2 and C). A very different picture is obtained for the materials from within the hummocks. The top layer consists largely (92%-94%) of fine material. The proportion of fines decreases to a minimum (21%-42%) at a depth of 30-40cm (B3) where the material is a mixture of stones and fines. An approximate similarity between the samples of the depression and the mound occurs at a greater depth (40-45cm below the depression and 60-70cm below the mound; location C). This is the level at which the yellowish-brown sandy matrix begins. The increase of coarse material at the mound centre is characteristic of the turf hummocks.

The particle-size composition of superficial deposits can influence the form and growth of ground-ice (Washburn, 1979, pp. 67-68) which in turn can affect hummock development. The grain-size distributions in the fine fraction of the samples collected from different depths in three hummocks were analysed and the results are shown in Fig. 9.2.3. A close similarity exists at all three sites for the intermediate layers (B2 and B3), which have 13%-16% silt and clay (<0.063mm). For the top layer (B1) the proportion of silt and clay is slightly lower (10%-12%).

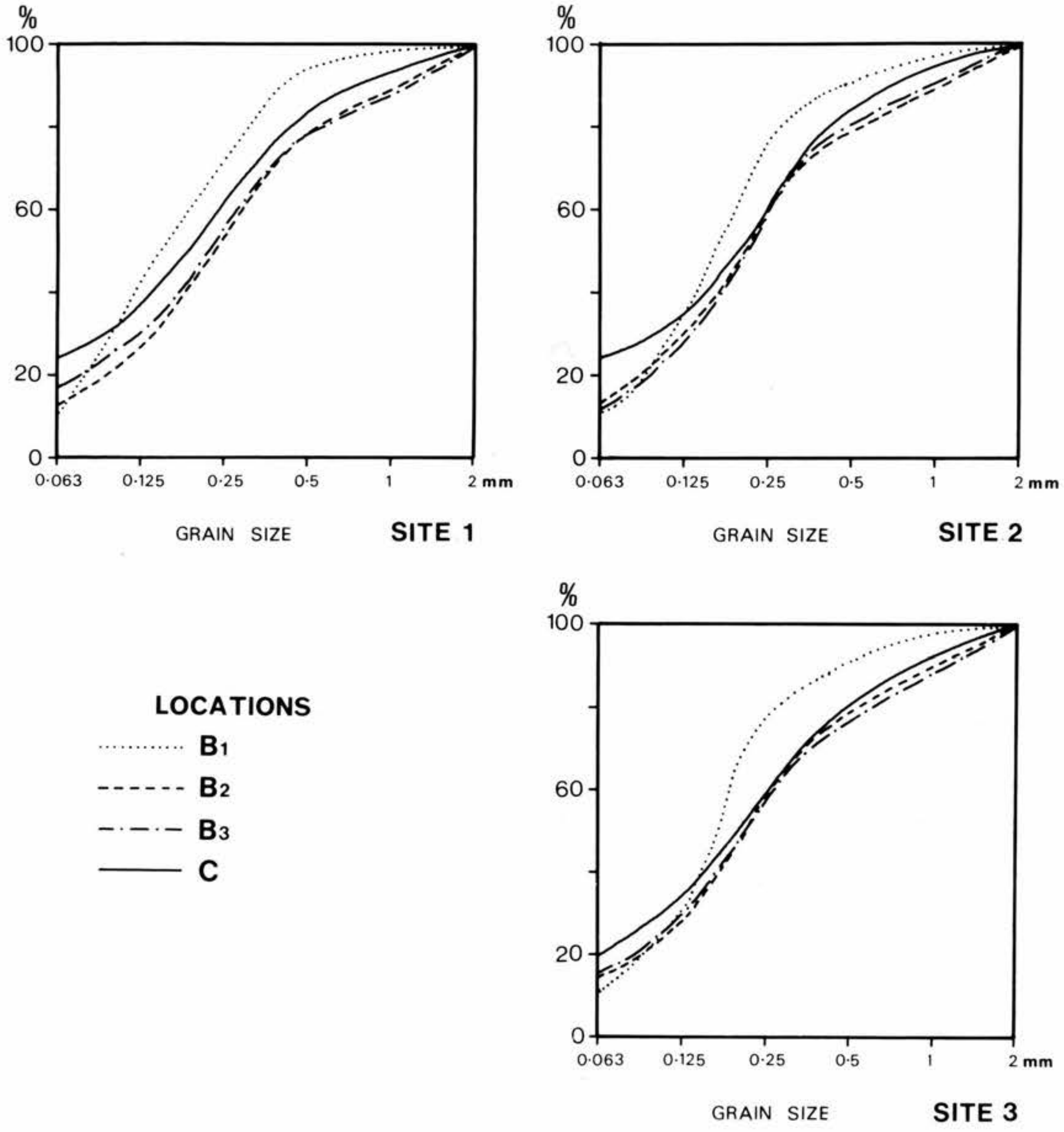


Fig. 9.2.3

Grain-size distributions for samples of fine material collected from the three turf hummocks. Locations B1, B2, B3 and C are shown in Fig. 9.2.2.

According to Terzaghi (1952) a deposit can be considered susceptible to frost heaving if it has several percent of particles smaller than 0.07mm (considered to be the upper limit of silt). The relatively high clay-silt component in the features suggests they are susceptible to the formation of ice lenses on freezing and thus to pronounced frost heave. The downward increase in silt and clay is probably the result of pedogenesis, very fine particles having been eluviated from the upper layers and washed into the lower layers.

9.2.6 Formative mechanisms

Several hypotheses have been put forward for the formation of hummocks in cold environments, of which differential frost penetration and related variations in cryostatic pressures in the ground have been proposed by many workers (e.g. Beskow, 1935; Sharp, 1942; Billings and Mark, 1961; Lundqvist, 1969; Schunke, 1977). Variations in cryostatic pressure have largely been attributed to vegetational diversity. Lundqvist, in agreeing with Beskow, favoured two possible origins : (i) Local unevenness of the ground surface results in patches of thicker vegetation which protect the underlying mineral soil from frost penetration so that the surrounding soil becomes frozen first; as frost penetrates under the enclosed unfrozen patch upward pressure is exerted. The repetition of this process results in 'earth hummocks'. (ii) Lundqvist also agreed with Sigafoos and Hopkins (1951) that differential surface freezing can induce hydraulic pressure which draws soil material to the ground surface to form hummocks. A possible explanation of hummock formation is attempted here on the basis of the present findings.

The hummock section in Fig. 9.2.2 shows a core zone of stones and fines underneath the vegetation cover. Assuming the initial surface profile flat, it appears that the zone underwent a circular type of frost sorting. This is reflected in the concentration of stones at A1 (the rim surface) and relatively fine material at B1 and B2 (the centre). Such frost sorting could have generated differential freezing, resulting in initial differences in micro-relief for the hummock formation. A cold climate is required at this stage to permit such deformation of soil. The next stage presumably involved a period when this frost-sorting process abated and the colonization by vegetation took place as a result of climatic amelioration. Thicker vegetation developed upon the fines while thinner vegetation extended upon the areas of coarse material. Although Galloway (1961a) assumed that such features were colonized by vegetation after they had been stabilized, it seems probable that the development of vegetation of varying thickness selectively upon the coarse material and the fines made the ground surface more vulnerable for differential frost penetration and frost heaving in a later cold period. As suggested by many workers the rate of ground freezing in this situation is likely to have been faster in the areas of coarse material underlain by green mosses and grass than in the areas of fines owing to the better insulation provided by the thicker vegetation mat. A progressive increase in hummock height can be related to these environmental conditions. The consequence of the differential freezing process was that ground pressure was exerted from the rapidly frozen coarse areas outward on the areas of finer material to force this up to form distinct mounds, the turf hummocks. The bulging layer of stones in the hummocks implies upward pressure in the features. Nicholson (1976) suggested that irregular freezing fronts in certain forms of patterned ground can cause a pressure in unfrozen soil and that a type of circulatory movement can result whereby the unfrozen soil is forced down and laterally from under the border of the forms towards the central areas and then upward. A similar view was maintained by Schunke (1977) who, in explaining hummocks in Iceland, stressed the effect of lateral pressure arising from freezing of interhummock areas.

The presence of the cap of sandy loam in the hummocks can be explained by the fact that under the existing cool moist climate, surface leaching is the most prominent pedogenic process. The distinct light grey colour of this zone is probably due to podzolization.

It has been pointed out that hummocks maintain their typical form on relatively level areas and grade into hummock-stripes as the slope increases to 5^{o}-8^{o}. Since the hummock-stripes have essentially the same profile and vegetation as the hummocks it is reasonable to believe that the formation of the latter involves the same process with the added effect of slope. The hummocks tend to connect up in bands of elongate hummocks in the downslope direction. On the steepest possible slope (8^{o}) for the hummock-stripes, where individual features almost disappear and merge into single elongated mounds, having very even spacing separated by linear depressions, a typical vegetation-covered relief-stripe pattern emerges. A regular sorted micro-relief stripe system at the initial stage seems to be the key factor.

In general turf hummocks on the Drumochter hills appear to be fairly stable under intact vegetation cover. But upon the slopes exposed to the prevailing wind, particularly on the south-western slopes, several of them are being disintegrated (Plate 9.4). This degradation probably starts as strong wind damages the surface vegetation.

9.2.7 Age and present activity

Turf hummocks on the Drumochter hills are restricted to relatively even ground at high altitudes. It is possible that they are older than the small sorted circles found at the same altitudes but of more recent origin than many of the mass movement features like massive gelifluction lobes and terraces and large polygons and stripes which occur in several parts of the Grampian Highlands. The initial period of circular frost sorting, that presumably provided the base for the turf hummocks, could have corresponded to the time in the early Flandrian when frost sorting in the high summit areas was on a greater scale than at present. It seems improbable that the initial frost sorting occurred earlier because many frost-sorted features occur well inside the presumed Loch Lomond Advance limit on the Gaick Plateau (cf. Sissons, 1974) in the eastern part of the area investigated. Although it is not certain whether any intermediate cold spells during the mid-Flandrian helped the emergence of hummocks in their present form, it is likely that suitable surfaces at higher altitudes in the Scottish Highlands were favourable for hummock formation through differential frost penetration during the 'Little Ice Age'. Considering the present milder climate, when only a limited frost sorting and heaving is possible, it can be suggested that these turf hummocks are mostly inactive.

SECTION III SYNTHESIS AND CONCLUSIONS

CHAPTER 10

Conclusions

A wide variety of periglacial features exists in the Grampian Highlands. On a generic classification gelifluction lobes, turf-banked terraces, ploughing blocks and two types of miniature patterned ground features (sorted circles and turf hummocks) have been studied in detail in the three study areas. The study of distribution revealed that periglacial features generally occur from about 600m up to the highest elevation. Gelifluction features are common on moderate to gentle slopes while patterned ground features, in most cases, occur in the summit areas of relatively low slope gradient.

The classification of gelifluction lobes as debris lobes, boulder lobes and vegetation-covered small lobes (solifluction lobes) is based on the characteristics of their component material. Debris lobes comprise stones and fines, boulder lobes comprise medium to large size boulders with very little fines and solifluction lobes are formed predominantly of fine material. It has been suggested that the compositional difference between debris lobes and boulder lobes is the reflection of lithological control : frost weathering of siliceous and semipeltitic schists and flags in the Drumochter and the Creag Meagaidh hills has produced stones and cobbles with considerable amounts of fines, giving rise to the debris lobes, whereas boulder lobes are common in the Cairngorm area as a result of granular disintegration of granite by frost action. Solifluction lobes are restricted to the high summit areas where fine material is abundant and ground remains moist throughout the year largely due late-lying snow patches.

The study revealed that all types of lobe occur within the range of 5^{o}-35^{o} slope gradient, although the mean slope gradient for the solifluction lobes (16^{o}) is distinctly lower than those of the two other types (between 19^{o} and 21^{o}). The study of lobe aspects in the Drumochter hills indicated that northerly, north-westerly, southerly and south-easterly slopes are preferred for all types of lobe. The convex hillslopes with these aspects were found to have provided abundant material for forming lobes and lobate sheets. Correlation testing of major lobe parameters with altitude and hillslope angle showed that debris lobes in the Drumochter and the Creag Meagaidh hills tend to become morphologically less dominant as altitude increases and slope gradient decreases whereas boulder lobes in the Cairngorms are morphologically dominant on the higher altitudes with lower slope gradients. It has been inferred from the study of structural characteristics that the three types of lobe have responded to different mechanisms. For the debris lobes a combined activity of gelifluction and frost creep has been suggested. It has been proposed that the most likely mechanism for the boulder lobes in the Cairngorms is similar to that of a rock glacier, in which interstitial ice expansion in the rock debris causes downslope movement of the feature under permafrost conditions. Solifluction lobes have been attributed to the activity of localized liquefaction (solifluction) resulting from the thawing of segregated ice-lenses. Small stone-banked debris lobes and solifluction lobes have been found to exhibit some contemporary activity. The two-year recording showed that on the debris lobes surface clasts, 3" nails and 6" nails moved 28.8, 27.3 and 24.3mm respectively and the movements in the 4/5 summer months exceeded those in the rest of the year. The measurement by the inserted iron tubes into a solifluction lobe; showed that a maximum movement of 50mm at the surface diminished almost to nil at a depth of 200mm.

It has been inferred from the study that most of the boulder lobes and debris lobes were formed during the lateglacial (Loch Lomond Stadial) following large-scale frost shattering and subsequent frost heave and frost creep activities. Boulder lobes formed and moved downslope during much of the stadial and became stagnant when the severe climate ended while, owing to gelifluction activity, debris lobes remained active until the early part of the Flandrian. No boulder or debris lobe was found inside the presumed Loch Lomond Advance limits. This implies that these types of lobe have not formed since final deglaciation; conversely, the presence of a number of solifluction lobes inside this limit in the Drumochter hills suggests that they at least have formed and remained active in postglacial times.

Three types of turf-banked terraces were recognized : normal terraces, lobate terraces and oblique terraces. They were found to be composed predominantly of finer material banked by turf or dwarf-type of vegetation. It was also found that turf-banked terraces are commonly related to vegetation-covered (solifluction) sheets on moist ground of the upper slopes. The study revealed that terraces occur on slopes of 6°-35° with a tendency to increase towards moderate slopes (10°-25°). Lobate terrace areas often coincide with the solifluction lobes and lobate sheet areas. The two features were distinguished in terms of their pattern of downslope inclination of tread and vegetation cover. The sheets consequently incline with the slope whereas the terrace treads become increasingly flat and sparsely vegetated as the slope gradient increases. It was found from the study of aspects in the Drumochter area that southerly and south-westerly aspects have wider spreads of terraces than any other aspects. Correlation analyses for horizontal (normal and lobate) terrace parameters with altitude and hillslope angle for the three areas revealed that the influence of altitude is significant only for the Cairngorm terraces while hillslope angle exercises control in all the three areas. Riser height, riser angle and thickness of terraces tend to increase significantly as the hillslope steepens. It has been suggested that strong wind has flattened the treads of the horizontal terraces. The dominant mechanisms for the majority of the horizontal terraces appear to have been frost-creep and gelifluction activities. A number of normal terraces, which are approximately parallel with the wind have been interpreted as transitional between wind stripes and terraces. Locally dominant wind appears to have been responsible for the downslope inclination of the oblique terraces. The two-year study of present-day activity of two small turf-banked terraces showed that surface clasts, 3" nails and 6" nails moved 16.0, 9.5 and 9.6mm respectively. It has been suggested that this movement resulted form the combined activity of frost-creep and gelifluction with the frost-creep dominating for the surface clasts.

In common with the solifluction lobes a number of small turf-banked terraces were found inside the presumed Loch Lomond Advance limit in the Drumochter area. Hence it has been suggested that some of them have formed and moved downslope in postglacial times.

Ploughing blocks were found to be widespread on vegetation-covered moist slopes of 4°-36° gradients above about 650m on all aspects. A wide range of size variation (from cobbles to large boulders) was found for the ploughing blocks. The correlation study revealed that the associated micro-features are significantly related to altitude and block size but not to slope angle. With increase in altitude furrrows tend to be longer while furrow depths and bow-wave heights become shorter. It has been suggested that ploughing blocks on the higher slopes are more active under the present climatic conditions. This has further been supported by the recording of the present-day activity of seven blocks : movements from a minimum of 5mm to a maximum of 1.4mm were obtained and the blocks on the higher ground moved farthest.

Small sorted circles were found in the summit areas largely on deflation surfaces and on large turf-banked terrace treads. The study of structure and sorting revealed that in all cases the rim of stones was restricted to a surface layer of about 5cm thickness resting on a bed of clay-loam with occasional stones. For these active miniature features associated with superficial sorting it has been proposed that frost penetration is only a few centimetres and the most effective cycle of freeze-thaw is diurnal. It was found that horizontal-radial surface sorting takes place mainly in the spring largely by needle-ice activity.

Turf hummocks were found on high ground in the summit areas where vegetation cover is complete. As the slope increases they grade into hummock-stripes and then hummock-terracettes. Excavation revealed that the top part of the hummock is composed of fine-grained sandy loam mixed with stones that bulges up parallel to the surface. It has been proposed that after the initial formation of micro-relief, possibly caused by frost sorting, the development of vegetation controlled the process of ground freezing and helped the zones of fines to be heaved up to form hummocks. All turf hummocks are inactive in the present-day.

The general relationships between periglacial features and climate in the areas studied appear to be as follows :

Major gelifluction features such as boulder lobes, large debris lobes and large turf-banked terraces probably developed and remained active in lateglacial times under a much harsher periglacial climate. Except for boulder lobes and associated features the other dominant mass movement features apparently continued to move downslope in early postglacial times and became stagnant as vegetation and high-ground peat developed. Under the present milder climate frost penetration in the ground is slight, amounting to a maximum of about one metre and the most effective cycle of freeze-thaw is diurnal. The predominant mass movement process at the present-day appears to be solifluction. Miniature features like small stone-banked debris lobes, solifluction lobes and small turf-banked terraces are active to-day on a limited scale. Ploughing blocks are also active on moist slopes of higher altitude. On the exposed slopes and summit areas the deflation activity of wind is prominent. In the high-level summit areas on exposed regolith of finer material superficial frost-sorting, largely by needle-ice activity, operates in the development of small sorted circles and stripes. The other contemporary periglacial activities seem to be associated with rockfalls, localized small-scale landslides and debris flows.

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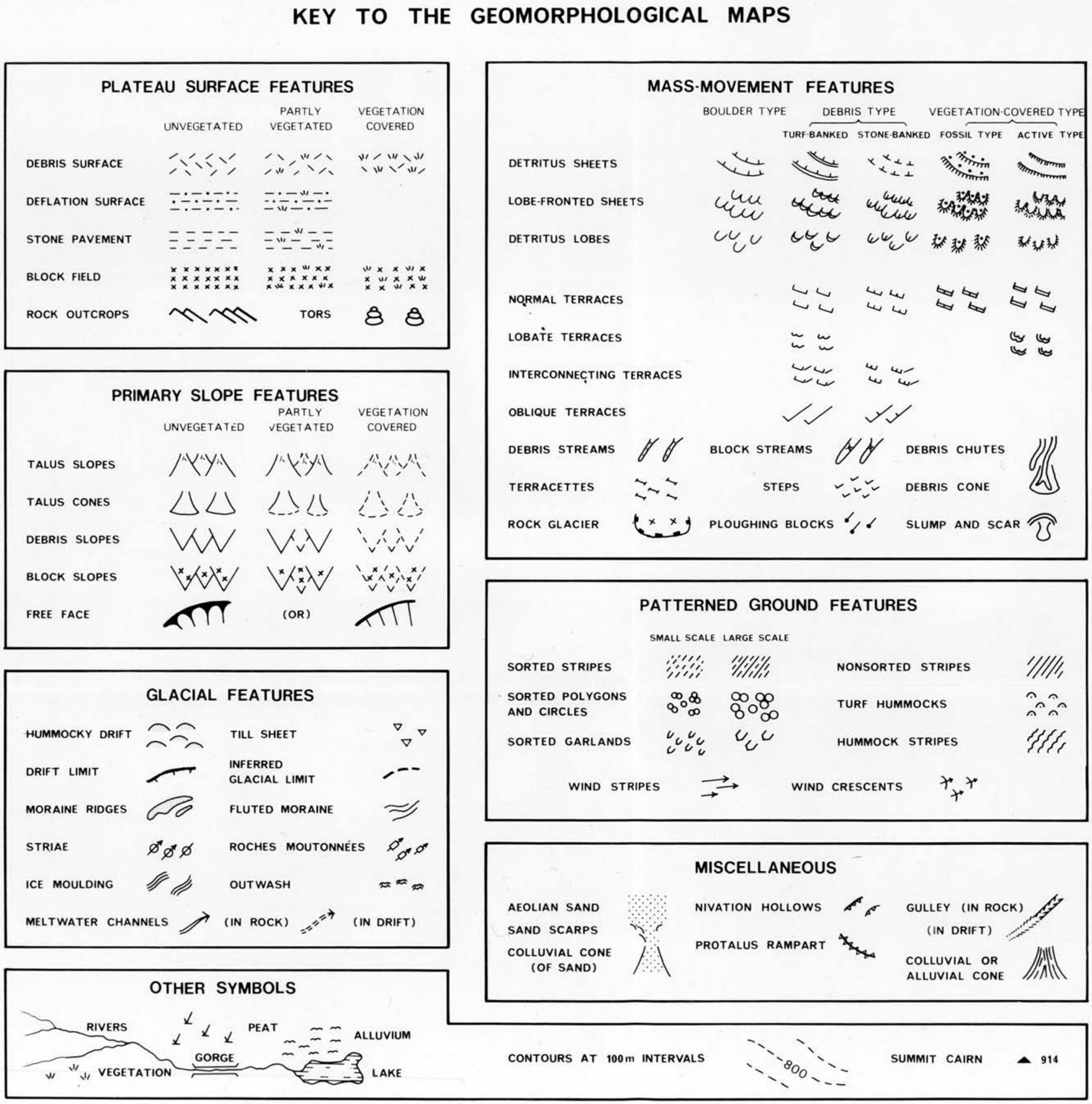

Fig. 5.1 Key to the geomorphological maps.

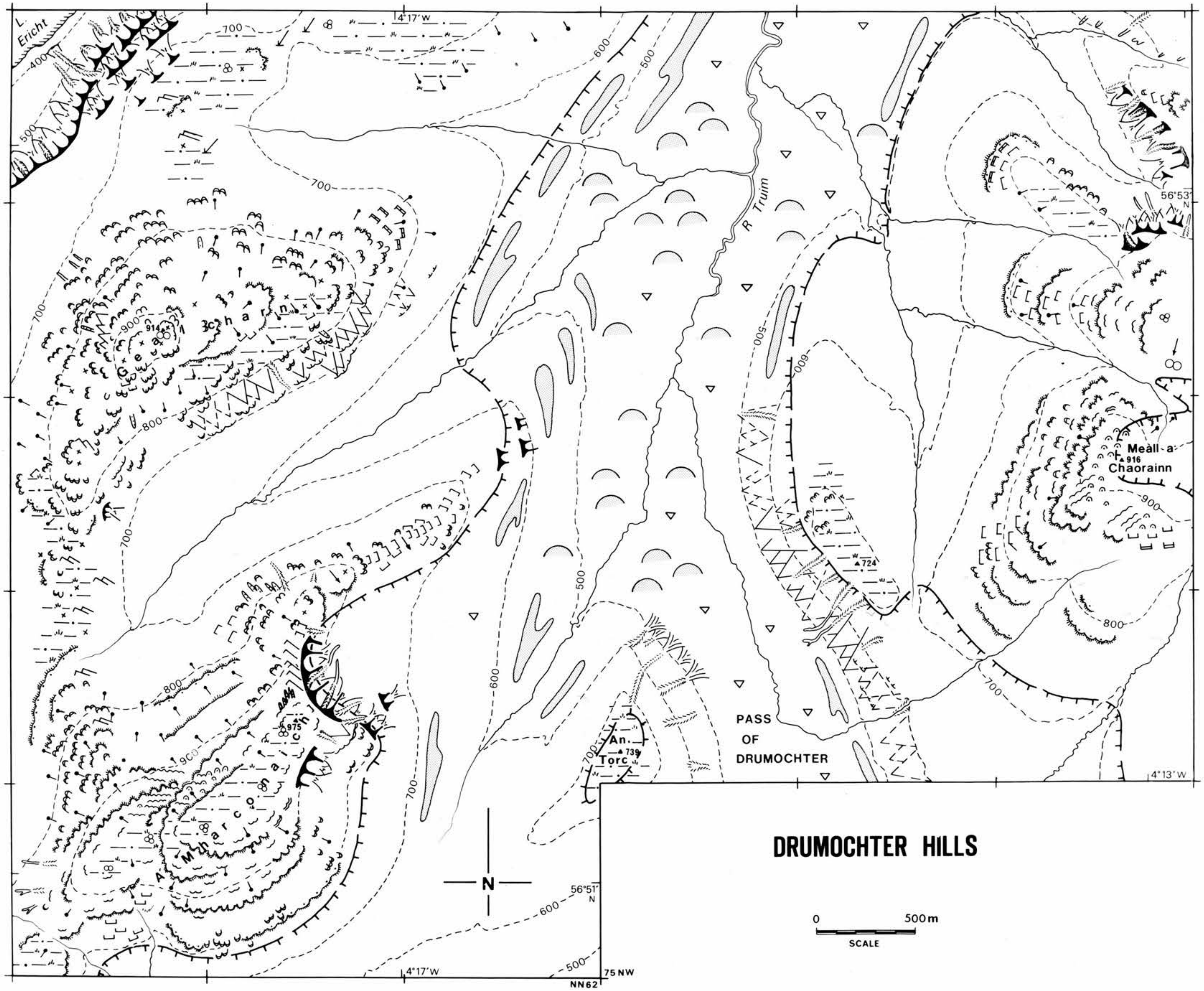

Fig. 5.2 Geomorphological map of the Drumochter area.

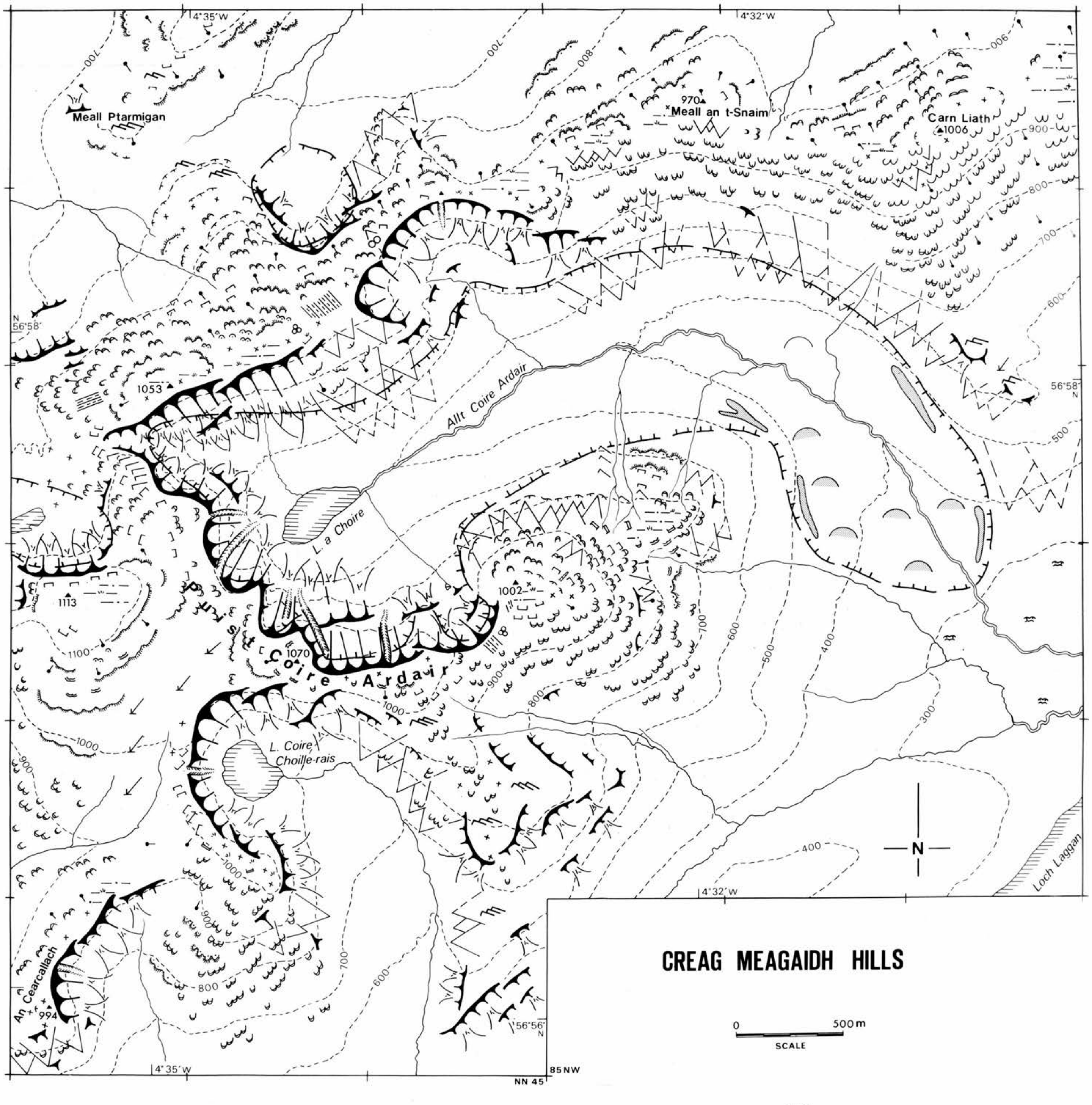

Fig. 5.3 Geomorphological map of the Creag Meagaidh area.

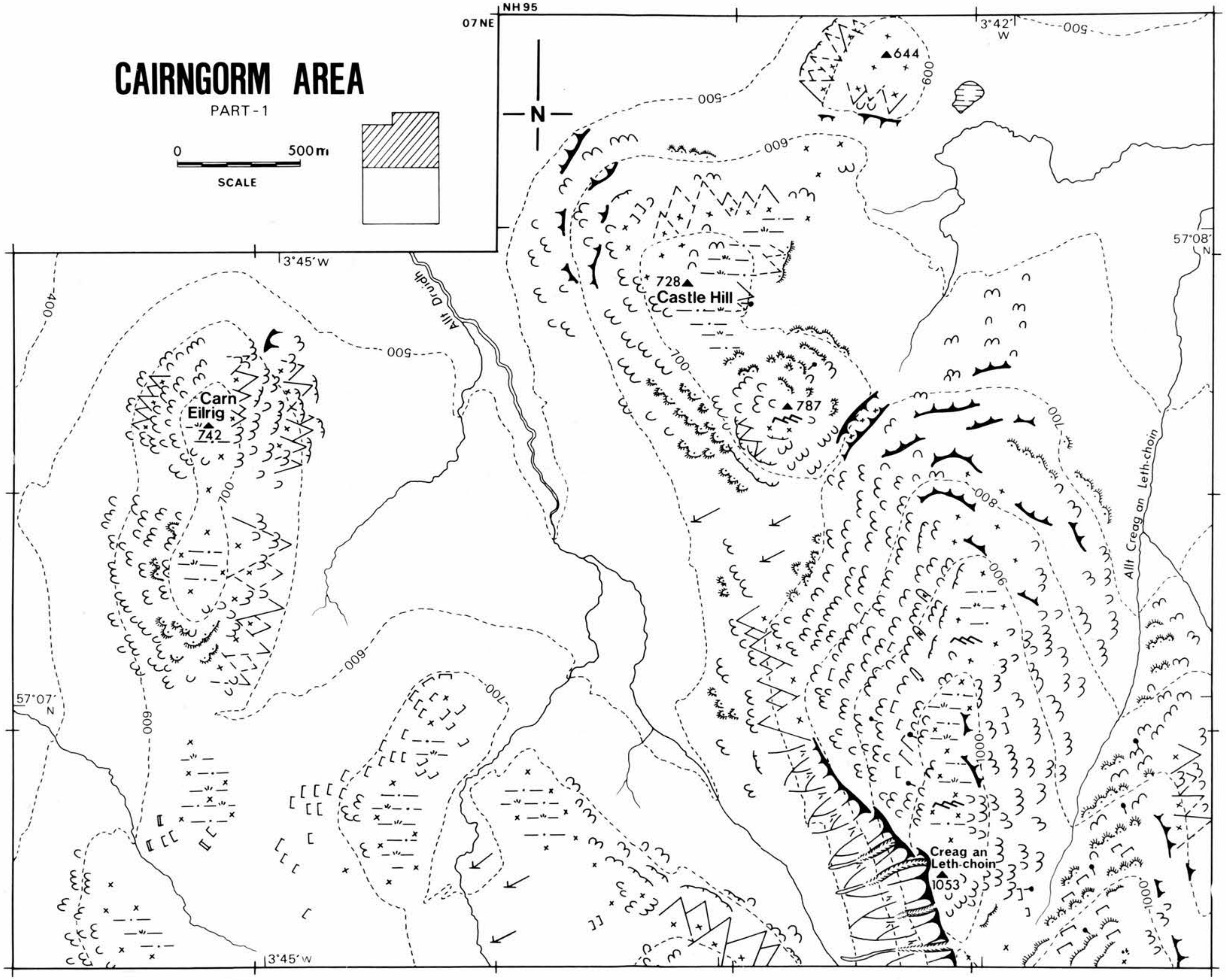

Fig. 5.4 Geomorphological map of the Cairngorm area (northern part).

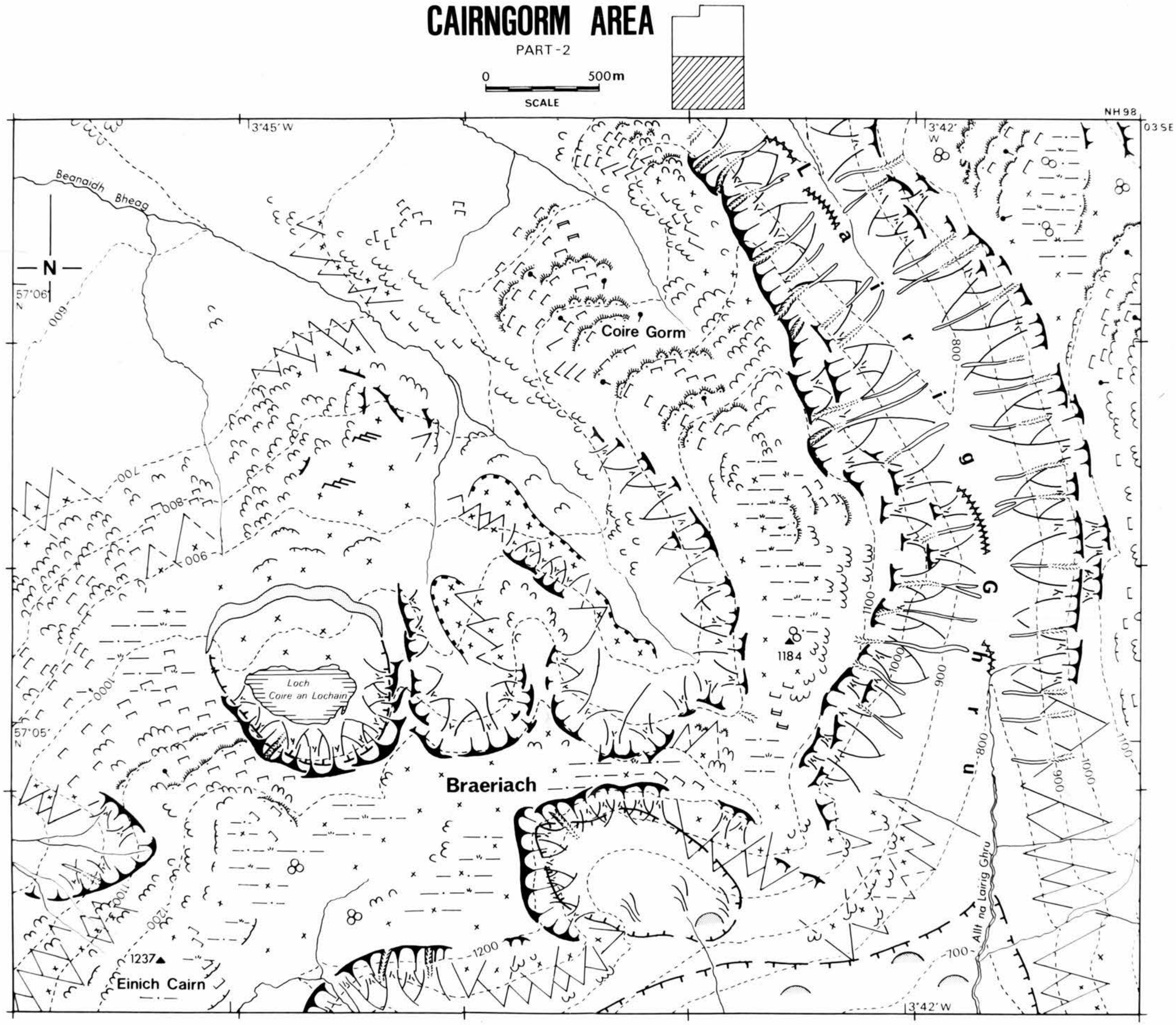

Fig. 5.5 Geomorphological map of the Cairngorm area (southern part).