PERIGLACIAL LANDFORMS AND ENVIRONMENTS

ON MOUNTAINS

IN THE NORTHERN HIGHLANDS OF SCOTLAND

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Doctor of Philosophy

University of Edinburgh

1981

Volume II

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CHAPTER 10 PATTERNED GROUND

10.1 Introduction

Although patterned ground is produced by a variety of mechanisms under non-periglacial conditions, for example in warm arid and semi-arid environments (Hunt and Washburn, 1966; Cooke and Warren, 1973) on intertidal platforms (Kostyaev, 1973; Ball, 1976) and on debris-covered glaciers (Washburn, 1956b; Ballantyne, 1979), landforms of this type are most frequently associated with cold environments where frost is the dominant formative mechanism (Washburn, 1956a, p. 824). The striking appearance of some patterned ground forms in upland Britain (particularly sorted stripes) is probably responsible for their early (Ward, 1876) and extensive (Ball and Goodier, 1970, p. 208) documentation, even though such features are much less widespread than, for example, the mass-movement forms described in the previous chapter. Three classes of periglacial patterned ground may be distinguished in upland Britain, namely sorted, nonsorted and wind-eroded (table 7.1). The first two categories follow the distinction made by Washburn (1956a, 1969a, b, 1973, 1979) between geometric patterns defined by concentrations of coarse and/or fine detritus and those defined by other means, such as relief and vegetation. The recognition of wind-eroded patterned ground as a third category follows Ball and Goodier (1974; Goodier and Ball, 1975), who demonstrated the importance of such features on some British hills.

10.2 Sorted Patterned Ground

Washburn (1969a, pp. 123-49) suggested that it is desirable to differentiate small- and large-scale sorted forms as their modes of formation and significance may differ. Both he and Jahn (1975, p. 43) adopted a width of one metre as marking the difference between the two types, a procedure adopted here for mapping purposes. The two types are widely believed to represent shallow (short-term) and deep (annual) freezing respectively (Troll, 1944; Washburn, 1969a), but as Washburn (1979, p. 160) subsequently pointed out, intermediate forms exist (e.g. Preusser, 1973) and caution must be exercised in using any arbitrary scheme of differentiation.

Small-scale patterned ground in upland Britain often shows signs of recent activity, but large-scale forms have invariably been considered to be relict (Tufnell, 1969; Ball and Goodier, 1970; Ryder and McCann, 1971). Godard (1965, p. 632), however, recognised three "generations" of sorted circles or polygons, the largest being " ... des cercles géants de plusieurs mètres de diamètre ...", the second ranging from 0.4 to 1.0 m in diameter and the smallest, which he considered active, rarely exceeding 0.2 to 0.3 m. In attributing different sizes of feature to different periods of formation, however, Godard ignored the possibility that small- and large-scale features may form contemporaneously (Washburn, 1979, figure 5.27) and that width is probably partly related to the size of sorted clasts (Goldthwait, 1976). The pattern is complicated by descriptions by King (1968, 1971a) of what he termed "fine" and "coarse" patterned ground in the Cairngorms. In this case the "fine" features often exceeded one metre in width or diameter and despite evidence of movement of disturbed surficial material seem unlikely to be capable of forming under present conditions.

In this account a distinction is drawn between patterned ground that is apparently capable of re-forming when disturbed ("active") and that which is not ("inactive"), even though the latter may show signs of recent clast displacement resulting from needle-ice action or frost heave. Criteria for distinguishing current activity include lack of lichen, moss or vegetation cover and differential heave of fine material in winter with concomitant erection of clasts in coarse stripes and polygon margins. The most convincing evidence of present activity relates to direct observations of formation or re-formation of sorted polygons up to 60 cm in outside diameter and of stripes up to 70 cm in repeat distance (Miller et al., 1954; Tallis and Kershaw, 1959; Ballantyne et al., in prep.; figures 10.1 to 10.4), such dimensions being maxima, in the author's experience, for apparently active sorted patterns in upland Britain. Most examples of active sorted patterned ground in this country reach dimensions only half as large as those cited above (tables 10.1 and 10.2).

Although examples of small-scale sorted patterns are found on An Teallach (067866, map 2) and in the eastern Fannichs (185732, map 4), these appear to be inactive. The fine centres of the polygons



Figure 10.1: Active sorted circles ("polygons") at c.500 m on the Ruinsival-Scurr nan Gillean ridge, Rhum.



Figure 10.2: Small active sorted stripes at c.700 m altitude, Scurr nan Gillean, Rhum.



Figure 10.3: Active sorted stripes at 660 m altitude on the south flank of Tinto Hill, Lanarkshire.



Figure 10.4: The Tinto stripes under winter conditions (19 January 1980) showing the heaving of "fine" stripes that results from the formation of lenses of segregated ice (figure 10.7).

Table 10.1

Characteristics of some active sorted polygons in upland Britain

Location	Lithology	Maximum diameter (cm)	Maximum repeat distance (cm)	Maximum clast length (cm)
Storr, Skye	basalt	25	35	15
Mull	basalt	30	-	-
Orval, Rhum	basalt	25	30	12
Morvern	basalt	-	35	-
Ruinsival, Rhum	peridotite	15	-	-
Scùrr nan Gillean, Rhum	felsite	20	30	15
Tinto Hill	felsite	30	40	16
Lake District	slate	-	40	15
North Wales	slate (?)	-	45	10
Glen Lyon	schist	20	30	15
A'Mharconaich, Drumochter	gneiss	30	40	15

Notes:

(i) "Diameter" refers to diameter of fine centre.

(ii) "Repeat distance" is distance from midpoint of coarse margin on one side to the same point on the opposite side.

(iii) Occasional larger clasts are found at all these sites, but these are not always "sorted" into coarse borders.

Sources: Simpson, 1932; Hollingworth, 1934; Tallis and Kershaw, 1959; Godard, 1958, 1965; Ryder and McCann, 1971; unpublished observations.

Table 10.2

Characteristics of some active sorted stripes in upland Britain

Location	Lithology	Maximum width (cm)	Maximum repeat distance (cm)	Maximum clast length (cm)
Scùrr nan Gillean, Rhum	felsite	15	20	15
Ard Nev, Rhum	granophyre	12	25	7
Tinto Hill	felsite	45	70	16
Cairngorms	granite	10	20	10
B. a'Chuallaich (S. Grampians)	schist	25	40	15
High Pike, Lake District	slate	-	50	15
Blencathra, Lake District	slate	-	40	15
Grasmoor, Lake District	slate	-	-	15

Notes:

(i) "Width" refers to width of fine stripes.

(ii) "Repeat distance" is the distance from the midpoint of one coarse stripe to the midpoint of the next.

(iii) Occasional larger clasts are found at all these sites, but these are not always "sorted" into coarse stripes.

Sources: Hollingworth, 1934; Hay, 1936; Miller et al., 1954; Caine, 1963b; Ryder and McCann, 1971; unpublished observations.

on An Teallach are vegetated (figure 10.5) and exposed portions of surrounding clasts are rounded by microgelivation, indicating prolonged inactivity. The Fannich examples highlight the difficulties of defining activity: frost heave and resulting clast displacement are apparently active at this site as many of the small stones that cover the central fine area display surfaces that are lichen-free (figure 10.6), yet the exposed surfaces of the larger clasts on the polygon margins are lichen-covered, suggesting inactivity. It seems likely either that the Fannich features formed during a period of slightly more severe climate (they are 60-90 cm in outside diameter, slightly larger than any known to be active at present), or that they have reached an equilibrium size at which the coarse margins have stabilized.

Although active patterned ground is absent from the original study areas, active stripes and polygons occur at fairly low altitudes on Rhum (e.g. around 378942, map 7, figures 10.1 and 10.2, and on Orval and Ard Nev in the western hills, map 8). Two factors explain this apparent paradox. The first is lithology; tables 10.1 and 10.2 show that most documented examples of active patterned ground occur on rocks such as basalt, felsite, shale and schist that break down under frost weathering to form a diamicton in which the fine fraction contains an abundance of silt and fine sand. Excavation of fine stripes during periods of ground freezing (Caine, 1962, 1963b; Ballantyne et al., in prep.) have shown that such fine material favours the growth of ice lenses (figure 10.7) and therefore upfreezing of stones (Beskow, 1930; Corte, 1966; Kaplar, 1965, 1970) and updoming of fine stripes or the fine centres of polygons (figure 10.4). In regolith that is not frost-susceptible, such as the Torridon Sandstone regolith of An Teallach, these processes are unlikely to be effective. Furthermore, the size of clasts in a frost-weathered deposit produces an additional constraint. The maximum length of sorted clasts in active patterned ground in upland Britain has been cited for various sites as around 15 cm (Miller et al., 1954; Godard, 1958; Caine, 1963b; Ryder and McCann, 1971) or less (Tallis and Kershaw, 1959; tables 10.1 and 10.2). In the author's experience active patterned ground in upland Britain is rarely well-developed on debris where the fine and/or stone fractions are too coarse to satisfy the above conditions.



Figure 10.5: Small but apparently inactive sorted circles ("polygons") at an altitude of c. 750 m on the northern plateau of An Teallach.

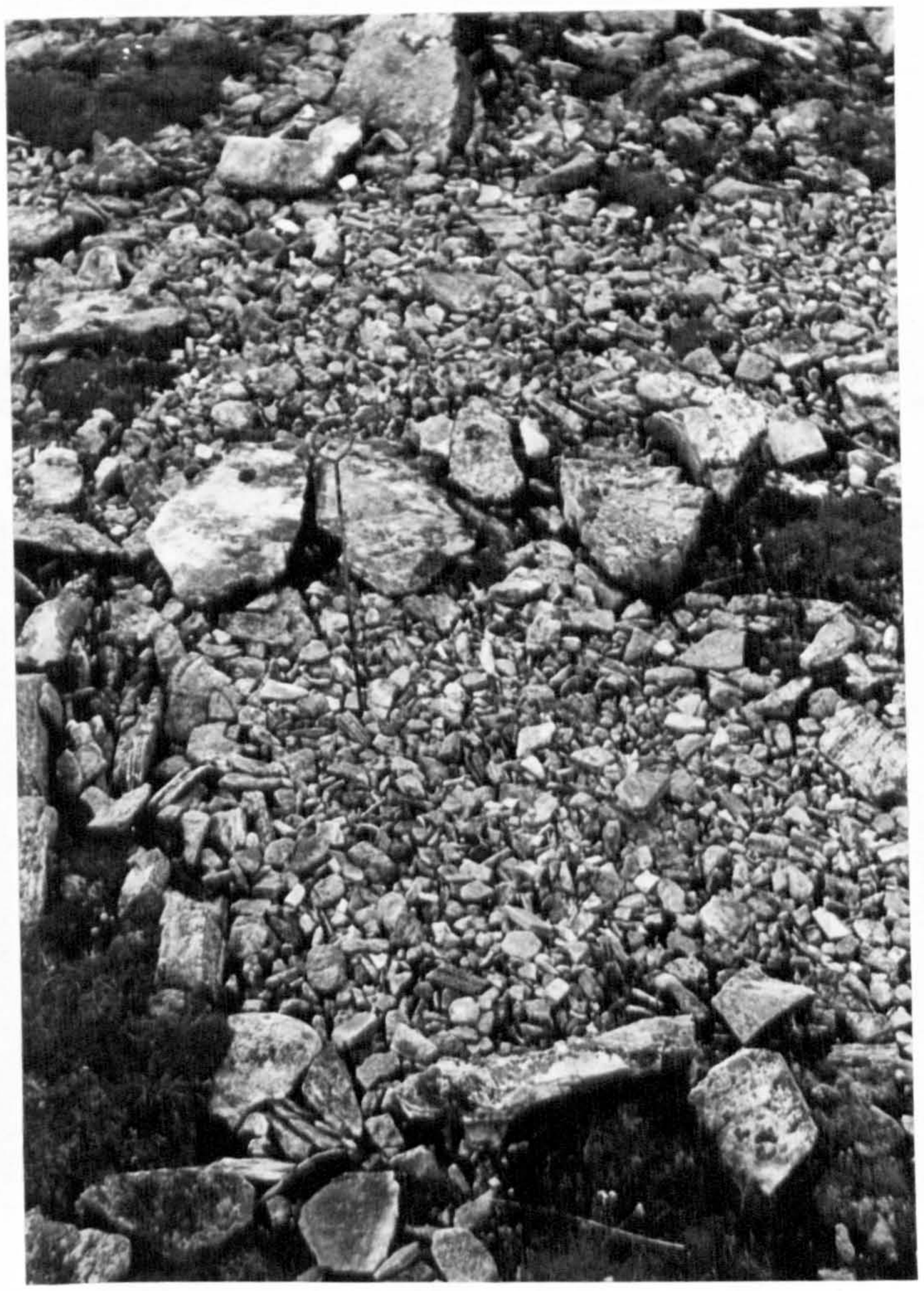


Figure 10.6: Sorted circles ("polygons") near the summit of Meall a'Chrasgaidh (934 m) in the eastern Fannichs. Only the smaller clasts in the centre of the circle show signs of recent movement. The pin is c. 35 cm long.

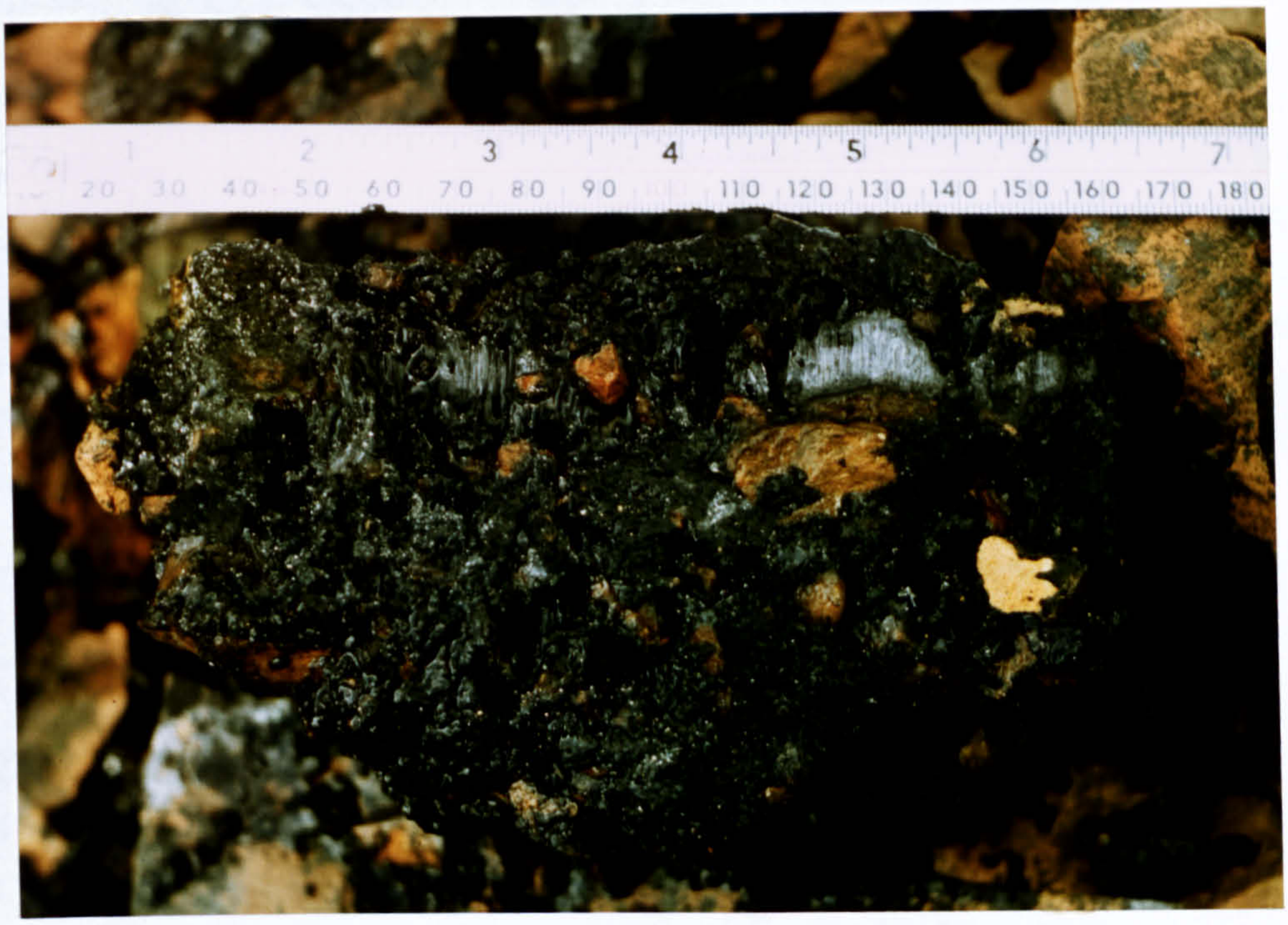
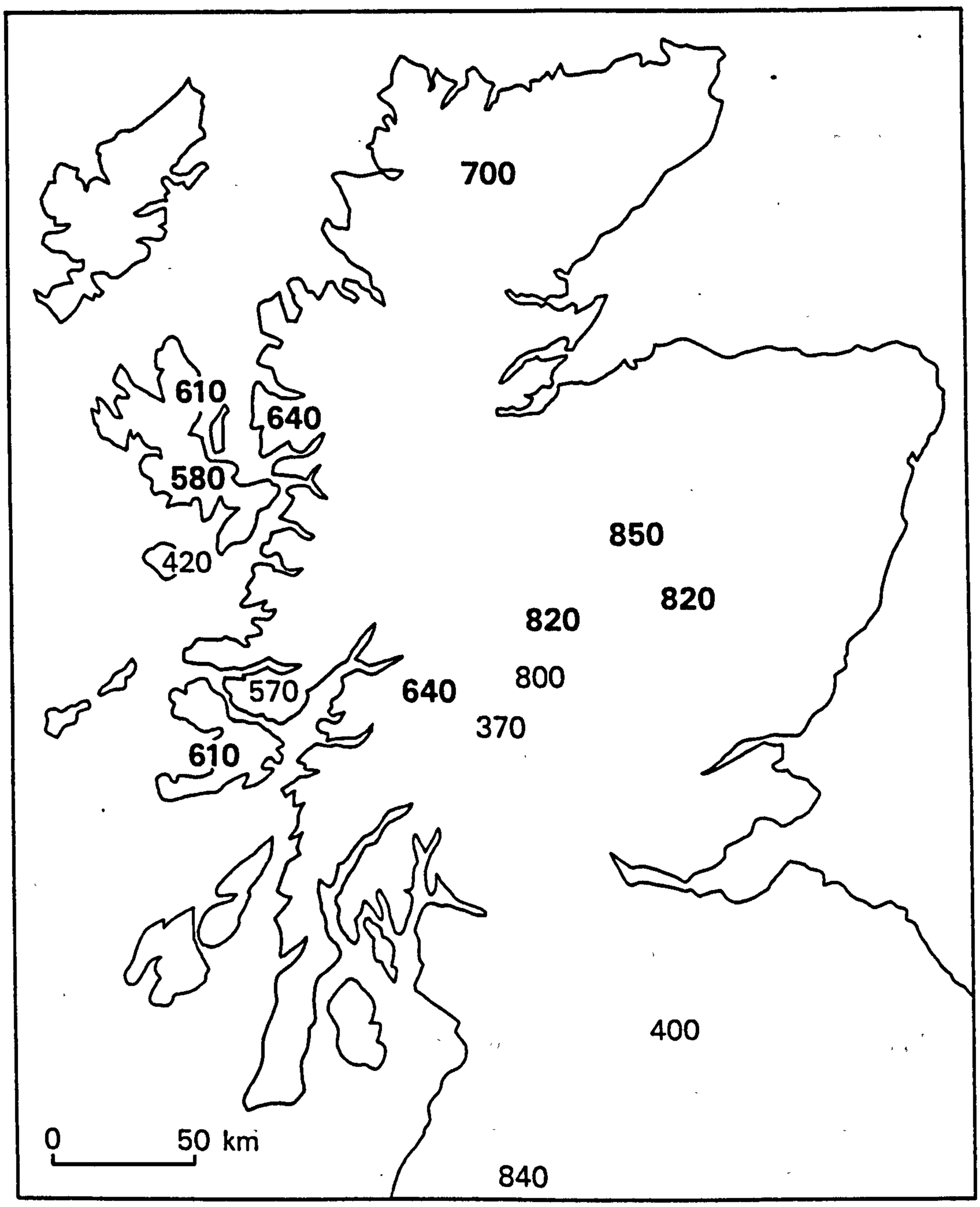


Figure 10.7: Lenses of segregated ice developed in a block of frozen ground from under a "fine" stripe on Tinto Hill.

The second major constraint on active patterned ground development is vegetation cover. Sorted patterned ground cannot develop where there is continuous cover and in many areas where it does form is restricted to unvegetated pockets, as on Orval (map 8). Galloway (1961a, figure 3) provided a crude map showing that the altitude at which granite mountains support 50% or less vegetation cover declines westwards and northwards over Scotland, from about 1070 m on Lochnagar to 430 m on St. Kilda and 360 m on Shetland, a pattern that he related to increased exposure to high winds. The lowest altitudes at which active patterned ground features occur also exhibit a general westward and northward decline across Scotland (Kelletat, 1970a; figure 10.8), and as patterned ground often extends to the lower limit of vegetation-free terrain (at least where the regolith is favourably constituted) it is reasonable to assume that this pattern is related to that of the lower limits of vegetation-free ground.

Further evidence demonstrating the importance of vegetation cover in limiting patterned ground distribution is provided by areas in which sorting is active at anomalously low altitudes, such as Tinto Hill (active sorting at 400 m; Miller et al., 1954) and in the southern Grampians (370 m; figure 10.8). The low altitude reached by active stripes on Tinto Hill was attributed by Galloway (1958) not to "natural" exposure but to removal of vegetation and organic soil cover by overgrazing and burning, which have exposed regolith of suitable constitution on relatively low ground. The figure of 370 m for the southern Grampians relates to polygons found by the author on schistose quarry tailings on which vegetation had not yet developed. Although Gregory's (1930) report of patterned ground by Loch Lomond must be discounted as the features he described are apparently the product of mechanisms other than frost-sorting (Kostyaev, 1973; Ball, 1976), active frost-patterned ground near sea level on Unst, Shetland has been reported by Spence (1957) on ground where the serpentine-derived regolith is inimical to plant cover but of suitable constitution to permit sorting. This implies that only a very mild freezing regime is required to produce small-scale patterned ground provided that the regolith is of favourable composition. This conclusion was also reached by the author and co-workers



(in metres)

Figure 10.8: The lower limits of active patterned ground development at various sites in Scotland. The figures in heavy print are based on Kelletat (1970a); other figures are based on the author's observations.

(Ballantyne et al., in prep.) as a result of investigations on Tinto Hill, where a mild freezing regime (figure 5.7) produced rapid re-formation of sorted patterns on disturbed ground. The main controls on patterned ground distribution in upland Britain are therefore not directly climatic, but relate to vegetation cover and the composition of regolith. The latter explains the lack of such features on the coarse Torridon Sandstone debris of An Teallach, the former their absence from the vegetation-covered schist plateaux of the Fannichs and Ben Wyvis.

Large-scale patterned ground features appear to be less common in upland Britain than active forms, although according to Tufnell (1969) large fossil polygons are "widespread" on the higher parts of the N.W. Pennines where they exceed 15 m in diameter on Knock Fell. Fossil stripes with a repeat distance of 5-8 m have been described by Ball and Goodier (1968) at altitudes of 425-490 m in the Rhinog Mountains, North Wales. In general, however, most reported large-scale forms are much smaller. The mean inside diameters of "fine" and "coarse" polygons in the Cairngorms are given by King (1968, 1971a) as 0.7 m and 1.0 m respectively, and polygons and stripes on Sron an t-Saighdeir (map 8) range in width from 2 to 3 m (Godard, 1965; Ryder, 1968; Ryder and McCann, 1971; Ballantyne and Wain-Hobson, 1980). Godard (1965) described polygons of median diameter 2.2 m at 760 m on Beinn an Fhurainn (NC 290217) in Assynt, and features of similar size have been observed by the author at around 1000 m on Fafernie (NO 215822) in the S.E. Grampians and at a similar altitude on Beinn a'Chlachair (NN 478788) south of Glen Spean.

Conflicting opinions have been expressed regarding the age of such features. Ball and Goodier (1968, p. 58) considered that " ... the location, low altitude and scale of the Rhinog stripes ..." indicated formation prior to the "pre- and post-Allerød periods of the Lateglacial". Foster (1970) maintained that the Rhinogs were not glaciated during the Late Devensian and suggested that the stripes were formed at this time. This explanation cannot be extended to large-scale patterned ground in Scotland, however, where the Late Devensian ice-sheet is considered to have covered most if not all high ground (chapter 2). King (1968, 1971a)

suggested that large-scale stripes and polygons in the Cairngorms formed during the Little Ice Age, but as his evidence consists of lichenometric measurements unrelated to a suitable dated control curve this conclusion must be considered unfounded. Godard (1965) and Ryder and McCann (1971) suggested that the large-scale patterns they described were of Lateglacial age, but provided no evidence.

The only examples of large-scale (> 1 m) sorted patterns within the mapped area are those on Sron an t-Saighdeir in the Western Hills of Rhum (map 8), previously described by Godard (1965), Ryder (1968), Ryder and McCann (1971) and Ballantyne and Wain-Hobson (1980). The polygons at this site are roughly circular in plan, consisting of "rings" of boulders surrounding vegetated centres (figure 10.9). The outside diameter of these polygons ranges from 195 cm to 287 cm, and on shallow gradients they merge with boulder stripes of similar width. Sorting is pronounced: 50 boulders sampled at random from the margin of one polygon yielded a mean diameter ($\overline{(a + b + c) / 3}$) of 17.9 cm (S.D. = 7.0 cm), whereas the mean diameter of 50 sampled from the centre was only 8.9 cm (S.D. = 3.4 cm).

All the examples of large-scale polygons known to the author (i.e. those on Sron an t-Saighdeir, Fafernie and Beinn a'Chlachair) together with those illustrated by Godard (1965, photographs 8 and 9) and Tufnell (1969, plate 3) occur on blockfields, and indeed may be more accurately described as debris islands (defined by Washburn (1979, p. 129) as " ... sorted circles amid blocks or boulders ...") as Tufnell (1969, p. 307) suggested. Exposed boulders on the margins of the Sron an t-Saighdeir polygons, like those over the rest of the blockfield, have been slightly rounded by ~~microgelivation~~ granular disintegration and are generally sub-angular in appearance. Under the polygon margins, as elsewhere on the blockfield, subsurface boulders are generally sharply angular. As argued in section 8.3.3, this difference indicates prolonged stability. Since the degree of rounding of surface clasts on the margins of the polygons is similar to that over the rest of the blockfield (compare figures 8.16 and 10.9), it is reasonable to infer that polygon and blockfield formation were contemporaneous. As all available evidence points to blockfield formation during the Lateglacial cold periods, it seems likely that the polygons also formed during the Lateglacial, as Godard (1965) and Ryder and McCann (1971) suggested.

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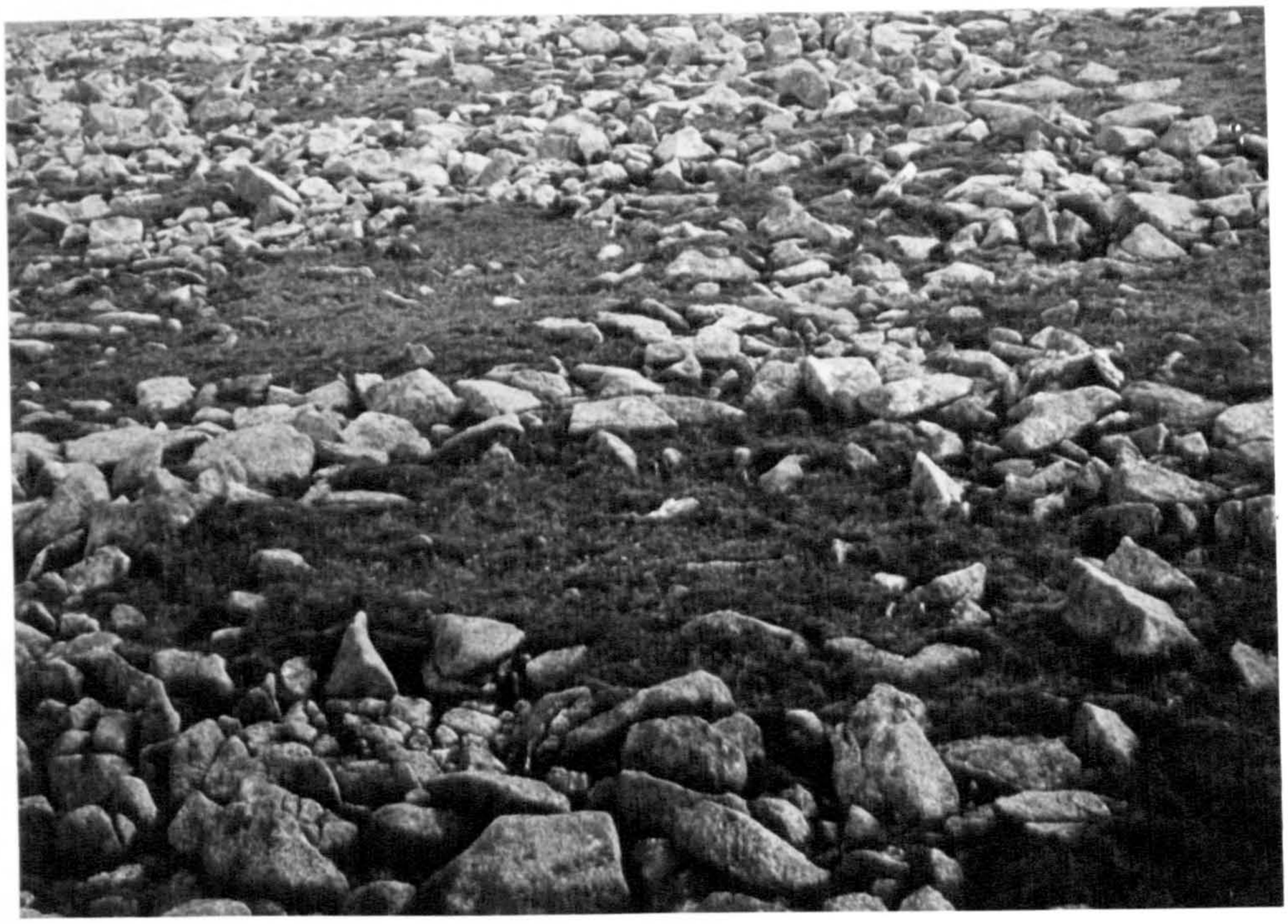


Figure 10.9: Large-scale inactive sorted circles ("polygons") or debris islands at c. 510 m altitude on Sron an t-Saighdeir, Rhum.

This view is supported by the fact that large sorted polygons are normally associated with permafrost conditions so that fossil forms " ... are commonly regarded as reasonable evidence of former permafrost ..." (Washburn, 1979, p. 145). Although the same author cautioned that further study of the palaeoenvironmental significance of large-scale patterned ground is required before relict forms are regarded as proof of former permafrost, others have been less cautious. Goldthwait (1976, p. 34) stated that " ... extensive ice-rich permafrost is implicit in every regional occurrence of large patterned soils (> 2 m)" and although Williams (1975, p. 97) noted the formation of large-scale forms in temperate mountains under conditions of seasonal flooding or waterlogging, he concluded that " ... sorting patterns involving boulders, such as the giant polygons and stripes that occur on Dartmoor, strongly suggest the former presence of permafrost." The consensus of informed opinion is therefore that large-scale sorting is a strong but not conclusive indication of formation under permafrost conditions. It seems certain, however, that large-scale sorting requires deep annual ground freezing (Troll, 1958). As such conditions have not pertained in upland Britain since the onset of the Flandrian (chapter 2), it is reasonable to infer that large-scale patterned ground on British hills is of Lateglacial age or (in areas that escaped Late Devensian glaciation) even older.

It is difficult to generalize on the age and significance of small-scale frost-sorted patterns that are presently inactive in terms of the criterion stated above. Rounding of the exposed clasts that define the small (0.5-0.9 m diameter) polygons on An Teallach suggests that these are of the same age as the debris surface on which they are developed, hence probably of Lateglacial origin (section 8.4.3). As noted earlier, however, the 0.6-0.9 m diameter polygons on Mheall a'Chrasgaidh in the eastern Fannichs show signs of recent activity despite the apparent stability of their margins. On 15^{o} slopes adjacent to these polygons are sorted stripes with a repeat distance of 0.4-0.6 m. Although of similar dimensions to active features elsewhere (e.g. Tinto Hill) present activity at this site appears limited as the exposed surfaces of stones in coarse stripes are lichen-covered and vegetation has partly colonized the fine stripes. Colonization of fine stripes

by vegetation has also been described by Ball and Goodier (1970, p. 207-8 and figure 3b) in North Wales and, although the clasts in this case are larger (10-30 cm length) than those typical of active stripes, these authors observed updoming of the vegetated fine stripes during freezing. They interpreted this as representative of present activity, even though the cover of vegetation on fine stripes suggests otherwise. It may be that such features (together with some of the "fine polygons" of King (1968, 1971a) and the "second generation" features of Godard (1965)) formed under climatic conditions only slightly more severe than those at present, possibly during the Little Ice Age, but supporting evidence is lacking.

The absence of active sorted patterned ground features in the original study areas precluded investigations of sorting processes and rates of activity. The comments below are largely based on observations made on such features on Rhum, Tinto Hill and elsewhere.

Sections cut through sorted polygons and stripes (figure 10.10) revealed structures very similar to those illustrated in previous accounts of sorted patterned ground both in upland Britain (e.g. Hollingworth, 1934, figure 24; Miller et al., 1954, plate 2; Caine, 1963b, figure 6; Kelletat, 1970a, plates 8 and 9) and in other periglacial areas such as Spitzbergen (Huxley and Odell, 1924; Elton, 1927, figure 3) and Iceland (Schunke, 1975, figure 2). Small sorted polygons excavated by the author on Cornwallis Island, N.W.T., and the Jotunheimen Massif, Norway, were also structurally identical to those depicted in figure 10.10.

Common to all these forms, both active and relict, is an undulating surface of fines with variable stone content. The crests of the undulations mark the locations of polygon centres or fine stripes, and the troughs contain clasts that mark the polygon margins or coarse stripes. This structure suggests that clasts have migrated from the crests to the troughs. Such movement is widely believed to accompany differential heaving and updoming of the crests relative to the troughs during freezing and may occur by a variety of mechanisms including outfreezing of buried and embedded clasts (Corte, 1961, 1962a), needle-ice

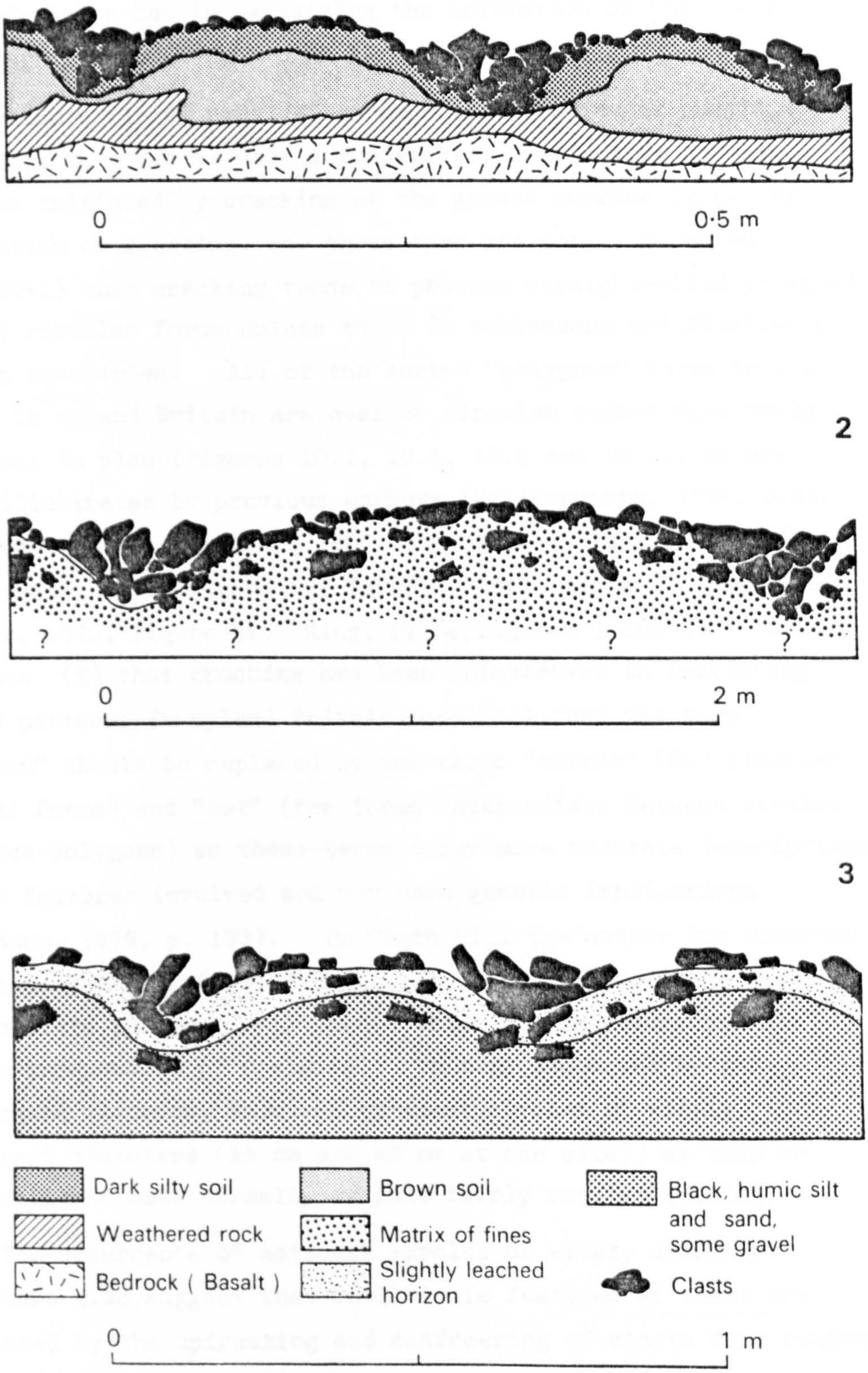


Figure 10.10: Sections through sorted patterned ground. 1 - active sorted circles ("polygons") on Orval, Rhum. 2 - relict sorted circles ("polygons"), Sron an t-Saighdeir, Rhum. 3 - active sorted stripes, Tinto Hill, Lanarkshire.

heave, frost creep and "microsolifluction" (Nicholson, 1976). Evidence for preferential movement of marker clasts from fine to coarse stripes in the Lake District has been described by Caine (1963b). However, the main problem in explaining the formation of sorted patterned ground lies not in accounting for lateral clast migration but in explaining the initiation of the crest and trough pattern.

Washburn (1979) provided an exhaustive review of possible mechanisms in which he made a fundamental distinction between features initiated by cracking of the ground surface (e.g. by dessication or freezing) and those that are not. He noted (pp. 160-1) that cracking tends to produce straight-sided polygons but not circular forms unless there is subsequent modification of polygon boundaries. All of the sorted "polygons" known to the author in upland Britain are oval or circular rather than truly polygonal in plan (figures 10.1, 10.5, 10.6 and 10.9), as are those illustrated by previous workers (Hollingworth, 1934, plate 7; Godard, 1958, plate 4b; 1965, photographs 8 and 9; Tallis and Kershaw, 1959, figure 1; Tufnell, 1969, plate 3; Ball and Goodier, 1970, figure 3f; King, 1971a, figures 1 and 2). This suggests (i) that cracking has been unimportant in initiating sorted patterns in upland Britain, and (ii) that the term "polygon" should be replaced by the terms "circle" (for circular or oval forms) and "net" (for forms intermediate between circles and true polygons) as these terms offer more accurate descriptions of the features involved and may have genetic implications (Washburn, 1979, p. 123). On Tinto Hill the author has observed the formation ab initio of small sorted circles, without any intermediate polygon development, which strongly suggests an origin independent of cracking. This is supported by the occurrence on Orval, Rhum, of adjacent circles of widely different diameters (15 cm and 40 cm at one site), as thaw or dessication cracks normally exhibit fairly regular spacing.

The occurrence of adjacent circles of widely different diameters also suggest that small-scale features at least are initiated by the upfreezing and outfreezing of clasts from randomly-spaced concentrations of frost-susceptible fines (Corte, 1961,

1962 a, b, 1966), a mechanism favoured by Goldthwait (1976) as responsible for initiating most sorted patterns and referred to as "primary frost sorting" by Washburn (1979, p. 167). Photographs taken at regular intervals of an area of disturbed ground on Tinto Hill over the winter of 1979-80 confirm that sorted circles there develop from existing concentrations of fines. A similar process was favoured by Caine (1962, 1963b) for the initiation of sorted stripes in the Lake District. However, Hay (1936) observed that such stripes give way upslope to a subsurface system of parallel rills, and observations made on Tinto Hill by the author and associates appear to indicate that such rills are of fundamental importance in initiating the troughs in which coarse material accumulates. In the case of small-scale stripes the stripe pattern is apparently initiated by rillwash but extensively modified by upfreezing and lateral migration of clasts from the areas of frost-susceptible fines that occupy the zones between rills (Ballantyne et al., in prep.).

Finally, it is notable that although only small-scale patterned ground is presently active in upland Britain, such features are capable of rapid formation and re-formation (Miller et al., 1954), and Tallis and Kershaw (1959) have shown that more fragile forms may also be rapidly destroyed by high winds and heavy rain. Observations on Tinto Hill have revealed that sorted circles may form on previously disturbed ground within a few weeks and that existing stripes may propagate over one metre downslope over disturbed ground in the course of a single rainstorm. Even more impressive are rates of surface clast movement associated with active stripes: Caine (1962, 1963a) recorded median rates of downslope displacement of 7-26 cm at eight sites in the Lake District over the winter of 1961-2, and on the slightly steeper slopes of Tinto Hill (23°) most of the marker stones monitored by the author moved over one metre downslope between November 1977 and May 1980, indicating mean rates of annual movement as high as any hitherto recorded for sorted stripes (Washburn, 1979, p. 154). Movement of surface clasts on Tinto Hill results from a combination of wash, needle-ice heave and frost creep associated with ice lens formation.

Only the last-mentioned appears to affect subsurface material which accordingly moves at much lower rates than surface stones (Ballantyne et al., in prep.).

10.3 Nonsorted patterned ground

Three types of nonsorted patterned ground are known to occur in upland Britain. The most common consists of turf or earth hummocks (thufurs), defined in section 7.3.4 as vegetation-covered domes of predominantly fine material separated by a network of depressions. On slopes steeper than about 5° turf hummocks sometimes become aligned downslope to form hummock stripes, equivalent to the "stripe hummocks" of Lundqvist, 1962 (figure 10.11). On still steeper slopes individual hummocks merge to form nonsorted "relief stripes" (sensu Nicholson, 1976) consisting of alternating ridges and furrows aligned downslope. The nonsorted stripes referred to here therefore differ from those defined by Washburn (1956a, p. 837) as " ... parallel lines of vegetation-covered ground and intervening strips of relatively bare ground". Washburn (1979, p. 152) considered hummock and relief stripes to be uncommon, but in Great Britain and Scandinavia these represent the dominant types of nonsorted stripe. Vegetation-defined stripes (nonsorted stripes sensu Washburn) are rare in Sweden (Lundqvist, 1962), absent in North Wales (Ball and Goodier, 1970) and have not been seen by the author in Scotland or Norway, but hummock and relief stripes occur in all these areas.

Nonsorted patterned ground in upland Britain was first recorded by Galloway (1958, 1961a), who interpreted "ring" and stripe patterns on Ben Wyvis as fossil sorted forms. Birks (1973) described hummocks and hummock stripes on Skye, and attributed both to differential freezing and upheaving as envisaged by Beskow (1930) and Lundqvist (1962). Tufnell (1975) described, classified and analysed the distributions and dimensions of hummocks in the N.W. Pennines, but apart from deciding that these were " ... similar to the Icelandic thufur and ... consequently of periglacial origin" (p. 365) he offered no explanation of formation. He speculated that hummocks may

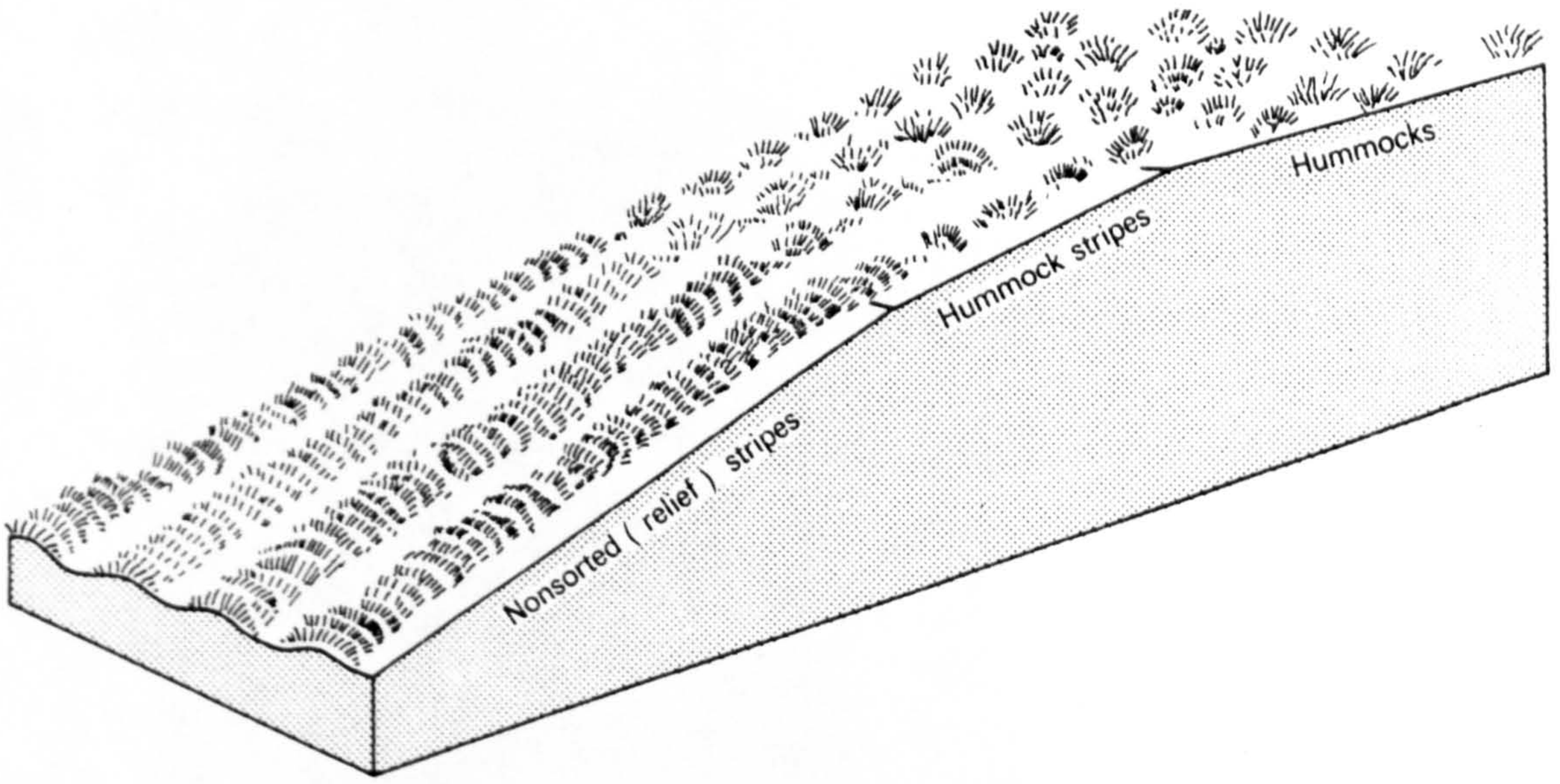


Figure 10.11: The transition from turf (earth) hummocks via hummock stripes to nonsorted (relief) stripes. Based on field sketches made on Ben Wyvis.

form under present conditions, noting that

> " ... small hummocks occur on ground which must have been thoroughly disturbed in the late 1940s/1950s when the radio station and masts (on Great Dun Fell) were built ..." (p. 367).

In contrast, Goodier and Ball (1970) considered small nonsorted stripes in North Wales to be fossil features dating from the Little Ice Age. This conclusion was based on the relationship between the stripes and stone-banked lobes that they believed to represent the geliflucted remains of a medieval wall. The validity of this interpretation is difficult to assess, and Little Ice Age origin for these stripes cannot be considered proven.

Turf hummocks occur on many Scottish mountains, particularly on schists (e.g. on Meall Glas in the southern Grampians, the Drumochter Hills and Glas Maol). Areas of hummock stripes and relief stripes are rarer: the author knows of only two examples outside the study areas, one near the summit of Merrick (Galloway), the other N.E. of Glas Maol (S.E. Grampians). Within the study areas only occasional groups of hummocks are found in the Fannichs (e.g. 209717, map 4) and on An Teallach (e.g. 070867, map 2), but Ben Wyvis boasts a superb assemblage of nonsorted forms. Much of the ensuing discussion is therefore based on features on Ben Wyvis, although separate consideration is given to the An Teallach hummocks as these are believed to be genetically different.

As on Skye (Birks, 1973), the Ben Wyvis patterns occur in Cariceto-Rhacomitrium lanuginosi summit heaths, with the sedge Carex bigelowii occupying sheltered locations between or on the lee (east) side of hummocks or stripes whose exposed flanks are covered with Rhacomitrium lanuginosum. The Wyvis hummocks vary widely in size (table 10.3) and, although apparently similar in dimensions to those described by Birks on Skye, are much lower than those on An Teallach and broader than the features described by Tufnell on the Pennines. Hummock stripes on Ben Wyvis are often broader than individual hummocks, with ridges typically 1.0 m in width separated by furrows 0.4-0.7 m across. Nonsorted stripes are often broader still, with repeat distances around 2 m and heights of 10-30 cm (figure 10.12). Hummock and nonsorted

Table 10.3

Dimensions of some turf hummocks in upland Britain

Site	Sample size	Height in cm.			Maximum Diameter in cm.		
		min.	mean.	max.	min.	mean.	max.
An Cabar, Ben Wyvis (451668)	50	6	16	32	32	63	127
Glas Leathad Beag, B. Wyvis (493709)	50	9	18	44	28	65	118
Coire nan Tota, An Teallach (069866)	50	20	49	92	24	71	156
Skye (Birks, 1973, p. 194)	-	15	-	30	40	-	180
Great Dun Fell (Tufnell, 1975, p. 360)	88	-	20	-	-	35	-
Knock Ore Gill (Tufnell, 1975, p. 360)	166	-	15	-	-	37	-



Figure 10.12: Nonsorted "relief" stripes on a gradient of 11° at 910 m altitude on Tom a'Choinnich, Ben Wyvis, showing the lack of lateral sorting beneath the vegetation cover. Galloway (1958, 1961a) claimed that such stripes represented relict sorted features.



Figure 10.13: Typical turf or earth hummocks at 1010 m altitude near the summit of Ben Wyvis, showing the light grey micaceous A horizon of a mature podzol and the absence of lateral sorting.

stripes tend to follow the direction of maximum slope (figure 8.22), although they often meander slightly (particularly on gentle slopes) and divide where the slope is convex (outward) in plan or join where the slope is concave in plan, thereby maintaining a roughly equal spacing. Individual stripes are traceable for up to 110 m downslope.

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

Trenches were dug across three south-facing stripes at 910 m on a slope of 11^{o} S.E. of Tom a'Chòinnich (464698) and across two hummocks at 1010 m S.W. of Glas Leathad Mór (462680). Both revealed well-developed podzols (figures 10.13 and 10.14) with clearly-defined horizons following the undulations of the surface. The stripe section displayed a concentration of clasts near to the surface (a feature of the stripes in North Wales described by Goodier and Ball, 1969), but this was not evident in the hummock section. The clasts in both (coherent angular pelitic gneiss and weathered platy schist) were generally flat-lying with no obvious preferred orientation and an absence of erected stones. Most interestingly, the concentration and size of clasts underlying the troughs was no different from that under the ridges (figure 10.14).

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

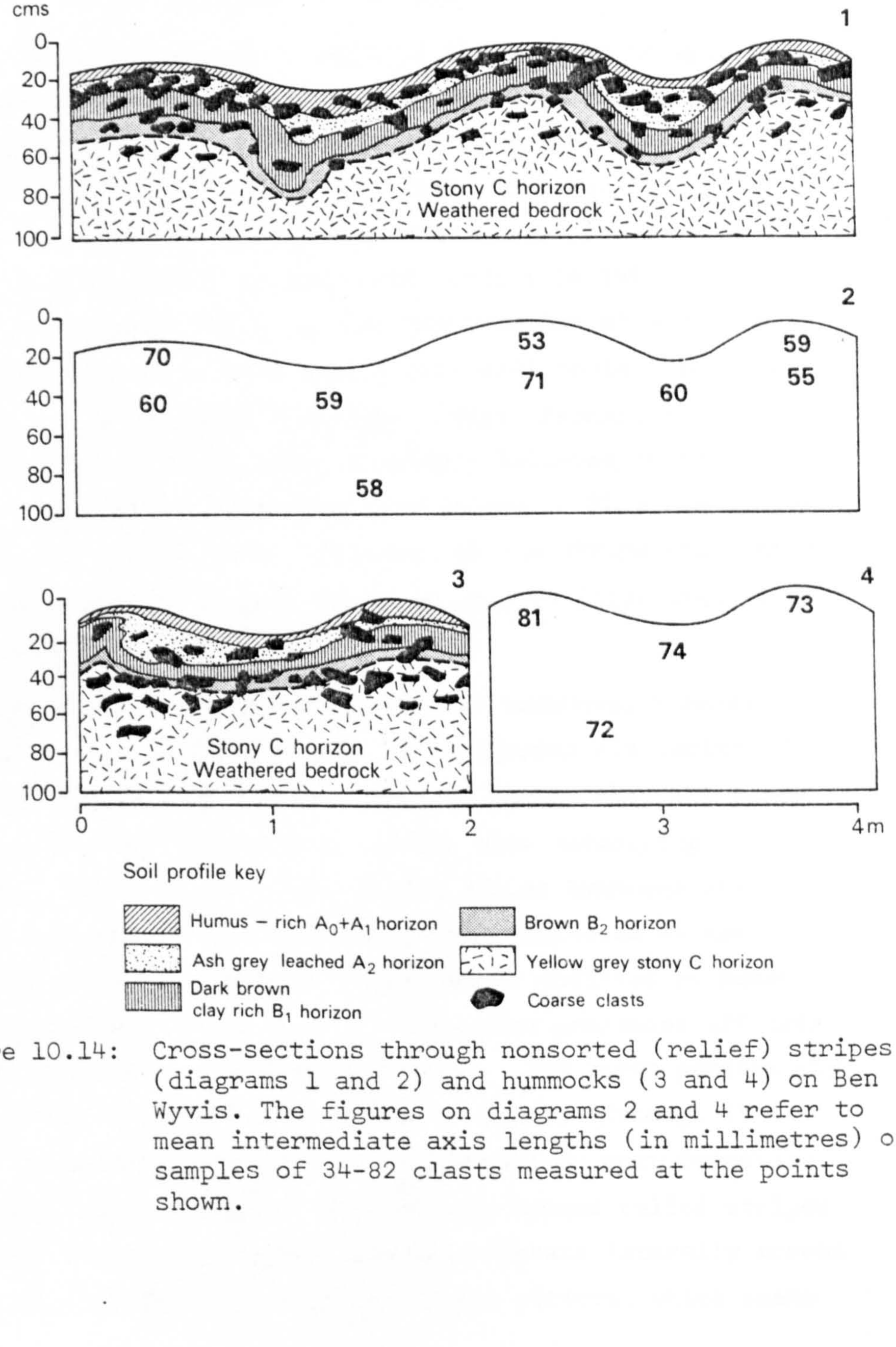


Figure 10.14: Cross-sections through nonsorted (relief) stripes (diagrams 1 and 2) and hummocks (3 and 4) on Ben Wyvis. The figures on diagrams 2 and 4 refer to mean intermediate axis lengths (in millimetres) of samples of 34-82 clasts measured at the points shown.

ineffective, as frost-churning would presumably disrupt the well-defined soil horizons. Thirdly, preservation of podzolic horizons and the lack of any obvious preferred orientation of excavated clasts indicate that recent solifluction has not been important at the stripe site despite the association of stripes and solifluction features elsewhere. Finally, the absence of differences in clast concentration and size between the hummocks or ridges and adjacent depressions conflicts with Galloway's (1958, 1961a) claim that these features represent vegetation-covered fossil sorted polygons and stripes.

Soil samples taken from a depth of 30 cm under troughs and crests at each site also proved similar in constitution (figure 10.15), comprising in all cases over 60% by weight fine and medium sand (60-600 μm) with a relatively high (c. 20%) clay-silt fraction. Samples taken from hummockless ground (456676) were relatively deficient in clay-silt content (6-14%). This difference may explain the irregular distribution of nonsorted patterns on Ben Wyvis in that a high clay-silt content is likely to increase ice segregation (Terzaghi, 1952; Penner, 1973) and therefore frost heave, which is widely believed to be responsible for hummock formation (see below). This conclusion must be regarded as tentative, however, as the stripe and hummock samples were collected from B_1 horizons rich in illuviated silt and clay particles.

In view of the transitional nature of hummocks, hummock stripes and nonsorted stripes and the structural similarity of hummocks and stripes, it is reasonable to assume that all three types of feature are the products of the same underlying processes. That stripes occupy slopes whilst hummocks are restricted to level or nearly-level ground indicates either that stripes represent hummocks subsequently modified by mass-movement (solifluction) or that the formative processes affected slopes and level areas in different ways. The first possibility is rejected for the following reasons. First, although it is possible to envisage "stretching" of hummocks by post-formation solifluction, the development of regularly-spaced relief stripes demands that irregularly-spaced hummocks migrate laterally across the slope to form the ridges of the stripe pattern, which seems

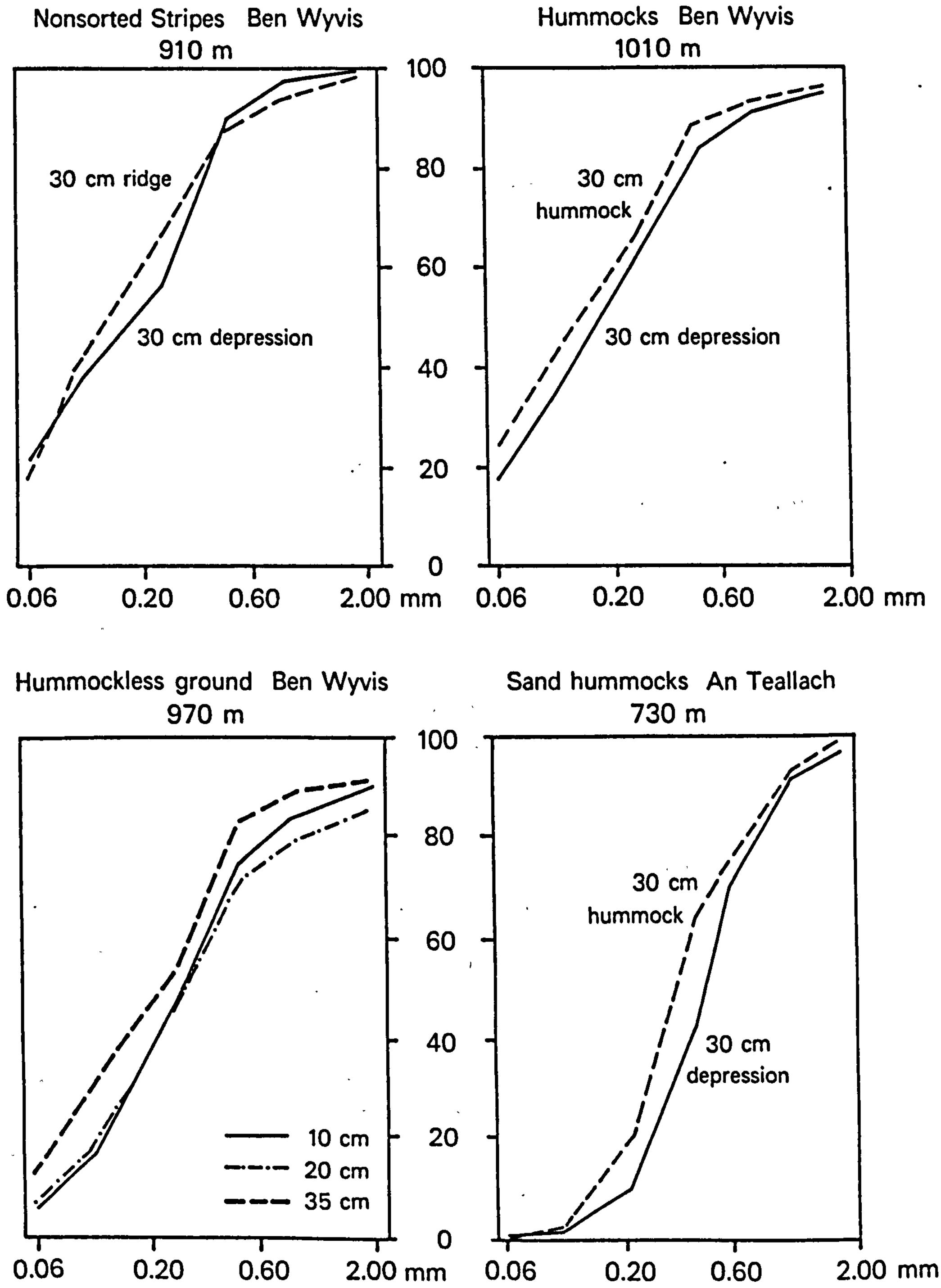


Figure 10.15: Grain-size distributions for samples of fine material collected from nonsorted (relief) stripes, turf (earth) hummocks and hummockless ground on Ben Wyvis and sand hummocks on An Teallach. The figures in centimetres refer to the depths at which sampling was carried out.

unlikely. Secondly, solifluction creates fabrics with a strong preferred downslope orientation (figure 9.27) but clasts in excavated stripes apparently lack orientational preference. Thirdly, hummock stripes occur on slopes of 1°, well below the lowest gradient (6°) on which solifluction forms (sheets or ploughing boulders) are found. Finally, it is unlikely that hummocks could survive over-riding by solifluction sheets, which tend to bury the pre-existing soil (figure 9.22).

Although hummocks are probably polygenetic (Beschel, 1966), it is widely accepted that hummock formation is usually initiated by local small-scale variations in soil constitution, moisture content, topography (swells and depressions or a crack pattern) or vegetation cover (e.g. Thoroddsen, 1913, 1914; Hopkins and Sigafoos, 1954; Zawadski, 1957; Lundqvist, 1962; Birks, 1973; Woo, 1975; Schunke, 1975, 1977). Such differences result in an uneven pattern of frost penetration, with pockets of unfrozen ground surviving amid frozen soil and/or slower frost penetration and consequently greater ice segregation and frost heave in some areas than others. Unfrozen pockets of soil are subject to mass displacement (defined by Washburn, 1969a, p.90 as " ... the <u>en masse</u> local transfer of mobile mineral soil from one place to another within the soil as the result of frost action") but the mechanism responsible is uncertain (Washburn, 1979, pp. 96-100 and 167-8). Nicholson (1976) argued that the establishment of oblique freezing planes is sufficient to cause upward migration of material in the unfrozen soil, but this was refuted by Washburn (1979, p. 99) who contended that unless adjacent soil was frozen to an impermeable base (such as a permafrost table), freezing stresses would be relieved by uplift of frozen soil as a unit. Others (e.g. Hopkins and Sigafoos, 1954; Washburn, 1956a; French, 1976, p. 33; Schunke, 1977; Tarnocai and Zoltai, 1978) favoured cryostatic pressure as the mechanism responsible for upward mass displacement and hummock formation. These authors envisaged that water-soaked material trapped beneath and on both sides by freezing (and therefore expanding) soil would be forced upwards, forming surface mounds. Mackay and Mackay (1976), however, pointed out that in fine-grained frost-susceptible

soils migration of water from unfrozen ground to the freezing plane results in dessication that reduces plasticity in the unfrozen material and allows release of cryostatic pressure through compaction. They also observed that pressures developed in clayey soils are greater during thawing than during freezing, which led Mackay (1979) to propose that wetting and expansion of the dessicated material during thaw results in upward mass displacement as the surrounding frost-heaved ground melts. Others (e.g. Fahey, 1965) have attributed hummock formation to differential frost heave where ice segregation is favoured in some areas (e.g. by granulometry or an insulating vegetation cover) more than in surrounding areas.

Although it is impossible to assess which (if any) of these mechanisms were responsible for mass displacement and consequent hummock and stripe formation on Ben Wyvis, the association of hummocks with presumably contemporaneous stripes allows inferences to be made regarding the nature of hummock and stripe initiation. Random soil and microtopographical variations can be ruled out: although these may constitute an irregular "net" pattern on level surfaces, they are unlikely to constitute a regular stripe pattern of slopes. Likewise, seasonal frost cracking (Thoroddson, 1913, 1914; Woo, 1975) or dessication cracking (Zawadski, 1957) may produce a regular net, but not stripes. On the other hand, vegetation cover on slopes in arid arctic environments often takes the form of alternating stripes of vegetated and unvegetated ground (nonsorted stripes sensu Washburn) where the vegetation is nourished by subsurface percolines (figure 10.16). On Ellesmere Island the writer observed several instances of transition from nonsorted vegetation-covered circles on level ground to vegetation-defined stripes on slopes, giving patterns strikingly similar in scale and appearance to those on Ben Wyvis. Similar transitions were observed by Washburn (1947, figure 2, plate 27) on Victoria Island and Pissart (1976) has emphasized the structural similarities between nonsorted stripes and nonsorted "polygons" (circles). Washburn (1979, p. 153) suggested that the relief stripes described by Goodier and Ball (1969) in North Wales and the Breckland stripes of eastern England (Williams, 1964; Watt et al., 1966; Evans, 1976)



Figure 10.16: Vegetation-defined nonsorted stripes on Ellesmere Island, N.W.T., Canada. The vegetation marks bands of moisture concentration.

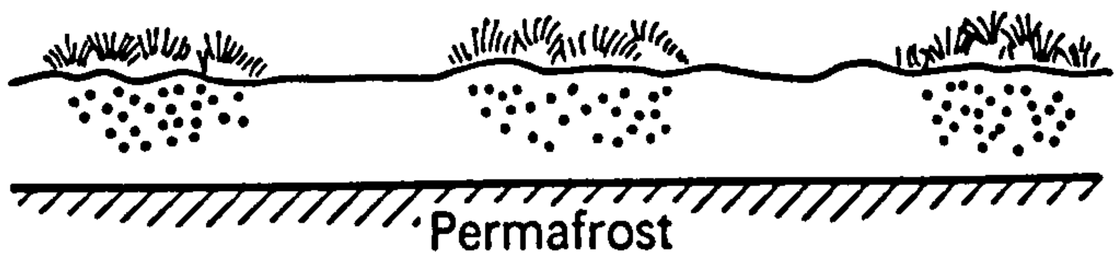
represent inactive nonsorted vegetation-defined stripes. The similarities between the Ben Wyvis stripes and hummocks and nonsorted vegetation-defined patterned ground in arid arctic areas also suggest that the former may have evolved from the latter.

A possible evolutionary sequence is shown in figure 10.17. Although speculative, this model accounts for all of the observed features of the Ben Wyvis stripe-hummock system, including the transition from hummocks to stripes, the regular spacing of stripes (which are assumed to follow regularly-spaced percolines), the meandering of stripes on gentle slopes and the apparent lack of present activity. It also explains the layer of clasts found immediately below the surface in the stripe section: instead of being heaved out of the soil (as with sorted stripes) these would have been trapped by the root mat and hence would have accumulated immediately below the surface. The model rests on the assumption that Ben Wyvis experienced arid conditions during at least part of the Lateglacial cold periods. Given Sissons' (1979b) estimate of 500-600 mm y^{-1} precipitation for 1000 m altitude in the N.W. Cairngorms during the Loch Lomond Stadial this seems reasonable, particularly as effective precipitation is likely to have been greatly reduced by high evaporation rates resulting from strong insolation and high winds.

The turf hummocks on An Teallach differ from those on Ben Wyvis (and other schist mountains) in several respects. Not only are they generally higher (table 10.3) but they are rounded rather than dome-shaped in profile and much more closely spaced (figure 10.18). Moreover, they occur on slopes of 4-18^{o} rather than on level ground and are not associated with hummock stripes or nonsorted stripes. The vegetation on the An Teallach hummocks is also different. The windward sides and exposed crests of hummocks are occupied by long-stemmed grasses and sedges, but the lee sides and inter-hummock troughs are typically covered by a Calluna vulgaris - Vaccinium myrtillus association (figure 10.19).

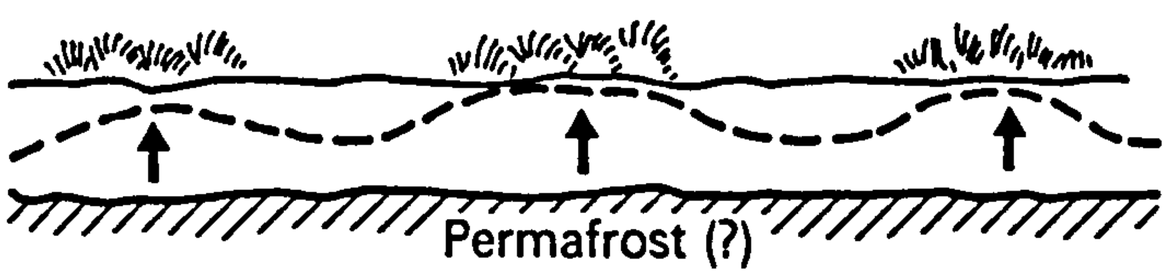
In distribution the An Teallach hummocks are limited to gentle to moderate lee slopes on which a thick (> 1 m) cover of windblown sand has accumulated (map 2; chapter 11). This suggests that their

1. Lateglacial



Active layer, with vegetated circles or stripes marking zones of moisture concentration.

2. End of Lateglacial / Early Flandrian



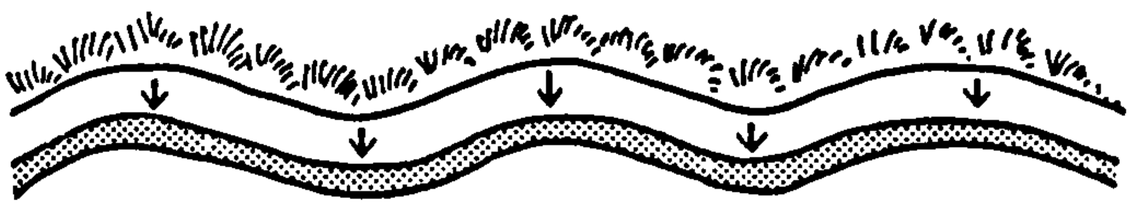
Undulating freezing plane induces mass displacement of unfrozen soil under wetter conditions.

3. Early Flandrian



Resulting hummocks and relief stripes perpetuate undulating freezing plane; continued mass displacement despite complete vegetation cover.

4. Flandrian



Podzolization: translocation of silt and clay to depths below those reached by most freezing cycles renders hummocks and relief stripes inactive.

Figure 10.17: Possible evolution of hummocks, hummock stripes and nonsorted (relief) stripes on Ben Wyvis.

1. Under arid periglacial conditions irregularly-spaced vegetated circles and regularly-spaced vegetation-defined stripes develop in zones of moisture concentration (see figure 10.16).
2. The insulating effect of vegetation cover results in more rapid frost penetration under bare ground. The resulting undulating freezing plane induces mass displacement under conditions of increased wetness.
3. Hummocks and stripes formed by upward mass displacement may have continued to develop as surface topography perpetuated irregular frost penetration.
4. Podzolization results in depletion of clay and silt in the A horizon, rendering the top c. 20 cm of the soil less frost-susceptible. Frost action is consequently diminished.



Figure 10.18: Large turf hummocks (sand hummocks) developed on niveo-aeolian sand deposits at 760 m altitude on An Teallach.

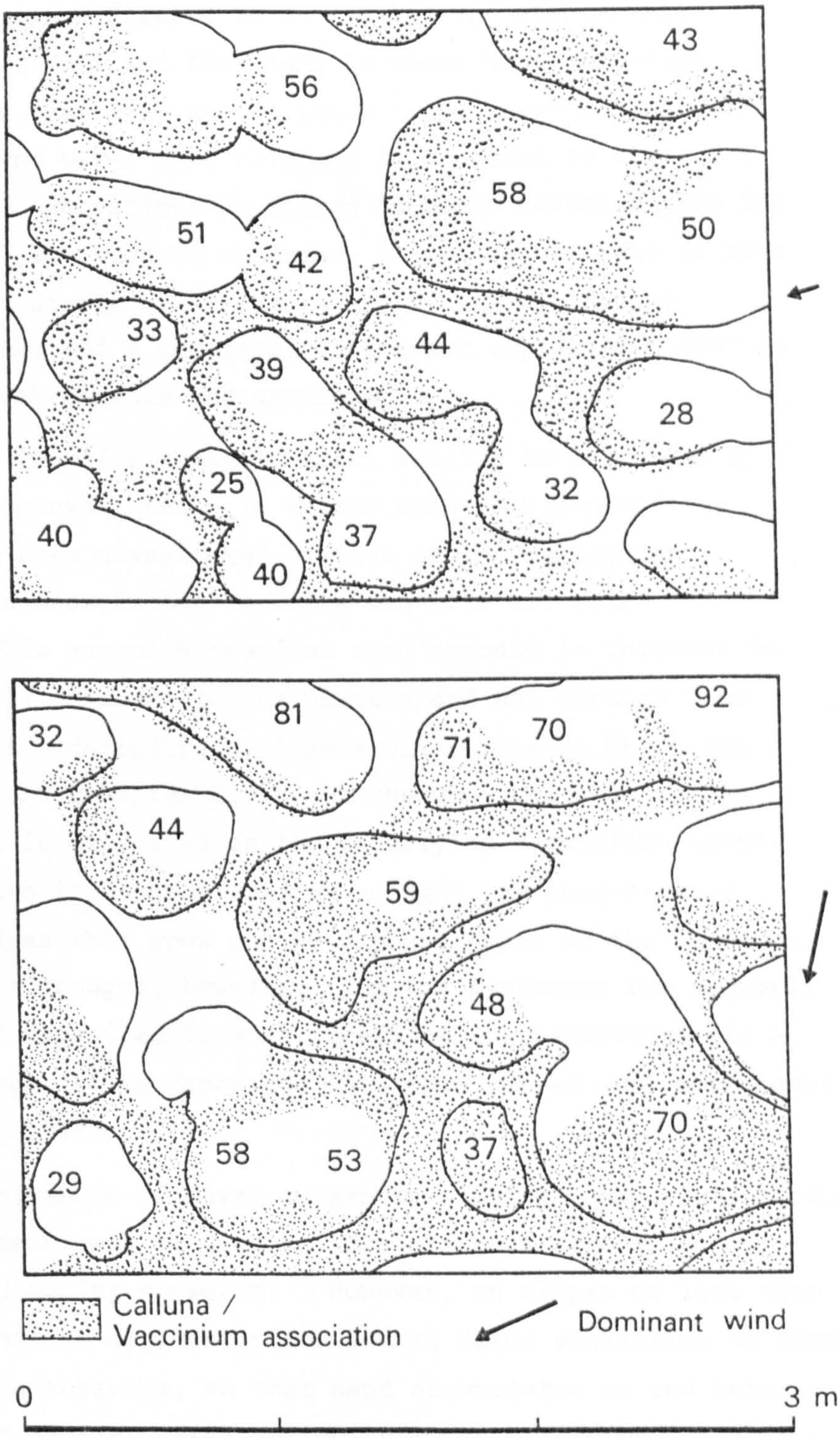


Figure 10.19: Vegetation cover on sand hummocks, An Teallach. The unshaded areas are mainly covered by long-stemmed grasses and sedges. The figures refer to hummock heights above the lowest points in the surrounding depressions (in centimetres).

formation may be related to the accumulation or erosion of such sand deposits. The internal structure of these hummocks supports this idea, as all excavated features consisted of structureless, predominantly medium to coarse sand (figure 10.20) of similar granulometric composition to aeolian sand deposits elsewhere on the mountain (compare figures 10.15 and 11.12; chapter 11). The lack of clay, silt and fine sand in these hummocks (figure 10.15) indicates that they are unlikely to be frost-susceptible even if sufficient water were retained in the sand to allow ice segregation, and excavations in frozen hummocks revealed pore ice but no lenses. The hummock sands are therefore unlikely to have experienced mass displacement due to any of the mechanisms described earlier, and a completely different explanation must be sought for hummock genesis and development.

The manner in which these hummocks develop is suggested by the following observations. In winter sand is blown off the relatively snow-free unvegetated plateau of An Teallach and deposited on lee snowpatches in Coire nan Tota and Coire a'Mhuilinn. This annual supranival sand deposit is thickest in areas immediately adjacent to the plateau and has through time built up the thick deposits of niveo-aeolian sand on which the hummocks are found (chapter 11). As the snow melts in spring supranival sand is deposited on the underlying vegetation cover. On hummock crests it becomes trapped amongst the long-stemmed grasses and sedges that grow on the exposed parts of the hummocks. The interhummock troughs, however, form the routeways for snowmelt runoff and sand deposited in such locations is transported via a network of troughs to be deposited in a thin spread over more level ground (cf Woo, 1975).

On adjacent areas of level or gently-sloping hummockless ground grasses and sedges tend to grow as tussocks that also trap supranival sand during snowmelt. However, on slopes of less than 4-5^{o} the gradient is apparently too low to allow eluviation of sand from between the tussocks, so that sand accumulates on and between the tussocks at similar rates and no hummocks are formed. This evidence strongly suggests that hummock genesis is due to preferential accumulation of niveo-aeolian sand on slopes that are steep enough



Figure 10.20: Section cut through sand hummocks on An Teallach, showing the absence of internal structures (variations in sand colour simply reflect moisture differences) and clastic detritus (compare with figure 10.13)

to allow nival meltwater to flush out sand from the areas between the tussocks. This interpretation is illustrated in figure 10.21 and explains not only the differences between the An Teallach and Ben Wyvis hummocks but also the restriction of the former to thick non-frost-susceptible niveo-aeolian sand deposits that have accumulated on lee slopes adjacent to plateaux. Although similar hummocks have been reported by Robinson (1977) on Torridon Sandstone hills in Applecross, the circumstances under which these features appear to form severely limit their distribution; the writer knows of no examples on lithologies other than Torridon Sandstone. Adoption of the term "sand hummocks" to describe such features may serve to distinguish them from hummocks formed by frost action.

10.4 Wind-patterned ground

As noted in chapters 2 and 5, frequent strong winds are characteristic of British mountain weather. The role of such winds in the formation of certain landforms (e.g. deflation surfaces, turf-banked terraces and sand hummocks) has already been discussed, and landforms and sediments produced by aeolian transportation and deposition are described in the following chapter. Wind erosion is also partly responsible for the creation of patterns formed by the alternation of vegetated and bare ground on plateaux and gentle slopes, features classified in chapter 7 as wind stripes (parallel to the dominant wind) and wind crescents (at right angles to the dominant wind). As such patterns are poorly developed in the study areas only a brief account of their characteristics is given here.

Wind-patterned ground in upland Britain was first reported by Crampton (1911) on the Caithness Hills. He described (p. 38) strips of vegetation aligned both parallel to and normal to dominant wind direction, the latter in the form of a series of waves or crescents produced by the downwind growth of prostrate Calluna leaving a bare trough of " ... naked older twigs with much lichen." Wind stripes and crescents parallel with and at right angles to locally dominant wind directions were also described

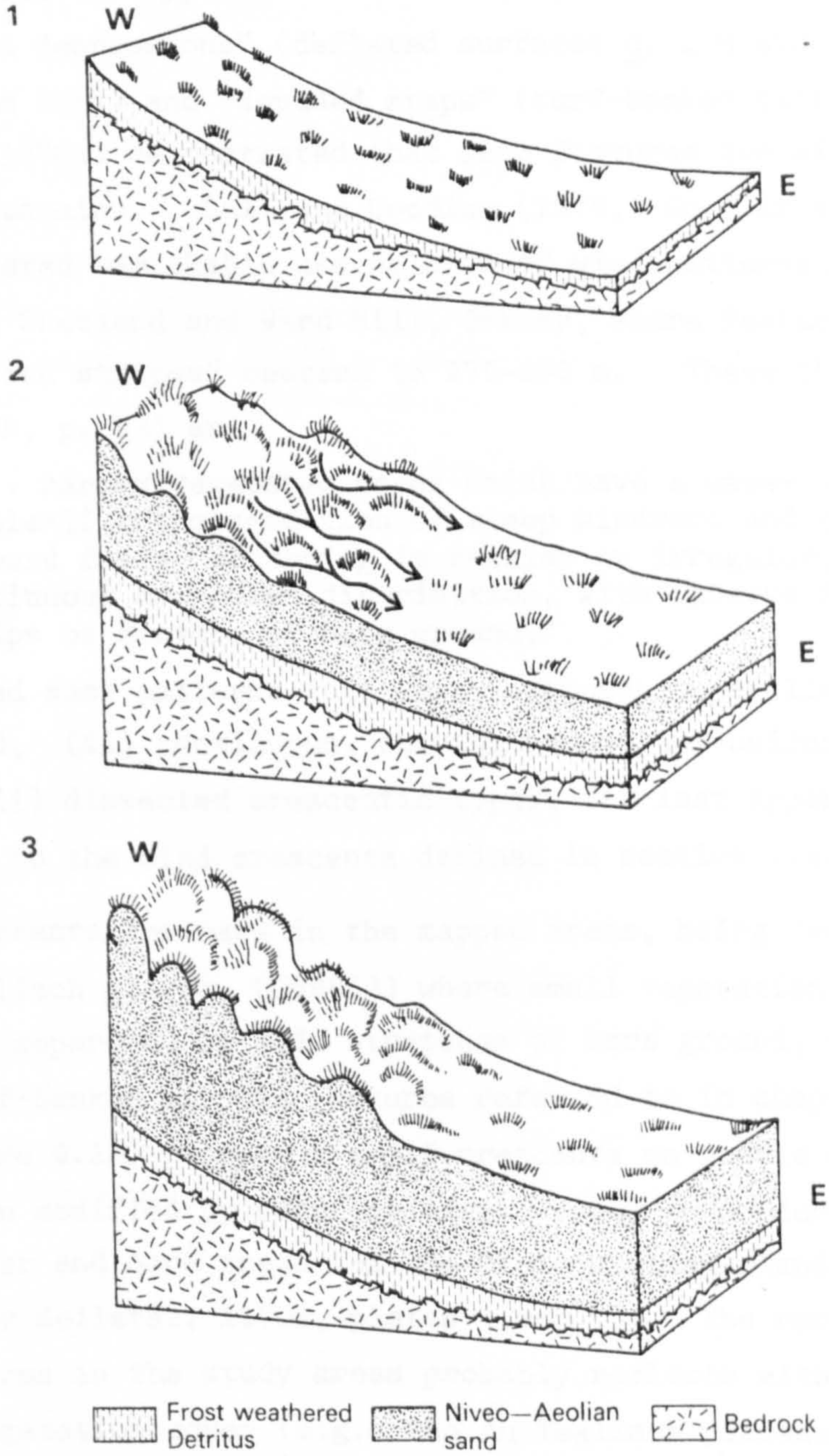


Figure 10.21: Sand hummock evolution through preferential accumulation of niveo-aeolian sand on tussocks and flushing of sand from between tussocks by nival meltwater (schematic).

in a series of studies of high altitude vegetation in the Cairngorms (Watt, 1947; Watt and Jones, 1948; Metcalfe, 1950; Burges, 1951; Ingram, 1956). These authors envisaged the slow migration of such patterns across the ground surface with erosion at the downwind edge of bare ground being compensated by deposition and vegetation accretion at the upwind edge. King (1968, 1971b) provided a detailed description of wind-patterned ground in the Cairngorms. He differentiated two types of what he termed "denuded surfaces", namely "denuded depressions" (deflated surfaces c. 1 m wide and typically 2-4 m long) and "denuded steps" (turf-banked terraces), and Kelletat (1970a) demonstrated that such features are widespread on Scottish mountains. Ball and Goodier (1974; Goodier and Ball, 1975) investigated remarkable assemblages of wind-patterned ground on Ronas Hill, Shetland and Ward Hill, Orkney, where features that they termed "wind stripes" descend to 275-300 m. These they described (1974, p. 93) as

> " ... narrow vegetated zones which have a wave- or ripple-like cross-section of steep windward and gentle leeward faces, occurring in regular or irregular, continuous or broken distribution, with intervening strips or sectors of bare ground."

They subdivided such patterns into (i) continuous, parallel and straight-sided, (ii) continuous, curving and of non-uniform width and (iii) dissected crescentic types, the last apparently corresponding to the wind crescents defined in section 7.3.4.

Wind crescents are rare in the mapped areas, being restricted to the An Teallach plateau (069862) where small vegetation crescents are separated by wide stretches of bare ground, although the small turf-banked terrace features referred to in chapter 7 as "steps" (figure 9.16) represent small crescents on gentle slopes that have been modified by surficial frost-creep to produce a vegetated riser and bare tread (cf the "Vegetationsgirlanden" illustrated by Kelletat, 1970a, plates 4 and 5). The rarity of crescentic forms in the study areas probably reflects either inadequate vegetation cover (e.g. the An Teallach plateau) or complete vegetation cover (e.g. Ben Wyvis); Ball and Goodier cite 37% cover and 55% cover for features on Ronas Hill and Ward Hill, but in the study areas similar values are found only in areas with rock outcrops,on slopes covered by turf-banked

terraces or in areas of wind stripes parallel to the dominant wind.

Wind stripes, defined in section 7.3.4 as "elongate deflation scars on otherwise vegetated terrain" appear to be the equivalent of the "denuded depressions" of King (1968, 1971b) and the "Deflationsformen" of Kelletat (1970a). These are found on all of the mountains mapped, but are largely restricted to cols (e.g. 079855, map 2; 150711, map 3; 184708, map 4; 457703, map 5; 379948, map 7; 341990, map 8) or exposed spurs (e.g. 057845, map 2; 151722, map 3; 185731, map 4; 369946, map 7; 327983, map 8), those on spurs often being subject to surficial frost creep and thereby forming deflation terraces (section 9.3.5; figure 9.12). Strong winds are characteristic of both types of location, being funnelled through cols and deflected around spurs.

Although some wind stripes are regularly spaced with deflated scars similar in dimensions to those described by King (1971b), others are irregular in both size and shape (figure 10.22). The windward edge of each scar usually terminates in a small scarp 5-15 cm high (King's "turf scarps"), and the scars tend to become shallower downwind, often ending in spreads of coarse sand (King's "sand ripples"). The scars are normally floored by a gravel lag similar to that found on deflation surfaces (figure 8.26). The position of the upwind and downwind edges of two wind stripes on Meall Garbh, An Teallach, were measured annually relative to fixed markers and proved unchanged over the period June 1976 to June 1979, suggesting that these stripes are relatively stable features and that rates of vegetation accretion and erosion at this site are low.

The development of wind-patterned ground is widely attributed to "Rasenabschälung" or turf exfoliation, a term coined by Sapper (1915) to describe the destruction of vegetation cover in Iceland. As demonstrated by Kim (1967), Troll (1973) and Schunke (1975), the primary process consists of the "loosening" of surface particles by frost heave and needle ice; loose particles are then removed by wind from exposed locations. King (1971b) provided

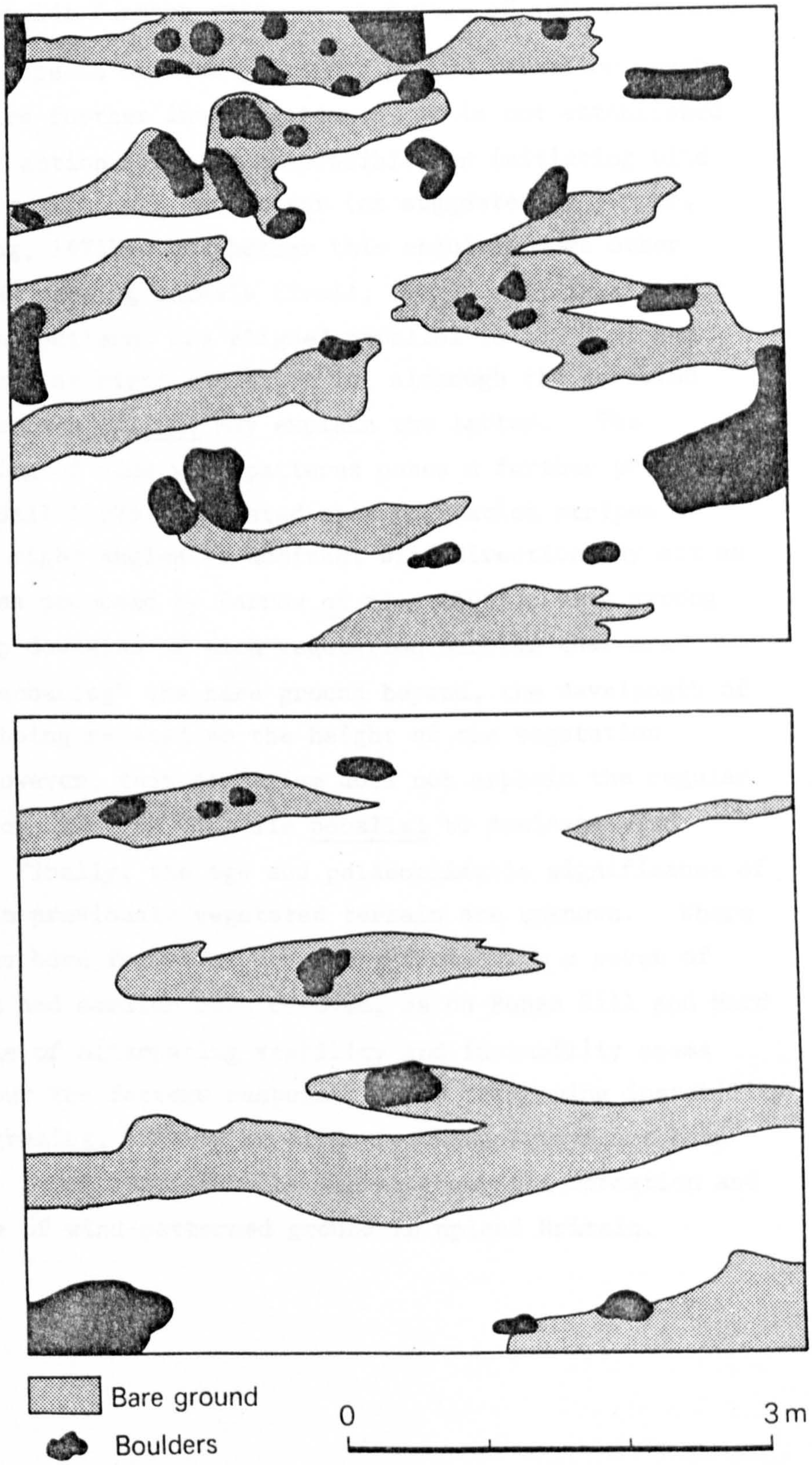


Figure 10.22: Wind stripes on Meall Garbh (top) and Glas Mheall Mor, An Teallach. Dominant winds blow from left to right in both cases.

data indicating the operation of this process on the surface of wind stripes in the Cairngorms, and the deflated appearance of wind stripes in the study areas together with observations of needle ice formations on the Meall Garbh windstripes in March 1977 provide further evidence in favour of this mechanism.

Several aspects of wind-patterned ground formation nevertheless require further investigation. It is not established whether frost action alone is responsible for initiating wind patterns by breaking the turf cover (as suggested by Sapper, 1915, and King, 1971b), or whether this requires some other agency such as grazing animals (Troll, 1973). It is also not clear why some patterns are aligned parallel to the dominant wind and others at right angles to it, although the downwind creep of prostrate Calluna may explain the latter. The regular spacing of some wind patterns poses a further problem. Goodier and Ball (1975) suggested that vegetation stripes or crescents at right angles to dominant wind direction may act as windbreaks, as proposed by Barrow et al., (1968), with strong eddies set up downwind of each vegetation barrier that are capable of "scouring" the bare ground beyond, the wavelength of the pattern being related to the height of the vegetation barrier. However, this mechanism does not explain the regular spacing of some stripes that lie parallel to dominant wind direction. Finally, the age and palaeoclimatic significance of wind scars on previously vegetated terrain are unknown. Where such features have formed on a surface from which a cover of aeolian sand had earlier been removed, as on Ronas Hill and Ward Hill, a cycle of alternating stability and instability seems indicated, but the factors responsible for triggering instability (e.g. overgrazing, burning or climatic change) have not been identified. Much remains to be learnt about the formation and significance of wind-patterned ground in upland Britain.

CHAPTER 11 WIND-BLOWN SAND

11.1 Introduction

The importance of wind as an agent of erosion on the upper slopes and plateaux of British mountains has been stressed in previous chapters (sections 2.6, 3.3.5, 5.6, 8.4.3, 9.3.5, and 10.5). Strong winds are not only responsible for exposing the regolith to frost action by impeding vegetation colonization and stripping away snow and vegetation cover, but also play a vital role in the development of turf-banked terraces, wind stripes and the extensive deflation surfaces that occupy high plateaux such as those of An Teallach (figure 8.26) and the Cairngorms. On some mountains the products of widespread deflation have accumulated in the form of sheets of aeolian sand. This chapter describes the characteristics and significance of such deposits.

Blown sand on British mountains was first described by Peach et al. (1913a, p. 112), who attributed deposits on Slioch and An Teallach to the disintegration of Torridon Sandstone, describing on the latter mountain " ... dunes comparable to those on the sea-shore". Godard (1965, pp. 167 and 631) provided a more detailed account of the "dunes périglaciaires d'altitude" on An Teallach. He concluded that as such "petites dunes" are vegetation-covered except for predominantly west-facing scarps, they represent relict features formed " ... pendant une période plus froide et plus sèche sous un climat nettement périglaciaire ..." (p. 167), and that present activity is restricted to erosion of dune margins. This view was endorsed by Sissons (1967, p. 225), who considered the An Teallach dunes to be "much larger" than those on other mountains (" ... very tiny features only a few feet high ..."). Later, however, Sissons (1976a, p. 109) abandoned the term "dune" in describing " ... sheets of sand up to several metres thick ..." on An Teallach and Quinag, and noted that " ... it is not known when the sand sheets accumulated or when their dissection began ...". An attempt was made by Ball and Goodier (1974; Goodier and Ball, 1975) to resolve these unknowns through investigation of aeolian sand deposits on Ronas Hill, Shetland and Ward Hill, Orkney.

Features that they termed "hill dunes" were found to contain buried "deep humic surface horizons" that they interpreted as evidence of "alternating cycles of stability and accumulation" (1974, p. 102). They suggested that sand deposition commenced in the early postglacial and that erosion of a previously more extensive "hill dune" cover began in the Little Ice Age, but they provided little supporting evidence.

The present chapter describes the blown sand deposits on An Teallach, the only mountain in the study areas on which such deposits occur. The morphology, distribution and stratigraphy of these deposits are described in sections 11.2 and 11.3, and measurements of present accumulation and erosion are reported in section 11.4. The age and environmental significance of the deposits are discussed in the final section (11.5).

11.2 Distribution and morphology

Lithology appears to play an important part in dictating the distribution of upland sand deposits. As noted by Sissons (1976a, p. 109), such deposits are particularly extensive on Torridon Sandstone hills (e.g. An Teallach, Sàil Mhór, Quinag, Slioch and Beinn Bhan). Those on Ward Hill are also on sandstone, and elsewhere they appear to be common only on granitic rocks such as the granophyre of Ronas Hill and the granites of Stob Ghabhar (S.W. Grampians) and the Cairngorms. Rather thin deposits of blown sand in the Rhum Cuillin are derived from weathered peridotite (map 7).

The association of sand deposits with coarse-grained plutonic rocks and sandstones probably reflects (i) the susceptibility of these rocks to granular disintegration under periglacial conditions (exposed boulders on sandstone and granite mountains are usually rounded) and (ii) the granulometry of frost-weathered products. On weathering, sandstone and granitic rocks yield predominantly sand-size detritus, with a low clay-silt content (chapter 6). Such sands are essentially cohesionless and therefore more readily entrained by wind than, for example, the relatively clay-silt-rich products of frost-weathered schists. Moreover, it is likely that the latter are more easily colonized

by vegetation (which inhibits deflation) on account of their clay content and greater moisture retention.

The form of upland sand deposits in Great Britain has been misrepresented in much of the literature on the topic. A dune, according to Bagnold (1954, p. 188) " ... may be defined as a mound or hill of sand which rises to a single summit". Features answering this description do not occur on An Teallach or on any other area of upland windblown sand known to the writer. Moreover, the "hill dunes" illustrated by Ball and Goodier (1974, photographs 7 and 8; Goodier and Ball, 1975, photographs 5 and 6) also appear to lack the morphological characteristics of true dunes. It seems likely that accounts of "dunes" on An Teallach and elsewhere refer not to true dunes but to the eroded vegetation-free scarps that border areas of vegetated sand deposits (Ballantyne, 1977). Sedimentary structures characteristic of true dunes (such as low-angle foreset beds and parallel slip faces produced by the avalanching of dry sand) were not found in sections cut in the An Teallach deposits (see below).

The sand deposits on An Teallach take the form of dissected sheets, about one metre or more in depth, that are often bounded by vegetation-free eroded scarps (figure 11.1). The surfaces of such sheets are regular or gently undulating, except where sand hummocks have developed (section 10.4), and completely vegetated with a protective cover of grasses and sedges. The most extensive deposits occur on the east-facing slopes of Coire nan Tota and Coire a'Mhuilinn, while a less extensive deposit occupies a west-facing slope above Coire Mór (061859, map 2). Small "islands" of sand occupy low cols on the plateau (e.g. 064871 and 064864) and occur on slopes of up to 29° on the N.W. flank of Glas Mheall Mór (figure 11.2). These "islands" are similar to the "Rasenzeugen" ("turf outliers") in Iceland that were illustrated by Troll (1973, photo. 2) and the "fragmentary dune remnants" described by Ball and Goodier on Ronas Hill and Ward Hill. All these authors suggested that such "islands" represent the remnants of a formerly more extensive deposit, an interpretation that seems reasonable for the An Teallach examples, which are often surrounded on all sides by scarps that are being actively eroded. On the plateau surface sand



Figure 11.1: Dissected sand sheets bounded by eroding scarps at c. 750 m altitude in Coire nan Tota, An Teallach.



Figure 11.2: Remnant "island" of sand on the slopes of Glas Mheall Mor, An Teallach, at c. 840 m altitude.

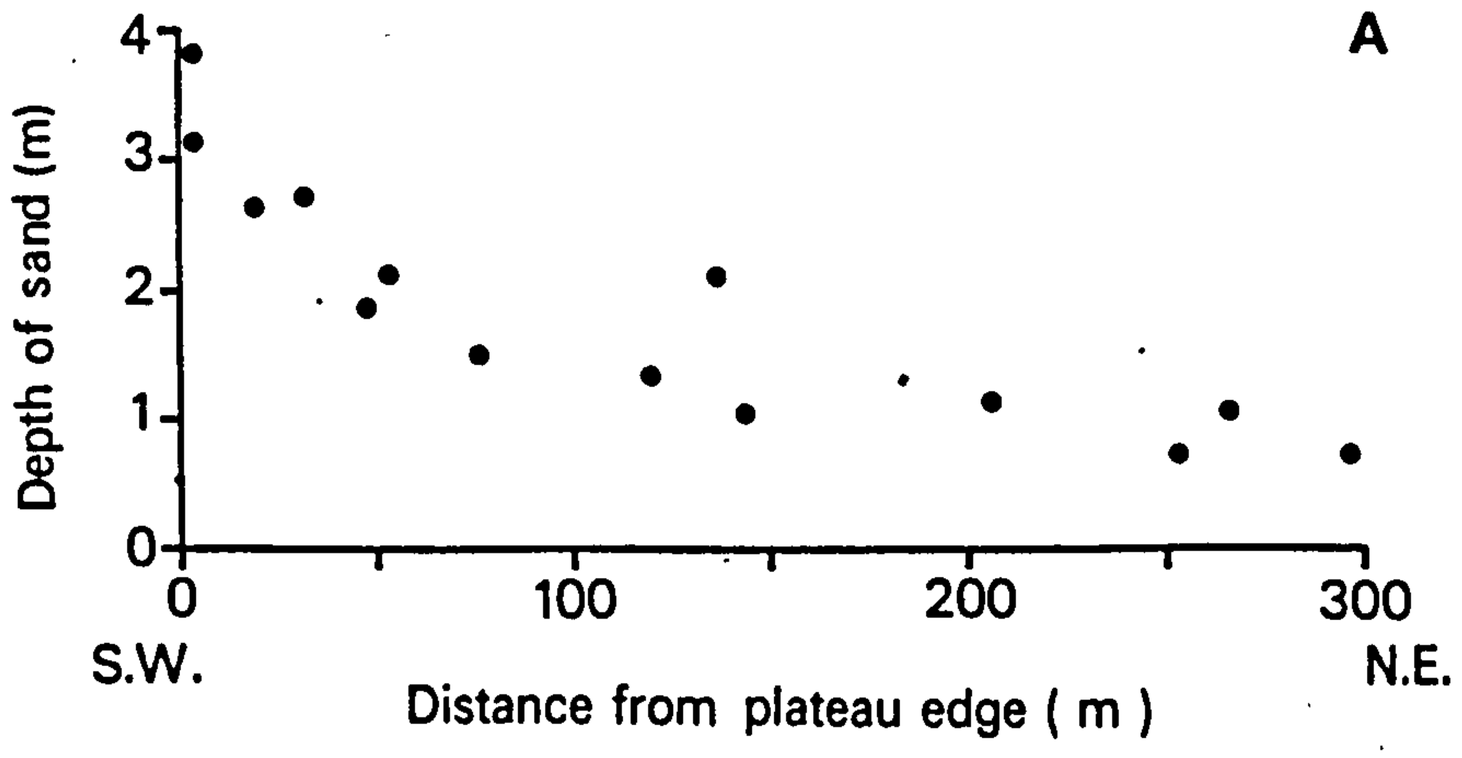
islands are restricted to areas below about 790 m; there is no evidence for former sand cover on the low hills that rise above the general level of the plateau at 062866 and 068858.

The depth of the sand exhibits interesting spatial variations. Deposits on windward slopes rarely exceed one metre in thickness and augering of three "islands" revealed maximum depths of 1.0-1.2 m. Much thicker deposits occur on the eastern margins of the deflated plateau surface at the heads of Coire nan Tota and Coire a'Mhuilinn, except in areas that lie in the lee of high points on the plateau. For example, the sands in the N.W. corner of Coire nan Tota (068870) reach depths of 2.7 m, and those in the S.W. corner (069867) reach 3.8 m. Between, however, the deposits lie in the lee of a small hill that rises c. 55 m above the general level of the plateau and do not exceed 1.4 m in depth. Similarly, deposits at the N.W. and S.W. extremities of Coire a'Mhuilinn reach just over 3.0 m in depth but those between (in the lee of a similar rise) are not more than 1.0 m deep. Augering revealed an approximately exponential decline in the depth of the thickest sand deposits with distance N.E. from the junction of the deflated plateau and the sand at the head of Coire nan Tota (figure 11.3). The significance of these patterns is discussed in the concluding section (11.5).

11.3 Stratigraphy and sedimentology

The stratigraphic and sedimentological characteristics of the An Teallach sands were examined at eight sites in Coire nan Tota and Coire a'Mhuilinn (table 11.1). At each site the bounding scarp was excavated until a vertical section from the surface of the deposit to the underlying regolith was exposed at the end of the trench. The characteristics of these sections were recorded (figures 11.4 and 11.5), along with those of sections in the walls of the trenches at sites A and H (hereafter referred to as sections A_2 and H_2). Samples were withdrawn from distinct horizons in each section for grain-size analysis.

All the sections revealed two distinct sand units. In some cases these are separated by an unconformity (sections



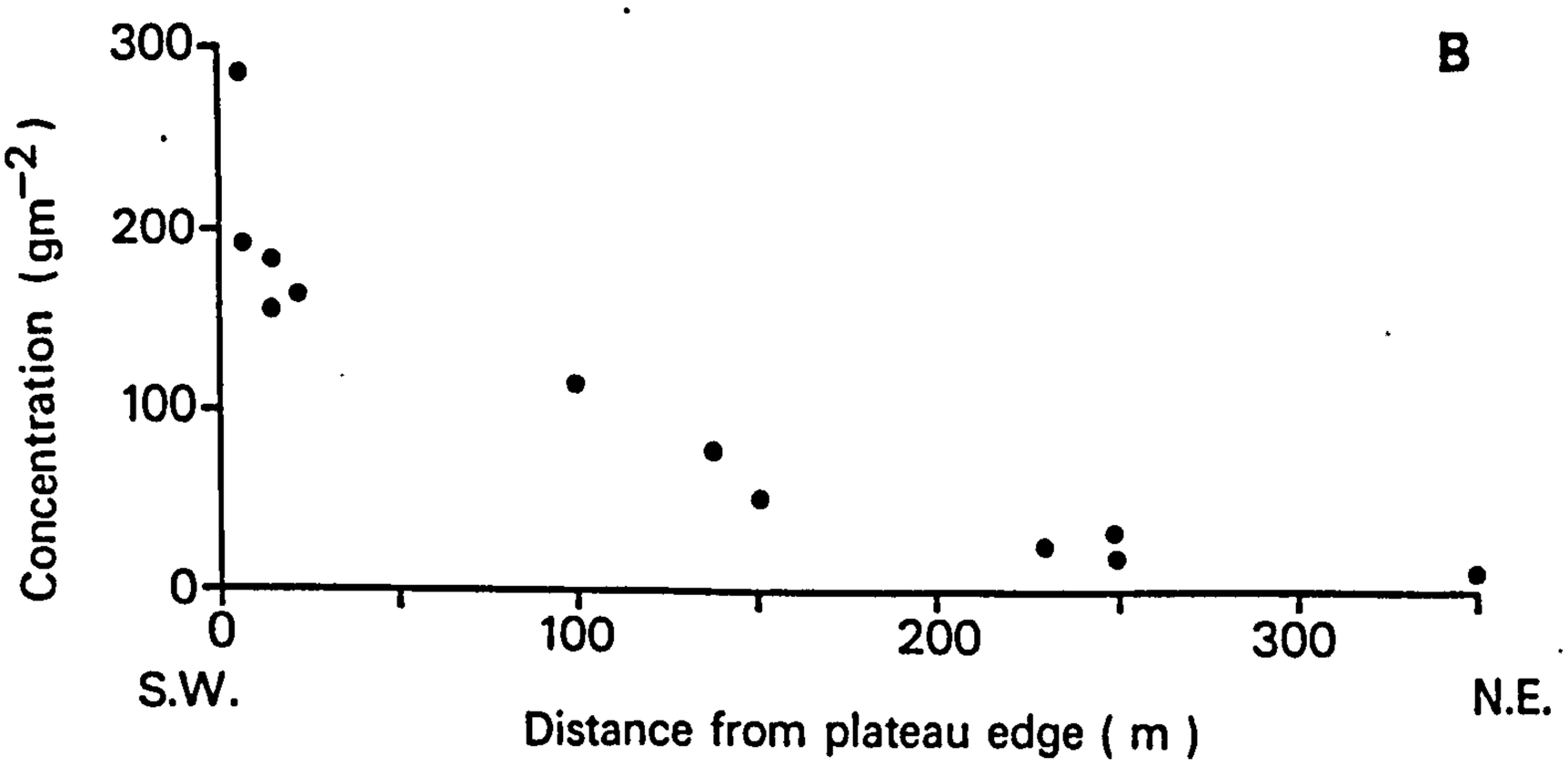


Figure 11.3: A. Decline in the thickness of blown sand deposits with distance N.E. from the edge of the plateau, Coire nan Tota, An Teallach.

B. Decline in the concentration of blown sand on snow N.E. from the edge of the plateau, Coire nan Tota, May 1977.

Table 11.1

Locations and characteristics of excavated sand sections

Site	N.G.R. (NH)	Altitude (m)	Depth (m) total	Depth (m) upper unit	Depth (m) lower unit	No. of samples total	No. of samples upper unit	No. of samples lower unit
A_1	072868	700	2.5	1.5	1.0	5	2	3
A_2	072868	700	-	-	1.0	6	3	3
B	068867	725	1.7	0.9	0.8	3	1	2
C	066866	745	3.8	1.6	2.2	5	2	3
D	067866	750	2.0	1.7	0.3	4	3	2
E	068855	790	3.0	2.0	1.0	6	2	4
F	068854	800	2.7	1.9	0.8	6	2	4
G	067853	820	2.8	2.3	0.5	6	3	3
H_1	071861	740	3.0	1.1	1.9	10	1	9
H_2	071861	740	-	-	2.2	6	0	6

Note: sections A_2 and H_2 represent the side walls of the trenches dug to expose sections A_1 and H_1.

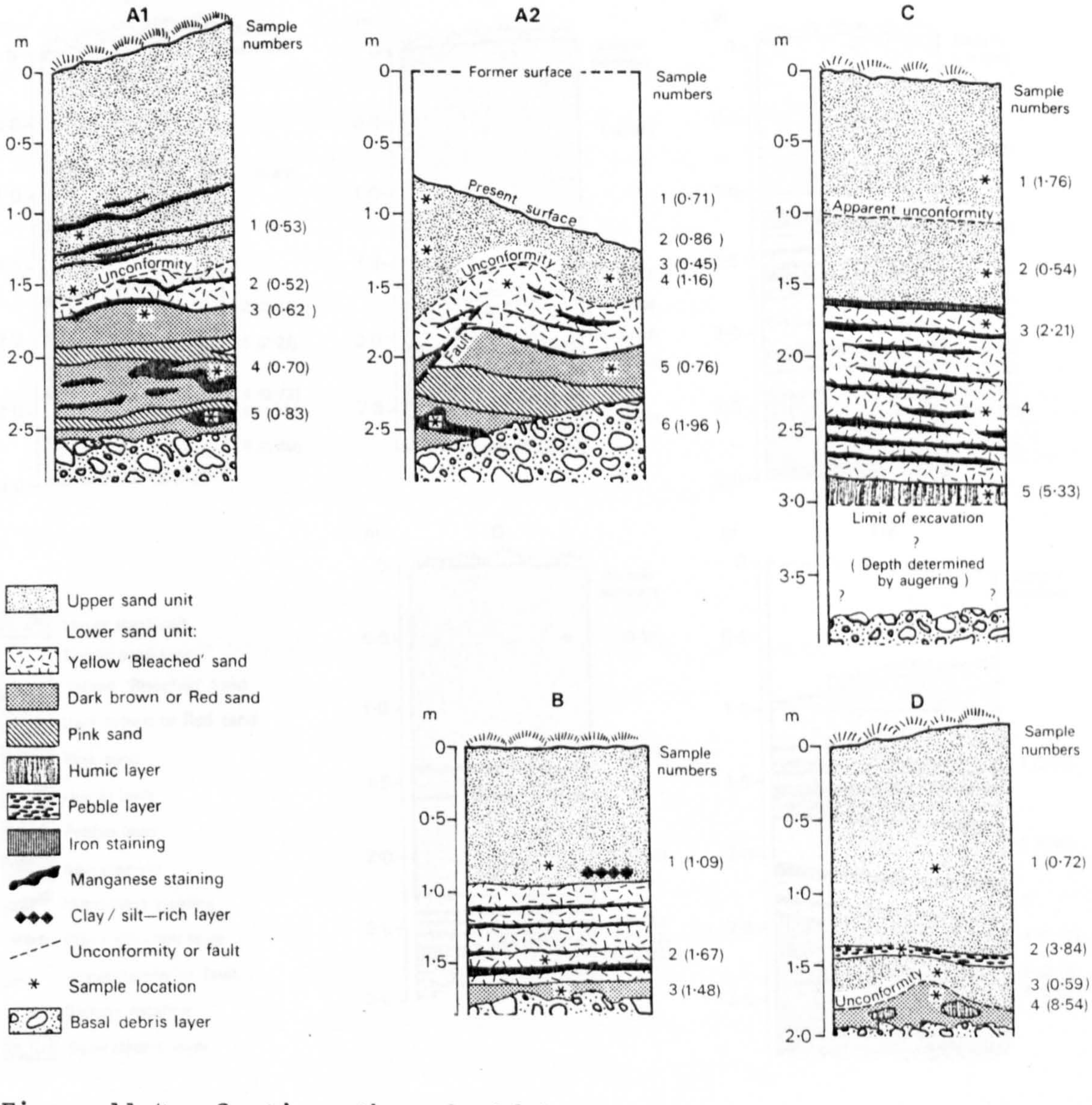


Figure 11.4: Sections through thick sand deposits in Coire nan Tota, An Teallach. Figures in brackets refer to percentage loss on ignition of samples.

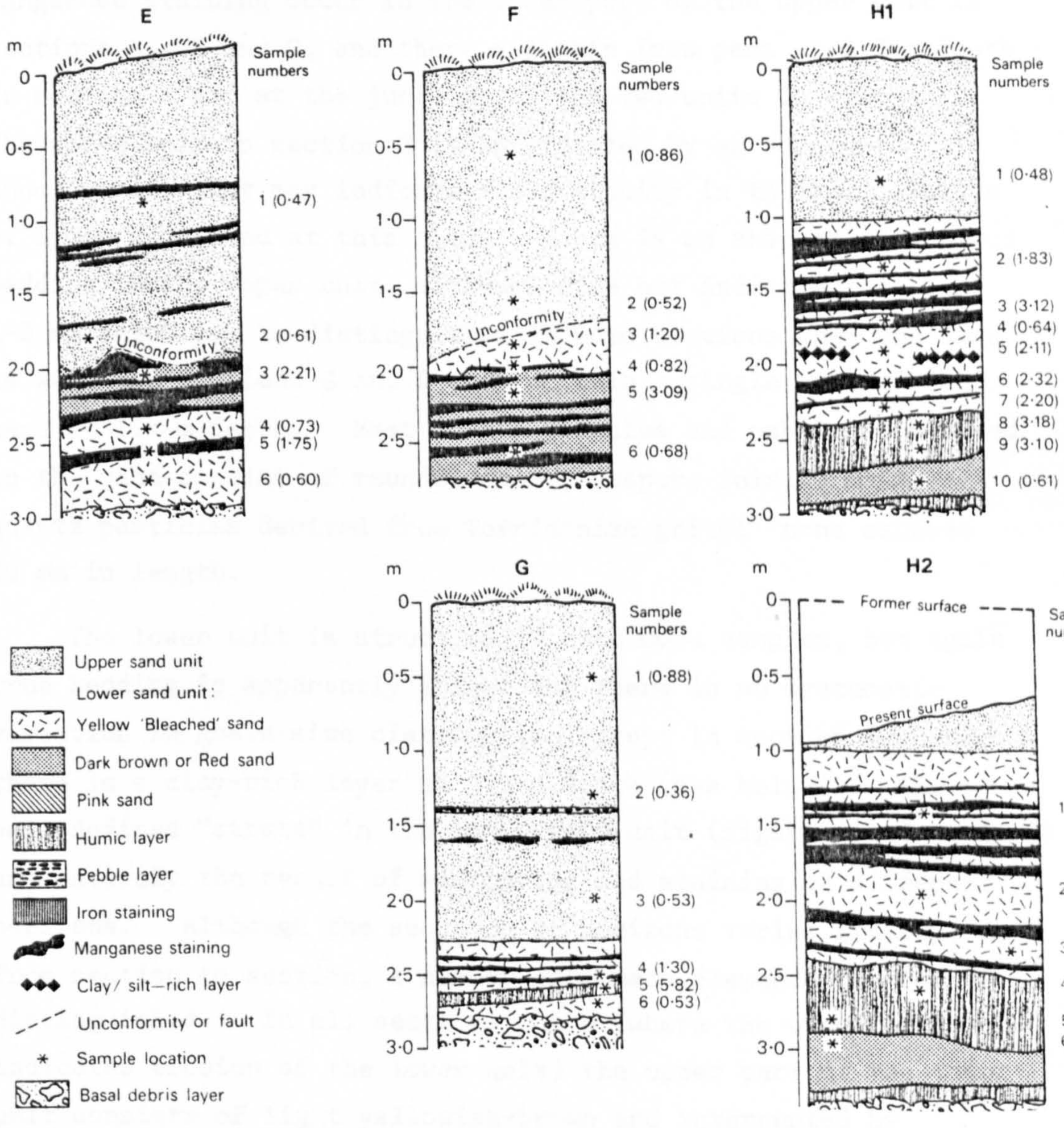


Figure 11.5: Sections through thick sand deposits in Coire a'Mhuilinn, An Teallach. Figures in brackets refer to percentage loss on ignition of samples.

A_1, A_2, D, E and F; figures 11.6 and 11.7), in others the lower unit merges with the upper (B, G, H_1, H_2; figure 11.8). The upper unit is invariably structurally simpler than the lower. It is 0.9-2.3 m thick in the excavated sections and ranges in colour from reddish-brown (typically around 4YR5/4) to brown (typically around 8YR5/4). In some sections (e.g. D and E) the colour of the upper unit varies little; more usually there is a poorly-defined banding of darker and lighter sand roughly parallel to the surface (e.g. figure 11.7). Indistinct grey bands of manganese staining occur in the lower part of the upper unit in sections A_1, E and G, and there are thin iron pans at 0.7 m depth in section E and at the junction of the two units in section C. The upper unit in section C is interrupted by an apparent unconformity that may indicate discontinuity in the accumulation of upper unit sand at this site. There is an absence of obvious bedding in the upper unit, although fine but indistinct laminae 1-3 mm thick may be distinguished in some sections when the sand is wet, and sections G and D each contain a single pebble-rich band at 1.4 m depth. Most of the granules and pebbles contained in the sand consist of rounded chert, jasper, felsite or vein-quartz particles derived from Torridonian grits; none exceeds 20 mm in length.

The lower unit is structurally much more complex, but again true bedding is apparently absent and there is no systematic variation in grain-size distribution except in section H_1, where there is a clay-rich layer at 2.0 m depth (see below). The well-defined "strata" in the lower sand unit (figures 11.6 to 11.9) are entirely the result of weathering and staining of different horizons. Although the sequence of horizons varies greatly from section to section, a number of common elements may be distinguished. In all sections but D (where the unconformity indicates erosion of the lower unit) the upper part of the lower unit consists of light yellowish-brown and interrupted by parallel bands of grey manganese staining. Although yellowish-brown sand sometimes persists to the base of the unit (section G), the lower parts of most sections consist of light or dark brown or reddish-brown sand that often alternates with bands of dark grey manganese staining. The lower layers of some sections



Figure 11.6: Sand section A_2. The unconformity separating the almost structureless upper sand unit from the more complex lower unit runs from the top right to the bottom left of the photograph. The lower unit is downfaulted parallel to the unconformity on the left of the diagram.



Figure 11.7: Sand section F, located at c. 800 m altitude at the head of Coire a'Mhuilinn, An Teallach. The section exposes 2.7 m of sand. A curved unconformity cuts the topmost (yellow) layers of the lower sand unit 0.7-1.0 m from the base of the section. Note the heavy manganese staining in the sand at the base of the pit.



Figure 11.8: Sand section B, located at 725 m altitude in Coire nan Tota. In this section the junction between the upper sand unit and the lower sand unit occurs about halfway up the section, but there is no evidence for an intervening unconformity.



Figure 11.9: Sand section H_2, located at c. 740 m altitude at the head of Coire a'Mhuilinn. The photograph depicts a depth of c. 2.2 m of lower unit sand, near the base of which are grey-green and black organic-rich horizons that apparently represent buried palaeosols that formed under waterlogged conditions. Pollen assemblages in these basal horizons suggest that they accumulated in the early Flandrian (see text).

(A_1 and A_2; figure 11.6) also contain layers of pinkish sand. In section A_2 there is a normal fault in the lower unit about 35 cm below and roughly parallel with the unconformity that separates the upper and lower units (figure 11.6).

At three sites (C, H and G) there is a distinct grey-green organic horizon near the base of the lower unit, that in section H_2 being 40 cm thick and underlain by a black organic layer 7 cm thick (figure 11.9). Loss on ignition values for these horizons and organic inclusions at the base of section D proved generally higher (3.1-10.1%) than those obtained for upper unit and non-humic lower unit sands (0.4-3.8% and 0.5-3.6% respectively; figures 11.4, 11.5 and 11.10). The pollen content of two samples from the humic horizon at site H was examined by T. Wain-Hobson. Of 300 grains counted for each sample, a high proportion consisted of inblown arboreal pollen, particularly Betula (17.6% and 20.3%) and Corylus (11.3% and 23.0%). Wain-Hobson suggested that these represent a birch-hazel woodland on lower ground comparable with those that existed at Loch Clair and Loch Sionascaig during regional pollen zone NWSIII, dated at between 8900 and 7900 B.P. (Pennington and Lishman, 1971; Pennington et al., 1972), but stressed that this interpretation must be treated with caution in view of the allochthonous nature of the arboreal grains. The high percentage of arboreal pollen in this deposit does, however, demonstrate that the sand at site H accumulated during the Flandrian.

The grain-size characteristics of the sections were investigated by sampling various levels within each unit (figures 11.4 and 11.5) and dry-sieving approximately 300 g of each sample at $\frac{1}{4}$ ϕ intervals. The results are summarized in table 11.2, and the grain-size distributions for samples taken from sections B, C and D are illustrated in figure 11.11, along with those of two samples from beach dunes in Gruinard Bay, 13 km N.W. of An Teallach. The range of grain-size distributions for all samples is illustrated in figure 11.12.

Although the sand deposits exhibit considerable overall variation in grain-size distribution, there is no systematic difference in granulometry between the upper and lower units

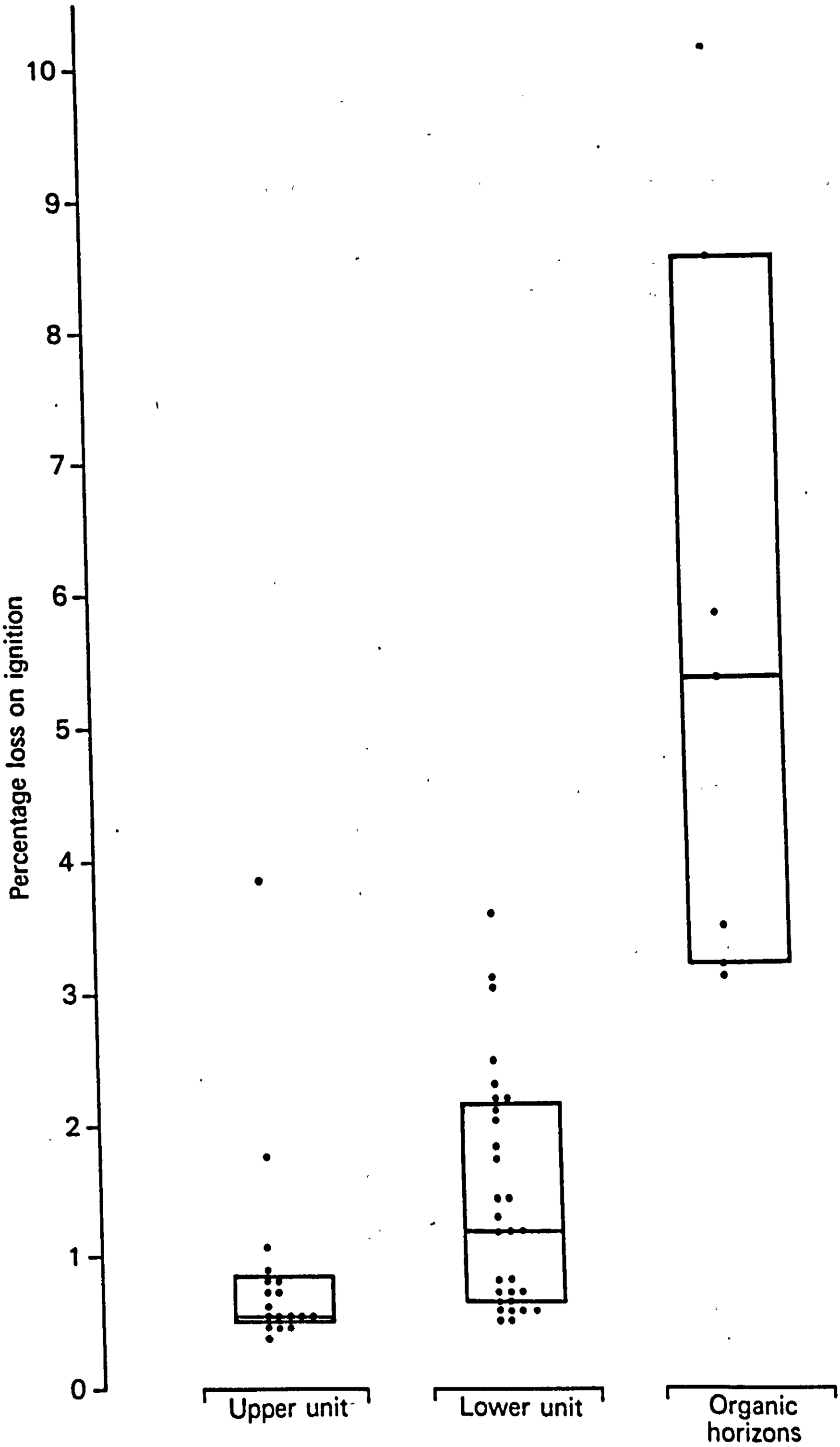


Figure 11.10: Percentage weight loss on ignition of samples from the windblown sand deposits on An Teallach. The horizontal lines represent the upper quartile, median and lower quartile values.

Table 11.2

Summary of Grain-Size Characteristics of Sand Deposits on An Teallach

(note: U = upper sand unit sample; L = lower sand unit sample)

Site	Sample	Depth (m)	Percentage by weight				
			Silt + Clay <63 µm	Fine Sand 63-212 µm	Medium Sand 212-600 µm	Coarse Sand 600-2000 µm	Gravel >2000 µm
A_1	U 1	1.1	1.1	11.9	55.2	26.8	5.0
	U 2	1.5	0.8	18.5	63.3	15.6	1.8
	L 3	1.7	1.5	15.6	59.2	23.0	0.7
	L 4	2.0	1.0	19.4	65.1	13.5	1.0
	L 5	2.4	2.2	20.5	58.2	17.4	1.7
A_2	U 1	0.9	1.0	21.5	62.2	13.6	1.7
	U 2	1.2	1.5	25.7	60.3	12.0	0.5
	U 3	1.4	1.0	13.1	64.5	20.7	0.7
	L 4	1.5	0.8	18.5	55.8	21.1	3.8
	L 5	2.0	1.2	16.3	58.4	20.0	4.1
	L 6	2.4	1.0	12.1	47.7	31.3	8.2
B	U 1	0.8	2.0	15.1	57.4	25.1	0.4
	L 2	1.5	2.7	21.4	43.1	26.7	6.1
	L 3	1.7	0.8	13.1	46.6	24.4	15.1
C	U 1	0.8	3.0	16.8	51.2	21.7	7.3
	U 2	1.4	1.2	17.6	63.8	15.8	1.6
	L 3	1.8	1.4	16.9	55.0	23.4	3.3
	L 4	2.4	0.7	12.2	47.5	29.6	10.1
	L 5	2.9	0.1	9.5	41.2	32.5	16.7
D	U 1	0.8	1.8	14.3	58.2	22.2	3.5
	U 2	1.4	3.8	23.3	53.9	15.6	3.4
	U 3	1.7	4.0	24.2	47.9	18.5	5.4
	L 4	1.8	3.2	22.6	51.0	20.8	2.4

Table 11.2 (continued)

Site	Sample	Depth (m)	<63 µm	63-212 µm	212-600 µm	600-2000 µm	>2000 µm
E	U 1	0.9	2.1	17.8	58.7	19.2	2.2
	U 2	1.9	0.8	12.8	53.9	28.5	4.0
	L 3	2.1	1.2	13.2	57.2	24.0	4.4
	L 4	2.5	3.0	15.3	53.4	23.9	4.4
	L 5	2.6	2.2	15.6	45.3	29.1	7.8
	L 6	2.8	2.0	13.9	49.6	26.6	7.9
F	U 1	0.6	1.8	19.5	54.1	18.8	5.8
	U 2	1.6	0.8	19.4	55.0	21.8	3.0
	L 3	1.9	4.9	17.3	49.0	25.0	3.8
	L 4	2.0	2.4	17.8	50.3	26.9	2.6
	L 5	2.2	0.7	8.5	45.0	38.0	7.8
	L 6	2.6	1.5	13.1	49.6	28.1	7.7
G	U 1	0.5	2.6	14.0	45.3	32.5	5.6
	U 2	1.3	2.6	19.2	46.1	22.8	9.3
	U 3	1.8	0.8	13.6	56.9	25.1	3.6
	L 4	2.0	1.5	18.0	50.6	25.6	4.3
	L 5	2.2	3.0	18.6	41.0	30.5	6.9
	L 6	2.6	1.5	12.8	49.5	28.6	7.6
H_1	U 1	0.8	1.3	10.2	61.9	23.1	3.5
	L 2	1.4	1.3	16.7	60.0	18.7	3.3
	L 3	1.7	2.0	24.9	55.5	16.4	1.2
	L 4	1.8	2.2	12.1	62.7	22.6	0.4
	L 5	2.0	8.1	15.0	51.6	24.1	1.2
	L 6	2.2	2.0	18.4	56.5	19.7	3.4
	L 7	2.4	2.2	11.9	66.7	18.5	0.7
	L 8	2.5	1.5	19.2	53.7	21.1	4.5
	L 9	2.6	2.4	18.8	53.1	21.8	3.9
	L 10	2.8	2.7	17.7	54.0	22.9	2.7
H_2	L 1	1.5	1.8	19.5	54.1	18.8	5.8
	L 2	2.0	3.0	16.2	53.5	23.6	3.7
	L 3	2.4	1.5	7.0	44.7	33.7	13.1
	L 4	2.6	1.3	11.8	48.6	34.7	3.6
	L 5	2.8	0.4	5.8	39.0	43.8	11.0
	L 6	3.0	1.8	20.9	53.7	19.7	3.9

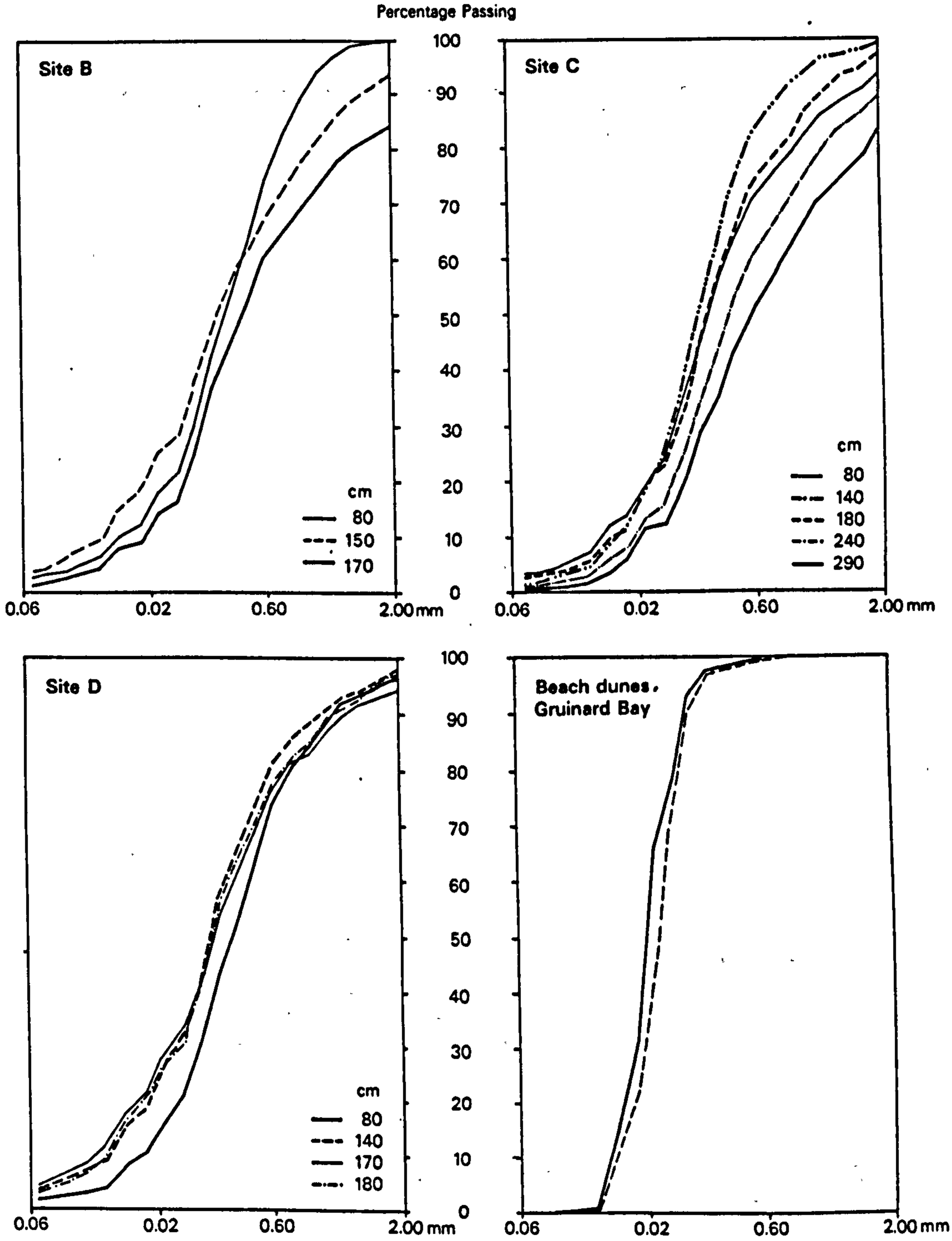


Figure 11.11: Grain-size distributions for samples taken at various depths from three sections cut in the An Teallach sand deposits and for two samples from beach dunes at Gruinard Bay, 13 km N.W. of An Teallach.

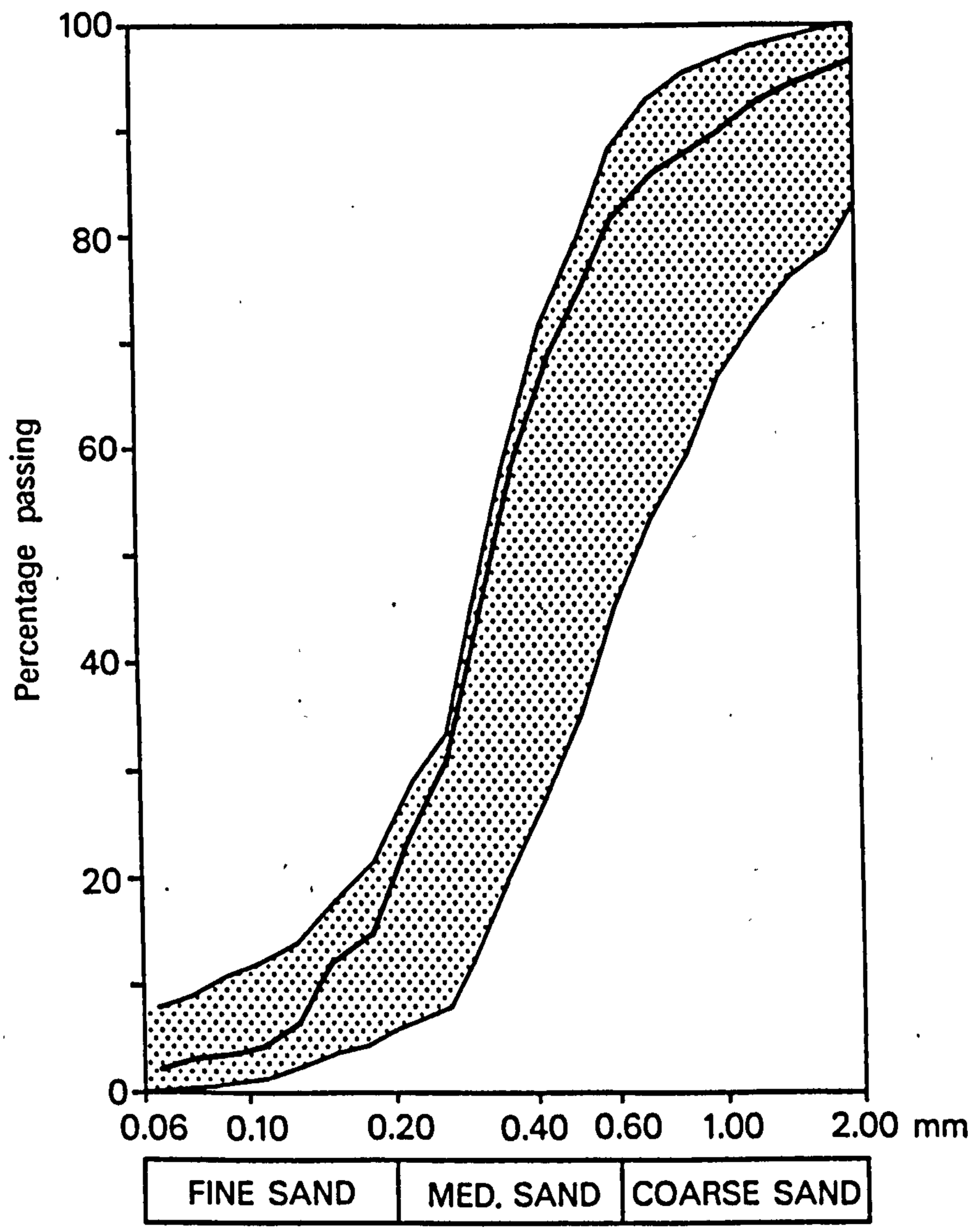


Figure 11.12: Grain-size distribution envelope (stippled) defining the grain-size limits of 57 samples of blown sand from An Teallach. The line within the stippled area represents the grain-size distribution of a sample of sand on snowcover, collected in Coire nan Tota on 26 May, 1977.

(table 11.2; figure 11.11), and in some sections (e.g. D, figure 11.11) grain-size distribution remains virtually unchanged with depth. Much of the variation evident in figure 11.12 reflects extreme values at the tails of the distributions for a small number of samples. For example, only two of the 57 samples (3.5%) contained more than 4% by weight of material finer than 63μm, the extreme value of 8.9% being obtained from a clay-rich horizon (sample H_1 5). Similarly, only five samples (8.8%) contained more than 10% by weight of material coarser than 2000μm. Medium sand (212-600μm) formed the dominant fraction in all samples but one (sample H_2 5): 39 samples (68.4%) contained more than 50% by weight medium sand and 52 samples (91.2%) comprised more than 45% medium sand.

In comparison with aeolian sands in desert and littoral environments, those of An Teallach are poorly sorted. On average, 93.5% by weight falls within the size range 63-2000μm, a range of 5 ϕ units. In contrast, over 95% by weight of the Gruinard Bay dune samples falls within a range of only $1\frac{1}{4}$ ϕ (150-355μm; figure 11.11), although this high degree of sorting may in part reflect derivation from previously-sorted beach sand. Briggs (1977, p. 77) illustrated a "typical" grain-size distribution for aeolian sand in which 95% by weight is contained within a range of 3 ϕ (approximately 100-850μm). One reason for the relatively poor sorting of the deposits is the presence of particles larger than those associated with windblown sands in other environments. For example, Bagnold (1954, pp. 120-1) provided grain-size distributions for "typical regular desert sands" in which the maximum grain size is 2 mm or less, yet all the An Teallach samples contained particles exceeding 2 mm in diameter (table 11.2). Some samples contained particles over 10 mm in width, the maximum measured width being 13 mm. As both the fluid and impact thresholds for grain entrainment increase nonlinearly with wind velocity for particles with diameters in excess of 50-60μm (Bagnold, 1954, p. 88; Warren, 1979, p. 327) the presence of particles over 10 mm in width in the An Teallach deposits indicates transport by very strong winds. The pebble-rich bands in sections G and D may represent deposition in the course

of a single storm with very high winds. The size distribution of gravel lag material on deflation surfaces (figure 8.28) suggests that most particles under 6-8 mm in width have been removed by wind.

Finally, it is notable that the medium sand fraction, which in most aeolian deposits consists of very well-rounded grains (Briggs, 1977), comprises dominantly subrounded or even subangular particles. Rounding of aeolian sand grains results from attrition during transport; the lack of rounding of grains in the An Teallach deposits suggests short transport distances and therefore local derivation.

11.4 Present activity

Godard (1965, p. 167) considered that erosion of the unvegetated scarps that border the sand deposits on An Teallach represents the dominant form of present activity, a view echoed by Ball and Goodier (1974; Goodier and Ball, 1975) in their accounts of upland blown sand in the Northern Isles. The severe dissection of such deposits (figures 11.1 and 11.2) certainly gives the impression of current erosion. However, Ball and Goodier (1974) also noted that the outline of a deposit that they examined on Ronas Hill in 1970-1 remained "distinguishable in detail" from that on 1948 aerial photographs. Similarly, comparison of 1948 and 1961 aerial photographs of sand deposits in Coire nan Tota and field observations of the same area in 1976-7 indicated that retreat of the sand margins during the intervening years had been negligible; the current rate of erosion of sand scarps is apparently slower than their heavily dissected appearance suggests.

Rates of scarp retreat in Coire nan Tota were assessed over the period 1 August 1976 to 5 June 1978. Pairs of erosion pins 30 cm long were inserted normal to the scarp faces at six sites on the former date and the "annual" rate of retreat at these sites was assessed by measuring the lengths of pins exposed on 17 July 1977. On the same date a further eleven pins were inserted in five scarps at the head of Coire a'Mhuilinn and on

the plateau. Exposure of pins at all sites was measured or re-measured on 5 June 1978. The results (figure 11.13) indicate fairly low rates of scarp retreat, with median rates of 2.4 cm y^{-1} for 1976-7 and 3.0 cm y^{-1} for 1977-8. There was no apparent correspondence between individual measurements and aspect or exposure: relatively sheltered scarps in Coire nan Tota actually retreated more rapidly than those bordering an exposed sand "island" on the plateau. More frequent measurements at three sites in Coire nan Tota suggested that retreat is generally more rapid in summer (figure 11.14). In part this may reflect protection of scarps under snowbanks during winter, but the frequency of hoof-marks at the base of sand scarps in summer supports Godard's (1965) suggestion that sheep sheltering behind and rubbing against the scarp during the summer dislodge sand that is subsequently washed away. In the absence of winter snowcover, needle ice probably also dislodges sand from the scarps (Troll, 1973), as does refreezing of snow and washing by nival meltwater (chapter 12) and rainsplash, the last-mentioned evident through pock-marks on the sand surface following heavy rain. Excavation of sand scarps by these agents eventually results in the formation of overhangs of vegetation and roots that periodically collapse, sometimes stabilizing the sand margin.

Current accumulation of blown sand in Coire nan Tota is manifest in the form of a layer of surface sand on snowcover in May and June. This sand cover represents cumulative deposition over the period during which there has been uninterrupted snow-cover. At sites of late snow-lie where snowcover is continuous throughout the winter it effectively represents total winter accumulation (i.e. over a period of approximately six months, December to May inclusive; figure 5.12), so that sampling of surface sand concentrations at such sites offers a means of assessing present rates of winter sand accumulation in this area.

On 26 May 1977, one square metre of sand-covered surface snow was collected at each of twelve snowpatches in Coire nan Tota, and the distance of each sampling site N.E. from the edge of the plateau deflation surface was measured by tape. On the same date two further samples were taken from a west-facing slope

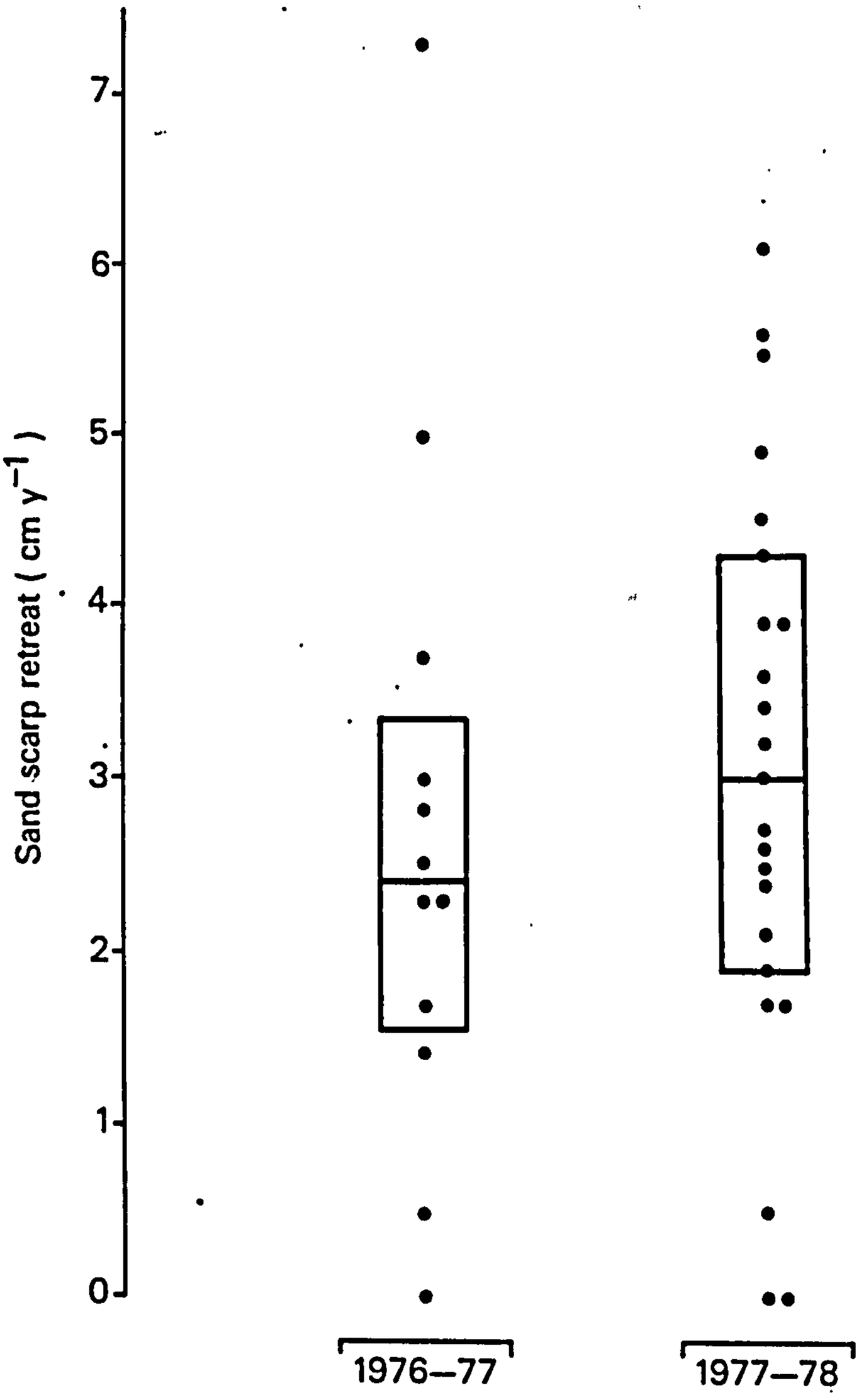


Figure 11.13: Measured amounts of sand scarp retreat, 010876 to 170777 and 170777 to 050678. The boxes define the median value (central horizontal line) and the upper and lower quartiles.

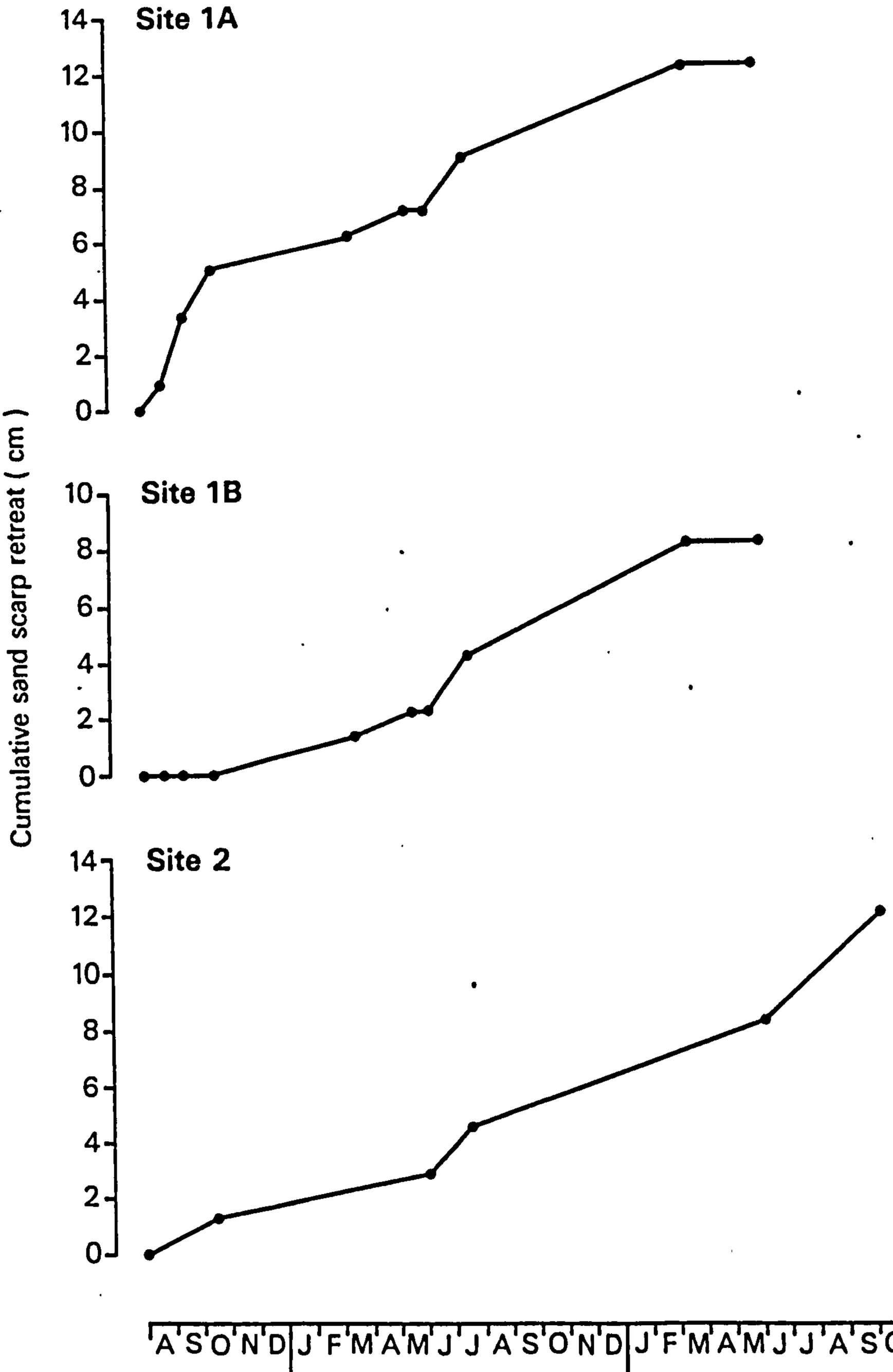


Figure 11.14: Measurements of cumulative sand scarp retreat at three sites in Coire nan Tota, April 1976 - October 1978.

on the other side of the plateau, and exactly one month later two additional samples were collected from lee slopes on Ben Wyvis. Each sample of melted snow and sand was filtered in the laboratory and the weights of the samples were determined after the filter papers and organic material had been burnt off in an oven at 600°C. The results are given in table 11.3.

Three points emerge from these data. First, as might be expected, present aeolian deposition on lee slopes on Ben Wyvis is negligible, presumably because the vegetation cover on the Wyvis plateau inhibits entrainment of fines by wind. Secondly, concentrations are much higher on the east-facing lee slopes of An Teallach than on the windward slopes. This indicates that the plateau rather than any area west of the mountain (such as Coire Mór) is the source area for the sand. Finally, sand concentrations in Coire nan Tota decline with distance N.E. from the edge of the plateau (figure 11.3, diagram B). As with the depth of sand deposits in Coire nan Tota (figure 11.3, diagram A), this decline is exponential.

Regression of the natural logarithm of sand concentration ($\log_e C_a$) against distance in metres N.E. from the edge of the plateau (D') yields

$$\log_e C_a = 5.30 - 0.0083\ D' \qquad (11.1)$$

or, taking the antilog of both sides,

$$C_a = 199\ e^{-0.0083\ D'} \qquad (11.1a)$$

Mean concentration of sand cover ($\overline{C_a}$) within a given distance (D) N.E. from the edge of the plateau is given by

$$\overline{C_a} = \frac{199}{D} \int_0^D e^{-0.0083\ D}\ dD, \qquad (11.2)$$

which integrates to give

$$\overline{C_a} = \frac{199}{0.0083\ D}\left[1 - e^{-0.0083\ D}\right] \qquad (11.2a)$$

Table 11.3

Concentrations of windblown sand on snowcover (g m^{-2})

1. Samples taken from Coire nan Tota, An Teallach, 26 May 1977 (figures in brackets represent distance N.E. from summit plateau in metres).

1.	288.2	(10)
2.	187.2	(10)
3.	178.6	(15)
4.	148.8	(15)
5.	158.7	(20)
6.	113.2	(100)
7.	71.8	(140)
8.	49.1	(150)
9.	25.3	(230)
10.	25.8	(250)
11.	24.8	(250)
12.	11.2	(350)

2. Samples taken from a west-facing slope at similar altitudes.

1.	4.2
2.	2.6

3. Samples taken from lee slopes on Ben Wyvis, 26 June 1977.

1.	1.1
2.	0.8

In 1977, sand cover on snow extended for about 400 m N.E. of the edge of the plateau. Setting D at 400 m yields a mean concentration of surface sand of 57.8 g m^{-2} for Coire nan Tota for that year. The area of appreciable supranival sand cover in Coire nan Tota in 1977 was mapped and calculated to be approximately 161,700 m^2 in extent. The total mass of sand blown on to snow, given a mean concentration of 57.8 g m^{-2}, is 9346 kg, almost ten metric tonnes. Although this figure must be considered a crude estimate in view of the small number of samples used in deriving mean concentration, it indicates that very considerable quantities of sand are presently being stripped from the plateau and deposited on lee slopes. Such quantities of sand are much greater than could be provided by erosion of the margins of the few small sand "islands" that occur upwind of Coire nan Tota and presumably represent deflation of the products of current microgelivation on the plateau surface. As freezing at 800 m is rare during the summer months (chapter 5) it seems likely that the summer contribution of blown sand is small, particularly as strong winds are less frequent in summer.

This in turn suggests that most windblown sand accumulates on snow, so that the An Teallach sands represent niveo-aeolian rather than aeolian deposits. Significantly, the grain-size distribution of a sample of supranival sand (sample 1 from Coire nan Tota) falls entirely within the envelope defined by the distributions of samples from the sand deposits (figure 11.12). In niveo-aeolian deposits fine particles transported by moderately strong winds become mixed with coarser material carried by very strong winds as the snow downmelts. Also, small saltating grains may be trapped in soft snow after short travel distances whilst large grains comprising the traction load may travel considerable distances on icy surfaces, so that diminution of grain-size downwind of the source is not evident. These considerations explain both the relatively poor sorting and absence of systematic grain-size variations in the An Teallach sands.

11.5 Discussion

The following points have been established.

1. The sand deposits of An Teallach are of essentially niveo-aeolian origin. They are derived locally through granular disintegration of Torridon Sandstone as a result of frost weathering.

2. Considerable quantities of sand are transported from the plateau by wind under present conditions. These are deposited on snow on east-facing slopes and to a much lesser extent on west-facing slopes.

3. Pollen taken from organic sand near the base of one section indicates that nearly 3.0 m of sand have accumulated at this site during the Flandrian, probably since the Early Flandrian. There is no reason to suppose that the entire deposit did not accumulate during the Flandrian.

4. Unvegetated sand scarps at the margins of sand deposits are retreating at rates averaging a few centimetres per year. Isolated "islands" of sand on the plateau probably represent eroded remnants of a formerly more extensive cover, although there is no evidence for former cover on upstanding parts of the plateau.

5. The thickness of sand in such "islands", on west-facing slopes and on east-facing slopes in the lee of upstanding parts of the plateau surface is generally 1.0-1.4 m. Much deeper deposits (up to 3.8 m) occur on lee slopes downwind (east and N.E.) of the "cols" or lower parts of the plateau surface.

6. Such thicker deposits consist of two distinct units, granulometrically similar but of different colour and structural complexity. These units are sometimes separated by an unconformity.

These findings indicate that during the Flandrian the predominantly sand-size products of ~~microgelivation~~ granular disintegration on the higher and more exposed parts of the plateau have been blown by high winds to more sheltered locations where they have accumulated to form the deposits described above. In view of the present efficiency of wash in eroding exposed areas of sand (chapter 12), it seems likely that, as at present, the sand accumulated through being trapped by vegetation cover on to which it was deposited by melting snow. The vegetation presumably grew upwards through the accumulating sand, thereby stabilizing the deposit. This is indicated by the presence of roots and root casts at all levels in the excavated sections. Godard (1965, p. 167) implied that the deposits had at one time been unvegetated, but it is difficult to envisage the survival of unprotected sand on slopes swept by heavy rainfall, and supporting evidence for this view (e.g. dunes or washed horizons) is lacking.

Three characteristics of the An Teallach sands remain to be accounted for. First, no interpretation has been given to the existence of two distinct units in the sections excavated in thick sand. Secondly, the circumstances under which the plateau deposits now represented by remnant "islands" were eroded require explanation. Finally the restriction of thicker (>1.4 m) deposits to areas downwind of low cols has not been explained.

The main difference between the upper and lower sand units is that the lower unit shows signs of more prolonged weathering than the upper. The pale yellow colour of the upper part of the lower unit probably reflects the leaching out of more mobile constituents, such as iron and manganese. The dark grey and reddish bands in the lower parts of this unit represent accumulations of these constituents at levels probably related to fluctuating water tables (which must have risen intermittently as the deposit accumulated), although the organic horizons at the base of some sections apparently represent true buried soils, gleys that formed under waterlogged conditions (R.V. Ruhe, personal communication). In contrast, the upper sand unit is practically unweathered, containing only faint manganese bands

and sometimes a single iron pan. Such differences in weathering strongly suggest that the upper unit accumulated much more recently than the lower. The lower loss on ignition values obtained for the upper unit (median = 0.55%; figure 11.10) compared with the lower (median = 1.20%) suggest that the upper unit may also have accumulated much more rapidly, thereby incorporating less organic material. The presence of an unconformity between the two units at four of the seven excavated sites indicates that accumulation of the two units at these sites was not continuous but separated by a period during which the lower unit was eroded (figures 11.6 and 11.7).

The above evidence suggests the following sequence of development for the thicker sand deposits.

1. Development of plant cover, with formation of gley soils on debris surfaces at some sites (? Early Flandrian).

2. Relatively slow accumulation of 0.5-2.0 m of niveo-aeolian sand stabilized by vegetation cover.

3. A period during which some areas of sand were eroded, although in other areas accumulation may have continued.

4. A sudden change to fairly rapid accumulation of sand at all sites. The lack of weathering in the upper horizon suggests that this change occurred relatively recently. Accumulation continues at present but is to some extent balanced by erosion of sand from the margins of the deposits.

The sudden change in rate of accumulation or from erosion to accretion that marks the onset of stage 4 implies a sudden increase in the rate of sand supply. This may have resulted from climatic changes (e.g. increased frost weathering or stronger westerly winds), but the abruptness of the change suggests some other cause. One strong possibility is that the sudden increase in rate of sand accumulation on east-facing slopes downwind of the lower parts of the plateau coincided with the onset of erosion of niveo-aeolian deposits on these cols, deposits

now represented by the remnant "islands" described earlier. This explanation has the attraction of accounting not only for the sudden rapid increase in rate of deposition represented by the upper sand unit but also the restriction of thick sand deposits to areas downwind of cols that at one time apparently contained much more extensive deposits of sand than occur at present. This interpretation of the evidence was subsequently tested by excavating two sections in the thinner deposits in Coire nan Tota that lie in the lee (i.e. directly N.E.) of the 817 m hill at 062866. In both sections the deposit consisted almost entirely of lower unit sand, with only 15-25 cm of overlying upper unit sand (figure 11.15). This suggests that this area, which is not directly downwind of the cols from which pre-existing deposits were stripped, received little of the reworked sand. This is consistent with the explanation of the origin of the upper sand unit offered above.

The final unresolved question concerns the nature and date of the environmental change responsible for initiating rapid erosion of the col deposits. Ball and Goodier (1974) suggested that erosion of the sand cover on Ronas Hill may have resulted from climatic deterioration during the Little Ice Age. This suggestion is attractive in view of the freshness of the upper unit sands but is not entirely convincing in view of the relatively small differences between the climate of the Little Ice Age and that during earlier periods of Flandrian climatic deterioration, such as the beginning of the Sub-Atlantic period (section 2.5). A more credible possibility is that rapid erosion resulted from the introduction of hill sheep to the mountain in the 19th century. The grasses and sedges that grow on sand deposits constitute by far the richest grazing on the mountain and attract large numbers of sheep at present. Over-grazing of the vegetation protecting the col deposits may well have opened up the previously closed cover, exposing the col sands to deflation, which would have been accelerated by the destruction of sand scarps by sheltering sheep as described earlier.

In summary, the available evidence suggests that the An Teallach sand deposits developed in the following manner.



Figure 11.15: Section cut in a sand deposit that lies downwind of a rise in the plateau surface. Unlike sections cut in thicker deposits that occur downwind of cols, this section is composed largely of lower-unit sand.

1. Development of vegetation cover on slopes bordering the plateau and on lower parts of the plateau. Formation of gley soils in waterlogged sites. Probably Early Flandrian.

2. Slow accumulation of niveo-aeolian sand derived from the higher parts of the plateau and trapped by vegetation.

3. Localized erosion.

4. Rapid, relatively recent erosion of sands on exposed cols following deterioration of protective vegetation cover as a result either of climatic deterioration or the introduction of sheep. Concomitant accretion of reworked sand downwind of the areas of erosion.

At present, supplies of sand from the eroding margins of existing deposits on the plateau are virtually exhausted. Accumulation is maintained by aeolian transport of the products of frost weathering on the plateau but to some extent offset by slow erosion of the margins of deposits on lee slopes.

CHAPTER 12 THE ACTION OF SNOW AND RUNNING WATER

12.1 Introduction

Recent years have witnessed a reappraisal of the effectiveness of snow as a geomorphological agent in periglacial environments. Nivation, a term coined by Matthes (1900) to describe erosion associated with perennial and late-lying snowpatches, is not a single process but

> " ... a collective term used to designate all aspects of weathering or transport which are accelerated or intensified by the presence of late-lying snow" (Thorn, 1979a, p. 41).

Traditionally, nivation has been considered to comprise the following elements.

(i) Intensive freeze-thaw activity (such as frost shattering and frost creep) either at snowpatch margins, where freeze-thaw cycles are supposedly frequent and moisture abundant (e.g. Matthes, 1900; Hobbs, 1911; Ekblaw, 1918; Gardner, 1969c; Embleton and King, 1975, pp. 130-3), or in "randkluft" crevasses at the rear of snowpatches (e.g. Botch, 1946; Demek, 1968) or even at the base of the snow (e.g. Lewis, 1936; McCabe, 1939; Boyé, 1952; Dineley, 1954).

(ii) Accelerated chemical weathering (e.g. Boyé, 1952; Botch, 1946; Sim, 1962), reflecting moisture availability and possibly increased partial pressures of carbon dioxide (Williams, 1949).

(iii) Slopewash in the form of sheetflow or rillwash, reflecting the rapid release of nival meltwater in spring (e.g. Matthes, 1900; Lewis, 1936, 1939; McCabe, 1939; Rockie, 1951; Nichols, 1963; Dineley, 1954; Demek, 1968; St-Onge, 1969).

(iv) Accelerated solifluction, the result of ground saturation downslope of melting snow (e.g. Ekblaw, 1918; Lewis, 1936; Botch, 1946; Paterson, 1951; Rockie, 1951; Boyé, 1952; Williams, 1957; Cook and Raiche, 1962b; Demek, 1968).

(v) Snowcreep, the erosion of the ground surface and transport of debris by slowly-moving snow (e.g. Lewis, 1925; Rempp and Rothé, 1934; Imamura and Hirabayasi, 1935; Dyson, 1937, 1938; Haefeli, 1953; Costin et al., 1964).

A combination of some or all of these processes has been considered to be at least partly responsible for the development of features ranging in size from miniature hollows (Nichols, 1963) to hollows and benches a few tens of metres in length and width (e.g. Russell, 1933; Lewis, 1939; McCabe, 1939; Dineley, 1954; Henderson, 1956; Cook and Raiche, 1962b; St-Onge, 1969) to cryoplanation terraces hundreds of metres in extent (e.g. Eakin, 1916; Waters, 1962; Czudek, 1964; Demek, 1968, 1969; St-Onge, 1969; Reger and Péwé, 1976). It has also been suggested that nivation may form or at least initiate cirque-like features (e.g. Wright, 1914; Ahlmann, 1919; Russell, 1933; Groom, 1959; Watson, 1966) that may be the precursors of true glacial cirques.

Recently, however, measurements of process rates associated with perennial and late-lying snowpatches have led to a reassessment of the effectiveness of nivation activity. Detailed observations in the Colorado Front Range led Thorn (1976, 1979a, b) to conclude that there was no evidence for an increase in the intensity of mechanical weathering around or under snowpatches as moisture-rich sites tended to be insulated from freeze-thaw cycles whilst sites experiencing frequent cycles often lacked moisture. From an increase in the thicknesses of weathering rinds inside the zone covered by late-lying snow the same author inferred that such environments favour chemical weathering (Thorn, 1975, 1976), and measurements of solute concentrations in nival meltwaters led Thorn and Hall (1980) to the somewhat ambiguous conclusion that their results " ... produce a unified picture of rapid solution but of moderate intensity" (p. 119). Similar measurements made on carbonate terrains in the Canadian arctic have, however, indicated that solute concentrations are relatively low in nival meltwaters (Smith, 1969, 1972; McCann and Cogley, 1971; Cogley, 1972).

The importance of rillwash in transporting fine material during snowmelt is more certain. Thorn (1976, 1979a) demonstrated

that wash rates may be 20-30 times greater downslope of a melting snowpatch than on adjacent terrain, and concluded that

> " ... sheetwash and rivulet flow, subsequent to meltout, are the dominant processes in the transport of material by nivation" (1976, p. 1174).

The effectiveness of rillwash downslope of snowpatches in arctic areas was demonstrated by Wilkinson and Bunting (1975); on permafrost terrain this process is intensified by throughflow waters brought to the surface at snowpatches (Ballantyne, 1978). Rudberg (1970), however, found that the amount of material transported in this manner is sometimes small, and proposed that the principal geomorphological role of nival meltwater is the promotion of solifluction through ground saturation (Rudberg, 1974). The relative importance of wash vis à vis solifluction in association with melting snowpatches may reflect the granulometry of the regolith, as suggested by St-Onge (1969), and is certainly influenced by vegetation cover (over which rillwash is negligible) and distance from melting snow, as nival meltwater sometimes percolates into the regolith a short distance downslope of snowpatches (Thorn and Hall, 1980). It has been demonstrated that creeping snow may exert large shear stresses on objects (Costin et al., 1973) and transport clasts over distances of a few centimetres to a few metres in a single year (Jennings and Costin, 1978), but snowcreep transport appears to be confined to clasts overlying bare rock surfaces (Thorn, 1976).

The geomorphological role of running water in periglacial environments has also been subject to reappraisal. Until recently, the view persisted that the limited runoff season in most arctic and alpine areas precluded effective fluvial activity (e.g. Peltier, 1950). However, even arid arctic landscapes are dissected by deep gorges and crossed by wide, seasonally active sandar (Jenness, 1952; Robitaille, 1960; Rudberg, 1963, 1969), and measurements of sediment transport have shown that periglacial streams often carry loads exceeding those of rivers in lower latitudes or at lower altitudes (Arnborg et al., 1967; Church, 1972; McCann et al., 1972; McCann and Cogley, 1974; Nanson, 1974; Ballantyne, 1975). Three hydrological factors favour effective fluvial activity and slopewash

in periglacial environments:
(i) rapid melt of the snowpack in spring releases most of the accumulated winter precipitation over a period of a few weeks or even days in the form of a snowmelt flood; (ii) daily fluctuations in snowmelt discharges (reflecting diurnal oscillations of temperatures and radiation inputs) give rise to repeated high and geomorphologically effective flows during snowmelt; and (iii) the shallowness of the regolith and/or the active (or thaw) layer means that the infiltration capacity of periglacial terrain tends to be low. Runoff coefficients during snowmelt are therefore high, and periglacial streams tend to exhibit flashy responses to summer rainstorms (Cogley and McCann, 1976).

The snowmelt flood assumes greatest significance in arctic environments, where flow of all but the largest rivers is restricted to 3-4 months per year (Church, 1974; Cogley and McCann, 1975). In alpine areas flow may persist through the winter so that the contribution of the snowmelt freshet to total annual discharge is smaller (e.g. McPherson, 1971; Nanson, 1974). Finally, the incomplete vegetation cover of many periglacial areas favours rillwash (Czeppe, 1965; Wilkinson and Bunting, 1975) which supplies fine sediment to the stream system.

In summary, recent research has demonstrated that the principal geomorphological role of snow in periglacial environments appears to be the provision of large quantities of nival meltwater during the spring snowmelt period. Snow meltwater not only transports material directly as slopewash, but also promotes mass-movement through ground saturation and engenders high and geomorphologically significant river discharges. This chapter examines the extent to which this is (or has been) true of snow on the mountains of upland Britain, first through a discussion of the characteristics of nivation features and present geomorphological activity associated with late-lying snowpatches (section 12.2), then through a description of the effect of snowmelt on stream runoff (section 12.3). The final section in this chapter describes present rates of sediment transport in Ardessie Burn, which drains the western corries of An Teallach.

12.2 Nivation features in upland Britain

12.2.1 Relict features

The most convincing examples of relict nivation features in upland Britain described in the literature are a series of rock benches cut into hillslopes in S.W. England (which escaped Pleistocene glaciation). These are widely accepted to be cryoplanation terraces of essentially nivational origin (Guilcher, 1950; Te Punga, 1956; Waters, 1962, 1964). However, no firm evidence has been presented for cryoplanation in areas that were covered by the Late Devensian ice sheet. The "altiplanation benches" reported by King (1968) appear to the writer to be fairly level glaciated rock benches, and a supposed "altiplanation terrace" on Rhum described by Ryder (1968, 1975; Ryder and McCann, 1971) crosses the slope obliquely and appears to reflect structural control. Smaller rock-cut benches with treads approximately 30 m wide at 240-330 m altitude in N.E. Yorkshire have been interpreted by Gregory (1965) as nivation benches, but evaluation of this interpretation is thwarted by the lack of evidence supplied by its author.

Doubt must also be attached to Watson's (1966) interpretation of two cirques in Mid Wales as nivation features. Not only are these features much deeper than any described in the literature on nivation hollows, but Watson's explanation of them also requires the formation of snowpatches longer and thicker than many corrie glaciers, which seems unlikely. Both contain protalus ramparts indicative of the former presence of snowpatches, but in view of recent findings concerning the inability of nivation processes to accelerate the erosion of bedrock (e.g. Thorn, 1976) it seems more plausible that these are glacially-eroded corries that were subsequently occupied (possibly during the Loch Lomond Stadial) by perennial snowpatches. Similarly, most if not all of the huge "nivation hollows" mapped by King (1968) in the Cairngorms must be dismissed in view of his including in this category " ... any valley possessing a roughly circular or pear-shaped form with no evidence of corrie glaciation ... even if evidence of nivation is absent".

The question arises as to whether relict nivation features actually exist on the mountains of Great Britain. The presence of perennial snowpatches during the Loch Lomond Stadial is implicit in the development of protalus ramparts (e.g. Sissons, 1976b, 1979b, 1980), and there can be little doubt that many rock benches and gullies were occupied by late-lying snow, but convincing examples of relict nivation features have not been reported within the limits of the Late Devensian ice-sheet.

The author has studied a number of nivation hollows and benches developed on hillslopes on Ellesmere Island (Ballantyne, 1978). Like those described by, for example, Cook and Raiche (1962b) and St-Onge (1969), the Ellesmere Island features are usually fairly small, with across-slope dimensions of 4-110 m (figure 12.1). The most prominent characteristic of these features is an abrupt break of slope where the floor or tread meets the "backwall"; above the break of slope, generally concave "backwalls" rise from initial angles of around 30°, but the gradients of the treads do not exceed 6°. The treads constitute a "wash zone" across which rillwash was observed to transport fine sand and silt particles.

Features strikingly similar to those on Ellesmere Island occur on Ben Wyvis (compare figures 12.1 and 12.2), the finest examples being those around 459671. These are of similar size to the arctic features, and are likewise characterized by a sharp break of slope between "backwall" and tread. The treads slope away from the "backwalls" at angles of 3-5°. Even at present these bench-like features support remnant snowpatches, although as all but one face south these snowpatches normally melt by the end of June. Melting snow saturates the "wash zone" downslope of each snowpatch, but there is no sign of present activity: both treads and "backwalls" support a complete vegetation cover that effectively precludes erosion and rillwash. In view of the similarity of the Ben Wyvis features to those in the arctic it seems likely that the former represent relict examples of the latter, probably of Lateglacial age. As the main form of activity evident in association with the arctic features is rillwash, this is also likely to have predominated on Ben Wyvis,



Figure 12.1: Nivation bench at c. 500 m altitude near Vendom Fiord, Ellesmere Island (c.78° N.) in the Canadian Arctic Archipelago.



Figure 12.2: Nivation bench, probably of Lateglacial age, at c. 940 m altitude on Ben Wyvis.

although this interpretation awaits testing through examination of the sediments deposited in the now inactive "wash zones".

12.2.2 Active features

Only Tufnell (1971) has reported active nivation in upland Britain. In a paper describing aspects of snowpatch erosion in the northern Pennines, Tufnell advanced the view that nival meltwater "undoubtedly" contributed to accelerated boulder movement and the development and movement of small terrace features. He believed that cracks in the ground roughly parallel to and uphill of snowpatches together with one small slump feature and a single undermined boulder were representative of headward erosion and noted dirt on or within snowpatches derived, he supposed, from "cracking and disintegration of the ground" (p. 497). Tufnell also mentioned the development of rills downslope of melting snow, but did not state whether or not these carried sediment. The speculative nature of Tufnell's observations and the paucity of evidence he supplied hardly justify his conclusion that " ... snow is a major element in the current development of the landscapes of the area ..." (p. 497).

Within the study areas, evidence for active nivation is limited to An Teallach. Comparison of field observations made on the Fannichs and Ben Wyvis with aerial photographs taken at various dates indicated that late-lying snow tends to occupy the same sites (gulleys, glacially-eroded benches and hollows and the risers of sheets and lobes) every year. On examination, however, these sites revealed no evidence of nivation processes. Even during rapid melt the rillwaters draining snowpatches were observed to be sediment-free, and the absence of signs of disruption in the vegetation cover that underlies many snowpatches suggested that frost action had been minimal. It is, however, possible that increased rates of solution accompany prolonged snow-lie, or that concentration of nival meltwater promotes more rapid mass-movement downslope, but such effects were not evident from observation alone.

On the An Teallach plateau, where vegetation is sparse, rapid snowmelt sometimes results in sheetwash, particularly when melt is

accompanied by rainfall (figure 12.3). The competence of shallow unchannelled sheetflow over the gently-sloping debris surface is low, however, and sand grains were observed to be entrained by sheetwash only where slopes steepen to c. 5° or more. Much greater concentrations of sand are transported by the channelled flows of meltwater that emanate from late-lying snowpatches occupying the features mapped as nivation hollows at the head of Coire nan Tota (069865, map 2). These features are formed in easily-eroded niveo-aeolian sand deposits (chapter 11), and represent the only examples of actively eroding nivation hollows known to the writer in Scotland. Like the nivation benches on Ben Wyvis and on Ellesmere Island, the An Teallach nivation hollows are characterized by a break of slope at the rear of a gently-sloping wash zone (figure 12.4). There are no true "backwalls", however. The rear of some hollows consists of unvegetated debris, whilst the backslope of others is covered by sand deposits with a complete cover of grasses and sedges. The sides of the hollows are formed by scarps eroded in thick niveo-aeolian sand deposits. The wash zones have gradients of 2-5° and consist of vegetation-free surfaces crossed by ephemeral networks of shallow braided channels typical of those formed by wash over cohesionless sandy sediments (Carson and Kirkby, 1972, p. 191). When the snowpatches occupying the hollows are at their maximal extent they range in size from 45-60 m across-slope and 30-75 m downslope, with the resident snowpatches extending from the crest of the backslope to the front of the wash zone. All lie at the crests of lee slopes, in highly favourable locations for snow accumulation. Snow thickness in the hollows is estimated to reach 3-7 m.

Observations of current activity were made at two hollows, designated NH 1 (a small hollow facing 350° at 070867; figure 12.4) and NH 2 (the largest of the hollows, with an aspect of 45°, at 068865). Snowcover at these sites was monitored periodically during the winter of 1977-8 with reference to 2.5 m rods inserted to depths of 0.5 m near the middle of the backslopes. The 2.0 m exposed section of the rod at NH 2 was completely buried on all occasions when this site was visited between 3 December 1977 and



Figure 12.3: Sheetwash on the northern plateau of An Teallach

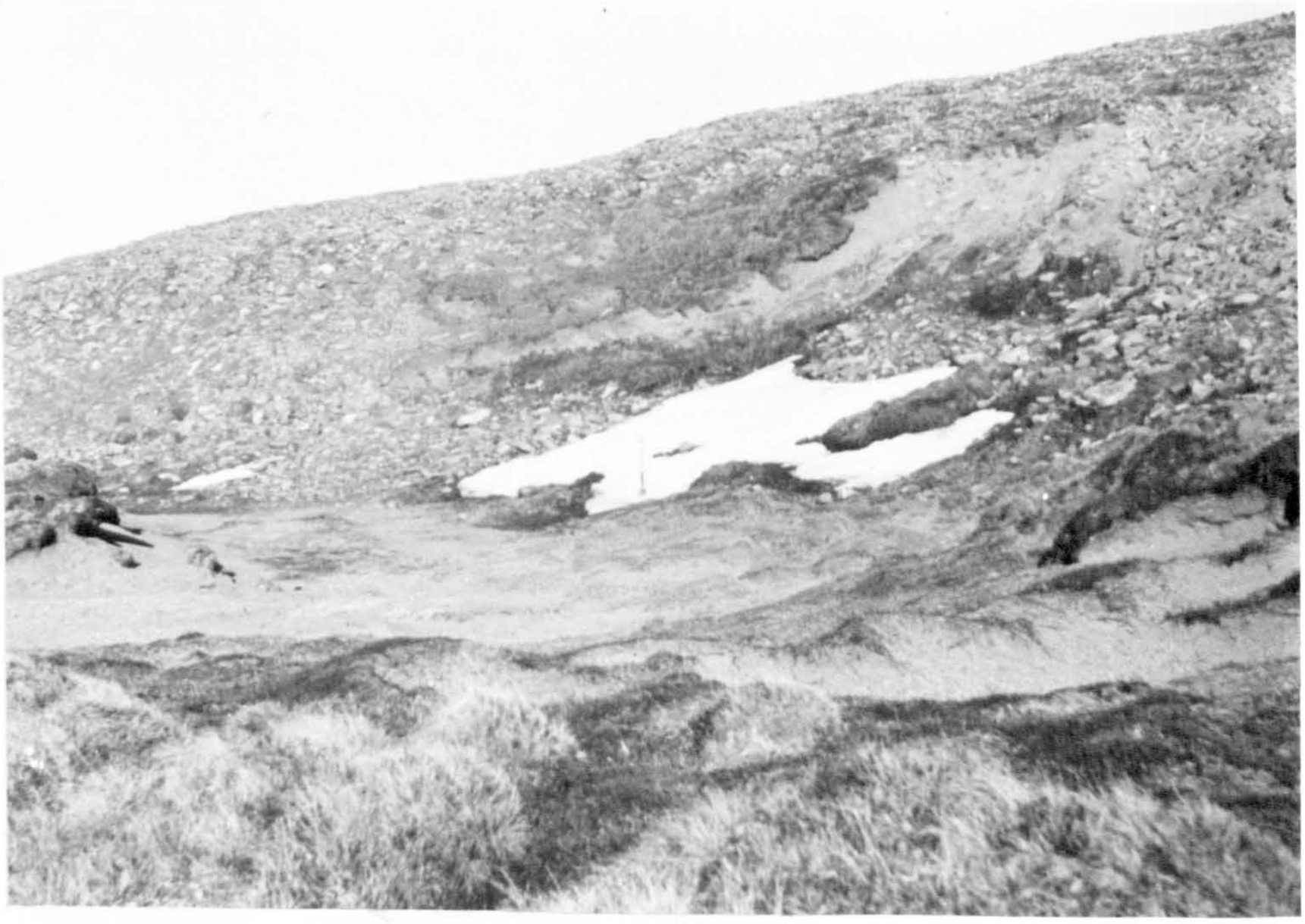


Figure 12.4: Nivation hollow NH 1, developed in niveo-aeolian sand deposits at 725 m altitude on a north-facing slope in Coire nan Tota, An Teallach.

1 June 1978, but by 19 June 1978 only 0.3 m of snow remained at this site. At NH 1, 1.3 m of snow was recorded on 3 December 1977, but only 0.6 m on 4 January 1978. Snow then reaccumulated; the rod was buried by 11 February and apparently remained so until May, 1.6 m of snow being recorded on 14 May. All snow at NH 1 melted by 1 June 1978. These data suggest that the snowpatches occupying the hollows experience only one major melt-out per year, in May or June, although melting in the first half of the winter may reduce the depth of cover.

Many authors (e.g. Matthes, 1900; Hobbs, 1911; Ekblaw, 1918; Gardner, 1969c; Thorn, 1976) have expressed the view that freeze-thaw activity is intensified at the margins of ablating snowpatches, a microenvironment supposedly characterized by a high frequency of freeze-thaw cycles and an abundance of water. This does not accord with observations made during the melt-out period at site NH 2. Comparison of the temperature records obtained from two unscreened thermographs, one placed adjacent to the snow in a "randkluft"-type crevasse between the snow and an enclosing sand scarp, the other on snow-free ground 5 m away, suggests that freeze-thaw cycles were actually slightly damped by proximity to the snow (figure 12.5). Moreover, no evidence was found for any form of freeze-thaw activity (e.g. frost-heave, disaggregation of the sand deposits, needle ice growth) on the snowpatch margins, although sand derived from the enclosing scarps was observed to adhere to the retreating snow. Such sand is probably incorporated into the snow during refreezing and compaction of the snowpack.

During melt, the snowpatches occupying the hollows retreated much more rapidly from the treads of the hollows than from the margins or the backslopes. Ablation was accompanied by rapid discharge of meltwater over the wash zones. In the early stages of melt the wash zones were often entirely inundated (figure 12.6). At site NH 2, where the discharge from the melting snow is confined farther downslope to a single small channel, discharges in excess of 1 litre s^{-1} (3.6 m^3 h^{-1}) were measured by timing the filling of a two litre bottle. In the later stages of melt flow became confined to the braided channel network. Later still the supply of meltwater became so depleted that runoff failed to reach the

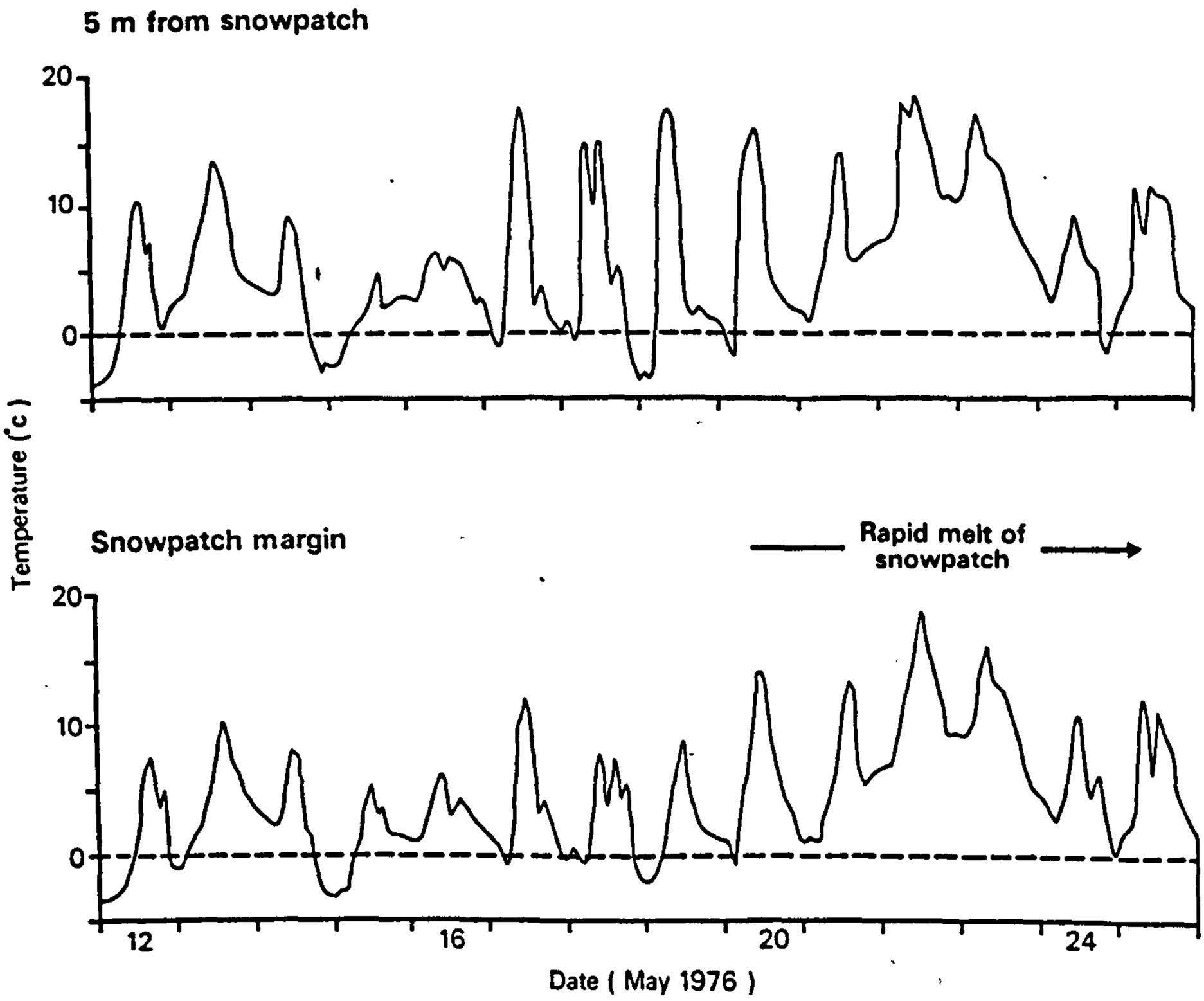


Figure 12.5: Air temperatures recorded on unscreened thermographs placed on snow-free ground 5 m from the snowpatch in nivation hollow NH 2 (top record) and in a "randkluft" crevasse at the snowpatch margin (bottom).



Figure 12.6:

Sheetwash over the wash zone of nivation hollow NH 2 during the early stages of snowmelt in 1977.



Figure 12.7: Sand deposited by nival meltwaters downslope of the wash zone of nivation hollow NH 2 in 1977.

downslope edge of the wash zone and percolated into the underlying sand within a short distance of the snowpatch margin.

During the earlier stages of melt, considerable quantities of sand were transported across the wash zones. Pits with a capacity of approximately 0.6 m^3 were dug across the meltwater exits at both observation sites before snowmelt commenced in 1977 and lined with polythene. Both filled with sand within three days. Assuming that one third of the infill consisted of voids and that the sand had a grain density of 2.65 g cm^{-3}, this accumulation implies a mean transport rate of at least 4 g s^{-1}. The material trapped in the pits included small pebbles weighing up to 14 g, indicative of high competency and therefore fairly rapid flow velocities.

The main source of the material transported across the wash zones is probably windblown sand deposited on the snowpatches. The location of the hollows coincides with that of the densest concentrations of supranival sand deposits (chapter 11). During snowmelt, these deposits formed well-defined dirt polygons (Ashwell and Hannell, 1966; Jahn and Klapa, 1968) that were sometimes transformed into stripes by supranival wash during rainstorms. Although these delicate forms occasionally survived deposition (for a brief period) on vegetated surfaces, most supranival material was either deposited directly on the wash zone or washed from the backslope on to the wash zone. The bounding sand scarps formed a further source of sediment. Meltwater in runnels at the margins of the hollows was observed to undermine the bounding scarps, causing localized slumping; the products of slumping were then rapidly removed by wash.

The treads of the nivation hollows, however, appear to supply hardly any sediment. Three erosion pins inserted in the wash zone at NH 2 were exposed by erosion during the early period of snowmelt in 1977, then buried by deposition as later snowmelt dropped its load and percolated into the underlying sand. All three were re-exposed the following spring. Superimposed on this general pattern were shorter periods of burial and exposure resulting from the migration of channels and bars in the braided system. The treads of the hollows therefore appear to act as

transport surfaces over which net erosion and net accumulation are minimal. Excavation of the wash zone at NH 1 revealed undisturbed niveo-aeolian sand deposits capped by a 2-4 cm thick washed layer. The shallow depth of the washed layer confirms that little accumulation takes place on the treads.

The main areas of sand deposition lie immediately downslope of the wash zones, where sand is deposited in thick, irregular spreads (figure 12.7). In some cases these have accumulated to form steep cones several metres long (Godard, 1965, p. 167). Similar though much larger cones of vegetation-covered washed sand occupy slopes up to 50 m high at the head of Coire a'Mhuilinn (073860). These have been deposited by small ephemeral streams that are nourished by both nival meltwater and surface runoff during rainstorms. Such streams flow for some distance along the base of the sand scarps that flank the edge of the plateau. At points where the streams break through the scarps they have deposited steep colluvial cones that have accumulated through washed sand being trapped by vegetation as the surface waters percolated into the deposit. Excavation through the foot of one such cone revealed alternating organic- and sand-rich horizons that suggest that periods of relatively rapid deposition alternated with periods of slow accumulation.

Finally, it is worth noting that the snowpatches occupying sites NH 1 and NH 2 underwent creep during the winter of 1977-8. This was evident through the bending of the rods inserted for assessing snow depth. These rods consisted of heavy-grade iron conduit tubing 1.6 cm in outside diameter; both were bent about 30^{o} from the vertical at the ground surface. This supports previous findings (Costin et al., 1973) of large shear stresses set up by creeping snow. Such snowcreep appears to be of little geomorphological significance on An Teallach, however, for although underlying vegetation was flattened there was no evidence that moving snow had accomplished basal erosion or transported material other than aeolian sand entrained on or within the snowpatch.

The above observations suggest that the principal geomorphological role of snowpatches within the study areas is the provision of meltwater that transports fine material over rather limited distances.

However, nival meltwater is apparently effective as an agent of erosion and transportation only (i) if it has access to unvegetated cohesionless fine material and (ii) when flow is sufficiently concentrated or rapid to permit entrainment of such material. These conditions severely restrict the distribution of effective nivational activity, and explain why active nivation in the study areas is limited to rather unusual sites on An Teallach. The restriction of nivation to such sites suggests that it is only of very local significance, although investigation of the solutional activity of nival meltwater and the role of snow runoff in accelerating mass-movement downslope are required before definitive conclusions can be drawn concerning the present effectiveness of nivation in upland Britain.

12.3 Stream runoff

The characteristics of stream runoff on An Teallach were assessed by continuous gauging of a small mountain stream during the winter of 1976-7. The high flow velocities and flashy responses of steep mountain streams make gauging difficult, a problem that was overcome by gauging the smaller (western) distributary of the Allt Coire a'Mhuilinn. The latter divides at 093867; the western distributary, hereafter referred to as Dundonnell Burn, carries only a small proportion of the total runoff from Coire a'Mhuilinn and is therefore easily gauged. The discharges obtained are of course much lower than the total discharge from the 2.33 km^2 catchment above the point at which the stream divides, but the pattern of discharge is similar and offers insights into the characteristics of winter runoff.

The discharge of Dundonnell Burn was recorded at a small pool at 097871 (100 m above sea level). River stage was recorded as a continuous chart trace on an Ott type X water-level recorder, and stage readings at 2 h intervals were abstracted from the chart. These stage readings were converted into discharge values using an empirically-derived discharge rating curve. This was obtained by establishing the relationship between individual stage values and equivalent stream discharges using the velocity-area method (Church

and Kellerhals, 1970), velocity being measured at six-tenths depth using a small Ott propeller-type current meter with readings taken at 10 cm intervals across the stream. The rating curve was calculated according to the procedure outlined in Robertson (1965); nonlinear regression yielded the rating

$$Q_d = 0.0000249\ (Y_d - 12)^{1.345} \qquad (r^2 = 0.997) \qquad (12.1)$$

where Q_d is discharge of Dundonnell Burn ($m^3\ s^{-1}$), and Y_d is stage of the same stream in centimetres (figure 12.8). The calculated two-hourly discharge values were then plotted as a continuous hydrograph (figure 12.9).

The most striking feature of the winter runoff of Dundonnell Burn is the lack of snowmelt influence. During most of the winter discharge closely mirrored precipitation at Dundonnell, high precipitation being accompanied by rapid rises in discharge and dry periods causing steadily declining runoff recessions. On a few occasions (12-14 December, 20-22 January and 6-7 March) the hydrograph shows diurnal oscillations that appear to be unrelated to precipitation and probably reflect snowmelt, but none of these reach particularly high discharges. Conversely, some precipitation events (e.g. 12-14 January) evoked no response in stream discharge, probably because the precipitation fell as snow on high ground. The discharge record for Dundonnell Burn therefore suggests that high flows during the winter months relate mainly to rainfall rather than snowmelt.

Unfortunately, no instrumental records of runoff were obtained for the spring period, when the contribution of snowmelt to streamflow may be expected to have been greatest. However, observations made on the Allt Coire a'Mhuilinn during a period of rapid snowmelt under anticyclonic conditions in May 1977 showed that although river stage rose appreciably during the morning, peaked in mid-afternoon then declined, the peak flows resulting from snowmelt were very much less than those engendered by rainstorms. This also appears to be true for rivers in the eastern Highlands (A. Werritty, personal communication). Snowmelt runoff, the dominant hydrologic event in arctic and alpine environments, appears to be of little importance in generating floods in the

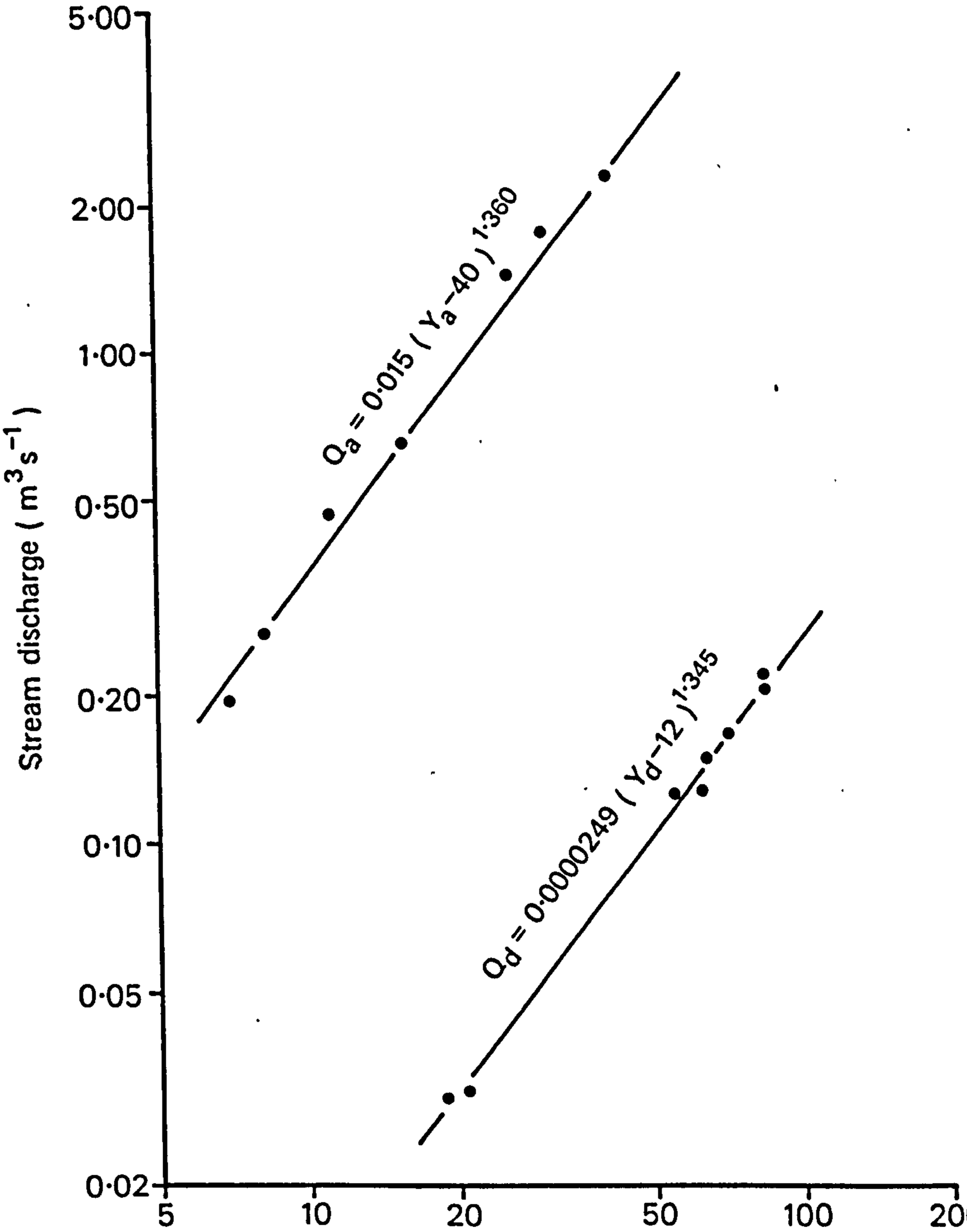


Figure 12.8: Rating curves for the discharge of Dundonnell Burn (Q_d) and Ardessie Burn (Q_a) plotted against respective levels of stage (Y_d and Y_a).

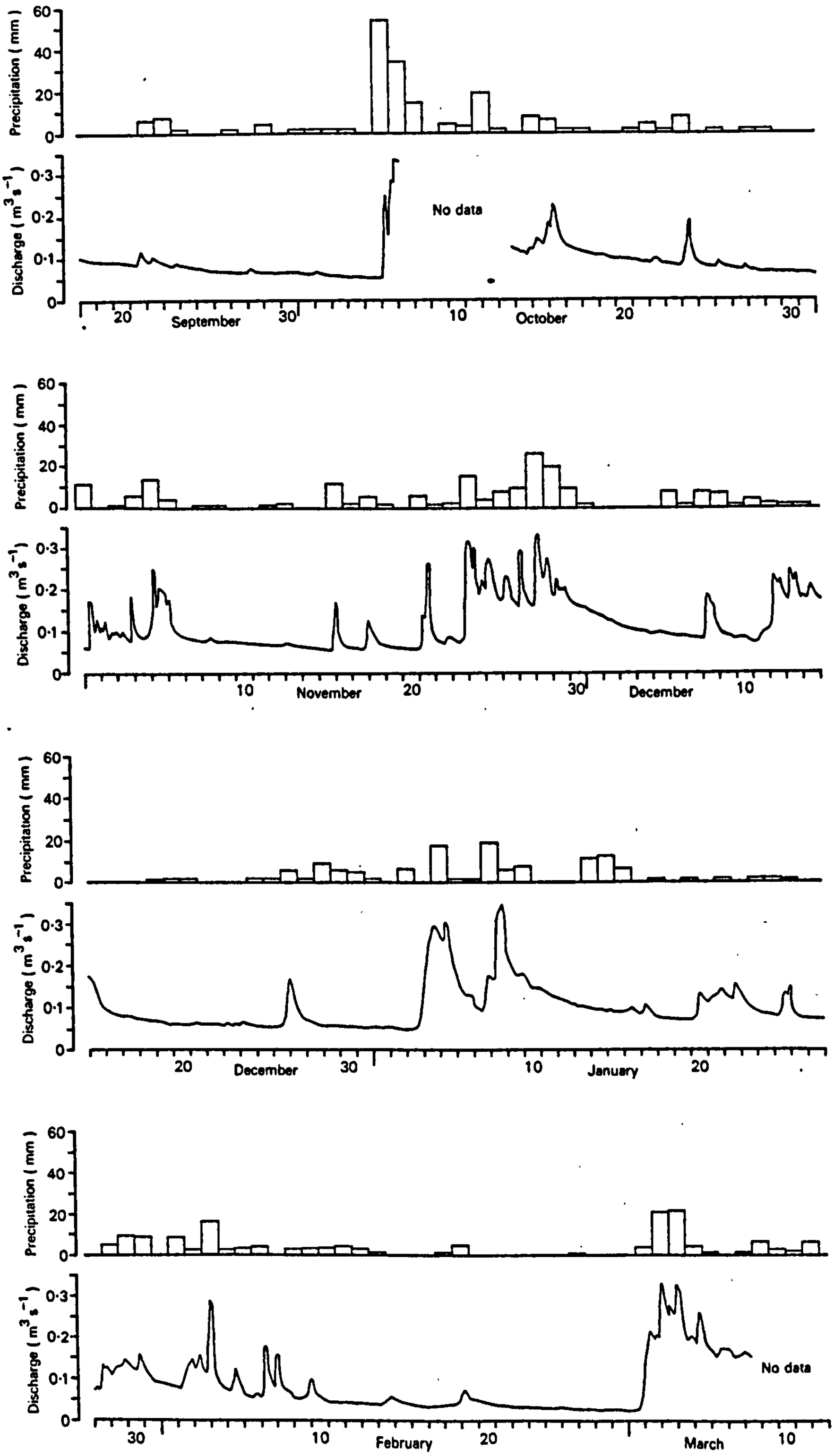


Figure 12.9: Discharge of Dundonnell Burn and precipitation at Dundonnell, 18 September 1976 to 8 March 1977.

maritime periglacial environment of upland Britain.

There are several reasons why this should be so. First, as thaw may occur several times in the course of a single winter, the snowpack on British mountains rarely accumulates to great thicknesses except where snow is blown on to lee slopes. Secondly, as Johnson (1975) pointed out, snow on the lower parts of mountain catchments often melts whilst that at higher altitudes remains frozen. This is accentuated by the often slow and sporadic increase in spring temperatures, which ensures that snowmelt extends over long time periods. Finally, the contribution of snowmelt is often "masked" by melt taking place during periods of rainfall. Flood discharges certainly result from such combinations of rainfall and snowmelt: Johnson (1975) found that the highest recorded discharges at 27% of all gauging stations in Scotland contained a snowmelt component. The discharge data and observations described above nevertheless suggest that high discharges in upland catchments in Great Britain result mainly from rainfall and that the contribution of snowmelt to high flows is small.

12.4 Sediment transport

12.4.1 Introduction

Although several forms of mass transport activity (e.g. rock-fall, debris flow, solifluction, wash and creep) contribute to the downslope movement of debris in upland catchments, only two agents of sediment transport, wind and rivers, are capable of removing material entirely from nonglacierized basins. In upland Britain the role of the former is apparently limited to localized redistribution of sediment (chapter 11), and rivers alone are responsible for complete removal of sediment from mountain catchments. The load transported by mountain streams is therefore of interest as it gives a measure of denudation rate, the net rate at which the land surface is being reduced by erosion.

River load comprises three components, namely dissolved load, suspended load and bedload. Accurate assessment of bedload is

difficult (Hubbell, 1964; Yalin, 1973) and attention is here focussed on only the dissolved and suspended components of river load. These were assessed for Ardessie Burn, which drains a 13.37 km^2 upland catchment that incorporates the entire west flank of the An Teallach Massif and the east slope of Sàil Mhór. This river was chosen for analysis as (i) all but 0.44 km^2 of its catchment lies above 300 m and (ii) a two year record of daily stage measurements was available for this stream from fish farm operatives at Ardessie.

12.4.2 Calculations

The calculation of dissolved and suspended sediment loads requires (i) derivation of a flow frequency curve defining the probability of any given stream discharge and (ii) establishment of the relationships between concentration of dissolved salts and discharge and between concentration of suspended sediment and discharge. These data can be combined to yield discharge-weighted mean concentrations for both components that are readily converted into load values.

A flow frequency curve was derived in the following manner. Fish farm records consisting of 731 daily readings of river stage for the period 1 September 1975 to 31 August 1977 were assumed to define a random and representative sample of stage measurements. A discharge rating curve was established using the procedure described for Dundonnell Burn in section 12.2, only with velocity readings taken at 30 cm rather than 10 cm intervals across the stream. Nonlinear regression of nine discharge-stage determinations gave the rating

$$Q_a = 0.015\ (Y_a - 40)^{1.360} \qquad (r^2 = 0.992) \qquad (12.2)$$

where Q_a is discharge of Ardessie Burn ($m^3\ s^{-1}$) and Y_a is equivalent stage in centimetres (figure 12.8). The 731 stage readings were then converted to discharge values according to equation 12.2 and these were grouped at 0.25 $m^3\ s^{-1}$ intervals to give a flow frequency curve in the form of a histogram (figure 12.10).

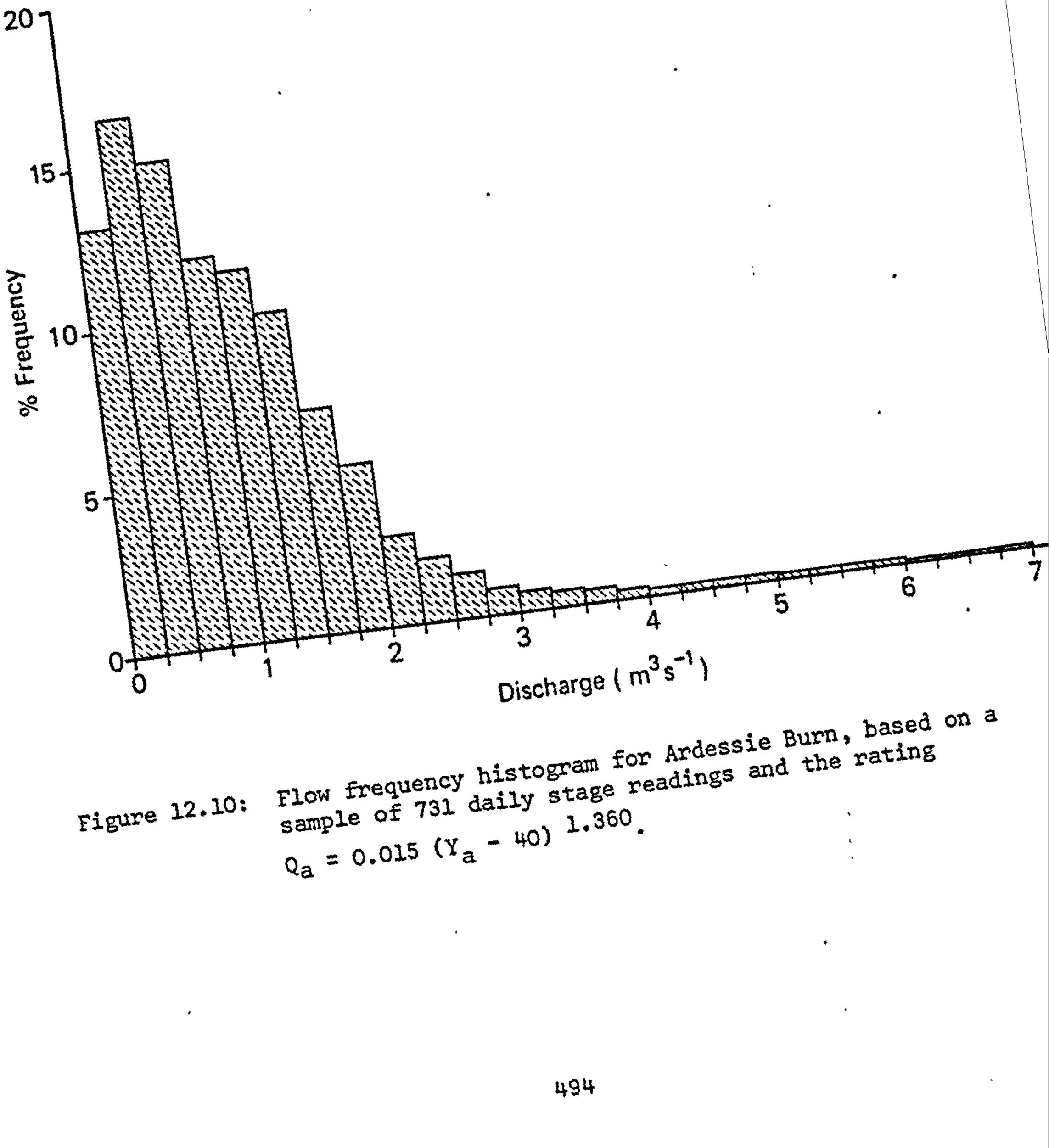


Figure 12.10: Flow frequency histogram for Ardessie Burn, based on a sample of 731 daily stage readings and the rating

$$Q_a = 0.015 (Y_a - 40)^{1.360}.$$

Suspended sediment concentrations in Ardessie Burn were sampled over a range of discharges during both rising and falling stage using a DH 48 depth-integrating suspended sediment sampler. The samples were returned to the laboratory where the volume of the sample was measured and the water filtered off. The filters and organic material were then burnt off at 600°C and the residue weighed. The results were calculated in mg l^{-1} and plotted against discharge on logarithmic graph paper. The plot (figure 12.11) showed that the relationship between suspended sediment concentration and discharge for rising stage differs markedly from that for falling stage. Regression gave

$$C'_s = 8.140\ Q_a^{1.616} \quad (n = 6,\ r^2 = 0.983) \qquad (12.3)$$

for suspended sediment concentration during rising stage (C'_s) and

$$C_s = 2.465\ Q_a^{1.059} \quad (n = 13,\ r^2 = 0.726) \qquad (12.4)$$

for concentration during falling stage (C_s).

The relationship between concentration of dissolved salts and discharge was obtained through analysis of measurements of specific conductivity made available by fish farm operatives. The data comprised 565 measurements of specific conductivity assessed in μmho cm^{-1} at 25°C. As each conductivity determination was related to a corresponding stage measurement, it was possible to convert the latter to discharge using equation (12.2) and to plot the relationship between conductivity (K) and discharge (Q_a). This proved weak, negative and nonlinear, with a wide scatter of points (figure 12.12, upper diagram). Regression yielded the relationship

$$K = 31.333\ Q_a^{-0.045} \quad (n = 565,\ r^2 = 0.052) \qquad (12.5)$$

which despite the low correlation coefficient is significant at the 0.00001 level (a reflection of the large sample size). The wide scatter of points is partly explained by the stronger relationship between conductivity and water temperature (figure 12.12, lower diagram) which is independent of discharge and probably reflects increased solution rates at high temperatures.

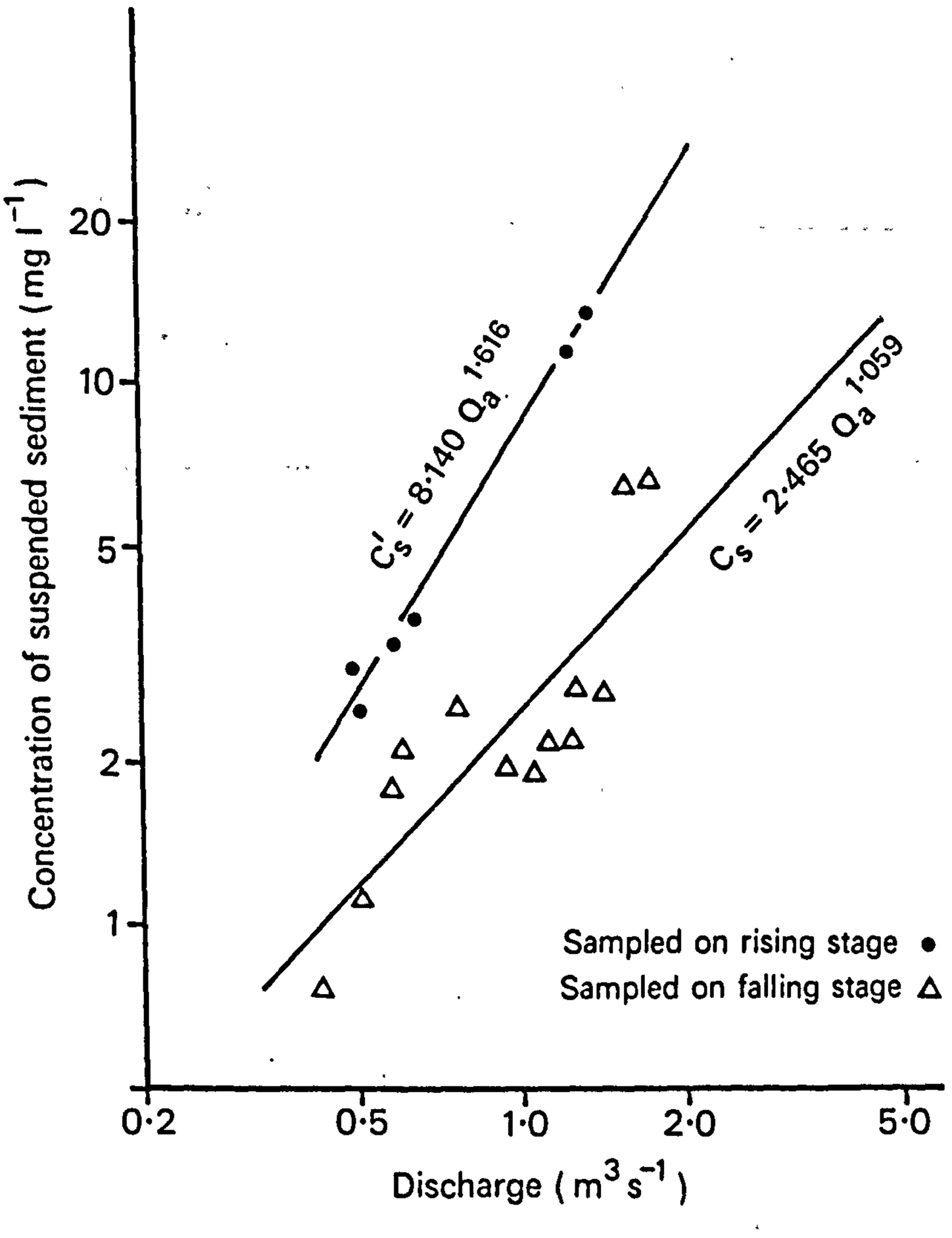
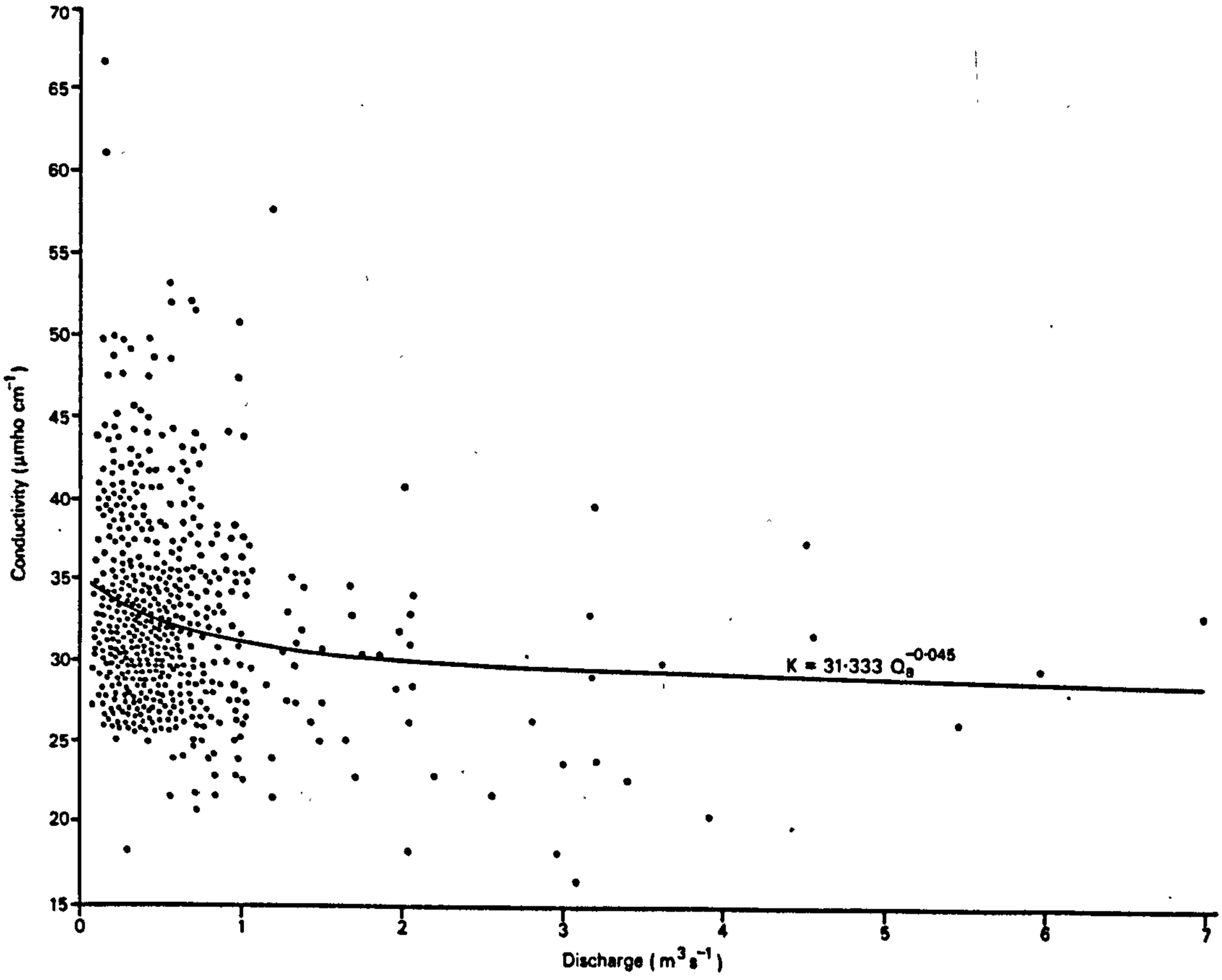


Figure 12.11: Sediment/discharge rating curves for concentration of suspended sediment during rising stage (C'_s) and falling stage (C_s) in Ardessie Burn.



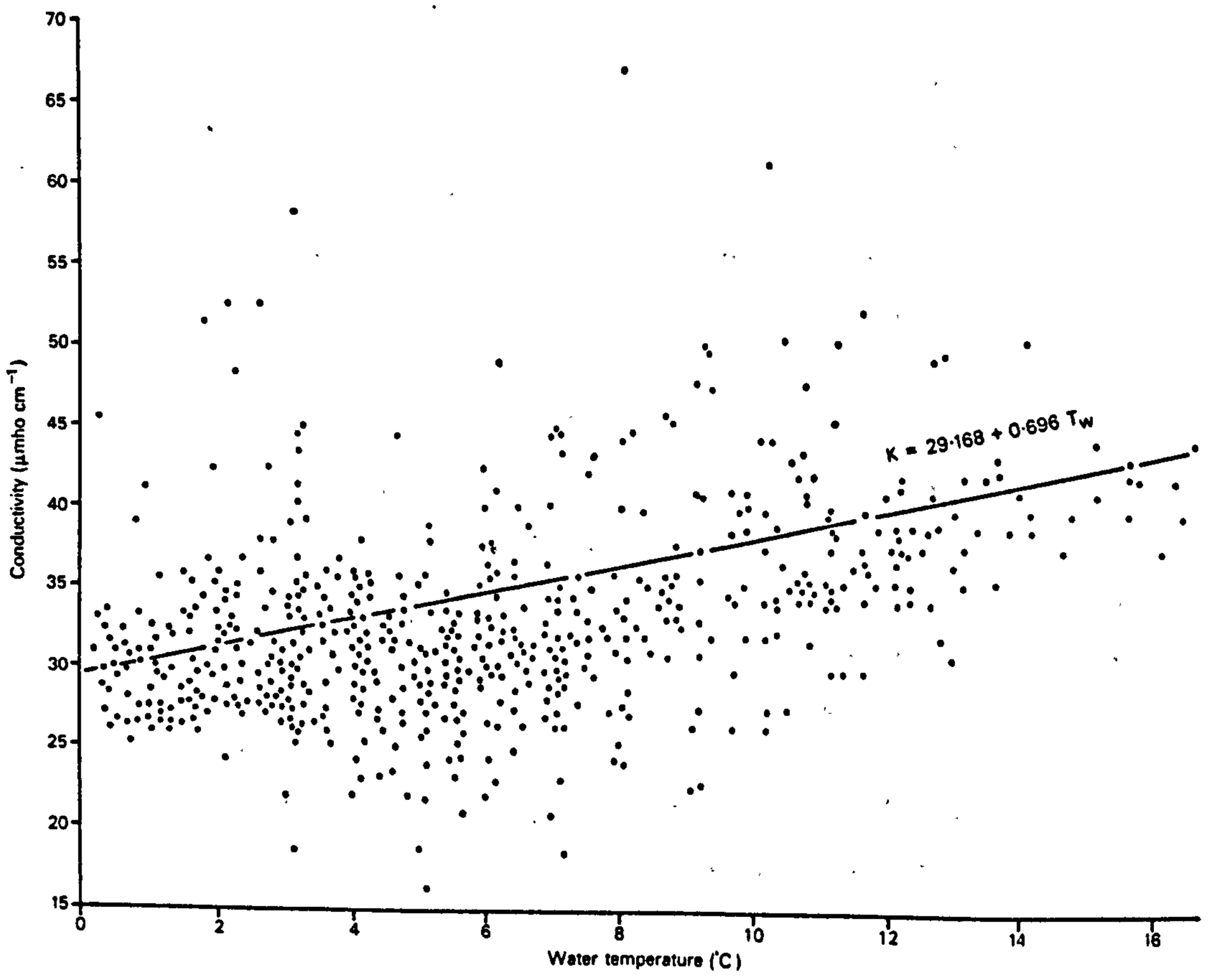


Figure 12.12: Scattergrams showing the relationships between specific conductivity (K) and discharge (Q_a) and specific conductivity and water temperature (T_W), Ardessie Burn.

There is a high degree of positive correlation between conductivity and total concentration of dissolved cations and anions, although because of differences in the weights of different ions the relationship between conductivity and salt concentration on a weight basis (C_d) is poorer and dependent on the composition of constituent salts. When the latter is unknown or variable, the general relation

$$C_d = 0.64\ K \qquad (12.6)$$

is usually employed to relate salt concentration in mg l^{-1} to conductivity in μ mho cm^{-1} (Bower and Wilcox, 1965). Combining equations (12.5) and (12.6) gives the relationship between concentration of dissolved salts and discharge as

$$C_d = 20.053\ Q_a^{-0.045} \qquad (12.7)$$

Discharge-weighted mean concentrations of suspended sediment during rising stage, suspended sediment during falling stage and dissolved salts were calculated using the general equation

$$C = \sum_{i=1}^{n} (C_i\ \ p_i) \qquad (12.8)$$

where p_i is the probability of the i th class of discharge (measured at intervals of 0.25 $m^3\ s^{-1}$; figure 12.10) and C_i is concentration in mg l^{-1} corresponding to the mean discharge of the i th class (i.e. the midpoint of the class). For rising stage, discharge-weighted mean concentration of suspended sediment was calculated as 12.16 mg l^{-1}; for falling stage, 2.72 mg l^{-1}. The equivalent figure for dissolved salts is 20.28 mg l^{-1}.

The mean annual discharge of Ardessie Burn over the period 1 September 1975 to 31 August 1977 was calculated to be 34 x 10^6 m^3. Before this figure could be employed to determine the mean annual load transported as suspended sediment, it was necessary to determine the percentage of time during which stage was rising. This information was not available for Ardessie Burn, but for Dundonnell Burn increasing stage occupied 9.9% of the period of record (figure 12.9). If a figure of 10% is assumed for Ardessie Burn,

the mean annual load transported in suspension may be expressed as

$$\overline{L_s} = (0.1\ \overline{C'_s} \cdot \overline{Q_t}) + (0.9\ \overline{C_s} \cdot \overline{Q_t}) \qquad (12.9)$$

where $\overline{L_s}$ is mean annual suspended load in grams, $\overline{Q_t}$ is mean annual discharge and $\overline{C'_s}$ and $\overline{C_s}$ are discharge-weighted mean concentrations of suspended sediment during rising and falling stage respectively. The mean annual load transported in solution ($\overline{L_d}$ in grams) is

$$\overline{L_d} = \overline{C_d} \cdot \overline{Q_t} \qquad (12.10)$$

where $\overline{C_d}$ is discharge-weighted mean concentration of dissolved salts.

Mean annual suspended load works out at 124.6 x 10^6 g (124.6 metric tonnes); mean annual dissolved load at 689.5 x 10^6 g (689.5 t). These values are equivalent to mean areal yields of 9.32 t km^{-2} y^{-1} and 51.57 t km^{-2} y^{-1} respectively. Assuming a mean density of 2.65 g cm^{-3} for the transported material, such yields represent mean net lowering of the land surface of 0.0035 mm y^{-1} and 0.0195 mm y^{-1} (3.5 m^3 km^{-2} y^{-1} and 19.5 m^3 km^{-2} y^{-1}). Total loss of material in suspension and solution is 60.89 t km^{-2} y^{-1} (c. 23 m^3 km^{-2} y^{-1}).

12.4.3 Discussion

The figures presented in the preceding paragraph can be regarded as no more than crude estimates in view of the assumptions made in their derivation. In particular, the validity of the figure for mean solute load is questionable as (i) a standard rather than empirically-derived relationship was employed to relate concentration of dissolved salts and conductivity (equation 12.6) and (ii) no account was taken of salt concentration in incident precipitation. Attempts to rectify both weaknesses through direct determination of concentration of dissolved salts and conductivity for samples of river water and rainfall failed because of the time required to return the samples to the laboratory, which

resulted in changes in both sets of values (Johnson, 1971). According to Gregory and Walling (1973, p. 172), the conversion factor relating total dissolved solids (C_d) to conductivity " ... normally falls between 0.55 and 0.75 ..." (0.64 was employed here), which suggests that discharge-weighted mean concentration of dissolved salts probably lies in the range 17.43 to 23.77 mg l^{-1}, and mean annual solute load falls between 592.6 t (44.32 t km^{-2} y^{-1}) and 808.18 t (60.45 t km^{-2} y^{-1}). As these figures incorporate an unknown contribution from precipitation falling in the basin they represent an overestimate for solute yield resulting from weathering and erosion within the catchment.

The extent to which the figures obtained are representative of sediment and solute yield from the higher parts of the catchment is also questionable as riverbank exposures of till in Coire Mór and the glen between Sàil Mhór and An Teallach probably supply a high proportion of the material carried in suspension during high flows (cf Kirkby, 1967, p. 377). In view of these considerations it is realistic to consider the figures only as generous order-of-magnitude estimates of the yield of fine sediment and dissolved salts from high ground on An Teallach.

Little comparable data are available from other periglacial environments, but such as do exist suggest that the suspended load of Ardessie Burn is very much lower than that of rivers draining arctic basins: 9.32 t km^{-2} y^{-1} for Ardessie Burn compares with estimates of 22.1 t km^{-2} y^{-1} for the Mecham River on Cornwallis Island (McCann and Cogley, 1974) and 174.0 t km^{-2} y^{-1} for the glacio-nival Schei River on Ellesmere Island (Ballantyne, 1975). Basin relief is much higher in the Ardessie catchment, so the lower yield presumably relates to differences in runoff regime and above all to the much greater cover of vegetation in the Scottish basin. The estimated solute yields are closer: the (overestimated) figure of 51.57 t km^{-2} y^{-1} for Ardessie Burn compares with figures of 33.1-44.2 t km^{-2} y^{-1} for the Mecham and 25.8 t km^{-2} y^{-1} for the Schei.

The total denudation rate implied by loss of material in suspension plus solution (60.9 t km^{-2} y^{-1}) is also low when

compared with estimates for other British catchments, although direct comparison is hindered by differences in measurement techniques. Al-Ansari and McManus (1979) calculated loss in the form of total solids load (suspended load plus bedload) of 187-238 t km^{-2} y^{-1} for the Earn catchment in Central Scotland (nearly all of which was transported in suspension) and presented a summary of earlier estimates: 56.2, 115.3 and 169.9 t km^{-2} y^{-1} for total solids loads in three tributaries of the Clyde Estuary (Fleming, 1970); 166.9 and 217.8 t km^{-2} y^{-1} for northern England (Hall, 1967); 178.9 t km^{-2} y^{-1} for Dumfriesshire (Geikie, 1868); and 42.4 t km^{-2} y^{-1} for Galloway (Kirkby, 1967). In all the above cases suspended sediment load is greater than that transported by Ardessie Burn. As bedload movement in Ardessie Burn appears to be limited to high flood events, it is reasonable to conclude that the available data indicate net rates of erosion that are low relative not only to those of more severe periglacial environments, but also to those of basins at generally lower altitudes elsewhere in Great Britain. It is also interesting to compare the rates of removal of material in Ardessie Burn with rates of mass transport on upland slopes; this is attempted in the following chapter.

CHAPTER 13 RATES OF MASS-TRANSPORT ACTIVITY

13.1 Introduction

The previous five chapters (8-12) contain data relating to present rates of mass-transport activity on the mountains of Great Britain. Where appropriate, these data were compared with previous measurements made on British mountains and with rates of activity reported from other, mainly periglacial, environments. No attempt has been made, however, to compare the relative effectiveness of different forms of mass-transport within the study areas. This chapter constitutes a synthesis and comparison of the mass-transport data presented in earlier chapters.

One obstacle to comparison of the rates at which different forms of mass-transport operate arises from the incompatibility of the units used to express rates of activity. Rockfall was assessed as rockwall retreat in mm y^{-1} (table 8.1). Present rates of frost creep and solifluction were expressed as downslope displacement of surface clasts or markers in mm y^{-1} (figures 8.34, 8.35, 9.32, 9.43; table 9.10) and a similar measure was used to express the rate of ploughing boulder movement (figure 9.53; table 9.11). Transport of windblown sand was evaluated in terms of the mass of sand (in tonnes) blown into a given area within a single winter (section 11.4) and removal of material from an upland catchment in solution and suspension was calculated in t km^{-2} y^{-1} (section 12.4). These measures cannot be compared directly and must be transformed into some common unit before the relative effectiveness of different forms of mass-transport can be assessed.

Jackli (1957) and Rapp (1960a) resolved this problem by expressing all forms of transport activity as the mass of sediment moved through a vertical distance in unit time (e.g. as t m^{-1} y^{-1}). Caine (1976) suggested a refinement of this measure based on the loss of potential energy that accompanies transfer of mass from a higher to a lower elevation. This may be expressed as

$$\Delta E = m.g. (h_1 - h_2) \qquad (13.1)$$

where m is mass of transported sediment, g is gravitational acceleration (effectively a constant, 9.8 m s^{-2}) and $(h_1 - h_2)$ represents the height difference between the initial altitude of the mass (h_1) and the final

altitude of the mass (h_2). If m is expressed in kilograms, and ($h_1 - h_2$) in metres, the dimensions of ΔE (work or energy loss) are joules (j); one joule is equivalent to the energy loss associated with the acceleration of a mass of one kilogram over a distance of one metre at 1 ms^{-2}.

Comparison of the effectiveness of different forms of mass transport requires that the area (A) and time (t) over which transport operates be taken into account. Energy loss per unit time has the dimensions of power (P), so assessment is made as "power per unit area", given by

$$P = k.m.g\ (h_1 - h_2)\ A^{-1}\ t^{-1} \qquad (13.2)$$

where k is some constant. If annual rates of sediment transport are expressed in watts per square kilometre (W km^{-2}; 1W = 1 j s^{-1}), equation 13.2 reduces to

$$P = 3.1054 \times 10^{-7}\ m\ (h_1 - h_2)\ km^{-2} \qquad (13.3)$$

Assessment of different forms of mass-transport in W km^{-2} therefore requires (i) measurement of the mass of transported sediment and the vertical displacement (or mean vertical displacement) of this mass per year, and (ii) adjustment of this value for operation of the process over 1 km^2 of terrain.

13.2 Calculations

13.2.1 Rockfall.

In section 8.2.6.3, rockwall retreat rates in Coire a'Mhuilinn were calculated from the axial dimensions of 183 clasts that had fallen from two rockwall sources of known area during a two-year period. For each measured clast the distance to the foot of the rockwall was measured to the nearest 5 m (figure 8.12) and the average slope between individual clasts and the foot of the rockwall was measured from surveyed profiles (figure 8.10). Using these data, energy loss associated with the fall of the 183 clasts was calculated as

$$\Delta E_R = g \sum_{i=1}^{183} m_i\ h_i \qquad (13.4)$$

Values of mass in kilograms (m_i) were derived from axial measurements

using

$$m_i = \frac{\rho \cdot k\,(a_i\ b_i\ c_i)}{1000} \qquad (13.5)$$

where ρ is clast density (assumed to be 2.65 g cm^{-3}), k is an empirically-derived constant relating actual clast volume to axial measurements (a sample of 20 clasts gave a mean value of 0.696 for k; 0.7 was assumed) and a_i, b_i, and c_i represent the respective length of the principal, intermediate and minor axes of measured clasts. Vertical distances travelled (h_i) were approximated by

$$h_i = \frac{H}{2} + d_i \sin \alpha_i \qquad (13.6)$$

where H is height of the rockwall source area and d_i and α_i are distance and mean gradient from the measured clasts to the foot of the rockwall (figure 13.1). Equation 13.6 assumes that falls of clasts of all sizes are randomly distributed from the foot to the top of the rockwall so that it is reasonable to consider the "average" initial altitude to be the midpoint of the rockwall (H/2).

Potential energy loss (ΔE_R) through rockfall over a two-year period from two sources with combined area 1817 m^2 was calculated to be 193680 j, equivalent to 96840 j y^{-1} or 1.689 W km^{-2}.

13.2.2 Frost creep

The calculations reported in this section were applied to measurements of downslope movement of surficial debris on unvegetated debris slopes and turf-banked terraces on An Teallach. These data are described and illustrated in sections 8.4.5 (figures 8.34 and 8.35) and 9.3.4 (figures 9.43 and 9.44) and summarized in table 9.10.

Downslope movement by frost creep comprises two components, namely creep of surface clasts and movement <u>en masse</u> of the top few centimetres of regolith. As creep of individual clasts may be considerably more rapid than that of the surface of the regolith (table 9.10), the energy loss resulting from frost creep (ΔE_F) was assessed as the sum of energy loss resulting from displacement of surface clasts (ΔE_C) and that resulting from mass-displacement of the regolith (ΔE_D) :

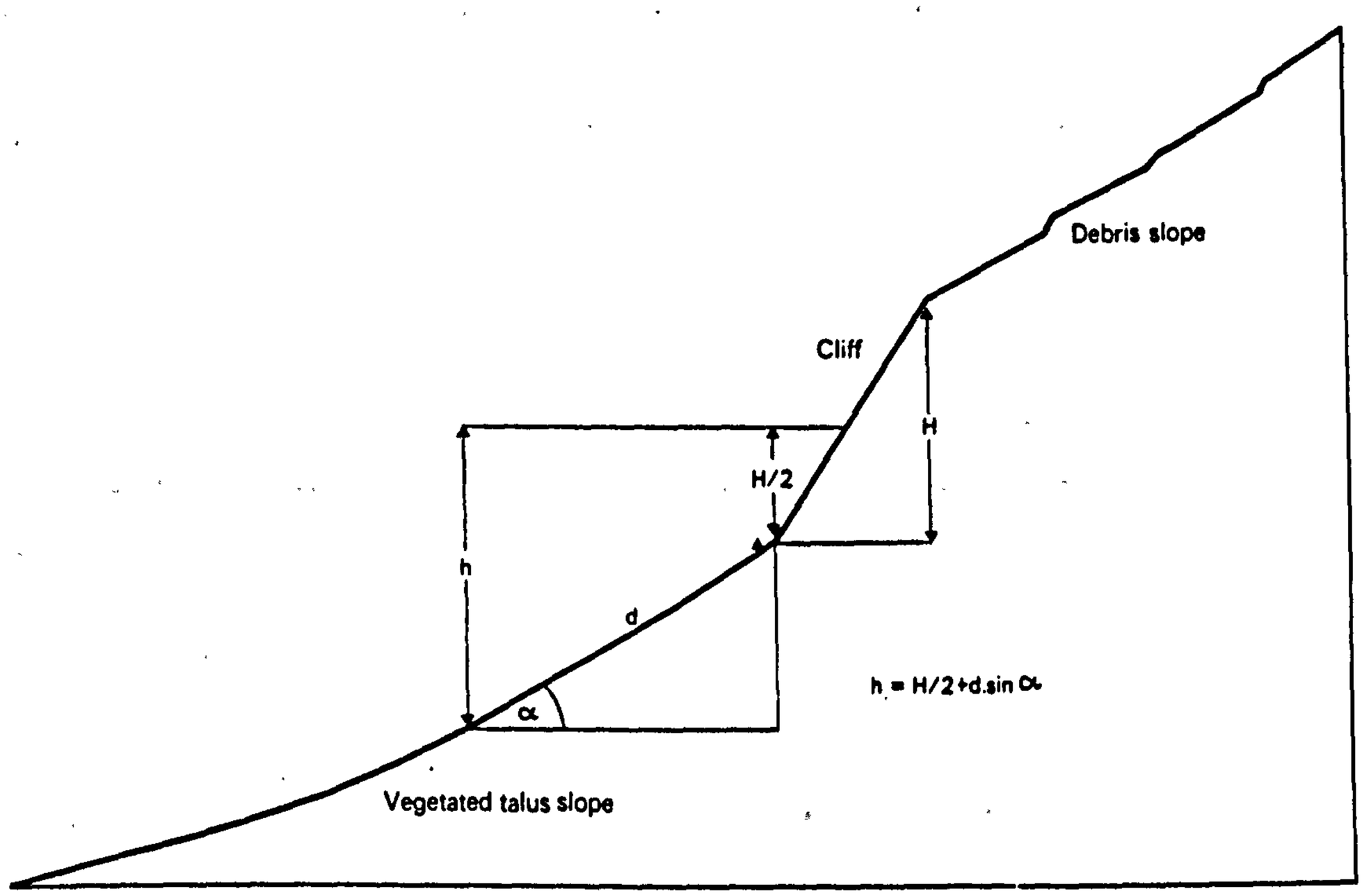


Figure 13.1: Derivation of h, the height of fall in equation 13.6.

$$\Delta E_F = \Delta E_C + \Delta E_D \qquad (13.7)$$

For any single surface clast, the energy loss that accompanies downslope movement is given by

$$\Delta E_C = m \cdot g\,(d \sin \alpha) \qquad (13.8)$$

where m is mass, d is displacement and α is surface gradient. The mean energy loss $\overline{\Delta E_C}$ for n measured clasts is

$$\overline{\Delta E_C} = \frac{g}{n} \sum_{i=1}^{n} m_i\,(d_i \sin \alpha_i) \qquad (13.9)$$

At the measurement sites, the displacement and axial dimensions of every second clast were measured. The mean concentration of clasts per square metre of ground surface (C) is therefore given by

$$C = \frac{4\,n^2}{W^2} \qquad (13.10)$$

where W is the sum of the widths (in metres) of all measurement sites. Combining equations 13.9 and 13.10 and adjusting for an area of 1 km^2 gives

$$E_C = \frac{4ng}{W^2} \cdot \sum_{i=1}^{n} m_i\,(d_i \sin \alpha_i) \times 10^6 \ jkm^{-2} \qquad (13.11)$$

where the m_i are evaluated from axial measurements according to equation 13.5.

Downslope movement of the ground surface was measured by recording the displacement of 3" and 6" nails inserted in the soil. Displacement was found to decline approximately exponentially with depth (figure 9.44). Assuming an exponential decline in displacement with depth, displacement at depth z (d_z) is related to displacement at the surface (d_o) as

$$d_z = d_o\, e^{-rz} \qquad (13.12)$$

where r is a constant reflecting rate of decline with depth. For the nine measured profiles (figure 9.44) the mean depth at which displacement declined to zero was 110 mm. Assuming $d_z = 0$ when z = 110 mm, the "area of displacement" (a) under the velocity profile described by equation 13.12 is given by

$$a = d_o \int_{-110}^{0} e^{rz} \cdot dz \qquad (13.13)$$

which on integration yields

$$a = \frac{d_o}{r} (1 - e^{-110r}) \qquad (13.13a)$$

For the nine measured profiles, the displacement at 40 mm depth (d_{40}) was on average equal to 0.256 d_o. Substituting 40 for z and 0.256 for d_z in equation 13.12 gives a value of 0.034 for r; substituting this value in equation 13.13a gives

$$a = \frac{d_o}{0.034} (1 - e^{-3.74})$$

$$= 28.713\ d_o$$

Using this value for a, energy loss accompanying downslope movement of the regolith may be calculated from the mean value of (a sin α) for all measured displacements of 3" and 6" nails using the expression

$$\Delta E_D = \frac{q \cdot g}{n} \cdot \sum_{i=1}^{n} a_i \sin \alpha_i \times 10^6 \text{ j km}^{-2} \qquad (13.14)$$

where q is the bulk density of the regolith. Five samples of regolith had mean bulk density 1.808 g cm^{-3} (1808 kg m^{-3}); 1.8 g cm^{-3} was substituted for q in the calculations.

The annual loss in potential energy resulting from frost creep was calculated separately for unvegetated debris slopes and terraced debris slopes using equations 13.11 and 13.14 to evaluate creep of surface clasts and creep of regolith respectively. The results are summarized in table 13.1.

13.2.3 Solifluction

Only a rough estimate of energy loss resulting from solifluction could be made because of the limited data available. Over the period August 1976 to July 1977, two solifluction lobes on steep slopes on Ben Wyvis experienced surface displacements averaging 3.9 mm (on a 27° slope) and 4.7 mm (on a 29.5° slope) (figure 9.32). Assuming

Table 13.1

Energy loss resulting from frost creep on unvegetated debris slopes and terraced debris slopes on An Teallach

	ΔE_C (10^6 j km^{-2})	ΔE_D (10^6 j km^{-2})	ΔE_F (10^6 j km^{-2})	P (W km^{-2})
Debris slopes				
1976-7	4.580	0.734	5.314	0.168
1977-8	4.633	0.707	5.340	0.169
1978-9	5.039	0.886	5.925	0.188
Mean (1976-9)	4.750	0.776	5.526	0.175
Terraced debris slopes				
1976-7	0.734	0.444	1.178	0.037
1977-8	0.713	0.376	1.089	0.035
1978-9	0.777	0.382	1.159	0.037
Mean (1976-9)	0.741	0.401	1.142	0.036

that these measurements represent total annual displacement and that displacement declines approximately linearly with depth (Williams, 1966; Benedict, 1970; Harris, 1977), the energy loss (ΔE_L) implied by the above measurements may be calculated as

$$\Delta E_L = q.g. \frac{z'}{2} (\bar{d}_o \sin \alpha) \times 10^6 \text{ j km}^{-2} \qquad (13.15)$$

where q is bulk density (assumed to be 1.8 g cm^{-3}), z' is maximum depth at which movement occurs and $\bar{d}_o$ is mean surface displacement. For the lobe on the 27° slope this calculation gives a figure of (1.567×10^7) z' j km^{-2}; the equivalent figure for that on the 29.5° slope is (2.046×10^7) z' j km^{-2}. The mean value is (1.807×10^7) z' j km^{-2}. The maximum depth at which movement takes place (z') is unknown, but on the assumption that it is equivalent to the depth of frost penetration is likely to lie in the range 0.1-0.3 m or even deeper. If z lies in the range 0.1-0.3 m, the potential energy loss per square kilometre implied by the mean value given above falls in the range $(1.807\text{-}5.421) \times 10^6$ j km^{-2}, or 0.057-0.172 W km^{-2}. This range, however, applies only to solifluction on steep slopes; no movement was recorded on a lobe on a 15° slope during the same period.

13.2.4 Aeolian transport

In section 11.4, mean concentration of windblown sand on latelying snow in Coire nan Tota was calculated to be 57.8 g m^{-2}, equivalent to a mass of 9346 kg deposited over an area of 161700 m^2. The energy loss that resulted from the removal of this volume of sand from its source on the plateau (ΔE_A) was calculated as

$$\Delta E_A = m\ g\ (\bar{h}_s - h_d) \times \frac{10^6}{A_s} \text{ j km}^{-2} \qquad (13.16)$$

where m is the mass of transported sand (9346 kg), and A_s and $\bar{h}_s$ are respectively the estimated area and the area-weighted mean altitude of the source of the sand (i.e. the plateau windward of Coire nan Tota). As the concentration of blown sand declines exponentially in a north-easterly direction (figure 11.3, diagram B), the altitude above and below which 50% of the sand was deposited (h_d) was calculated first as a distance N.E. from the edge of the plateau by substituting the mean concentration (57.8 g m^{-2}) for C_a in equation 11.1a (section

11.4). The calculated distance is 149 m, corresponding to an altitude of 712 m. From map measurements A_s was estimated as 435,000 m^2 and $\overline{h}_s$ was calculated to be 771 m. Substitution of these values in equation 13.16 yields a value of 12,423,467 j km^{-2} for ΔE_A, equivalent to 0.394 W km^{-2}.

13.2.5 River transport

In section 12.4.2 the mean annual suspended load and mean annual dissolved load transported by Ardessie Burn were calculated to be 124600 kg and 689500 kg respectively. Caine (1976) suggested that when the provenance of the transported material is unknown, energy loss associated with fluvial transport be calculated by substituting the area-weighted mean altitude of the catchment for h_1 in equation 13.1. This procedure was followed here: the area-weighted mean altitude of the Ardessie Burn basin was calculated to be 563 m, and h_2 was assumed to be zero (sea level). Substitution of 124600 kg and 689500 kg for m in equation 13.1 yielded corresponding energy losses of 5.142×10^7 j km^{-2} y^{-1} and 2.845×10^8 j km^{-2} y^{-1}, equivalent to 1.629 W km^{-2} (for transport of suspended sediment) and 9.017 W km^{-2} (for transport of dissolved solids).

13.3 Discussion

Few attempts have been made to compare the relative effectiveness of different agencies of mass transport in mountain areas. The most comprehensive studies relate to the Alps (Jackli, 1957), northern Scandinavia (Rapp, 1960a) and the San Juan mountains in Colorado (Caine, 1975, 1976), all "alpine" periglacial environments. The results of these studies and those of the calculations described above are summarized in table 13.2 in the form of W km^{-2}. Some of the figures were obtained from an earlier summary that employed the same units (Caine, 1976, table 2), others from a summary by Luckman (1977, table 2) in which these data were expressed in kg . m / m^2 / y (not kg / m per km^2, as Luckman stated), a form readily converted to W km^{-2}. Before comparing these results, however, it is necessary to consider the representativeness of the data used in their derivation and the influence of relief and slope on the results obtained.

Table 13.2: Measured rates of mass-transport activity for various mountain environments (W km^{-2})

Study area:	Northern Scotland	Upper Rhine	Karkevagge (N. Sweden)	William's Lake (Colorado)	Eldorado Lake (Colorado)
Original source:	This study	Jackli, 1957	Rapp, 1960a	Caine, 1975	Caine, 1975
Processes:					
Rockfall	1.689	1.047	0.405	0.133	0.050
Avalanches	-	3.298	0.463	0.001	0.002
Landslides, earth slides & debris flows	-	18.353	1.997	0.362	0.075
Frost creep	0.036 0.175	-	-	-	-
Solifluction	0.057-0.172	-	-	-	-
Slow mass movement	-	1.739	0.166	0.109	0.004
Surface wash	localized	-	slight	0.147	0.013
Wind	0.394	-	-	-	-
Dissolved salts	9.017	87.604	2.828	0.104	0.047
Suspended sediment	1.629	307.3	-	-	-

The rockfall figure for An Teallach relates to debris falling from a relatively low cliff flanked by vegetation-covered talus in Coire a'Mhuilinn. The rockfall inventory data relating to the steeper, higher cliffs of Glas Tholl (figure 8.14), together with the occurrence of "active" unvegetated talus at the foot of these cliffs suggest that rates of rockfall in the eastern corries of An Teallach are much greater than those measured in Coire a'Mhuilinn. The figure obtained for the latter locality is therefore a conservative estimate, particularly as it does not take into account infrequent falls of high magnitude.

The frost creep data are probably more representative, being based on three years' measurement of a large number of markers. The similarity of the rates measured for each of the three years (table 13.1) also suggests that the mean figures are reasonably representative of long term averages. As noted in section 13.2.3, however, the figures given for energy loss accompanying solifluction on Ben Wyvis can only be considered rough approximations, as the depth to which displacement occurred was unknown and as the figure obtained is based on a relatively small number of measurements relating to a single year's movement.

The estimate of energy loss associated with aeolian transport is probably conservative, as it was calculated on the basis of winter transport only. This is unlikely to be a serious source of error, however, as rates of transport during the summer are probably much lower than those during the winter (section 11.4). More seriously, the estimate is based on a small sample of measurements of supranival sand concentration relating to a single winter's accumulation. Finally, transport of large quantities of sand by wind is restricted to certain lithologies (section 11.2), and is not a typical feature of upland environments in Great Britain.

The weaknesses of the river load data were discussed earlier (section 12.4.3). In particular, the figure for energy loss associated with the transport of dissolved solids must be considered an overestimate as the solute load figure on which it was based includes a component of unknown magnitude contributed by precipitation rather than solution within the catchment.

In sum, it is reasonable to consider the estimates of energy loss only as individual "samples" that are indicative of (but not

necessarily representative of) long-term averages. The rockfall and aeolian transport figures are probably conservative estimates, and the figure for transport of dissolved solids is certainly an over-estimate. Moreover, with the exception of the solifluction figures, these estimates relate to mass-transport activity on Torridon Sandstone terrain and connot be assumed to be representative of other lithologies.

As Caine (1976) pointed out, some energy loss estimates (rockfall and fluvial transport) are directly dependent on relief, and differences in relief must be taken into account when comparisons are made between different areas. Thus, given equal rates of activity, the rockfall and river transport figures for An Teallach would be expected to be higher than those obtained by Caine for small basins with relatively low relief and lower than those calculated for the Alps and Karkevagge. Slope also affects some results through the inclusion of a sin α term in the equations used to calculate slow mass-movement; irrespective of downslope displacement (which in some cases is positively correlated with slope; section 8.4.5), the steeper the slope on which surface displacement is measured, the larger the vertical component of displacement. Finally, it is necessary to treat the figures relating to Jackli's (1957) study in the Alps with caution. The area studied was vast (4307 km^2) and most of Jackli's estimates are very rough approximations and extrapolations.

Of the slope processes measured on An Teallach, rockfall is clearly dominant, resulting in energy-loss values an order of magnitude greater than those resulting from slow mass-movement. This dominance may be considered a result of adjustment of the essentially glacial landscape to nonglacial conditions through the replacement of over-steepened rockwalls by relatively stable accumulations of talus. The figure for energy loss associated with transport of suspended sediment probably also reflects modification of the glacial landscape, in this case through erosion of riverbank exposures of till (section 12.4.3).

The rockfall figure is also larger than those estimated for the Alps, Karkevagge and Colorado. Although the Colorado figures may be expected to be lower on account of the lower relief of Caine's study areas, it is surprising that the An Teallach figure (which is probably a low estimate) should exceed those for the Alps and Karkevagge. In the author's experience rockfall from cliffs in the Jotunheimen Massif in Norway and the Aravis Range in the western Alps

is at least as frequent during the summer months as that from the cliffs of Glas Tholl. If this is true, as seems likely, of Karkevagge and the upper Rhine, it implies higher energy losses in these areas than on An Teallach (where the cliffs are lower) and suggests that the values calculated for the Alps and Karkavagge are underestimated.

The figure for frost creep on unvegetated slopes on An Teallach (0.175 W km^{-2}) lies close to the estimate for slow mass-movement in Karkevagge (0.166 W km^{-2}). The latter also falls near the upper end of the range of values estimated for solifluction on steep slopes on Ben Wyvis (0.057-0.172 W km^{-2}). This suggests that slow mass-movement operates at similar rates on the mountains of northern Scotland and on those of northern Scandinavia. A further similarity between the Scottish and Scandinavian data is the apparent overall predominance of transport of dissolved solids as an agent of mass-transport, although the Scottish figure must be considered an overestimate for the reasons given earlier.

In sum, the figures highlight the importance of rockfall and possibly transport of dissolved salts in the present denudation of An Teallach. Fluvial transport of material in suspension is difficult to evaluate as much of the suspended load is probably derived from erosion of till deposits in relatively low parts of the basin (400-450 m). Wind is effective in removing material (mainly sand) from exposed plateaux, but is only of importance above c. 500 m and on certain rock types; on lithologies other than sandstone and granitic rocks wind is probably of negligible importance as an agent of mass-transport. Surficial frost creep operates at relatively low rates even on unvegetated debris slopes, and is even less effective on partly-vegetated terrain (i.e. terraced debris slopes). Solifluction on steep slopes probably operates at rates similar to those of surficial frost creep. In general, the figures obtained for rates of mass-transport activity on An Teallach are of the same order of magnitude as those measured by Rapp (1960a) in northern Scandinavia, and the relative importance of different agents is also similar.

Although not assessed, the contribution of wash to denudation on An Teallach is likely to be small, as effective wash is localized and transports material only short distances (section 12.2.2). On lithologies on which vegetation cover is more complete (e.g. the Moinian rocks of Ben Wyvis) wash is probably even less important. Debris flow, also

not assessed, is probably a more potent agent of mass-transport in view of the transport distances and relatively large masses involved. Much depends on the frequency of debris flow activity, but although flow events are not uncommon (section 9.5.2.2) data on flow frequency are not available. In some areas of the Scottish Highlands (e.g. the Lairig Ghru) the abundance of recent debris flows suggests that this may be the dominant form of mass-transport presently operating on some slopes. A great deal more data are required on rates of mass-transport activity on the mountains of Great Britain before the role of different agents can be evaluated on a country-wide basis.

CHAPTER 14 SYNTHESIS AND CONCLUSIONS

14.1 Introduction

The aim of this study, as stated in section 1.2, was to establish the characteristics of past and present periglacial landforms, deposits, processes and environments on high ground in a sample area of the Scottish Highlands. This chapter constitutes both a synthesis of the findings of the study and a discussion of the major themes that have emerged.

One of the fundamental objectives of the study identified in section 1.2 was establishment of the range of periglacial phenomena that occur on British mountains. An *a priori* classification of these phenomena was presented in chapter 7. This classification, however, was of necessity generic rather than genetic, and during the course of subsequent discussion it sometimes proved necessary to redefine the initial classes. The first part of this synthesis is therefore devoted to presentation and discussion of a revised classification that groups landforms according to their age and genesis on the basis of the findings of the study (section 14.2).

In terms of age, the great majority of landforms investigated were found to fall into two major categories: those that appear to have been inactive since the end of the Loch Lomond Stadial, and those that are active at present. Little evidence was found in support of the hitherto widely-held view that climatic deterioration during the Little Ice Age initiated a renaissance of periglacial morphogenesis that resulted in the formation of features that are now inactive. It is therefore possible to relate most upland periglacial phenomena to one of two radically different climatic environments: that of the Lateglacial cold periods, and that of the present day. The characteristics of periglacial activity on the mountains of upland Britain during the Lateglacial cold periods are summarized in section 14.3, and a synthesis of present-day activity is presented in section 14.4. The final section (14.5) is devoted to discussion of some of the most important themes that have emerged from the study, the wider implications of upland periglaciation in terms of landscape development and directions for future research.

14.2 Towards a genetic classification

The discussions of landform genesis in chapters 8-12 revealed several weaknesses in the a priori classification outlined in chapter 7. Some forms of differentiation (e.g. vegetation cover on sheets and lobes) were shown to have little or no genetic significance, whilst some superficially similar features (such as the Ben Wyvis and An Teallach hummocks) were demonstrated to be genetically distinct. Such findings necessitated ad hoc terminological revision in the course of each chapter. Furthermore, some of the original terms employed introduce unnecessary ambiguities. The original scheme therefore requires modification if it is to provide a foundation for a genetic classification on which future mapping and research may be based. Suggested changes are summarized in table 14.1 and discussed below.

1. Slopes (section 7.3.2)

It is suggested that the term "debris-mantled slope" be substituted for "debris slope" as the latter has been used in a rather different context by some authors (e.g. Howarth and Bones, 1972).

2. Mass-movement features (section 7.3.3)

(i) Sheets, lobate sheets and lobes were originally subdivided into five groups on the basis of vegetation cover or constituent material, but only three genetically distinct groups were identified in the analysis (section 9.2.8), namely "massive boulder", "shallow boulder" and "solifluction" sheets and lobes. It is suggested that henceforth these types be referred to as "boulder", "debris" and "solifluction" features respectively.

(ii) Four forms of terrace - "horizontal", "lobate", "oblique" and "interconnecting" - were differentiated in the initial classification. Lobate terraces were subsequently recognized as merely morphological variants of the horizontal type, but two genetically distinct types of horizontal terrace were distinguished, namely "deflation terraces" and "normal terraces" (aligned respectively parallel and at right angles to dominant wind direction). There therefore appear to be three genetically-distinct types of turf-banked terraces (deflation, normal and oblique; section 9.3.5). The term "intersecting terrace" is, however, retained to describe features that result from interaction

Table 14.1

Changes in classification or terminology

Original term or grouping	Revised term or grouping
Debris slopes	Debris-mantled slopes
Vegetation-covered sheets & lobes	
Turf-banked sheets & lobes	Boulder sheets & lobes
Stone-banked sheets & lobes	Debris sheets & lobes
Boulder sheets & lobes	Solifluction sheets & lobes
Debris sheets & lobes	
Horizontal terraces	Normal and deflation terraces
Lobate terraces	(deleted)
Debris chutes	Debris flows
Slump features	Shallow slide features
(not represented)	Avalanche boulder tongues
Sorted polygons	Sorted circles
Sorted garlands	(deleted)
Turf hummocks	Earth hummocks
	Sand hummocks
Nonsorted stripes	Relief stripes
Wind stripes	Parallel wind stripes
	Normal wind stripes
Aeolian sand deposits	Sand sheets

of normal and oblique terraces.

(iii) The term "debris chute" is replaced by "debris flow", as most authorities consider "chute" to represent a gulley, usually rock-cut (personal communications from A. Kotarba, B.H. Luckman and A. Rapp, 1980). Similarly, the term "slump feature" is replaced by "shallow slide feature", which provides a more accurate reflection of the nature of slope failure and mass-movement associated with this landform type (section 9.5.2.1).

(iv) Convincing examples of avalanche boulder tongues of apparently recent origin were found in the Lairig Ghru (Cairngorms) after the initial classification was drawn up (B.H. Luckman, personal communication, 1979). This category is added to the revised classification scheme.

3. Patterned ground features (section 7.3.4)

(i) The term "sorted polygon" is replaced by "sorted circle" as "polygon" has misleading genetic implications when applied to features that are essentially circular, oval or irregular in plan (Washburn, 1979, p. 123; section 10.2).

(ii) The category of "sorted garlands" is deleted as superfluous; the transition from sorted circles to sorted stripes as gradient increases takes several forms, of which the appearance of poorly-defined garlands is but one.

(iii) The features described as "turf hummocks" were found to include two genetically distinct types: apparently fossil forms resulting from mass displacement (as on Ben Wyvis) and features formed by sand accumulation and selective eluviation (as on An Teallach). The two types are reclassified as "earth hummocks" and "sand hummocks" respectively. The term "relief stripes" is substituted for "nonsorted stripes" to distinguish "ridge and furrow" features from stripes defined by vegetation (nonsorted stripes sensu Washburn, 1956a, p. 837). In section 10.3, the former type was interpreted as having developed from the latter, examples of which have not been documented in upland Britain.

(iv) The category of "wind stripes" is subdivided to differentiate wind stripes aligned parallel to dominant wind direction ("parallel wind stripes") and those aligned across the

direction of the dominant wind ("normal wind stripes").

4. Miscellaneous (section 7.3.5)

The term "aeolian sand deposits" is inappropriate as these deposits result primarily from niveo-aeolian deposition. The alternative term "sand sheets" is suggested.

Any attempt to classify the periglacial features of upland Britain on the basis of age (or activity) and formative processes runs into two problems. First, although most types of feature are either of Lateglacial age or are active at present (and have presumably been active during much of the Flandrian), there are a number of exceptions. Debris slopes and debris lobes formed during the Lateglacial cold periods yet experience slow mass-movement under present conditions. Debris terraces and vegetation-defined non-sorted stripes of presumed Lateglacial age are thought to have been modified during the Flandrian to form normal turf-banked terraces and relief stripes respectively; the former are subject to mass-movement at present, the latter appear to be inactive. Finally, some features that may have formed earlier in the Flandrian are now largely inactive (e.g. vegetation-covered terraces and some patterned ground features).

The second problem is that many periglacial features reflect the operation of two or more processes. Turf-banked terraces, for example, are formed through a combination of wind action, frost heave and needle ice action, and sand hummocks are produced by the operation of both niveo-aeolian deposition and wash. Straightforward grouping of features in terms of either age and / or dominant process is therefore impossible.

In an attempt to overcome these problems, Ball and Goodier (1970) devised a classification for periglacial features in Snowdonia that allowed for various combinations of three basic processes (gelifraction, gelifluction and cryoturbation) and three formative periods (Lateglacial, recent historic time, present-day). A similar approach is adopted here (table 14.2), although the number of "process" categories is expanded to thirteen and only two formative periods are distinguished (Lateglacial and Flandrian / present-day) in view of the paucity of evidence for a marked increase in periglacial morphogenesis during "recent historic time" (i.e. the Little Ice Age).

The genetic classification presented in table 14.2 was constructed in the following manner. Different types of feature were first grouped in six "process groups" (frost weathering; rapid mass-movement; slow mass-movement; frost sorting or mass displacement; wind action; the action of snow or running water) that reflect the major form of activity responsible for the formation of each type. For each type of feature period of formation was first identified by means of crosses placed in columns labelled "Lateglacial" and "Flandrian / Present"; a question mark was used to indicate uncertainty. The dominant processes influencing each type of feature were then identified using a system of numbers to indicate when these processes have been operative. The number 1 indicates Lateglacial activity only; 2 denotes activity during the Flandrian and / or at present; 3 represents activity during all the above periods. A question mark is again used to indicate uncertainty.

One advantage of this system is that it allows periods of formation and periods of activity to be distinguished, so that it provides an economic description of the "history" of given features. Debris surfaces, for example, are described as having formed through a combination of macrogelivation, microgelivation, frost heave and frost sorting during the Lateglacial cold periods, with microgelivation, frost heave, deflation and wash operating on such surfaces during the Flandrian and / or at present. Another advantage of this form of classification is that it provides a convenient summary of the findings of the study concerning the age of periglacial features and the processes responsible for the creation or modification of these features.

14.3 Lateglacial periglaciation in upland Britain

Much of the fascination of studying periglacial phenomena on the mountains of Great Britain stems from the juxtaposition of features that are active and forming under the present rather mild "maritime periglacial" climatic regime with others that formed under the much more severe conditions of the Lateglacial cold periods. The periglacial features that form the subject of the study are therefore the products of two distinct climatic regimes, two environments so radically different that few of the features studied are common to both. This

Table 14.2: Genetic classification of periglacial landforms

(for explanation see text)

	Lateglacial	Flandrian / Present	Macrogelivation	Microgelivation	Rockfall	Slope failure & flow	Avalanches	Solifluction	Frost heave, mass displacement	Needle ice action	Frost sorting	Deflation	Wash	Rock glacier creep	Niveo-aeolian deposition
Frost-weathered regolith															
Debris surfaces, stone pavements	x		1	3					3		1	2	2		
Blockfields, blockslopes	x		1	2					1		1				
Debris-mantled slopes	x		1	3				3	3	2	1	2			
Tors, rock outcrops	x		1	3											
Rapid mass-movement features															
Talus sheets and cones	x	x	1		3		?								
Protalus ramparts	x		1		1										
Debris flows, shallow slides	?	x				3									
Avalanche tongues	?	x					3								
Slow mass-movement features															
Rock glaciers	x				1										1
Boulder sheets and lobes	x								1		1		2		
Debris sheets and lobes	x							3	1		1		2		
Solifluction sheets and lobes		x						2	2						
Ploughing boulders		x						2	?						
Blockstreams, debris streams	x							?	1		?		?		
Normal terraces		x						?	2	2		2			
Deflation terraces		x						?	2	2		2			
Oblique terraces		x						?	2	2		2			
Interconnecting terraces		x						?	2	2		2			
Debris terraces	x	?							3	2					
Vegetation-covered terraces		x						?	2	2		2			
Steps		x							2	2		2			

Table 14.2 (continued)

	Lateglacial	Flandrian / Present	Macrogelivation	Microgelivation	Rockfall	Slope failure and flow	Avalanches	Solifluction	Frost heave, mass displacement	Needle ice action	Frost sorting	Deflation	Wash	Rock glacier creep	Niveo-aeolian deposition
Frost sorting and mass displacement															
Large sorted circles	x	x							↓		↓		?		
Large sorted stripes	x								1		1		?		
Small sorted circles	x	x							3	?	3				
Small sorted stripes	?	x							2	2	2		2		
Earth hummocks	x	?							3				?		
Hummock and relief stripes	x	?							3				?		
Features produced by wind action															
Deflation surfaces	?	x								2		2	2		
Wind stripes and crescents	?	x								2		2			
Sand sheets		x		2											2
Sand hummocks		x											2		2
Features produced by the action of snow or running water															
Nivation hollows	x	x		?				?		2			3		
Sand scarps		x								2			2		
Colluvial cones	?	x											2		

section and that which follows summarize the characteristics of periglaciation on British mountains during the Lateglacial period and under the present climatic regime. As climatic changes during the Flandrian have been relatively slight, present geomorphic activity is probably fairly representative of the Flandrian period as a whole, although the intensity of such activity may have been greater during periods of cooler climate (e.g. the Little Ice Age) and less when conditions were warmer (e.g. the climatic optimum). There is no evidence, however, to indicate that the nature of periglacial activity changed significantly during the Flandrian. Both summaries are based mainly on the finding of this study, but information from previous research is included where appropriate; the relevant references appear in chapter 3. The mountain landforms characteristic of Lateglacial periglaciation are illustrated in figure 14.1, and those formed during the Flandrian in figure 14.2.

Although little is known about the climatic conditions that accompanied ice-sheet downwastage, reconstruction of some of the main features of mountain climate during the Loch Lomond Stadial suggests that the upland environment of northern Britain at this time was a periglacial environment par excellence. Ground above 600 m experienced an annual temperature regime reminiscent of those of present-day high arctic environments and characterized by intense, prolonged winter freezing and a much greater range of mean monthly temperatures than at present. Precipitation, however, was probably higher than in most arctic areas (at least on western hills), and a combination of abundant nival meltwater with high insolation and near-zero air temperatures during the brief summer period probably resulted in widespread freeze-thaw activity. As much of the winter snow was blown from exposed slopes and plateaux to nourish glaciers, high ground must often have been exposed to very low air temperatures. Vegetation cover on high ground was probably sparse and permafrost ubiquitous, with a deeper active layer and more effective freeze-thaw activity on south-facing than on north-facing slopes.

The abrupt contrast in the degree of frost weathering between mountain terrain that lay within the limits of the Loch Lomond Advance glaciers and that which was exposed to periglacial weathering at this time indicates that the Lateglacial climatic regime was highly conducive to the mechanical breakdown of bedrock. This took two forms: macrogelivation (the prising apart by expanding ice of

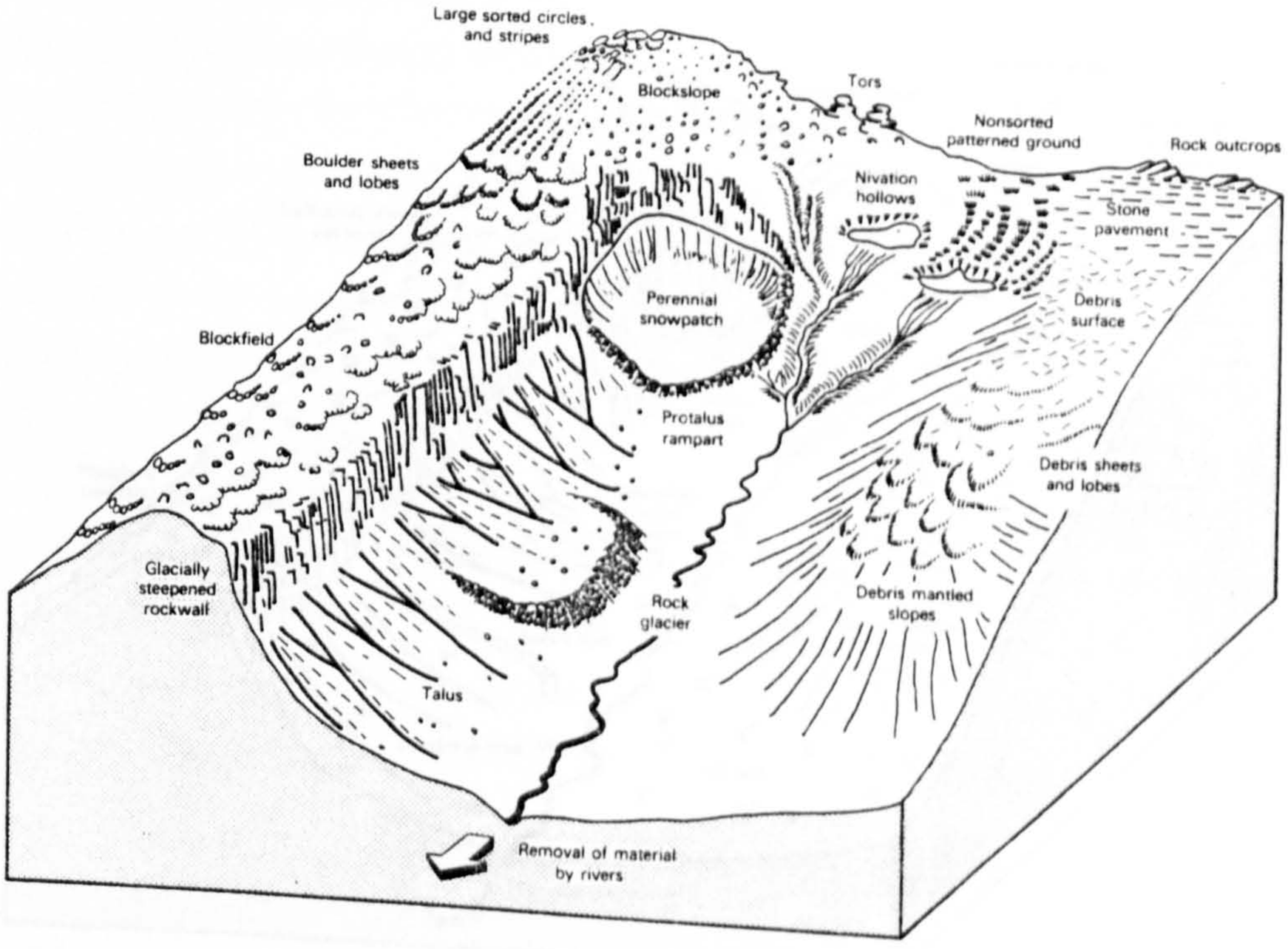


Figure 14.1: Periglacial features formed on British mountains during the Lateglacial cold periods.

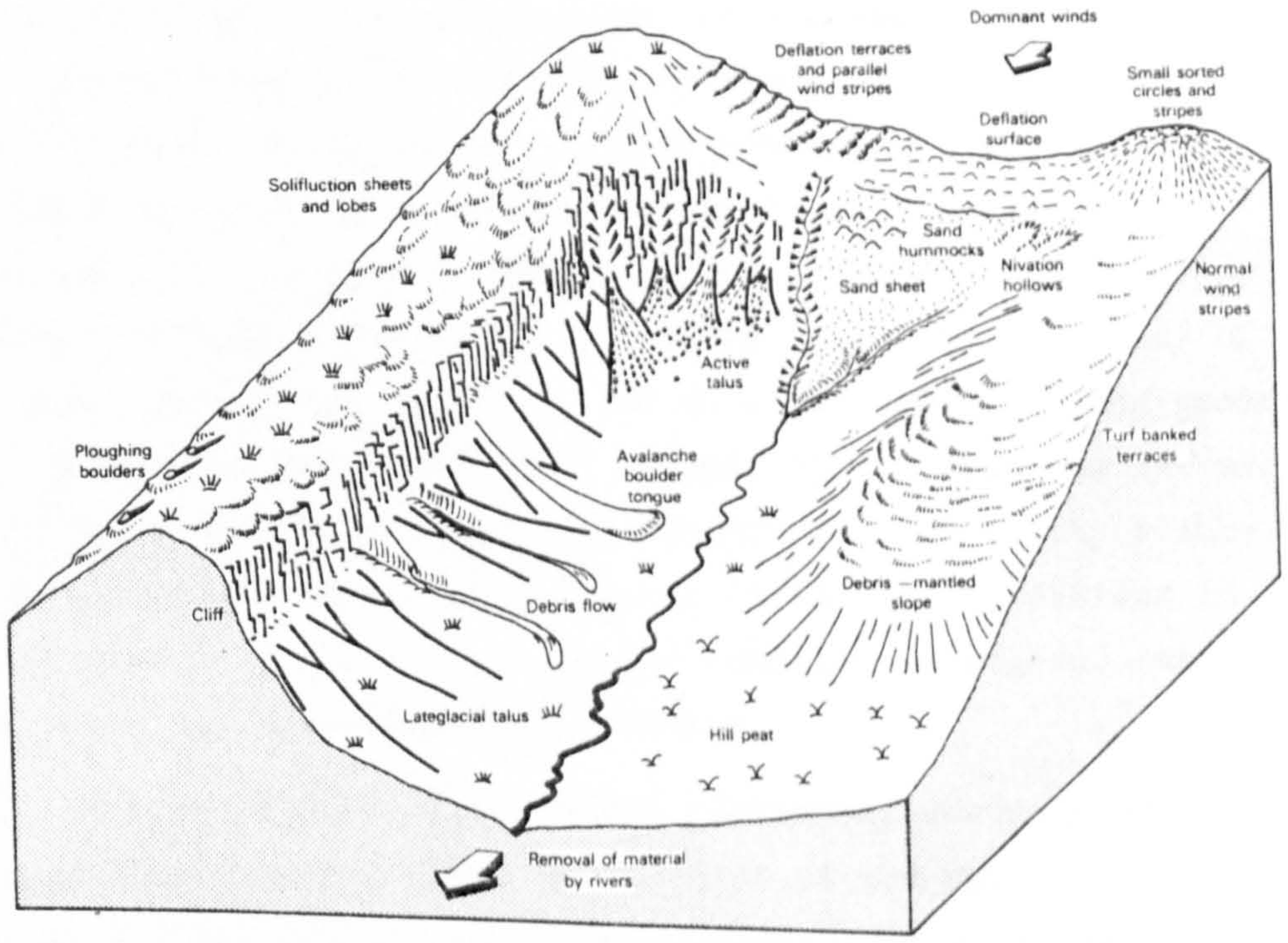


Figure 14.2: Periglacial features formed on British mountains during the Flandrian and active under present-day conditions.

rocks along lines of weakness such as joints and bedding planes) and microgelivation (granular disintegration and flaking). Macrogelivation was probably accelerated by the opening of dilation joints normal to the ground surface as a result of the unloading that accompanied downwastage of the Late Devensian ice-sheet. The relative effectiveness of these two forms of frost weathering and the nature of weathered products were largely conditioned by lithology. Well-jointed, fine-grained rocks such as quartzite, microgranite and siliceous schist were affected mainly by macrogelivation, yielding dominantly clastic detritus. Torridon Sandstone, micaceous schists and granite were often less resistant to microgelivation, partly on account of their greater porosity but probably also because the bonding between grains is weaker. As a result, Lateglacial weathering of these rocks on high ground yielded a diamicton of clasts embedded in a matrix of fines. The granulometry of the matrix strongly reflects grain or crystal size in the unweathered rock. Torridon Sandstone and granitic rocks weathered to a coarse sandy grus, whereas micaceous schists generally yielded a matrix of much finer material with a clay-silt component generally exceeding 10%. The shape of clasts produced by macrogelivation tends to reflect relative frequency of initial lines of weakness parallel and at right angles to the ground surface. Where the former are more closely-spaced than the latter (e.g. with most schists and Torridon Sandstone), dominantly slabby clasts are produced; when joint spacing is fairly equidistant in bothdirections (e.g. with fine-grained Cambrian Quartzite) the resultant detritus is predominantly blocky.

The products of Lateglacial frost weathering accumulated to form a mantle of detritus that covered most of the upper slopes and plateaux of British mountains, often completely burying the underlying bedrock except where tor-like outcrops protruded above plateau surfaces or where gradients exceeded about 40°. This "mountain-top detritus" rarely reaches great depths, however. On plateaux it is usually less than one metre thick, and although slope deposits may accumulate to greater thicknesses (a depth of 3.5 m has been reported for a site in the Southern Uplands) these often form no more than a veneer that is thickest on rock steps and in hollows. The overall effect is a smoothing of the terrain inherited from glaciation.

Two main categories of Lateglacial mountain-top detritus may be distinguished, namely blockfields and blockslopes (which are

characterized by a lack of fines at the ground surface) and debris surfaces and debris-mantled slopes (in which a matrix of fines occurs throughout the deposit). Both types are essentially autochthonous, both are restricted to high ground outside the limits of Loch Lomond glaciers and the distribution of both is strongly conditioned by lithology. The block deposits reflect the dominance of macro-gelivation on rocks such as quartzite and microgranite; the debris deposits reflect the efficacy of ~~microgelivation~~ granular disintegration on lithologies such as mica-schist and Torridon Sandstone. The plateau deposits (blockfields and debris surfaces) are essentially <u>in situ</u>, but fabrics measured on slope deposits (both blockslopes and debris-mantled slopes) have strong preferred downslope orientations indicative of movement. On An Teallach, a quartzite blockslope extends over 40 m downslope over Torridon Sandstone bedrock. As this blockslope has apparently been immobile for a long period of time, this movement probably occurred during the Lateglacial cold periods. Frost creep and solifluction are active on debris slopes, but present rates of movement are insufficient to account for the movement of quartzite clasts 600 m down an unvegetated debris slope on An Teallach during the Flandrian, and it seems likely that rates of movement on debris slopes were much greater during the Lateglacial cold periods than at present.

The structure of these deposits provides a strong clue as to the nature of Lateglacial mass-movement on blockslopes and debris slopes. The upper layers of bothedebris deposits and block deposits exhibit a fining-downward sequence indicative of repeated heaving and resettling of the entire deposit. On some debris surfaces this resulted in the formation of stone pavements, with clasts concentrated at the ground surface above a relatively stone-free layer of fines. Heaving of such deposits appears to have resulted from the annual freezing and expansion of ice in pore spaces and in voids between clasts, settling from the contraction and melting of such interstitial ice.

Below slopes steeper than about 40°, debris accumulated during the Lateglacial cold periods in the form of talus sheets and cones, many of which are now vegetation-covered and largely inactive. Although these are essentially the products of rockfall, the long trailing concavities that form the lower slopes of some Lateglacial taluses indicate modification resulting from the reworking of surficial

material by snow avalanches. Estimates of rockwall retreat based on the volumes of talus-foot rock glaciers and protalus ramparts range from 2.6-22.7 mm y^{-1} and suggest that rockfall rates during the Loch Lomond Stadial were very high.

Some of the most striking periglacial features on British mountains were formed by slow mass-movement of coarse detritus during the Lateglacial. The largest of these were rock glaciers that advanced from the base of talus slopes in the Cairngorms, the Lake District and the Isle of Jura, and at least one rock glacier apparently formed as the result of a massive landslide re-activating a Loch Lomond glacier.

Less spectacular but much more widespread are the sheets and lobes of coarse detritus that formed on the upper slopes of many British mountains during the Lateglacial cold periods. Two basic types may be distinguished, here termed boulder sheets and lobes and debris sheets and lobes. The former are more massive (generally 1-3 m thick, although they may reach 5.9 m in thickness) and tend to have relatively gently sloping risers (typically 20-30° on gentle and moderate slopes). Debris sheets and lobes rarely exceed 1.2 m in thickness and normally have much steeper risers (*c.* 50°). Both types, however, occupy slopes from approximately 6° to around 36°, both display a change in configuration from straight-fronted sheets on gentle slopes to lobate sheets on moderate slopes to over-riding sheets and individual lobes on steep slopes, and both are restricted in distribution to slopes that lay outside the limits of Loch Lomond glaciation. Boulder sheets and lobes have apparently been inactive since the end of the Loch Lomond Stadial, but the presence of palaeosol fragments, apparently of Flandrian age, under a debris lobe on Ben Wyvis suggests that some debris features at least continued to move during the Flandrian.

The differences between boulder features and debris features noted above are related to differences in internal structure. Boulder sheets and lobes consist primarily of a framework of large (sometimes very large) clasts. This framework may be open or partly infilled with fines but the fines do not form a true matrix and are often predominantly coarse-grained and non-frost-susceptible. Like block-slopes (on which boulder lobes are often best developed), boulder lobes exhibit a fining-downward sequence in their upper layers that is interpreted as indicative of movement by frost creep resulting from

annual expansion and contraction of the deposit associated with the formation and thawing of ice in voids.

Debris sheets and lobes are generally composed of rather smaller clasts. The uppermost openwork zone of these features also shows a fining-downward sequence but is relatively shallow and overlies a horizon in which clasts are embedded in a matrix of frost-susceptible fines. It seems likely that these features moved by a combination of frost creep and gelifluction, and that they experience intermittent solifluction during cold winters under present conditions.

The lower limits of boulder and debris sheets and lobes appear to decline northwards and westwards across upland Britain; the reason for this decline is not clear but it may relate to exposure. Boulder features appear to be best developed on south- and west-facing slopes (on which the Lateglacial active layer was presumably deepest).

Equally striking but much less common are some of the patterned ground features that formed during the Lateglacial cold periods. These include sorted circles or debris islands that are typically 2.0-3.0 m in diameter and associated sorted stripes of similar width. Such forms are most commonly found on blockfields or gently-sloping blockslopes and are indicative of deep annual freezing and probably permafrost. Smaller circles on An Teallach with diameters of 0.6-0.9 m also appear to be of Lateglacial age, as may be giant sorted polygons 15 m across reported on the Pennines.

Nonsorted patterned ground on the mountains of Great Britain includes earth hummocks, hummock stripes and relief stripes. These three types are genetically related and represent a continuum from hummocks on flat ground or very gentle slopes through hummock stripes to relief stripes on moderate to steep slopes. These forms appear to be relict and are interpreted as having evolved from Lateglacial forms defined by vegetation. If this interpretation is correct, it implies that some mountain areas experienced fairly arid conditions during the Lateglacial, as vegetation-defined patterned ground is best developed in arid arctic environments.

The most conspicuous Lateglacial landforms related to former perennial or latelying snowpatches are protalus ramparts, which occur in many mountain areas and indicate rapid rates of rockfall above stationary bodies of ice and snow of fairly stable dimensions. Small, apparently inactive nivation benches on Ben Wyvis are probably also of Lateglacial origin.

The periglacial landforms and processes that were active on the mountains of Great Britain during the Lateglacial correspond very closely with those identified by Washburn (1979, pp. 277-8) as typical of present-day subpolar highland environments. They are also characteristic of what Büdel (1948) termed the frost debris zone (Frostschuttzone). Active examples of the latter occur on the higher parts of the mountains of Iceland, Spitzbergen and Scandinavia (above c. 2000 m in south-central Norway and above c. 1000 m in northern Norway). Periglacial activity in such areas probably constitutes the closest present-day analogue for the Lateglacial periglaciation of upland Britain.

14.4 Present-day periglacial activity in upland Britain

The severity of the present-day climate on British mountains is related not to extreme cold nor to prolonged or frequent freezing, but to moderate cold combined with high precipitation and very strong winds. Mean annual temperatures exceed 0°C and even in midwinter temperatures lower than -10°C are infrequent on upland slopes and plateaux. Sub-zero air temperatures are rare between June and September, and there are fewer air freezing cycles than in most other periglacial environments (probably around 30-35 per year at 600-700 m). Most air freezing cycles are related to the alternation of relatively cold and relatively warm airmasses associated with the passage of frontal systems rather than to diurnal heating and nocturnal cooling. Even in midwinter, periods of freezing may be interrupted by above-zero temperatures.

In the absence of extremely low air temperatures, snowcover provides effective insulation against ground freezing; diurnal freeze-thaw cycles penetrate to only 5-6 cm depth in the absence of snow and are virtually eliminated when snowcover is present. More prolonged periods of sub-zero air temperatures may result in freezing of the ground to depths of 50 cm or more, although depth of ground freezing may be reduced (and period of freezing prolonged) by snowcover. "Annual" freeze-thaw cycles probably occur on high ground, but their existence has not yet been demonstrated.

Precipitation on the mountains of Great Britain is everywhere high, reflecting a general increase in wetness with altitude: on An Teallach, precipitation at 670 m is more than twice as great as that at sea-level. In winter, a large component of precipitation

falls as snow, but as the snowpack rarely accumulates to great thicknesses (except locally) because of winter thaws, and as spring melt is sporadic and protracted, snowmelt does not result in geomorphologically significant floods unless it is triggered by heavy rainstorms. Duration of snow-lie increases approximately linearly with altitude; on Scottish hills snow-lie between 600 m and 900 m lasts on average from 100-165 days per year. In favoured locations on the highest peaks small snowpatches may survive the summer.

Possibly the most distinctive climatic feature of the maritime periglacial environment of upland Britain is the strength of the wind. Wind plays a fundamental role in the formation of certain types of upland landforms and lays ground open to the action of frost and other agents by stripping snowcover and vegetation from exposed ground. On An Teallach, gusts of 40 m s^{-1} were recorded at 600 m, and gusts exceeding 50 m s^{-1} are probably not uncommon at higher altitudes.

Despite such high winds, vegetation cover is extensive on many hills, where it tends to limit the range of present periglacial activity. The main vegetation-free areas are slopes and plateaux of coarse mountain-top detritus, either block deposits or debris deposits with a coarse-grained matrix (e.g. on Torridon Sandstone and granitic rocks). Where present, hill peat also protects the ground from most forms of present-day geomorphic activity. Peat occurs up to 900 m on some hills but is often absent or extremely localized above 700 m.

Under the present comparatively mild climatic regime frost weathering is largely restricted to microgelivation, although freshly-cracked clasts are very occasionally found on some lithologies. The operation of ~~microgelivation~~ granular disintegration during the Flandrian is most evident in the contrast in angularity between the exposed and buried portions of clasts on debris surfaces and blockslopes. Lithologies on which rounding of exposed surfaces is most pronounced (e.g. Torridon Sandstone and coarse-grained basal Cambrian Quartzite) were found to be most susceptible to granular disintegration in freeze-thaw experiments; those on which rounding is minimal (e.g. fine-grained Cambrian Quartzite and siliceous schist) remained

virtually intact when subjected to identical conditions. The areal extent of present microgelivation is limited by a widespread cover of vegetated regolith (the product of Lateglacial frost weathering). In the absence of such a cover, however, ~~microgelivation~~ granular disintegration of susceptible rocks may be highly effective even under present conditions: most of the c. 10 tonnes of sand blown into Coire nan Tota on An Teallach during the winter of 1976-7 was probably provided by granular disintegration of bedrock and exposed clasts on the plateau areas upwind.

The operation of rockfall throughout the Flandrian is attested by the development of talus cones and sheets in corries that were occupied by glaciers during the Loch Lomond Stadial. Present activity is evident in the form of fresh, lichen-free clasts on the surfaces of talus slopes and corresponding fresh scars on the rockwalls above. In Glas Tholl, An Teallach, 37 rockfalls were recorded in 58 hours and large boulders near the apex of an active talus cone were displaced over the winter of 1976-7 by a large rockfall and debris flow activity. Several large rockfalls have apparently occurred within the last c. 15 years at this site. Rockfall continues to nourish vegetated talus of essentially Lateglacial age, although rates of activity are comparatively low: a mean rockwall retreat rate of 0.015 mm y^{-1} was calculated from rockfall on to a vegetated talus sheet in Coire a'Mhuilinn, An Teallach. Small scale rockfalls produce a pattern of fall-sorting on talus slopes, but more massive rockfalls sometimes do not reach the foot of the slope and thereby destroy any such pattern. Avalanches are probably only of very local importance (e.g. in the Lairig Ghru) in modifying the form of talus slopes.

The blockfields and blockslopes formed on some lithologies during the Lateglacial have apparently experienced little modification during the Flandrian and are essentially inactive at present. Debris surfaces and debris-mantled slopes, however, are subject to various forms of geomorphological activity under present conditions. Processes acting on such areas fall into three broad groups: mass-movement processes (frost creep, solifluction and slope failure), frost sorting and deflation, all of which have produced distinctive landforms.

Frost creep appears to be most effective on unvegetated debris

slopes. Surface clasts are displaced by needle ice heave and move more rapidly (on average c. 10 mm y^{-1} on An Teallach) than markers inserted in the ground (c. 4 mm y^{-1}). Downslope displacement declines approximately exponentially with depth and is effectively confined to the top few centimetres of the regolith.

On partly-vegetated slopes frost creep is responsible for the formation of turf-banked terraces. Three basic types may be distinguished: deflation terraces, which result from the modification of wind stripes by frost creep; oblique terraces, which form as the result of immobilization of creeping detritus by vegetation; and normal terraces, which are here interpreted as debris terraces (possibly of Lateglacial age) modified by vegetation colonization of the terrace risers on lee slopes. The interaction of normal and oblique terraces on some slopes produces the phenomenon here referred to as interconnecting terraces. Frost creep is less effective on terraced debris slopes than on unvegetated debris slopes, partly because the turf banks impede movement and partly because tread angles are gentler than general slope angles. On An Teallach, mean rate of clast displacement on terrace treads was c. 4 mm y^{-1} between 1976 and 1979 and markers inserted in the regolith moved on average 3.5 mm y^{-1} during the same period.

Whereas turf-banked terraces are found on debris slopes underlain by a variety of lithologies, solifluction features are developed only on regolith that contains a relatively fine-grained matrix and is consequently frost-susceptible. Like boulder and debris features, solifluction features display a change in configuration from straight-fronted sheets on gentle slopes through lobate sheets to over-riding sheets and individual lobes on steep slopes, and occupy a range of slopes of 6-36°. The lower limit of active solifluction appears to decline northwards and westwards across northern Britain. Limited measurements of rates of solifluction on Ben Wyvis suggest that present activity is less than in more severe periglacial environments. The maximum surface displacement recorded was 17.4 mm y^{-1} on a 29°slope; virtually no movement was recorded on a lobe located on a 15° slope.

Solifluction is probably also responsible for the occasional movement of debris sheets and lobes formed during the Lateglacial, and

is almost certainly the mechanism underlying present ploughing boulder movement, the distribution of the latter being intimately associated with that of solifluction features. Measured displacements of seven ploughing boulders in the Fannich Mountains ranged from 6-34.5 mm y^{-1} over a two-year period and were strongly influenced by gradient.

Slope failures are apparently most frequent on steep debris slopes covered by shallow cohesionless regolith. They take two forms, both triggered by heavy rainfall: highly localized failure and liquifaction, resulting in debris flows that erode gulleys and deposit levées and lobes of detritus, and larger shallow slide features. Debris flows appear to occur almost annually in some areas, but shallow slides are apparently rare. The plane of failure for both types of feature normally exceeds 32^{o}.

Frost sorting on debris surfaces and debris-mantled slopes is reflected in the occurrence of active sorted circles up to 60 cm in outside diameter on the former and active sorted stripes up to 70 cm in repeat distance on the latter, though most active forms are about half as large as the figures cited. Active sorting is restricted to vegetation-free ground where the regolith consists of a frost-susceptible diamicton containing few clasts exceeding 15 cm in length. As sorting may apparently be initiated under a very mild freezing regime, the lowest altitude at which sorting is evident in any area is determined by factors other than air temperature. A westward decline in the lower limits of active patterned ground is relatable to a similar decline in the lower limits of vegetation-free terrain (reflecting westward increase in exposure).

Active sorted circles in upland Britain appear to be formed by upfreezing and outfreezing of clasts from randomly-spaced concentrations of frost-susceptible fines. On slopes, linear concentrations of frost-susceptible fines are produced by rillwash, and frost-sorting enhances and modifies the initial pattern to produce regularly-spaced stripes. Patterned ground may form (or re-form) in the course of a single winter, and more delicate forms may be destroyed by high winds or heavy rainfall. Surface clast movement on active stripes is as rapid as any recorded in other periglacial environments: on Tinto Hill in southern Scotland a line of surface clasts moved c. 1 m down a

23^{o} slope in the course of three winters.

The most impressive legacy of recent wind action on high ground is the formation of deflation surfaces, featureless unvegetated expanses of half-buried boulders and coarse lag gravels from which surficial fines have been swept away. Such surfaces are typical of regolith with a cohesionless sandy matrix (e.g. Torridon Sandstone and granite). On some hilltops, cols and exposed spurs, however, deflation has been selective, producing alternating bands of vegetated and unvegetated ground that are aligned either along the direction of dominant wind (parallel wind stripes) or across the direction of dominant wind (normal wind stripes and wind crescents). Whilst it is generally accepted that such features are the products of "Rasenabschalung" or turf exfoliation (a combination of loosening of surface material by frost heave and needle ice growth and removal of fines by wind) it is not known whether this process alone is responsible for the initiation of wind stripe formation. Moreover, the formation of wind stripes both parallel and normal to dominant wind direction remains to be accounted for, as does the regular spacing of some stripes.

On rocks that weather to cohesionless sand, the wind-transported products of ~~microgelivation~~ granular disintegration sometimes accumulate in the form of sheets of vegetation-covered niveo-aeolian sand deposits. These develop through the accumulation of windblown sand on the winter snowpack; when the snow melts the sand becomes trapped amongst the underlying vegetation. On tussock-covered slopes eluviation of sand from between the tussocks results in the growth of sand hummocks up to almost one metre high.

On An Teallach, soils buried at the base of sand sheets contain pollen assemblages that appear to be of early Flandrian age, which suggests that most if not all sand accumulation on the upper parts of this mountain took place during the Flandrian. Most parts of the sand sheets on An Teallach are around one metre in depth, but thicknesses of up to almost four metres are found downwind of cols. Sections cut in these thicker deposits revealed two distinct sand units, often separated by an unconformity. The lower unit is much more weathered than the upper, which appears to have accumulated in the relatively recent past. It is inferred that the upper unit reflects stripping

of pre-existing deposits (now represented by isolated fragments) from low cols on the plateau upwind. Erosion of the sand sheets on the cols may have been triggered by climatic deterioration during the Little Ice Age but it is more likely to have resulted from the introduction of hill sheep in the 19th century.

Considerable quantities of sand continue to be deposited on lee slopes on An Teallach. An estimated 10 tonnes accumulated in Coire nan Tota alone over the winter of 1976-7, most of it probably the product of recent ~~microgelivation~~ granular disintegration. Such deposition is partly offset by erosion of the unvegetated scarps that form the margins of the sand sheets. Sand scarp retreat results from a combination of needle ice growth, rainsplash, wash and sheep trampling, and averages around 2-3 cm y^{-1}.

The only examples of active nivation hollows in upland Britain known to the writer occur along the upper margins of the An Teallach sand sheets. Late-lying snowpatches provide meltwater that transports sand over the unvegetated wash zones that form the floors of the hollows. The transported sand accumulates downslope in irregular spreads or small cones. Much larger cones composed of reworked niveo-aeolian sand have been deposited by ephemeral streams that flow along the upper margins of sand sheets in Coire a'Mhuilinn, An Teallach. It appears, however, that rivers are presently removing only moderate amounts of material from upland basins. The areal yields implied by calculated values of annual suspended and dissolved load transported by Ardessie Burn (which drains the west flank of An Teallach) are 9.32 t km^{-2} y^{-1} and 51.57 t km^{-2} y^{-1} respectively. Both values probably overestimate the true yield for terrain above 600 m, yet combined they suggest an erosion rate (60.89 t km^{-2} y^{-1}) that is low when compared with estimates for other periglacial environments.

However, if all forms of present mass-transport are reduced to a common unit reflecting both mass transported and vertical displacement of this mass over a given time and area (e.g. W km^{-2}), fluvial transport emerges as probably the most effective form of present denudation in mountain areas, followed by rockfall. More significantly, the various forms of mass-transport active on high ground in Great Britain appear to operate at rates comparable with (and sometimes greater than) those of similar forms of activity in alpine areas. Thus despite the absence of climatic characteristics typical of other

periglacial environments, such as extreme cold, prolonged or frequent freezing or permafrost, various forms of geomorphic activity appear to be at least as active in upland Britain as in more typically "periglacial" environments. Moreover, the range of features active at present on the mountains of Great Britain is probably as diverse as any under more severe climatic regimes. For although many "typical" periglacial landforms are no longer active on British hills, other features (such as turf-banked terraces, wind stripes and sand hummocks) have developed that are not even mentioned in standard texts on periglacial geomorphology (e.g. Washburn, 1973, 1979; Embleton and King, 1975; Jahn, 1975; French, 1976). Significantly, all of these forms are in part a reflection of the geomorphic activity of strong winds. Exposure, rather than cold, is the climatic factor that distinguishes present-day periglaciation on high ground in Great Britain from that of other cold-climate environments.

14.5 Themes and prospects

It is appropriate to conclude by placing the findings of this study in broader perspective through discussion of (i) some of the major themes that have emerged, (ii) the role of periglaciation in the evolution of British mountain landscapes, and (iii) strategies for future research.

Unquestionably the dominant theme that has emerged from this study is the importance of lithology (or, more specifically, the response of different rock types to periglacial weathering) in determining the nature of past and present periglacial activity in any area. So strong is the influence of lithology that it is possible to predict with reasonable success the range of periglacial features likely to be encountered on any rock type, providing that the weathering characteristics of the rock are known. Lithologies on which macrogelivation has been dominant (e.g. quartzite and siliceous schist) are associated with a fossil landscape of blockfields and blockslopes, massive boulder sheets and lobes and large sorted circles and stripes. Rocks that have yielded a coarse-grained matrix on weathering (such as Torridon Sandstone and most granitic rocks) tend to support deflation surfaces, sand sheets, unvegetated debris-mantled slopes and turf-banked terraces. Those that have broken up

to produce a frost-susceptible diamicton (e.g. micaceous schist) are associated with earth hummocks, relief stripes, debris sheets and lobes, solifluction features and active sorted patterned ground. More than any other single factor, lithology has determined the nature and distribution of Lateglacial and recent periglacial activity on the mountains of Great Britain.

The second major finding that has emerged from the study concerns the polarization of upland periglacial features into those that formed during the Lateglacial cold periods and are presently inactive, and those that formed during the Flandrian and continue to develop at present. It appears that few Lateglacial features have remained active under the much milder climatic conditions of the Flandrian. It is therefore possible to view the development of upland periglacial landforms in terms of two utterly different periglacial environments (as attempted in the previous two sections), that of the Lateglacial cold periods and that of the present day. Such polarization conflicts with the widely-held but poorly-evidenced supposition that many features now inactive formed only a few hundred years ago during the Little Ice Age. Whilst this relatively minor climatic deterioration may have brought about a slight intensification of some forms of periglacial activity (such as frost sorting and deflation), there is no positive evidence to suggest that it was accompanied by the widespread formation of forms that are now inactive.

Opinion rather than evidence has also dominated thinking concerning the present efficacy of periglacial activity on British mountains. Worsley (1977, p. 217), for example, concluded that

> "despite some devotees who emphasize the amount of current periglaciation, there is no way of escaping the fact that approximately 10,000 B.P. truly periglacial environments within the British Isles were abruptly terminated and have not since returned."

Statements such as the above can be supported only through adoption of the pragmatically unsound premise that "truly periglacial environments" are defined by some arbitrary climatic parameter such as mean annual temperature. If the view is adopted, as on the first page of chapter one, that periglacial environments are "... those in which cold-climate nonglacial processes have operated to produce distinctive landforms and deposits", then the upper reaches of British mountains are indeed "truly periglacial environments".

They are not, however, "typical" periglacial environments. Permafrost and extreme cold are absent, as are active examples of many "typical" periglacial features such as rock glaciers and protalus ramparts. Conditions on high ground in Great Britain constitute an environmental type that is poorly documented in existing texts on periglacial geomorphology. This environmental type, here referred to as "maritime periglacial", is characterized by a wide range of landforms, only some of which are common to other cold-climate landscapes. The features formed under maritime periglacial conditions form a characteristic assemblage that is no less "periglacial" than the rather different assemblages encountered on the arid lowlands of Ellesmere Island or the rocky upper slopes of the mountains of Jotunheimen, both periglacial environments but with few landforms in common. Both "devotees" and detractors of present-day periglaciation in upland Britain have often failed to appreciate this important point.

It would be wrong, however, to present the impression that the mountain landscapes of Great Britain have been dominated by periglacial activity. This is far from the case. The imprint of glaciation is still fresh on the mountains in the form of corries, oversteepened rockwalls, ice-moulded rock and valleys infilled with glacial drift and crossed by remarkably fresh-looking moraines. Apart from some of the very largest Lateglacial features, such as rock glaciers and protalus ramparts, periglaciation has in general produced only very small landforms, and periglacial activity has in many areas done little to modify the essentially glacial landscape. The most significant effects are evident on rockwalls and steep slopes. The former are slowly being replaced by talus slopes; the latter are sometimes scarred and gullied by debris flows. On gentler slopes and plateaux periglacial activity has resulted only in the burial of rock outcrops under a shallow veneer of frost-weathered detritus and a general smoothing of the terrain inherited from glaciation. Much too little time has elapsed since the disappearance of the last glaciers for periglaciation to have played a significant role in reshaping mountain landscapes.

A great deal may nevertheless be learned through further study of the characteristics of periglacial features in upland Britain. One approach, already fruitfully adopted by the author and co-workers in

a study of patterned ground formation on Tinto Hill, is to consider the relatively accessible periglacial areas on British mountains as "laboratories" for the monitoring and investigation of present periglacial activity with a view to formulating general explanations of processes that are active over a wide range of periglacial environments, processes such as solifluction, frost creep and debris flow. Another is to monitor rates of mass-transport activity within small mountain catchments in order to model the pattern of present-day denudation and the principal ways in which the glacial landscape is adjusting to nonglacial conditions. A third possible strategy is to extend studies of the distribution of both relict and active phenomena over a much wider area than was attempted in the present study through a programme of detailed large-scale mapping. This would permit not only evaluation of local influences (such as slope and rock type) but identification of large-scale trends (such as the general westwards and northwards decline in the lower limits of certain features). The latter, once established, could be interpreted in terms of past and present climatic controls.

The above suggestions represent general strategies that appear to the writer likely to yield useful results, but encompass only a few of the many possible directions for future research. The scientific study of periglaciation on the mountains of Great Britain is still in its infancy.

Appendix THE MEASUREMENT OF SURFICIAL MASS-MOVEMENT

A1.1 Introduction

A number of techniques have been devised for the measurement of soil creep and other forms of slow mass-movement on slopes (e.g. Williams, 1957, 1962; Washburn, 1960; Kirkby, 1967; Young, 1972; Anderson and Finlayson, 1975). None of the published techniques, however, was found to satisfy the requirements of the present study. These were as follows.

1. The measurement technique adopted had to allow for repeated measurement of the downslope displacement of individual clasts and the near-surface regolith under conditions of frost disturbance and high exposure.

2. As small displacements were anticipated, the measurement technique had to be sensitive to downslope displacements of one millimetre or less.

3. To minimize the chance of disturbance by animals or people, the measurement sites should be as inconspicuous as possible.

4. As the sites were to be installed in remote locations, it was desirable to avoid the necessity of transporting heavy survey equipment (such as a theodolite) to the measurement sites.

5. As a large number of measurement sites were to be established, it was very desirable that the measurement technique adopted should not require the purchase of expensive items or the construction of sophisticated instruments.

In short, it was required that the sites set up should be simple, robust and inconspicuous, that the materials necessary should be cheap and portable, and that the technique should be sufficiently sensitive to detect downslope displacements of one millimetre or less.

A1.2 The mass-movement sites

Two types of mass-movement site that appeared to satisfy the above criteria were designed during the winter of 1975-76 and installed at a site near Edinburgh in April 1976 to test their feasibility. The design that proved more successful was adopted and is illustrated in figure A1.1. The procedure for installing such sites was as follows.

1. Two metal poles (heavy duty conduit tubing of outside diameter 1.3-2.5 cm) were driven vertically into the ground to depths of at least 0.6 m (normally more). The second pole was driven in 2-3 m horizontally across-slope from the first. The line between the poles defined the mass-movement site.

2. Notches were cut into the back or top of each pole using a hacksaw. A line (the "datum line") was then stretched between the two notches and secured.

3. Markers were then installed approximately vertically below the line. These consisted of (i) 3" and 6" nails inserted fully into the regolith so that only the nail heads remained exposed and (ii) drawing pins attached point upwards to the upper surfaces of clasts using epoxy adhesive ("Araldite"). The nails were installed to record displacement of the upper layers of the regolith, the pins to record displacement of surface clasts.

4. The position of the nails and the pins was then measured relative to that of the datum line stretched between the two poles. This was accomplished by suspending a plumb-bob from the line at a position directly upslope or downslope of the marker until the point of the bob hung at the same level (above the ground) as the marker. A simple pulley mechanism on the line on which the bob was suspended facilitated adjustment of the height of the bob. The distance from the point of the bob to each

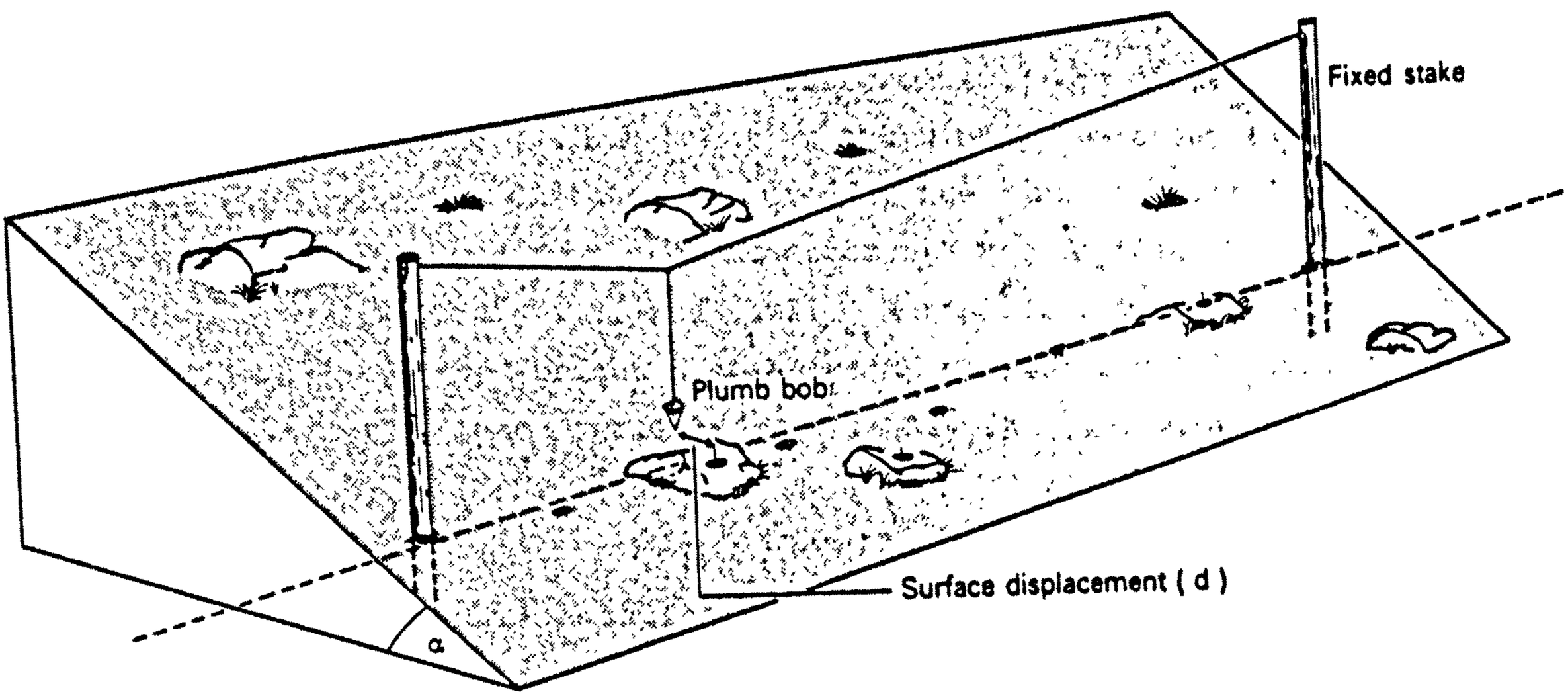


Figure A1.1: Schematic illustration of a mass-movement site. For explanation see text.

marker (i.e. to the upslope edges of nail heads and the points of drawing pins) was measured using a pair of screw-adjustable dividers. The distance between the points of the dividers was then measured against a precision metric rule to the nearest 0.1 mm.

5. Finally, the distance from each marker to the left-hand pole (looking upslope) was recorded to ensure that each marker could be located when measurements were repeated and that there should be no confusion in the identification of individual markers. The line and plumb-bob were then withdrawn.

Measurement of the displacement of markers simply involved repeating the measurements described above after a suitable time interval and calculating the difference in the distance from each marker to the bob point at the time of re-measurement from the equivalent distance measured at the time of installation. The results obtained from such measurements are depicted in figures 8.33, 8.34, 9.32 and 9.43. A similar procedure was used to measure the surface displacements of rubber tubes and columns of glass beads installed vertically into the ground (figure 9.44).

A1.3 Accuracy and repeatability

The main source of possible inaccuracy in the use of this technique lies in the risk of displacement of one or both of the poles that mark the ends of the datum line through disruption by animals, human interference or frost heave. Disturbance by animals or human interference was usually evident in the form of removal, bending or loosening of the poles, fur or wool attached to the poles and/or signs of trampling. All apparently disturbed sites were abandoned. Frost heave is more difficult to detect unless a pole is subject to obvious tilting, but is believed to have had no effect on the sites depicted in figures 8.33, 9.32 and 9.43 as zero readings were frequently recorded at most of these sites. If one or

both poles had been subject to disruption, the chances of zero displacement being recorded for one or more markers would be very small indeed.

The accuracy of the measurement procedure was assessed by making repeated measurements at debris slope sites 1 and 2 on An Teallach (figure 8.33) on 17 September 1977. The displacements of markers at both sites were measured first by the author, then by an assistant, then (after a suitable time interval) by the author. The results of the earlier measurements were unknown to both when the later measurements were carried out. The results (expressed as displacement from the datum measurements made when the site was installed on 13 July 1976) are given in table A1.1. As might be expected, absolute measurement variability tended to increase with displacement from the datum line, although variability expressed as a percentage of displacement is generally greater for small displacements. Median percentage variability was 8.7%; median absolute variability was only 0.3 mm. As absolute variability exceeded one millimetre for only two of the readings (both involving displacements exceeding 45 mm and therefore very small percentage variability) the displacements depicted in figures 8.33, 8.34, 9.32 and 9.43 are considered to offer an accurate reflection of the true displacement of markers over the measurement periods.

A1.4 Drawbacks

Although the measurement technique outlined above satisfies the criteria set out in the introduction to this appendix, it suffers from three drawbacks.

1. Measurement can only be carried out under calm conditions, otherwise the plumb-bob does not remain stationary. On An Teallach the number of days on which measurements could be carried out was very limited.

2. Pins tended to become detached from clasts as a result of winter freezing.

Table A1.1

Repeatability measurements at debris slope mass-movement sites 1 and 2, An Teallach

(see text for details)

Site 1

Marker :	P	P	6	P	P	P	3	P
1st Reading :	6.2	12.3	2.0	0.0	45.0	2.8	-6.2	52.1
2nd Reading :	6.0	12.6	1.8	0.0	46.2	3.0	-6.0	53.5
3rd Reading :	6.1	12.7	2.1	0.0	44.8	3.1	-6.5	54.0
Variability :	0.2	0.4	0.3	0.0	1.4	0.3	0.5	1.9
% Variability :	3.3	3.3	16.7	0.0	3.1	10.7	8.3	3.6

Site 2

Marker :	6	3	P	6	P	P	3	P	3	6	P
1st Reading :	2.4	0.0	1.8	0.9	3.8	3.8	4.1	0.0	1.8	0.0	1.6
2nd Reading :	2.4	0.0	2.0	0.7	4.1	3.8	3.8	0.2	1.5	0.0	1.4
3rd Reading :	2.2	0.0	2.0	0.9	4.3	3.9	4.2	0.0	1.5	0.0	1.7
Variability :	0.2	0.0	0.2	0.2	0.5	0.1	0.4	0.2	0.3	0.0	0.3
% Variability :	9.1	0.0	11.1	28.6	13.2	2.6	10.5	-	20.0	0.0	21.4

Note : % Variability calculated as $\left(\frac{\text{Maximum reading}}{\text{Minimum reading}} - 1\right) \times 100\%$

3. Disturbance by animals in particular resulted in progressive reduction of the number of usable sites; after three years less than half of the original sites could be used.

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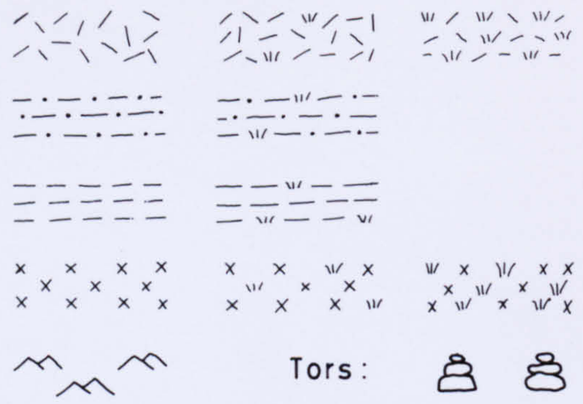
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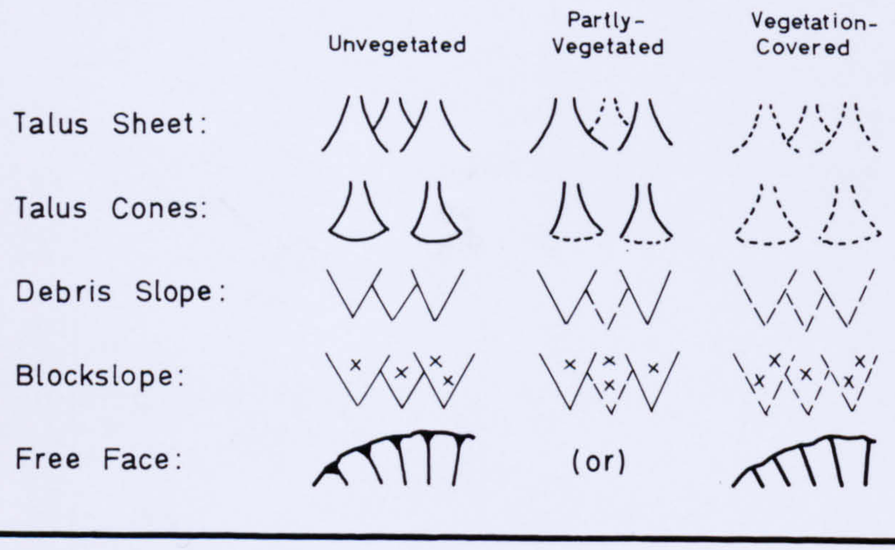
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Fig 7.1 Key to the Geomorphological maps

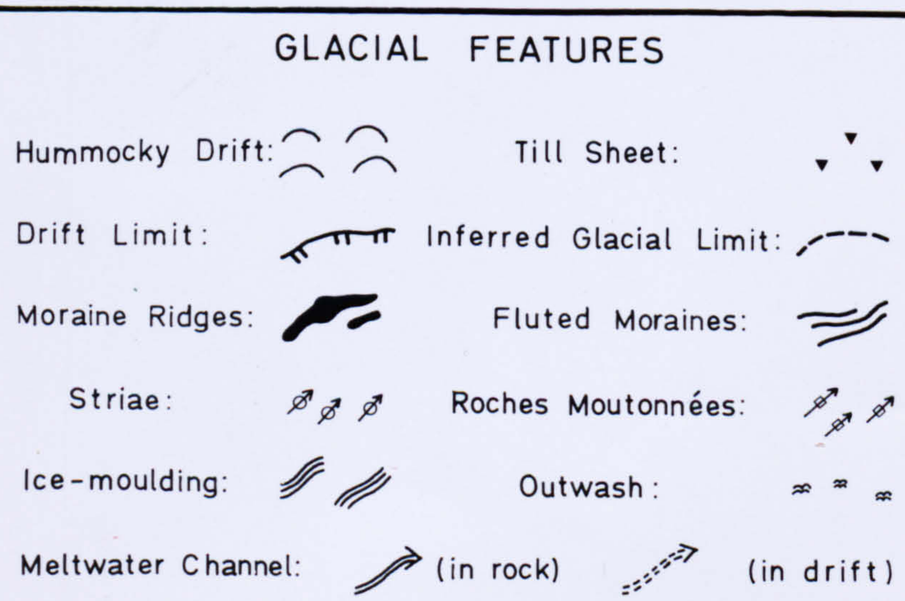
PLATEAU SURFACE FEATURES

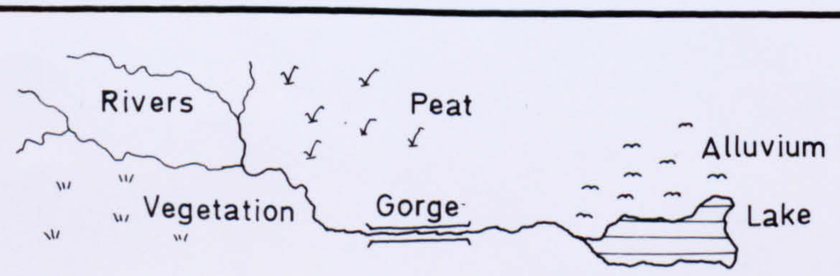


SLOPES

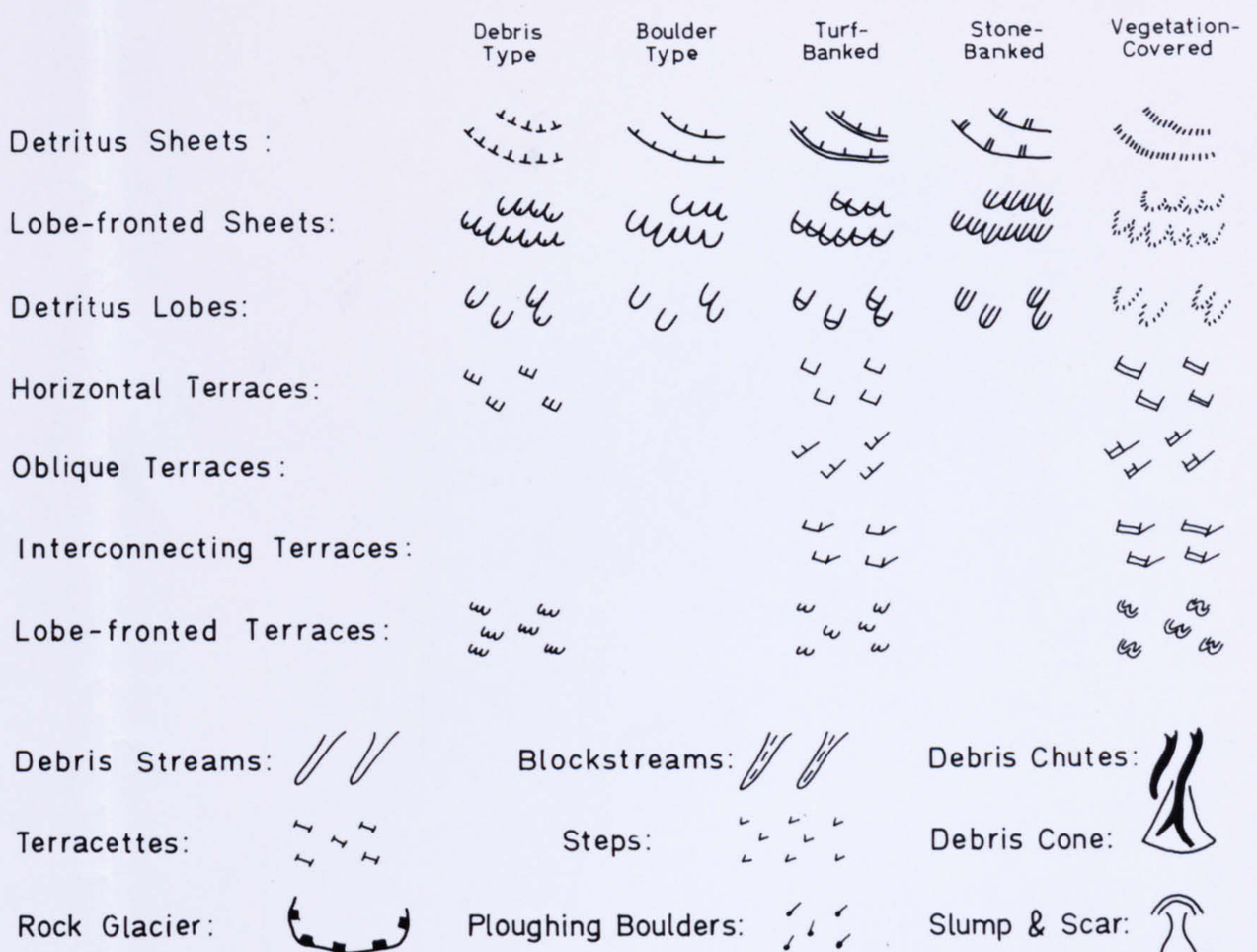


GLACIAL FEATURES

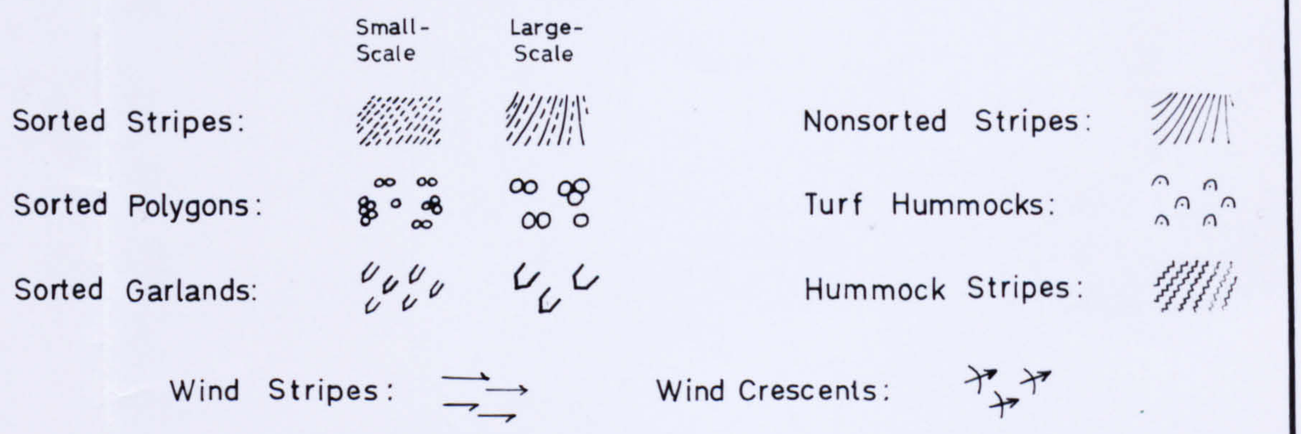




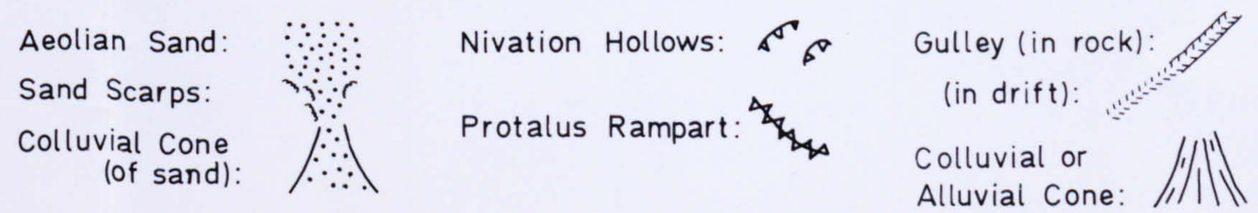
MASS-MOVEMENT FEATURES



PATTERNED GROUND FEATURES



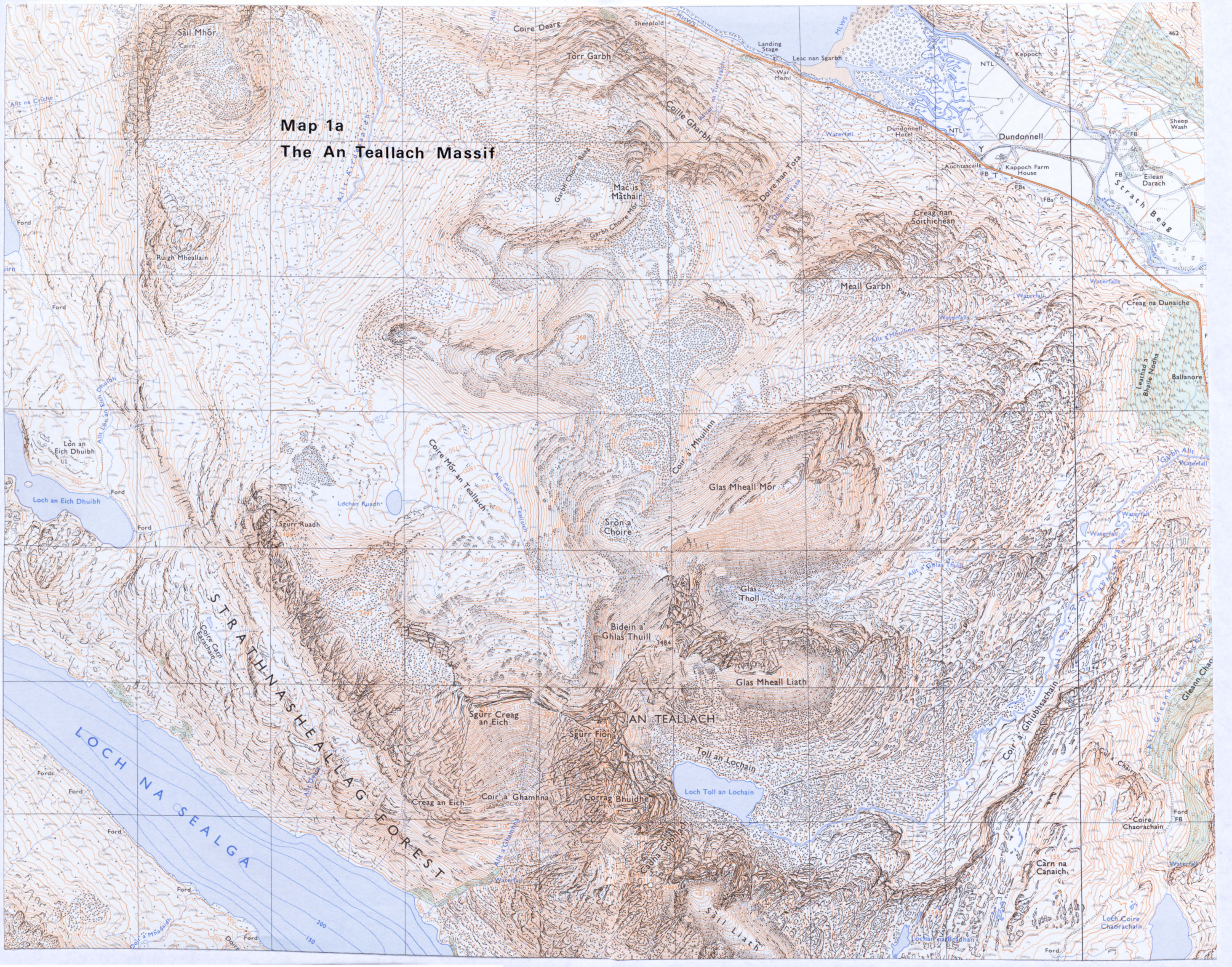
MISCELLANEOUS

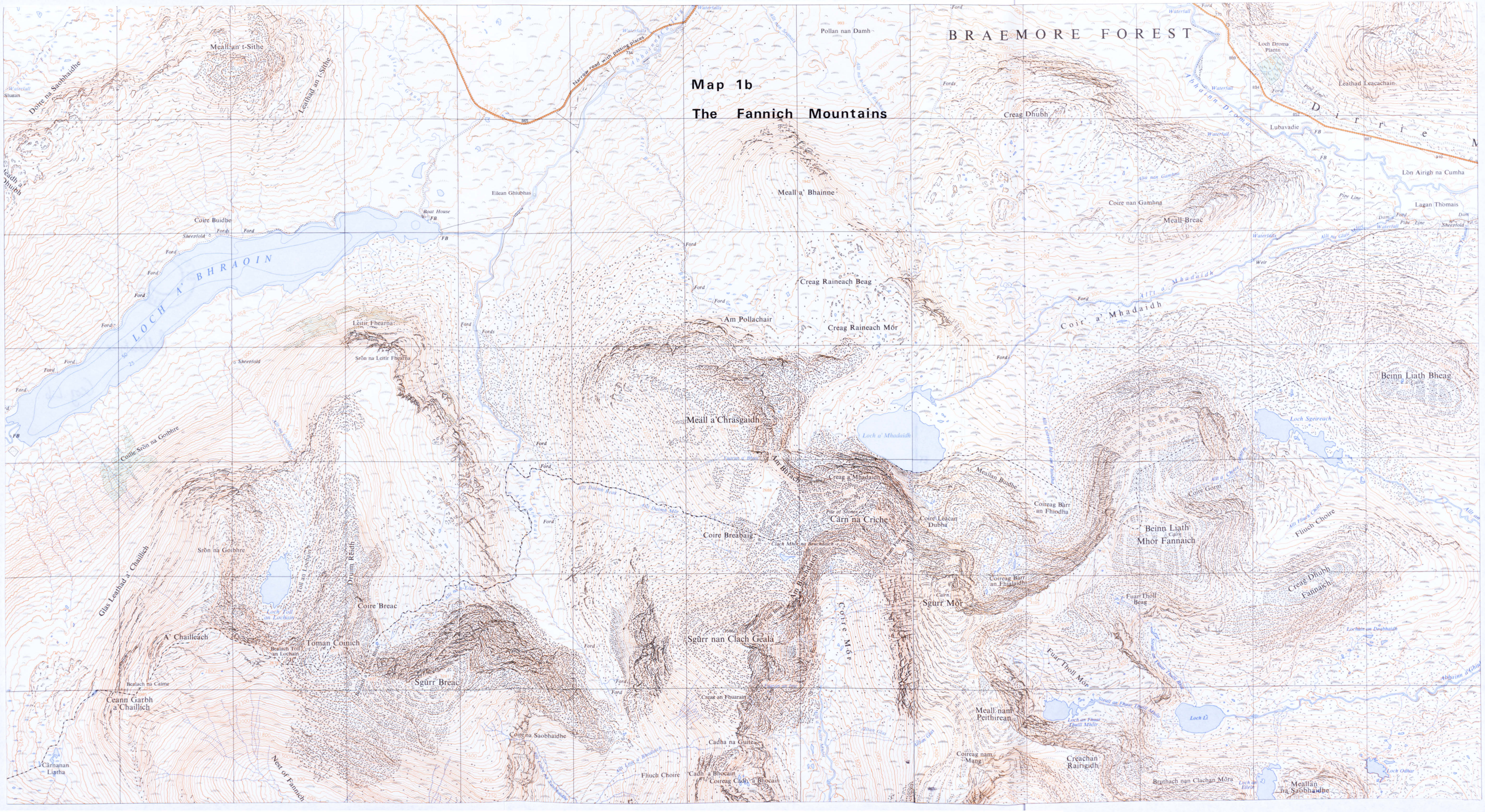


Contours at 100 m intervals: 900

Summit cairn: ▲831

Map 1a
The An Teallach Massif




Map 1b
The Fannich Mountains
BRAEMORE FOREST
LOCH A' BHRAOIN
Meall an t-Sithe
Doire na Saobhaidhe
Leathad an t-Sithe
Pollan nan Damh
Narrow road with passing places
Creag Dhubh
Loch Droma Piantn
Leathad Leacachain
Lubavadie
Lòn Airigh na Cumha
Lagan Thòmais
Meall a' Bhainne
Eilean Ghiubhas
Coire Buidhe
Coire nan Gamhna
Meall Breac
Creag Raineach Beag
Creag Raineach Mòr
Am Pollachair
Leitir Fhearna
Sròn na Leitir Fhearna
Coire a Mhadaidh
Beinn Liath Bheag
Meall a'Chrasgaidh
Loch a' Mhadaidh
Loch Sgeireach
Creag a' Mhadaidh
Am Bhlàr
Coire Leacan Dubha
Meallan Buidhe
Coireag Barr an Fhiodha
Coire Gorm
Càrn na Criche
Coire Breabaig
Beinn Liath Mhòr Fannaich
Fliuch Choire
Sròn na Gaibhre
Glas Leathad a' Chaillich
Drum Reidh
Coire Breac
Sgùrr Mòr
Coireag Barr an Fhiaraidh
Fuar Thòll Beag
Creag Dhubh Fannaich
A' Chailleach
Toman Coinich
Sgùrr nan Clach Geala
Coire Mòr
Fuar Thòll Mòr
Sgùrr Breac
Meall nam Peithirean
Ceann Garbh a'Chaillich
Creag an Fhuarain
Coire na Saobhaidhe
Cadha na Cuite
Creachan Rairigidh
Coireag nam Mang
Cadh' a Bhocain
Coireag Cadh' a Bhocain
Bruthach nan Clachan Mòra
Càrnanan Liatha
Nest of Fannich
Meallan na Saobhaidhe

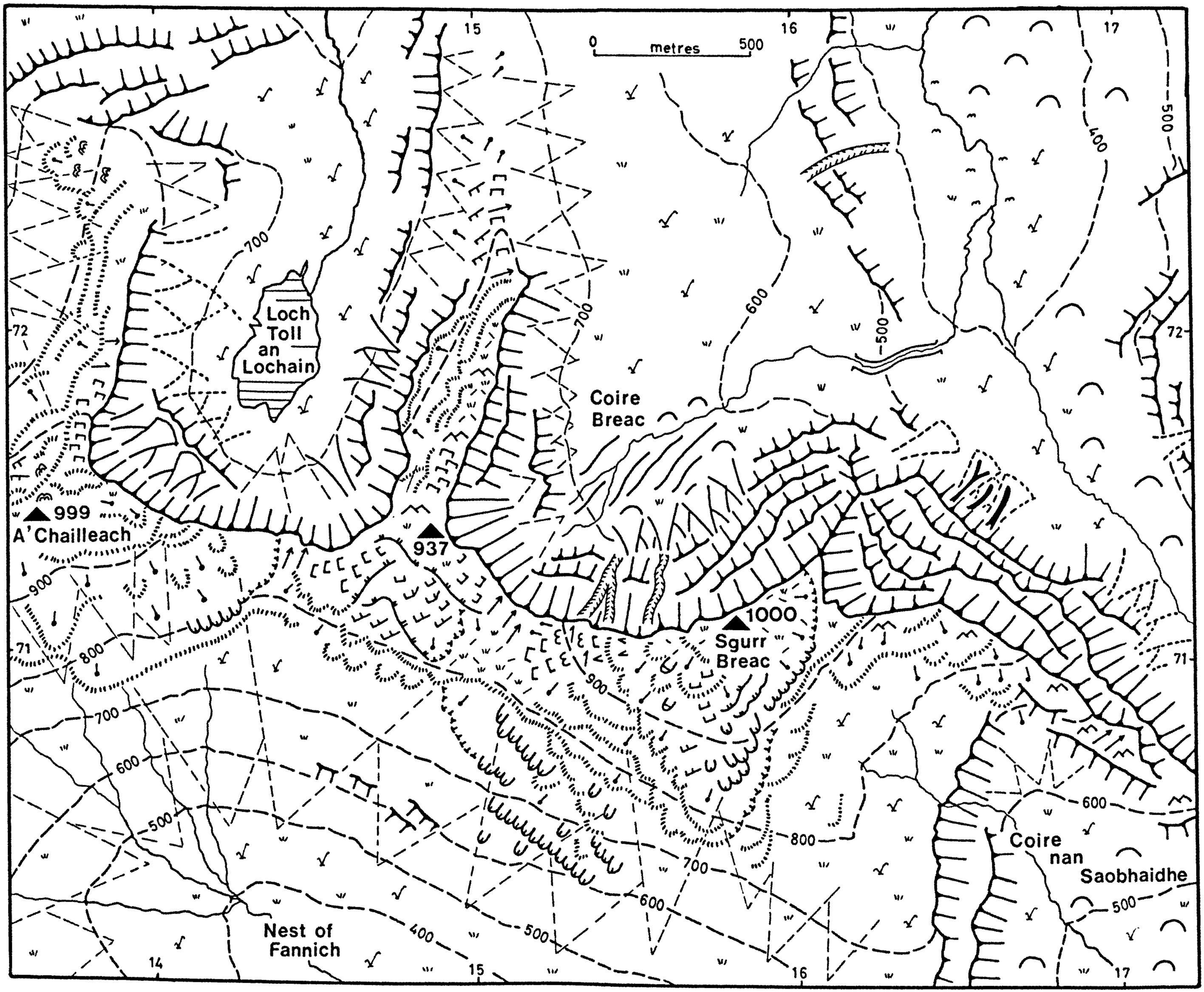
Map 1c
The Ben Wyvis Massif

Loch Coire Bheachain
1940
1818
Coire Dubh
Feur-lochan
Allt Feur-lochain
Clach nan Cluas
Creag Bealach Cuilaidh
Allt Bealach Cuilaidh
Loch Bealach Cuilaidh
Creag an Sgoir
1699
Allt Creag an Sgoir
Coire Creag an Sgoir
Coire Lochain
Allt Coire Lochain
Meall a' Mhaimidh
Fiaclach
Coire Granda
Culzie Lodge
2116
Queen's Cairn
WYVIS FOREST
Allt Lochan nan Druidean
Coire Lochain
Loch nan Druidean
Coire Mhic Fhearchair
Glas Leathad Beag
2610
Coire Lochain
2914
2987
2961
3044
3018: Cairn
Coire nan Laogh
Coire nam Fuaran
2142
Three Lairds Hillock
Carn Gorm
Bealach a' Chlaidh Ghuirme
1521
1532
1554
Meallan Donn
Tom a' Choinnich
Coire Dubh
Glas Choire
Meall na Drochaide
2309
Allt a' Choire Dhuibh
Bealach Tom a' Choinnich
Loch a' Choire Mhoir
2752
Coire Misirich
Loch Misirich
Allt Tom a' Choinnich
Coire Tom a' Choinnich
Coire nan Con
BEN WYVIS
Leacann Bhreac
1491
Cnoc na Bana-mhorair
Allt an Glas
Leathad Dubh nan Iaron
Meall a' Chrimig
1775
FODDERTY CP
3433
3288
An t-Socach
3305
Cairn
Allt Coire Mhisirich
Allt a' Choire Mhoir
Coire Mor
2204
Meall nan Tunn
2229
1824
Meall an t-Slugain Duibh
1863
Allt an t-Slugain Duibh
Allt a' Ghharbh Bhaid
Allt an Tric
GARBAT FOREST
Coire an t-Socaich
Glac nan Gearran
Glas Leathad Mor
3195
Coir' Allt a' Chabair
Allt a' Chabair
3227
Carn a' Chaiptein (Cairn)
Cairn 3064
Coire na Feola
Allt Coire na Feola
Cairn
Coire na Comhlaich
Allt Coire Comhlaich
An Cabar
Cairns
3118
Rock Hut
Shelter
2940
Cairn
Meall na Speireig
1892
2023
Fords
Allt nam Eiridh
Allt a' Bhealaich Mhoir

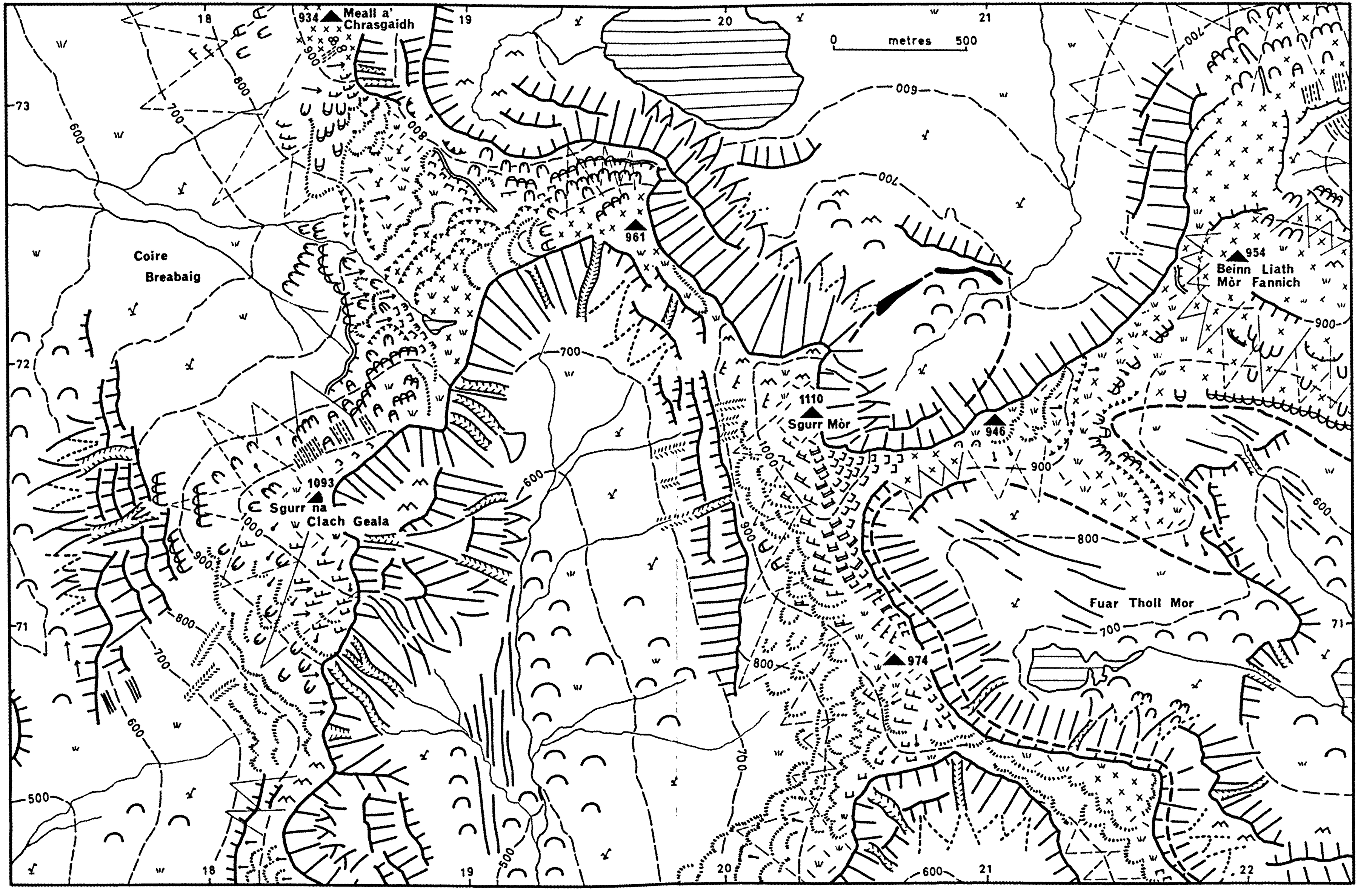
Map 2: An Teallach



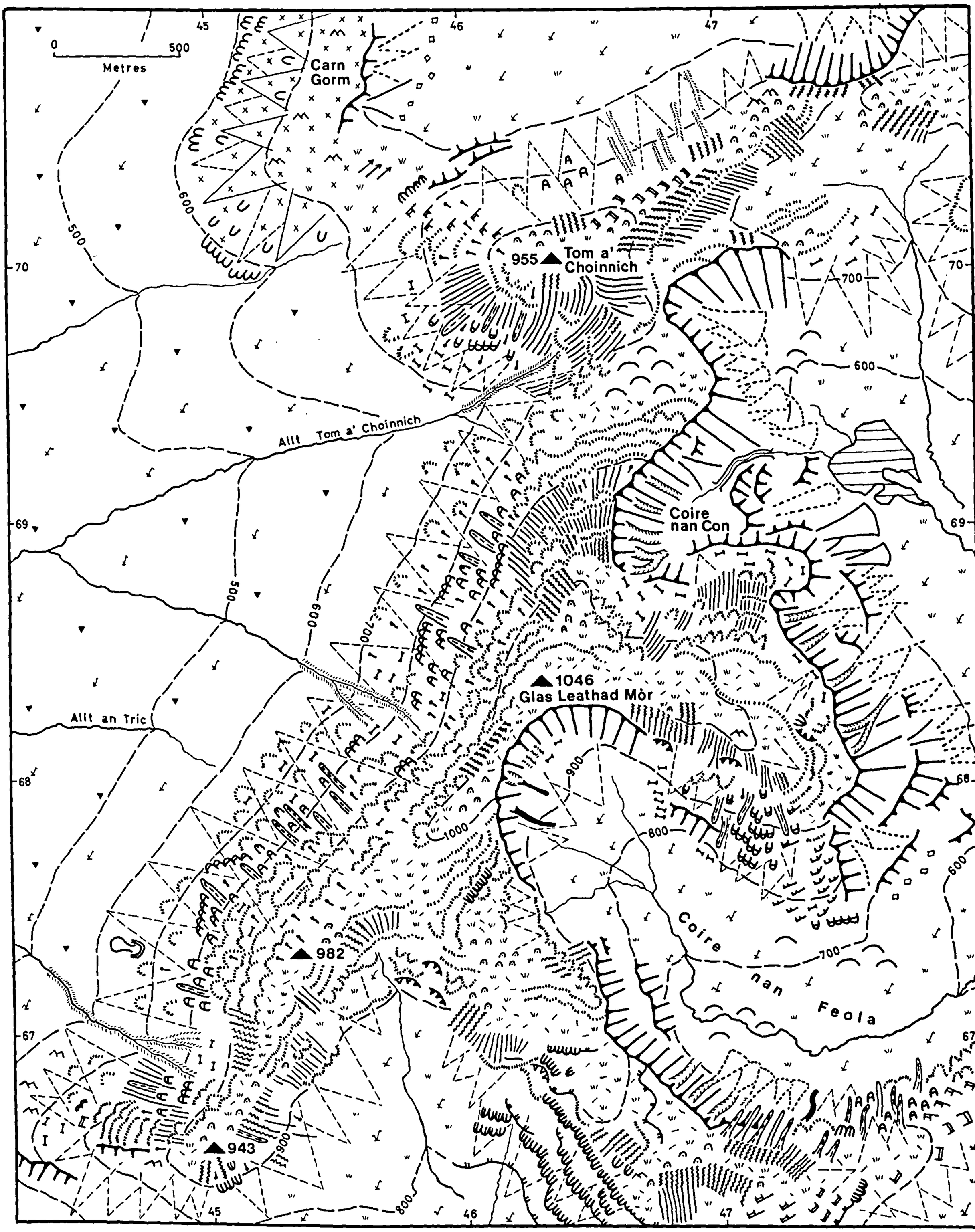
Map 3: The Western Fannichs



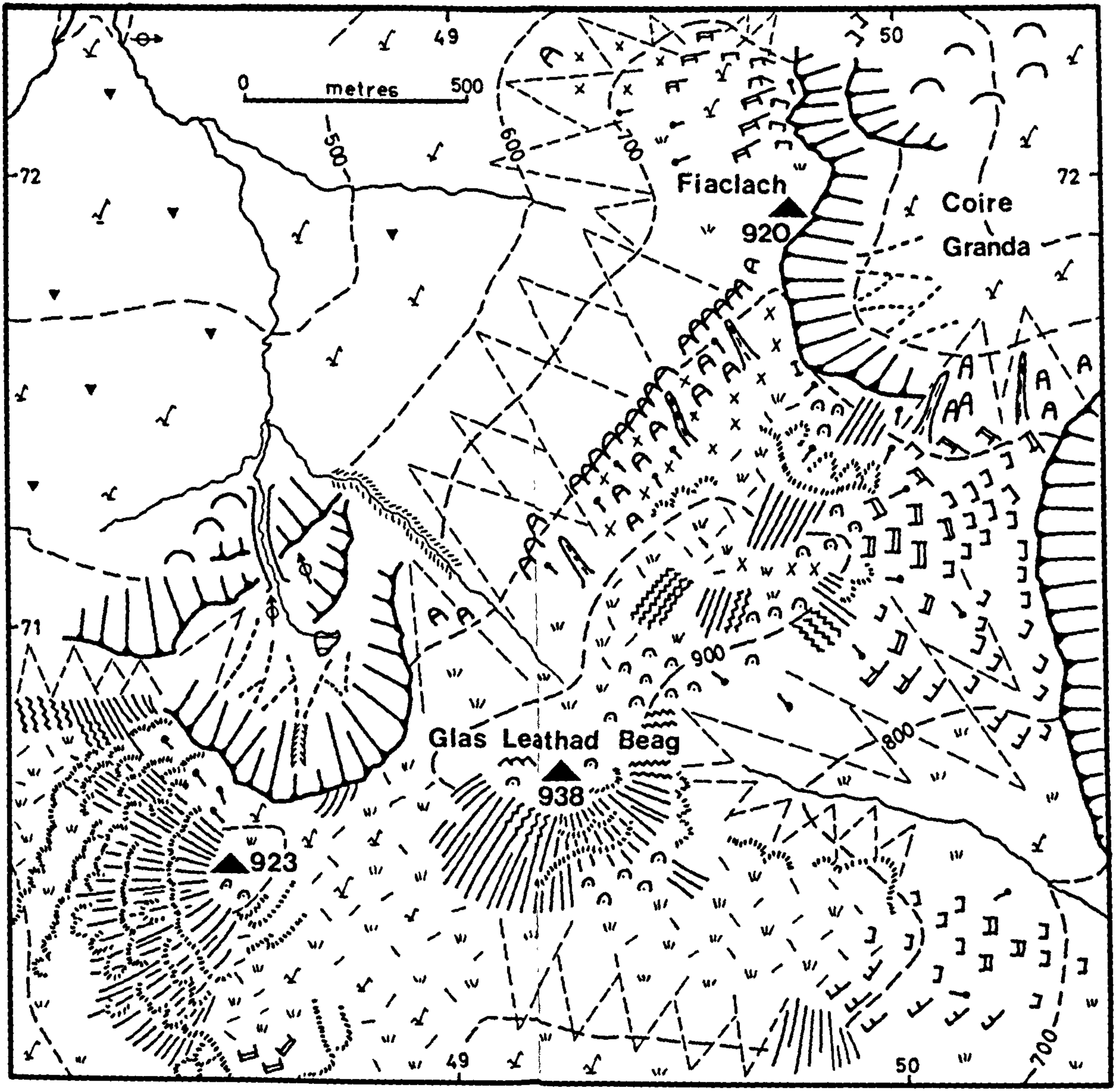
Map 4: The Eastern Fannichs



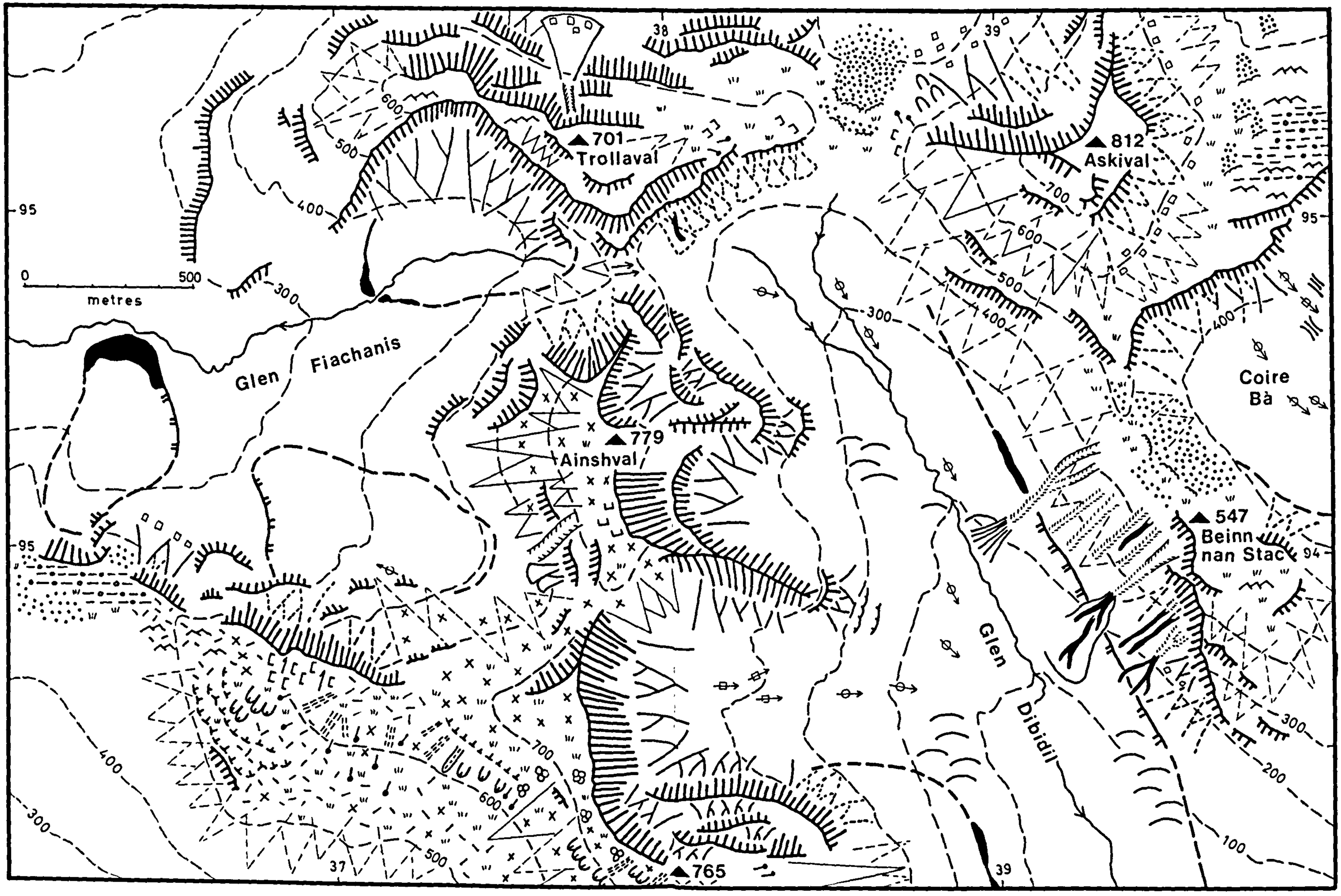
Map 5: Ben Wyvis



Map 6: Ben Wyvis North—East



Map 7: The Rhum Cuillin



Map 8: The Western Hills of Rhum

