

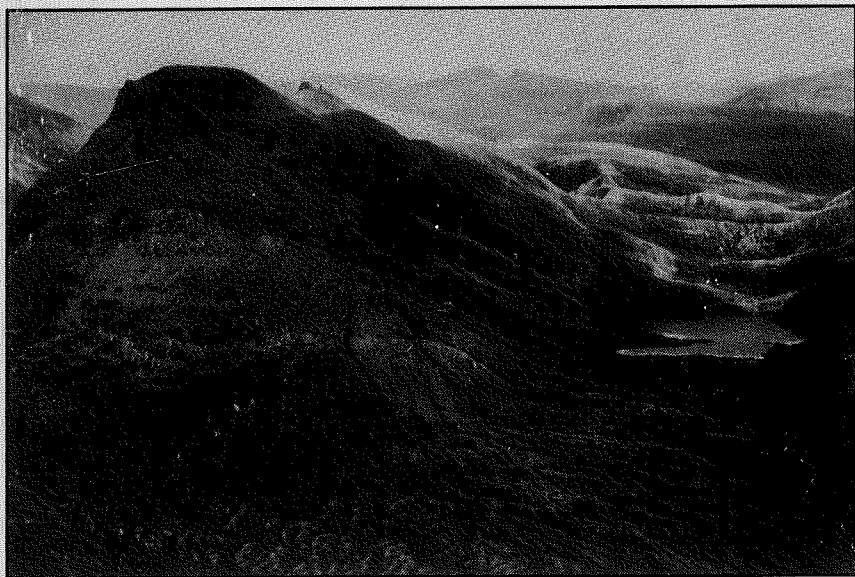
WESTER ROSS

Field Guide

Edited by

C K Ballantyne & D G Sutherland

Quaternary Research Association



1987

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Cover illustration: Maol Chean Dearg and Coire an Ruadh-Staic viewed from the north-west from Beinn Damh, Torridon.

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SHORT FIELD MEETING

May 29th - 31st, 1987

WESTER ROSS

FIELD GUIDE

EDITED AND COMPILED BY: C.K. Ballantyne and D.G. Sutherland

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*Dave Hodgson sadly was killed before he could publish his detailed work on moraine genesis in the Torridon area. We have included data from two of his sites keeping as close as possible to the ideas and wording in his PhD Thesis.
[DGS & CKB]

1. INTRODUCTION

Wester Ross is the name given to that part of the North-West Highlands that lies between Ullapool in the north and Lochcarron in the south, and extends eastwards from the west coast as far as the village of Garve (Figure 1.1); it is defined approximately by latitudes 57°20'-57°50'N and longitudes 4°50'-6°00'W. Like much of the North-West Highlands, this is an area of spectacular scenery and complex geology. The basic geological structure of the area was brilliantly elucidated by B.N. Peach, J. Horne and their co-workers in the Geological Survey of Scotland at the beginning of this century (Peach *et al.*, 1907; Peach and Horne, 1930), and in three memoirs these same geologists laid the foundations of present knowledge of the Quaternary Geology of Wester Ross (Peach *et al.*, 1912, 1913a, 1913b). This early research has been summarised in a regional memoir by Phemister (1960).

Only in the last quarter century, however, has the Quaternary of Wester Ross been explored in detail. A starting point was provided by the French geomorphologist Alain Godard, whose compendious monograph *Recherches de géomorphologie en Écosse du nord-ouest* (1965) considered, amongst other things, the nature of the pre-glacial landscape, the effects of glacial modification, the extent of the last ice sheet and later local glaciation, the periglacial landscapes on high ground, raised shorelines and sea-level change, and the nature of postglacial landscape evolution. Further studies relating to the glacial history of the area and associated high sea-levels were published around the same time by McCann (1963), Kirk and Godwin (1963) and Kirk *et al.* (1966). More recent work in the area has involved the delimitation of former glaciers inferred to have formed in Wester Ross during the Loch Lomond Stadial of c. 11,000-10,000 B.P., the mapping of the limits of earlier glacial readvances associated with the overall retreat of the last ice sheet, analyses of certain types of glacial landforms and sediments, studies of raised shorelines, reconstruction of Lateglacial and Flandrian vegetation changes and research concerning active and relict periglacial phenomena on high ground.

For the Quaternary scientist, three features of Wester Ross are of particular interest. First, the area contains some of the most spectacular Quaternary landforms in the British Isles. Of particular note are some of the multiple moraine sequences associated with both the Loch Lomond Readvance and the earlier Wester Ross Readvance, outstanding examples of hummocky and fluted moraines, well-developed raised shorelines and a wide range of upland periglacial phenomena. Indeed, some of the Quaternary landforms and deposits of Wester Ross, such as the rockfall-induced 'rock glacier' on Beinn Alligin, the huge

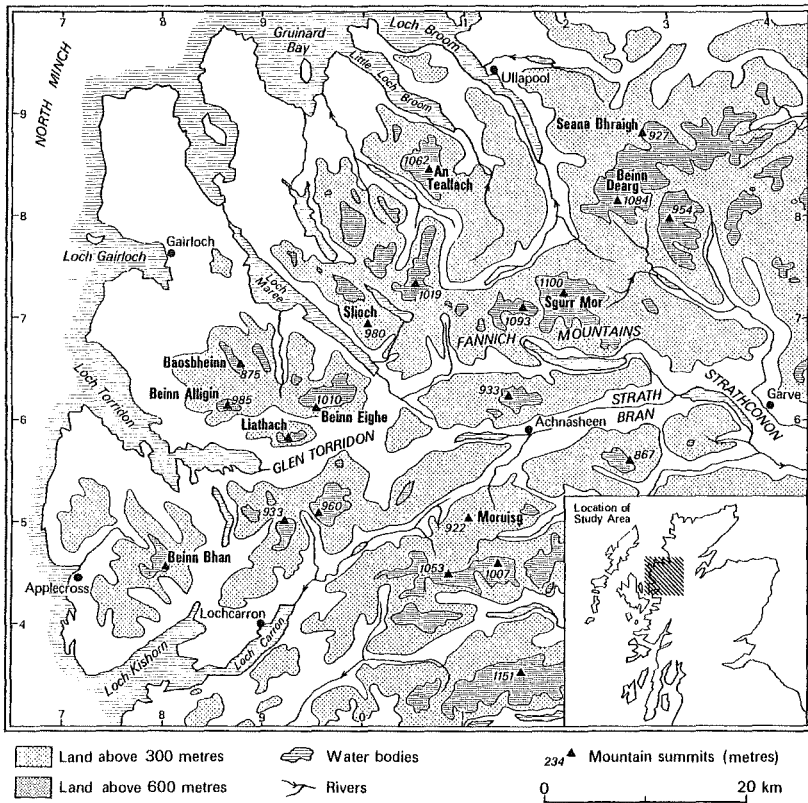


Figure 1.1: Wester Ross: Relief.

protales rampart on the flanks of Baosbheinn, the Achnasheen terraces and the niveo-aeolian deposits on An Teallach are probably without parallel in the British Isles. Secondly, the area is unusual in that it affords unequivocal geomorphological evidence that the downwastage and retreat of the last ice sheet was interrupted by readvances or stillstands of local or possibly regional extent. Finally, various aspects of the Quaternary of Wester Ross provide fertile ground for controversy and debate. Notable examples include the interpretation of the significance of mountain-top detritus and its relationship to the upper limits of the last ice sheet, the interpretation of 'anomalous' erratics in relation to the former position of the ice-sheet, the significance of various ice-sheet retreat phases and their possible correlation, and interpretation of the raised shoreline evidence. It is of interest, too, that many remoter parts of Wester Ross have never been investigated in detail, and that little attempt has hitherto been made to substantiate conclusions based on morphological or morphostratigraphic evidence with detailed stratigraphic or biostratigraphic investigations. The last quarter-century of Quaternary research in Wester Ross may have provided answers to some questions, but it has also generated others of equal or possibly greater importance.

RELIEF

Almost all of Wester Ross consists of strongly-dissected glaciated upland. Apart from the lower ground in the north-west of the area, only the deepest valleys extend below 300 m altitude, and extensive tracts lie above 600 m (Figure 1.1). Many of the larger massifs culminate in a series of summits over 900 m above sea level, of which the highest are Sgurr Mór (1110 m) and Sgurr na Clach Geala (1093 m) in the Fannich Mountains, Liathach (1054 m) and Beinn Eighe (1010 m) in the Torridon Hills, Beinn Dearg (1084 m), An Teallach (1062 m) and Mullach Coire Mhìc Fearchair (1019 m). Most of the principal valleys are structurally controlled and trend either approximately NW-SE or approximately SW-NE. All have the form of glacial troughs, two of which breach the main north-south watershed forming the only through routes to Easter Ross: the Dirrie More to the north between Loch Broom and Garve, and Strath Bran to the south (Linton, 1949; Dury, 1953; Kirk *et al.*, 1966). Many troughs have been overdeepened by glacier ice, and the resultant rock basins are now occupied by numerous freshwater lochs (such as Loch Maree and Loch Fannich) or by fiords (such as Loch Broom, Little Loch Broom, Loch Torridon and Loch Carron). In contrast to the mountainous scenery of much of Wester Ross, the north-western part between Loch Gairloch and Little Loch Broom consists of rather monotonous undulating lowland under 300 m in altitude. Some of this area consists of ice-scoured 'knock

and lochan' topography, with low rocky knolls and numerous small lochs, but most is mantled by drift and peat.

Despite strong glacial dissection, many of the mountains of Wester Ross support fragments of plateau at various altitudes. These and lower valley benches have been interpreted by Godard (1965) as a series of planation surfaces. The most widespread surfaces recognised by Godard are: (i) a tilted and warped *surface supérieure* that descends westwards across Wester Ross from c. 900 m to c. 750 m; (ii) a warped *surface intermédiaire* that rises from c. 500 m in the vicinity of Loch Maree to c. 600 m on Beinn Dearg and falls in altitude both north and south of this axis; (iii) a less modified *surface écossaise* at 230-300 m that is most extensive near the coast and takes the form of extensive valley benches farther inland, for example near the head of Little Loch Broom and at the south-east end of Loch Maree; and (iv) a *niveau pliocène* that rises inland from c. 100 m to c. 200 m in coastal areas and is best represented in the area between Loch Ewe and Gruinard Bay. Godard argued that all of these surfaces had been produced by sub-aerial erosion during the Tertiary. However, although there is no doubt regarding the reality of plateau areas and valley benches at different levels throughout Wester Ross, their correlation is perhaps rather less certain than Godard suggested, for three main reasons. First, his original work was based on topographic maps of limited accuracy. Secondly, individual fragments (particularly of higher surfaces) are rather widely spaced, and Godard himself was forced to recognise intermediate levels of poorer development to accommodate all plateau fragments within his scheme. Finally, the role of differential uplift along fault lines is largely unknown.

GEOLOGY

Wester Ross is divided into two fundamentally different geological provinces by the Moine Thrust, which runs NNE-SSW across the area (Figure 1.2) and represents the most pronounced of a series of Late Caledonian overthrusts, involving a displacement of at least 15 km and possibly as much as 120 km (Johnson, 1983, p.64). The Moine Thrust separates the Hebridean craton to the west from the orthotectonic zone of the Caledonides to the east. West of the Thrust relatively unaltered Torridonian, Cambrian and Mesozoic sedimentary rocks overlie a Lewisian basement; Lewisian rocks also crop out as a series of inliers to the east of the Thrust, where they are surrounded by Moinian metasediments that are themselves intruded by granitic plutons and overlain in the easternmost part of the area by Devonian sandstones and conglomerates (Figure 1.2).

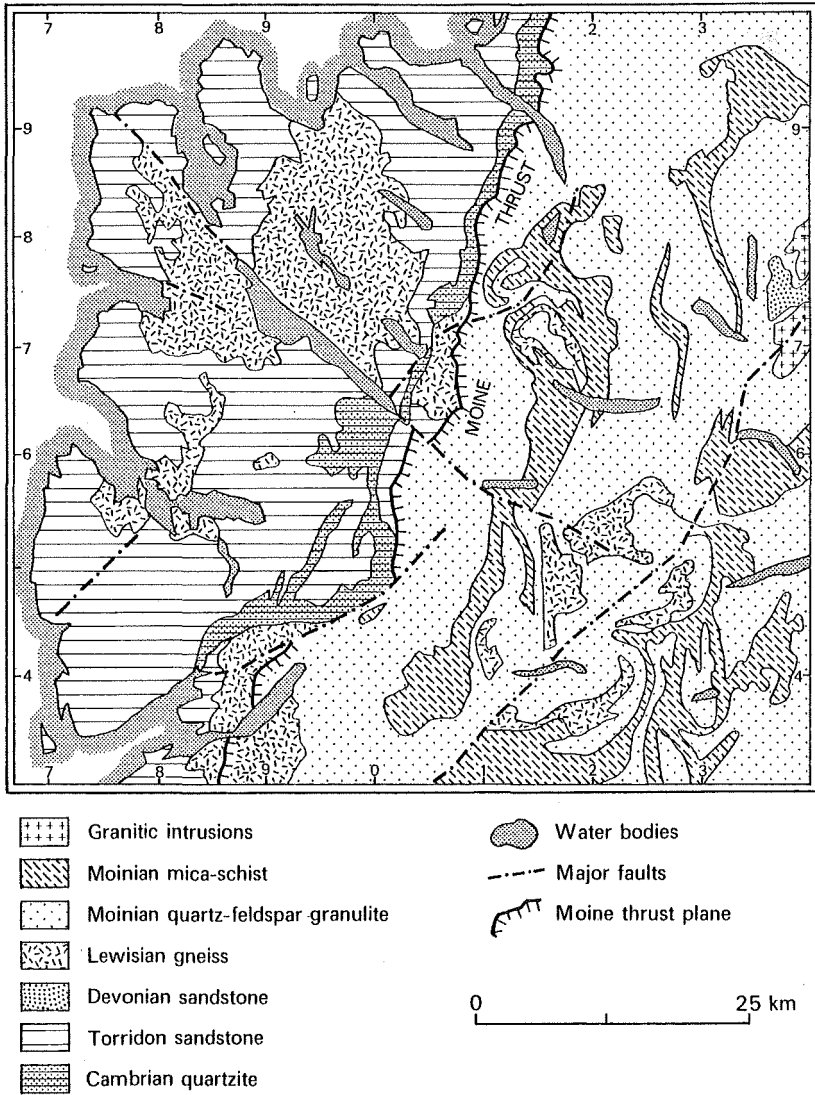


Figure 1.2: Wester Ross: Geology.

The basement of crystalline rocks that collectively form the *Lewisian Gneiss* or *Lewisian Complex* comprises the oldest rocks in Great Britain, dating back to c. 2900 Ma. Watson (1983) recognised a threefold chronological subdivision of the Lewisian. West of the Moine Thrust are rocks of the *Scourian complex* (c. 2900-2300 Ma.) and those of the *Laxfordian complex*, the latter comprising Scourian and younger rocks transformed during the Laxfordian period (c. 2300-1700 Ma.). East of the Moine Thrust are Lewisian rocks incorporated in the basement of the Caledonian fold belt, including Scourian and Laxfordian rocks transformed at c. 1000-400 Ma. (Figure 1.2). The bulk of the Lewisian complex is made up of banded gneisses whose components range in composition from ultramafic to acid. These rocks have been metamorphosed and sometimes migmatised at high temperatures and pressures, and include metasediments such as mica-schists, marbles and calcsilicate rocks together with mafic, possibly metavolcanic gneisses that form narrow belts alternating with felsic gneisses. Intrusive igneous rocks include basic dykes and sills as well as large volumes of intermediate to granitic rocks with associated pegmatites. In Wester Ross, the most common Lewisian rocks are acid biotite- and muscovite-biotite-gneisses. In the extreme north-west part of the area the Lewisian rocks characteristically underlie glacially-scoured 'knock-and-lochan' lowlands, though farther inland erosion of the overlying Torridonian strata has revealed an ancient pre-Torridonian land surface with up to 400 m of local relief (Godard, 1965; Stewart, 1972), and Lewisian rocks crop out at altitudes up to 967 m.

To the west of the Moine Thrust, the Lewisian basement is overlain by three groups of sedimentary cover rocks of widely different ages. By far the most widespread in Wester Ross are the sandstones of the Torridonian system, which underlie more than 60% of the terrain west of the thrust. Strata of Cambrian age are largely restricted to a fairly narrow belt adjacent to the thrust (Figure 1.2), and small pockets of Permian, Triassic and lower Jurassic sediments crop out at several coastal locations, notably around Applecross village and in a narrow belt between Gruinard Bay and Loch Ewe (not shown in Figure 1.2).

After c. 1000 Ma the undulating landscape developed on Lewisian rocks as a result of prolonged erosion following the Laxfordian event experienced burial by the sediments of the Torridonian system, 'Torridonian' being an informal term employed to designate the largely continental red clastic rocks of north-west Scotland. The earliest Torridonian deposits were those of the Stoer Group, which consist of fanglomerates overlain by red sandstones and mudstones, and which are most widespread in outcrop near the head of Loch Ewe. Some 200 Ma later the Torridon Group began to accumulate, eventually achieving a maximum thickness of c. 7 km and covering a much wider area. The lowest Torridon Group sediments (the Diabeg Formation) are

red breccias and sandstones that partly buried the ancient post-Laxfordian land surface, and which pass upwards into grey shales of possible marine origin. Over much of Wester Ross, however, the ancient 'Lewisian' landscape is directly overlain by the later and more extensive Applecross and Aultbea Formations. These comprise gently-tilted and practically unaltered felspathic sandstones with occasional conglomeratic layers. They are predominantly of fluvial origin; Williams (1969) suggested that in Wester Ross and Sutherland the Applecross formation includes at least two vast alluvial fans deposited by rivers that drained a mountainous landmass to the north-west, somewhere in the vicinity of the present Outer Hebrides.

In Wester Ross, Torridon Sandstone underlies both lowland along the coast and, farther inland, some of the most spectacular mountains on the British mainland. These include An Teallach (1062 m), Slioch (980 m), Beinn Alligin (985 m), Liathach (1054 m) and Beinn Eighe (1010 m), although the actual summits of the last two mountains are composed of Cambrian Quartzite.

Further vigorous erosion followed the deposition of the Torridon Sandstone strata, such that the succeeding Cambrian rocks rest with marked unconformity on both Torridon Sandstone and Lewisian Gneiss. The Cambrian sequence in this area comprises conglomeratic basal quartzite up to 60 m thick overlain by up to 90 m of 'pipe rock' (a fine-grained quartzite riddled with worm casts) that is in turn overlain by shales, mudstones, grits and limestones. The first two members of the sequence are often referred to collectively as 'Cambrian Quartzite' and are much more widespread in outcrop than the less resistant overlying members. In many places the Cambrian Quartzite forms a conspicuous ice-scoured escarpment that dips eastwards under the Moine Thrust, though outliers also form resistant caprock on Torridon Sandstone mountains west of the main outcrop. Examples include not only Liathach and Beinn Eighe in the Torridon Hills, but also the three most easterly summits in the An Teallach massif. In contrast, the pockets of Mesozoic rock in the coastal zone invariably underlie low ground.

The geological development of the Caledonides east of the Moine Thrust was very different from that of the Hebridean Craton to the west, and apart from inclusions of altered Lewisian Gneiss (see above) and occasional slices of partly altered Torridon Sandstone and Cambrian Quartzite in the thrust zone, the rocks of this area are entirely different. With the exception of the above and a very limited outcrop of Devonian sandstone and conglomerate in the easternmost part of the area (Figure 1.2), all the rocks east of the thrust belong to the Moine Series. Chronologically, these fall into two groups: the 'old' Moines, which appear to have been originally deposited c. 1300-1200 Ma (before either of the Torridonian groups) and

which were subject to alteration and deformation during both the Grenville and Caledonian orogenies; and the 'young' Moines, which may be roughly equivalent to the Torridon Group in age of deposition and which experienced alteration only during the Caledonian orogeny.

Over nearly all of Wester Ross the Moine Series is represented by metasedimentary rocks collectively referred to as Moine Schists. For the most part these comprise quartz-feldspar granulites and mica-schists. The Moine Schists often present a banded aspect owing to the alteration of more quartzo-felspathic with more micaceous layers. This small-scale banding reflects in miniature the composition of the Moine Series by alternating granulite and mica-schist groups (Figure 1.2). There is little correspondence between the two types and relief, however, as each underlies both high and low ground.

In the easternmost part of the area lie two major granitic intrusions, those of Inchbae and Carn Chuinneag, emplaced at c. 560 Ma (before the Caledonian Orogeny). The dominant rock of these masses is a coarse-grained biotite-granite or granite-gneiss known as the Inchbae augen-gneiss (the 'augen' being large porphyritic crystals of orthoclase or microcline) and the Carn Chuinneag augen-gneiss or granite.

During the final stages of the Caledonian cycle, massive uplift and deep erosion occurred with some 25-30 km of material being removed from the metamorphic Caledonides during the period 500-410 Ma (Watson, 1985). Non-marine Devonian sediments were deposited on this erosion surface across much of the Northern Highlands and numerous outliers of these sediments occur today east of a line running approximately from Achnasheen to Strathy Point on the north coast. The base of these sediments thus marks the sub-Devonian land surface, and it can be inferred from their distribution that the summit levels of the present land surface stand not far below the Devonian land surface. Indeed, facies variations and palaeocurrent analyses in the Old Red Sandstone indicate that in south-east Caithness and the Great Glen, Devonian valleys that contained rivers flowing to the north-east and east are being re-exhumed by present-day erosion (Watson, 1985).

West of the Achnasheen-Strathy Point line there are no indications of Devonian sediments, but sediment eroded from west of this line occurs in the Middle Old Red Sandstone of Orkney and Easter Ross and in the Upper Old Red Sandstone of the Clyde region, implying continued erosion of the western areas throughout this period.

During the Late Palaeozoic and Early Mesozoic, extensional tectonics succeeded the previous compressional regime and the central part of the western uplifted area was downfaulted to produce the Mesozoic sedimentary basins

such as the North Minch and Sea of the Hebrides basins to the west of Wester Ross (Evans, *et al.*, 1982; Lovell, 1983). Only minor areas of Permo-Triassic sediments occur on land on the eastern margin of these basins, as in western Applecross and between Loch Ewe and Gruinard Bay. Palaeocurrent analyses of the basin margin sediments indicate derivation of the deposits on the east of these basins from the Scottish mainland.

Towards the end of the Mesozoic there was uplift followed by planation of the previously-deposited Mesozoic sediments (Godard, 1965; George, 1966), and thin marine Cretaceous sediments were deposited throughout the area of the Minches and the Sea of the Hebrides. It was across this low relief surface that the Early Tertiary lavas were deposited, and their altitude, thickness and attitude imply that they probably originally covered the very western margin of the Applecross Peninsula. During the Early Tertiary, prior to the deposition of Oligocene sediments (Smythe and Kenolty, 1975; Evans *et al.*, 1979) major warping took place with accompanying uplift of the Scottish mainland, possibly of the order of 500 m (Watson, 1985). This phase of uplift imparted a major eastward tilt to the Scottish Highland block and initiated the pattern of drainage which has persisted in its main outlines till the present day despite locally intense glacial erosion. Watson (1985) has argued for a single phase of uplift in the Early Tertiary rather than the pulsed uplift at various times during the Tertiary favoured by those who have attempted to explain apparently distinct 'erosion surfaces'.

GLACIAL HISTORY

INTRODUCTION

The Officers of the Geological Survey who first mapped and described the Quaternary landforms and deposits of Wester Ross (Peach *et al.*, 1912, 1913a, 1913b; Phemister, 1960) recognised three periods of glacial conditions in this area, as follows.

1. A period of maximum glaciation when the whole region was apparently enveloped in ice, which for the most part moved westward and north-westward, irrespective of the minor features of the country.
2. A stage when high ground along the present north-south watershed nourished extensive glaciers that became confluent in the valleys and spread over the lower plateaux as a continuous sheet. During this phase the western mountains rose as nunataks above the ice field.

3. A period during which each prominent mass of high ground became an independent ice centre and nourished its own glaciers, which followed the natural trend of the valleys. Terminal moraines in corries indicate occupation by glacier ice during this final glacial episode.

Subsequent research on the glacial history of Wester Ross has largely supported this threefold sequence, though inevitably some details of interpretation have changed. The 'maximum glaciation' identified by the Geological Survey essentially corresponds to the maximal extent of the last ice sheet; the evidence for the 'confluent glacier stage' appears to relate for the most part to local readvances or stillstands that interrupted the downwastage of the last ice sheet; and the 'valley glacier stage' corresponds to renewed glaciation during the Loch Lomond Stadial of c. 11,000-10,000 B.P.

THE LAST ICE SHEET

Chronology

Direct evidence for the timing of ice sheet initiation, expansion and culmination is not available in northern Scotland. Ocean core evidence, however, indicates that the last period of major mid-latitude ice sheet build-up occurred at around 75,000 yr BP (Shackleton and Opdyke, 1973; Ruddiman *et al.*, 1980), and ice-sheet glaciation of Scotland at this time has been suggested by Sutherland (1981) to explain the development of high-level shell beds and by Sissons (1982b) in connection with the formation of high-level rock platforms in the Inner Hebrides. This concept remains unproven, but receives support from evidence in Ulster for contemporaneous Scottish and Irish ice during the Early Midlandian (Devensian) (Bowen *et al.*, 1986) and from the evidence of deposition of glaciomarine sediments in the North Sea basin at this time (Cameron *et al.*, 1987). Amino acid ratios in shells contained in glacial deposits in northern Lewis indicate that the sea had access to the North Minch during a marine phase that has been dated to >45,000 yr BP and <80,000 yr BP (Sutherland *et al.*, in prep.), and this marine event may be that hypothesised by Sutherland (1981).

Whatever the status of the concept of an Early Devensian initiation of the last Scottish ice sheet, there is evidence to indicate that during the period from c. 35,000 yr BP (and possibly somewhat earlier) to c. 25,000 yr BP (and possibly somewhat later) large areas of northern Scotland were deglaciated. The principal evidence comes from the Creag nan Uamh caves at Inchnadamph (c. 60 km north of Achnasheen) where U-series dates show growth in one speleothem occurred between $38,000 \pm 6,000$ yr BP and $26,000 \pm 3,000$ yr BP and at $30,000 \pm 4,000$ yr BP and $26,000$

$\pm 2,000$ yr BP in two others, suggesting non-glacial conditions at these times (Atkinson *et al.*, 1986). From the same caves two separate single reindeer antlers have been radiocarbon dated to $27,333 \pm 810/-740$ yr BP and $24,590 \pm 790/-720$ yr BP. A deglacial phase at around this time is also indicated by the Tolsta Head site in northern Lewis, where lacustrine sediments have been radiocarbon dated to $27,333 \pm 240$ yr BP (von Weymarn and Edwards, 1973). Amino acid ratios and radiocarbon dates from ice-transported marine shells at Garrabost on the Eye Peninsula of Lewis also indicate that the sea entered the North Minch at least towards the end of this period (Sutherland and Walker, 1984; Sutherland *et al.*, in prep.), probably in response to renewed expansion of the Scottish ice sheet.

The culmination of the Late Devensian ice sheet expansion in northern Scotland is not dated. In England, the maximum extension of the southern margin of the ice sheet has been dated to 18,000-17,000 yr BP, whilst in western Ireland the maximum occurred some time prior to c. 17,000 yr BP (Bowen *et al.*, 1986). However, stratigraphic relations between Highland and Southern Upland tills in south-central Scotland show that the southern ice centres expanded subsequent to the more northerly (Sutherland, 1984a; in press), possibly in response to the southern movement of a zone of increased precipitation associated with the oceanic polar front (Sissons, 1981b). This model is in accord with the occurrence during the Late Devensian of ice-free areas on the northern margins of the Scottish ice sheet (Sutherland and Walker, 1984; Sutherland, 1984), and raises the possibility that the time at which the ice sheet reached its maximum extent may have been significantly earlier along its northern margin than farther south.

Much of the decay of the Late Devensian ice sheet occurred when the climate was still extremely cold (Sutherland, 1984a, in press) and precipitation starvation appears the most reasonable explanation although increased mass loss through calving as world sea level rose in response to the decay of the Laurentide and Scandinavian ice sheets may also have occurred. In the Northern Highlands the timing of this period of ice retreat is not well dated. If Sissons' (1982b) model of climatic control on rock platform development is correct and if the association between the Wester Ross Readvance moraines and erosional as well as depositional shoreline features indicated by Sissons and Dawson (1981) is also correct, then the Wester Ross Readvance may be tentatively dated to 13,500-13,000 yr BP, the approximate time when the oceanic polar front migrated northwards of the western Scottish coast (Ruddiman and McIntyre, 1973). A radiocarbon date of $12,810 \pm 155$ yr BP from organic silts at Loch Droma (NH 253 755) in the heart of Wester Ross (Kirk and Godwin, 1963) is probably in error by c. 1000 years (see below) and does not provide a critical limiting date on deglaciation. The only

other relevant date in the Northern Highlands is that from Cam Loch (NC 220 138) in Sutherland, where a basal date to the lacustrine sediments, if correct (cf. Sutherland, 1980), provides a minimum age of deglaciation in that area of $12,960 \pm 240$ yr BP (Pennington, 1975).

Directions of ice movement

Abundant evidence provided by striae and erratics indicates that the last ice sheet at its maximal extent moved in a westerly to north-westerly direction across all but the most easterly parts of Wester Ross. High-level striae orientated approximately WNW have been recorded on several mountains to the west of the main north-south watershed, for example at 890 m on the Fannich Mountains, at a similar altitude on An Ruadh-stac (NG 921 481), at 840 m on Sgùrr na Feataig (NH 056 454), at 710 m on the summit of Glas Bheinn at the head of Loch Carron (NG 901 436) and at 550 m on the slopes of Beinn Làir above Loch Maree. Elsewhere in the area deflection of basal ice by major mountains is recorded by slight variations in the direction of striae. Those east of An Teallach, for example, record a localised northerly deflection of ice movement, whilst striae at 600 m on the south side of Beinn Dearg point due west. To the east of the Fannich Mountains, however, the general orientation of striae and ice-moulding is to the east or south-east, indicating that the final ice movement in this area was easterly (Peach *et al.*, 1913a, 1913b).

Consistent with the evidence for general ice movement to the WNW is the evidence provided by erratics of Moine Schist, Lewisian Gneiss, 'thrust' Torridon Sandstone and Cambrian Quartzite that rest high on mountains west of the Moine Thrust (Table 1.1). Some of these erratics imply remarkable upward transport over short distances. The boulders of 'thrust' Torridon Sandstone that rest on the Cambrian Quartzite of Sàil Liath, An Teallach, for example, must have been transported at least 450 m upwards over a distance of possibly as little as 3 km and certainly no greater than 6 km. Boulders of 'thrust' Lewisian Gneiss near the summit of Slioch similarly imply upwards transport of at least 300 m over a distance of no more than 4 km, and Cambrian Quartzite erratics on the same mountain indicate even steeper transport paths. Over the relatively low ground in the north-west of the area, former ice movement in a westerly or north-westerly direction is indicated by abundant Cambrian Quartzite and Torridon Sandstone erratics overlying Lewisian Gneiss and, conversely, by Lewisian Gneiss erratics on the Torridon Sandstone peninsulas flanking Loch Ewe (see Figure 1.2). In addition, serpentine and peridotite boulders from an island outcrop in Fionn Loch (NG 945 804) have been traced for over 7 km to the north-west of the source (Peach *et al.*, 1913a).

Table 1.1

High-level erratics west of the Moine thrust

| Mountain | Grid Reference | Distance WNW from Moine Thrust | Maximum Erratic Altitude | Erratic Lithology |
|----------------------------|-------------------|---|--------------------------------|----------------------|
| Sàil Liath, An Teallach | NH 072825 | 3 km | 900 m | MS, TTS |
| Scurr Bàn | NH 056745 | 3 km | 980 m | TLG |
| Beinn Tarsuinn | NH 039728 | 4 km | 936 m | MS, LG and CQ |
| Slioch | NH 005689 | 7 km | 980 m | MS, LG and CQ |
| Meall a' Ghuibais | NG 978638 | 7 km | 878 m | MS, CQ |
| Beinn an Eòin | NG 905646 | 15 km | 855 m | MS, CQ |
| Beinn Eighe | NG 975600 | 4 km | 690 m | MS |
| Sgòr Ruadh | NG 959505 | 5 km | 885 m | MS |
| Maol Cheann-dearg | NG 924489 | 7 km | 933 m | CQ |

TTS: 'thrust' Torridon Sandstone

CQ: Cambrian Quartzite

TLG: 'thrust' Lewisian Gneiss

LG: Lewisian Gneiss

MS: Moine Schist.

The most intriguing evidence afforded by erratics in Wester Ross relates to the distribution of boulders of Inchbae augen-gneiss (Figure 1.2). These have been traced eastwards up to an altitude of c. 700 m on the western slopes of Ben Wyvis, across Black Isle and as far east as Buckie, 100 km from the source outcrop (Peach *et al.*, 1912). They have also, however, been recorded *north-west* of the outcrop, and apparently indicate former ice movement through the Dirrie More, across the main north-south watershed to Loch Broom. Large numbers occur north-west of Loch Droma and at Inverlael at the head of Loch Broom, where an erratic of Devonian conglomerate, apparently from the outlier near Inchbae, has also been found. Isolated examples have also been recorded on the south shore of Loch Broom up to 32 km north-west of the outcrop. The distribution of augen-gneiss erratics to both the east and the north-west of the outcrop would appear to imply that the former ice-shed lay across the augen-gneiss outcrop, some 10 km ESE of the present watershed near Loch Droma (Peach and Horne, 1892; Peach *et al.*, 1912).

This simple interpretation, however, conflicts with evidence of eastwards carry of erratics from much farther west in areas to the north and south of Wester Ross (Sutherland, 1984a, figure 6), and is also at variance with the evidence of striae, which record a general easterly movement across the augen-gneiss outcrop and surrounding low ground. The evidence of readvance moraines relating to downwastage of the last ice sheet also places the former ice shed well to the west of the augen-gneiss outcrop, in the vicinity of the Fannich Mountains. Peach *et al.* (1912) suggested that the conflicting evidence outlined above could be resolved in terms of westwards migration of the ice-shed following the ice-sheet maximum. This suggestion, however, conflicts with the evidence provided by the build-up of glacier ice in the area during the Loch Lomond Stadial, which suggests that the initial ice-shed is likely to have been located in the mountains west of the present watershed, rather than on the lower ground to the east. If the distribution of Loch Lomond Stadial glaciers *does* provide a reasonable analogue for the build-up of the last ice sheet (cf Sissons, 1981b), the north-westerly carry of augen-gneiss erratics from the Inchbae outcrop would appear to imply eastwards migration of the ice-shed of at least 10 km during or following ice-sheet accumulation and westwards migration of a similar magnitude during downwastage. Alternatively, Peach *et al.* (1912) suggested that the more westerly augen-gneiss erratics may represent *remanié* clasts derived from a westerly outlier of Devonian conglomerate that has since been entirely eliminated by glacial erosion, though there is no independent evidence for this. Finally, it is possible that the northwestwards carry of augen-gneiss erratics relates to an earlier glaciation, but again evidence is lacking.

Extent of the last ice sheet

The 'period of maximum glaciation' identified by the Officers of the Geological Survey was for many years believed to involve westward movement of ice from the mainland across the Outer Hebrides (e.g. Phemister, 1960). It has now been demonstrated, however, that the last ice movement over much of the Outer Hebrides was eastwards, which implies the former existence of a major independent ice mass on these islands (von Weymarn, 1974; Coward, 1977; Peacock and Ross, 1978; Flinn, 1978). The western terminus of the last mainland ice sheet at its maximal extent is at present uncertain. Sissons (1980a, 1981a), writing of the Devensian ice sheet, suggested that after an early advance across the Outer Hebrides, for much of the Devensian the margin of the Scottish mainland ice would 'normally' have been located near the eastern limit of high-level rock platforms in the Inner Hebrides (Sissons, 1982b). He also suggested (Sissons, 1981a) that during climatic deteriorations, presumably during the Late Devensian, the ice sheet would have advanced into the Sea of the Hebrides and the Minches, terminating, however, to the east of the Outer Isles. Sutherland (1984a) interpreted a large drift ridge in the North Minch as an end moraine of the last ice sheet and suggested on the basis of its size and singular nature that it may have been formed at the ice maximum.

The northern margin of the Outer Hebrides ice cap during the Late Devensian has been shown by Sutherland and Walker (1984) to occur in north-west Lewis. Interpretation of BGS seismic records has indicated moraines on the sea floor a short distance NNW of the north of Lewis (Sutherland, unpublished). The proximity of these to the moraine identified by Sutherland and Walker in Northern Lewis makes a Late Devensian age for these offshore features very probable. Correlatives of the offshore moraines can be traced to the north-east, and imply deposition by a lobe of mainland ice that was confluent off northern Lewis with Outer Hebridean ice. These moraines are therefore considered to mark the maximum extent of the Scottish mainland ice to the north of the Hebrides during the Late Devensian. If this is correct, confluence of the ice from Wester Ross with ice from the Outer Isles during the Late Devensian is implied.

Assessment of the altitude and thickness of the last ice sheet over Wester Ross has also engendered conflicting views. The evidence of high-level erratics led Peach et al., (1912, 1913a, 1913b) to assume that even the highest ground was covered by glacier ice during the 'period of maximum glaciation', though Gunn (in Peach et al., 1913a) inferred from the absence of erratics on the highest parts of An Teallach that the summit of this mountain may have remained a nunatak. The erratic evidence, however, now appears inconclusive, as it cannot be ascertained whether all high-level erratics were emplaced by the last ice sheet

or by an earlier (and thicker) ice sheet. It is notable in this context that the highest erratics are normally at a considerably greater altitude than the highest surviving striae.

A second approach to establishing the altitude of the surface of the last ice sheet over the North-West Highlands of Scotland has been through theoretical reconstructions based on the lateral extent of the ice sheet and assumed ice-sheet profiles (Boulton *et al.*, 1977, 1985; Gordon, 1979; Andersen, 1981). Most reconstructions also indicate that all Wester Ross was submerged under the last ice sheet, but as these assume that the margin of mainland ice lay beyond the Outer Hebrides (an assumption that conflicts with the abundant evidence for an independent Outer Hebridean ice cap), such reconstructions have dubious validity. An exception is the Boulton *et al.* (1985, figure 22) 'alternative model', which accepts the Sutherland and Walker (1984) ice margin in northern Lewis and implies that the ice surface in the Northern Highlands may have been below the summits of the highest mountains.

The more limited lateral extent of the last ice sheet indicated by recent findings (Sutherland, 1984a) implies that many mountains in northern Scotland probably remained above the ice sheet as nunataks and hence were subject to severe periglacial conditions throughout much of the Devensian. This consideration revives the possibility that the upper limit of the last ice sheet may be defined by the lower limit of certain relict periglacial features. A map showing the supposed ice surface across northern Scotland during 'maximum glaciation' was constructed by Godard (1965, p.605) on this premise, and indicates an ice surface at 900m along a line drawn from Little Loch Broom to Applecross, with the ice surface at 950 m against An Teallach. Godard's reconstruction appears to have little validity, however, as evidence of pronounced frost action exists on mountains in Wester Ross at altitudes much lower than the level of his proposed ice surface. More recently, Ballantyne (1984) observed that in this area the transition with increasing altitude from glacially-scoured bedrock to slopes mantled by a thick cover of *in situ* frost-shattered detritus is not gradual (as would be expected if climate were the only control on the altitudinal limits of such detritus) but on most lithologies occurs over a few tens of metres. This strongly suggests that the boundary represents the upper limit of a former ice surface. Ballantyne noted that in Wester Ross the lower limit of severely frost-shattered detritus on the Fannich mountains and on An Teallach descends westwards (Figure 1.3), and suggested that it may be related to the Wester Ross moraines (see below), but subsequent research on the lower limits of frost-shattered detritus on Baosbheinn and Beinn an Eòin (south of Loch Maree) suggests that these lie high above the Wester Ross moraine in this area (Ballantyne, unpublished; Figure 1.3). This implies that the periglacial

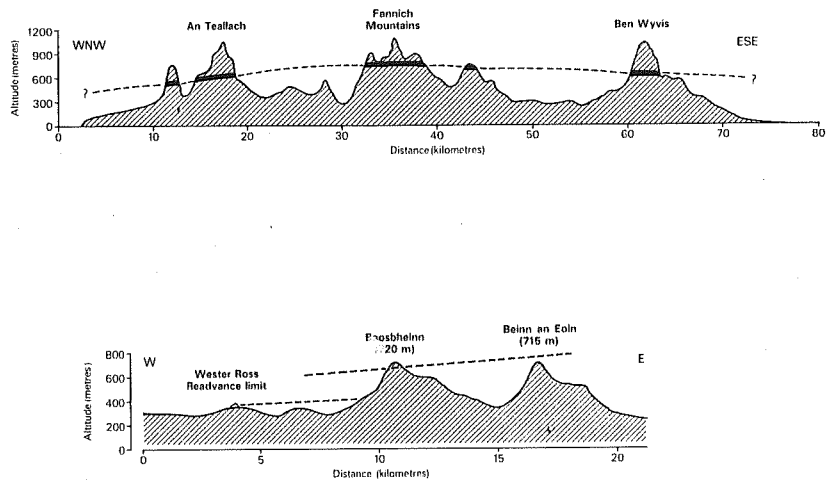


Figure 1.3: Top: extrapolated ice sheet surface profile drawn across Wester and Easter Ross and based on the mapped lower limit of thick *in situ* frost-weathered detritus (thick line) on the massifs shown (Ballantyne, unpublished). More recent research by W.J.Reed, however, suggests that the 'trimline' altitude on An Teallach may be rather higher than shown here.

Bottom: the upper line depicts the approximate former ice surface position implied by *in situ* frost-weathered detritus on the northern part of Baosbheinn and by its absence from the northern part of Beinn an Eòin; the lower line depicts the approximate level of the ice surface at the culmination of the Wester Ross Readvance.

limit defines the surface of an earlier and thicker ice mass than that which terminated at the Wester Ross Readvance moraines.

Subsequent work on this topic by W.J. Reed (unpublished) has demonstrated that a periglacial 'trimline' associated with the last Scottish ice sheet can be identified on many mountains in Wester Ross. Above the trimline extensive areas of *in situ* periglacial mountain-top detritus occur, contrasting with ice-scoured bedrock found a short distance downslope. The rapid change from frost-shattered to ice-scoured bedrock suggests that the trimline represents the position of the last Scottish ice sheet at its maximal extent; if this is the case, it implies that rock surfaces on many lithologies were little affected by frost action during ice-sheet downwastage or the subsequent Loch Lomond Stadial. It also implies that erratics that occur above the trimline were not emplaced by the last ice sheet but in the course of an earlier and more extensive glaciation. In places the trimline is obscured by the later downslope movement of periglacial detritus or by lithological variations, but despite local uncertainties introduced by these factors a regional pattern of increasing ice surface altitude from c. 700 m on An Teallach to greater than 800 m in the vicinity of the Fannich Mountains and Beinn Dearg is indicated by the trimline evidence (Figure 1.3). Reed's work on this topic indicates that the last 'ice sheet' in Wester Ross in fact took the form of a thick ice field, with several major ice streams separated by nunataks radiating from mountains in the vicinity of the present watershed and terminating an unknown distance offshore. Detailed analysis of trimline altitudes in Wester Ross is currently being undertaken in an attempt to reconstruct the three-dimensional surface form of the former ice surface in both Wester and Easter Ross.

If the trimline identified by Reed and Ballantyne (Figure 1.3) does indeed approximate the surface of the last ice sheet at its maximal thickness, this has several important implications. It is apparently consistent with the evidence summarised by Sutherland (1984a) which indicates that the dimensions of the last ice sheet in northern Scotland were much less than previously believed; in particular it is consistent with termination of the last ice sheet in the Minch. The trimline evidence, however, apparently conflicts with that of the Inchbae augen-gneiss erratics as outlined above, and lends credence to the view that these, like some high-level erratics, were originally emplaced by an earlier and more extensive glaciation during which the ice-sheet was located some distance to the east of the present north-south watershed.

READVANCES ASSOCIATED WITH THE LAST ICE SHEET

The 'confluent glacier stage' identified by Peach *et al.* (1912, 1913a, 1913b) was identified primarily on the basis of low-level striae, which indicate topographically-controlled ice movement away from centres of dispersion lying close to the present watershed. In the north of the area the Fannich Mountains were identified as the primary centre of ice dispersion and ice movement was envisaged around the flanks of outlying nunataks such as An Teallach, Slioch and the Letterewe mountains north-east of Loch Maree. Farther south, the mountains around Loch Monar were identified as the major centre of dispersion. The ice moving from the Monar source at this stage was envisaged as having met ice from the mountains north and west of Strathcarron such that ice was forced northeastwards as well as westwards, coalescing with ice from the Fannichs at Achnasheen. The combined ice stream was interpreted as having continued eastwards to reach its limit at terminal moraines 'at the mouth of Strathconon, on the Black Isle, and along the shores of the Cromarty Firth' (Peach *et al.*, 1913b, p.92). Moraines apparently relating to the confluent glacier stage were also identified in the vicinity of An Teallach (Peach *et al.*, 1913a). It seems, however, that the 'confluent glacier stage' was envisaged as a phase in ice sheet decay rather than a glacial readvance or series of readvances.

Similarly, in their account of the deglaciation of Ross-shire along a transect stretching NW-SE from Ullapool to Inverness, Kirk *et al.*, (1966) interpreted moraines and other ice-marginal features in terms of three or more 'withdrawal stages'. Much of the evidence provided by Kirk *et al.* appears of dubious validity, however, particularly that relating to supposed moraine limits at Ullapool, along the slopes above Loch Broom, at the head of Loch Broom (the 'Glackour moraine') and near Garve. Most of the definite former ice limits proposed by these authors relate to later local glaciation during the Loch Lomond Stadial (i.e. their 'Garbhrair stage'). Within the last decade, however, much new evidence for former glacier limits associated with the retreat of the last ice sheet in Wester Ross has been identified. This is summarised below.

The Wester Ross Moraines

The Wester Ross moraines were originally mapped by Robinson and Ballantyne (1979) and interpreted by them as marking the limit of a readvance (the Wester Ross Readvance) that interrupted the retreat of the last ice sheet. The most extensive moraines (the Redpoint, Gairloch and Aultbea moraines) define the former extent of a lobe of ice nearly 25 km in width that occupied lochs Gairloch and Ewe and the surrounding low ground (Figure 1.4). Subsequent mapping has shown that the lateral limits of this lobe

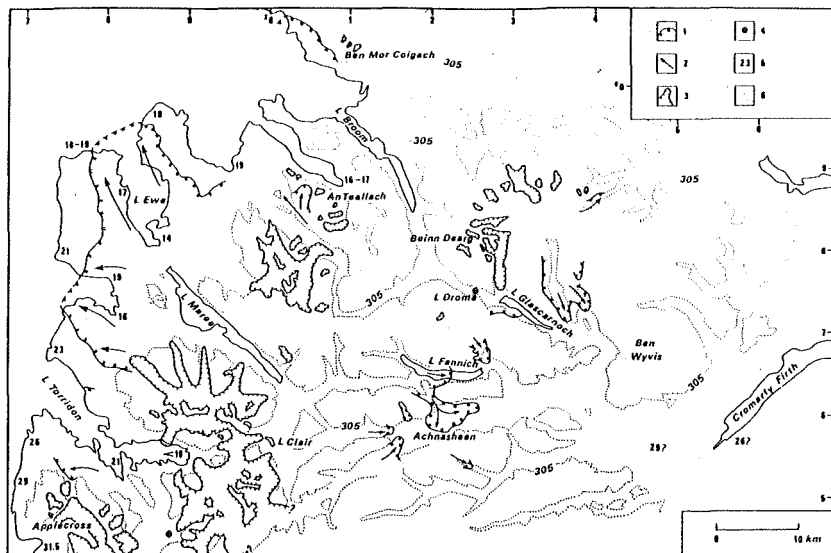


Figure 1.4: Glacial stages in Wester and Easter Ross, after Sutherland (1984a, figure 10). 1. Wester Ross Readvance moraines based on Robinson and Ballantyne (1979), Sissons and Dawson (1981) and Sissons (pers. comm.), and moraines in Easter Ross based on Sissons (1982a) and unpublished mapping by Sissons (pers. comm.). 2. Ice flow directions related to the above moraines. 3. Loch lomond Readvance limits after Sissons (1977). 4. Lateglacial pollen sites after Kirk and Godwin (1963) and Robinson (1977). 5. Marine limits (m) after Kirk et al. (1966) on the east coast and Robinson (1977) and Sissons and Dawson (1981) on the west coast. 6. Contour.

apparently extended across the Little Gruinard River c. 1 km south of Gruinard Bay in the north (Sissons and Dawson, 1981) and across the north-west flank of Baosbheinn to the south (Ballantyne, 1986a). Robinson and Ballantyne (1979) also suggested that a pronounced lateral moraine south of Loch Torridon (the Applecross moraine) marks the southern limit of a lobe of ice that occupied Loch Torridon at the same time, and morainic deposits at Craig (NG 775 638) may mark the northern limit of the same lobe. More speculatively, a drift ridge and sequence of three ice limits in a valley immediately north-west of An Teallach (the An Teallach moraines) have also been correlated with the Wester Ross Readvance by Robinson and Ballantyne. If correct, this implies that at the time of the readvance ice encircled An Teallach and lay at c. 500 m O.D. to the south of the massif but only 300-350 m O.D. in the trough now occupied by Little Loch Broom. Glacial occupation of the Little Loch Broom trough was also inferred by Sissons and Dawson (1981) from the absence in this area of a raised shoreline (the Main Wester Ross Shoreline) which they interpreted as having formed at the time of the readvance. Finally, the Wester Ross Readvance limit may also be represented by a pronounced lateral moraine that rises southeastwards along the slopes of Ben More Coigach from the village of Achiltibuie, 15 km north-west of Ullapool. If this correlation is correct, it implies that a third large lobe of ice occupied all of Little Loch Broom and Loch Broom at this time, as well as a considerable area offshore.

At present, the 'readvance' status of the ice limit represented by the Wester Ross moraines rests entirely on morphological evidence. In particular, the Applecross and Redpoint moraines are associated with a marked change in the direction of striae, and both truncate ice-moulded till ridges aligned north-west (Robinson, 1977; Robinson and Ballantyne, 1979; Figure 1.5). The readvance limit is not, however, associated with a pronounced drop in the marine limit (Sissons and Dawson, 1981), which suggests that the event was of limited duration. The timing of the readvance is unknown, but, as noted earlier, may be tentatively dated to 13,500-13,000 B.P., the approximate time when the oceanic polar front migrated northwards of the western Scottish coast (Ruddiman and McIntyre, 1973).

The Achnasheen Moraines

The Achnasheen moraines were first described by Peach *et al.* (1913b) in association with the formation of a glacier-dammed lake in Strath Bran, and were subsequently mapped in detail by Sissons (1982a). These moraines define the termini of four ice masses: (1) ice that advanced north-eastwards up Strath Carron and terminated about 1 km from the village of Achnasheen; (2) ice that moved eastwards and terminated just beyond the eastern shore of Loch a'Chroisg; (3) a small local glacier that descended

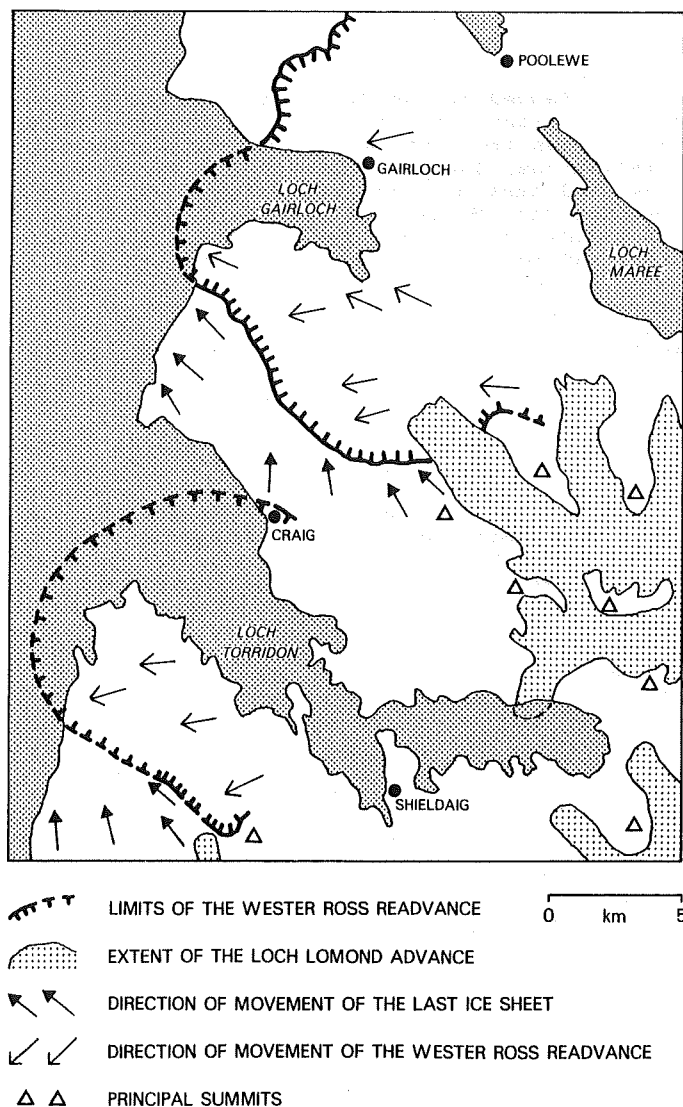


Figure 1.5: Former ice limits and directions of ice movement as indicated by striae in the Loch Torridon and Loch Gairloch areas.

from a shallow corrie on the south-east slopes of Fionn Bheinn; and (4) a broad lobe that issued southwards from the area now occupied by Loch Fannich and spread across Strath Bran (Figure 1.4). That the last-mentioned at least represents a readvance (the Achnasheen Readvance) is demonstrated by lake sediments underlying the moraine. Sissons argued that the dimensions of the three principal ice masses are inconsistent with those of glaciers formed elsewhere in Wester Ross during the Loch Lomond Stadial, and suggested that the Achnasheen Readvance may correlate with the Wester Ross Readvance. Such an interpretation, however, would apparently place the contemporaneous ice shed well to the west of the present watershed (Figure 1.4), which conflicts with the pattern of striae as interpreted by the Geological Survey. If, as suggested by the pattern of striae, the Fannich Mountains continued to act as a centre of ice dispersal during the overall wastage of the last ice sheet, it seems unlikely that the two readvances were contemporaneous, as this would imply a highly asymmetrical ice mass that terminated only a few kilometres from the ice shed in the east and south but extended over 40 km to the west and north-west. If the former ice shed remained in the vicinity of the Fannichs during overall wastage of the last ice sheet, then it seems probable that the Achnasheen Readvance post-dated the much more extensive Wester Ross Readvance.

The Strath Vaich and Strath Rannoch moraines

A possible correlative of the Achnasheen Readvance is represented by former ice limits in the neighbouring glens of Strath Vaich and Strath Rannoch (Figure 1.4). These are marked by conspicuous lateral moraines and drift limits, and associated with eskers inside the former ice limit and outwash terraces outside it (Peach *et al.*, 1912; W.J. Reed, unpublished). Kirk *et al.* (1966) correlated these limits with their 'Garbhrair Stage' (i.e. Loch Lomond Readvance), but Sissons (in Sutherland, 1984a, p. 207) believed that this was unlikely as the dimensions of the former ice mass implied by these moraines seem inconsistent with those of Loch Lomond Stadial glaciers in the vicinity. The northern limit of the same ice mass may be represented in Glen Mòr by a clear drift limit which descends to the floor of that valley at NG 416 873 (W.J. Reed, unpublished; Figure 1.4). The age of these ice limits is unknown, and like the Achnasheen moraines they can only be related to the Wester Ross Readvance if the contemporaneous ice shed lay well to the west of the present watershed.

Ice limits in the vicinity of the Fannich Mountains

Sissons (in Sutherland, 1984a, figure 10) mapped two possible ice sheet readvance limits in the vicinity of the Fannich Mountains: a supposed end moraine that rises westwards from the southern shore of Loch Glascarnoch and a complex of end and lateral moraines that terminate some 500

m north of the eastern end of Loch Fannich (Figure 1.4), the latter having previously been interpreted by him as representing the limit of the Loch Lomond Readvance in this area (Sissons, 1977, figure 8). If these limits are indeed those of an ice sheet readvance, they may represent links between the limits at Strath Vaich and those at Achnasheen. However, remapping of this area by W.J. Reed has cast doubt on the reality of the Glascarnoch limit identified by Sissons, and has shown that the moraines at the eastern end of Loch Fannich apparently relate to a body of local ice that was nourished in the corries of the Fannich Mountains and extended north-eastwards towards Loch Droma and the western end of Loch Glascarnoch. The significance of both these limits in terms of retreat stages or readvances of the last ice sheet is therefore uncertain.

The Loch Achall moraine

At the western end of Loch Achall, c. 3 km north-west of Ullapool, a low end moraine crosses the valley on the north side of Ullapool River and is continued eastwards by a distinct drift limit along the north side of the valley (Kirk et al., 1966; Ballantyne, unpublished). This moraine cannot represent the limit of the Loch Lomond Readvance, which according to Sissons (1977, figure 7) terminated c. 17 km upvalley in the corries of Seana Braigh; nor can it represent the limit of the Wester Ross Readvance if the limit of that event is represented by the moraine at Ben More Coigach, almost 20 km north-west of Loch Achall.

The Gleann Méinich moraine

A well-defined double end moraine marks the limit of ice moving ESE down Gleann Méinich out of Strath Bran, and is continued on either side of the valley by clear lateral moraines and drift limits (Peach et al. 1913a, p. 97 and plate VI; Sissons, 1977). As Sissons has pointed out, Gleann Meinich lacks a local catchment so that the limit here must be that of ice that spilled out of Strath Bran. The Glen Méinich moraine, however, lies well outside the limits of the Achnasheen Readvance (Figure 1.4) and must represent an earlier (possibly local) glacial readvance or stillstand during overall ice-sheet retreat.

Little Gruinard River

W.J. Reed (unpublished) has mapped an extensive area of hummocky moraines defined by a clear drift limit along the upper reaches of Little Gruinard River near its outlet from Fionn Loch c. 4 km inside the limit of the Wester Ross Readvance as mapped by Sissons and Dawson (1981). The significance of this drift limit is uncertain.

The Slioch Moraine

North-west of the summit of Slioch, a lateral moraine c. 500 m long rises up to 15 m above the surrounding ice-scoured bedrock between NG 991 699 and NG 995 695 at c. 460 m altitude and defines the south-western limit of a former ice mass that occupied the Loch Garbhaig and Lochan Fada troughs. This limit lies well within that of the Wester Ross Readvance (which reaches a similar altitude at Baosbheinn, 14 km farther west; Ballantyne, 1986a) and is again of uncertain significance.

In addition to the abovementioned former ice limits, other evidence that may relate to readvances of the last ice sheet in Wester Ross and the surrounding area is described briefly in Peach *et al.* (1912, 1913b). Of greatest interest in this respect are possible drift limits or lateral moraines along the north-western face of Ben Wyvis in Easter Ross and in the area south and east of Strath Carron. Such evidence awaits detailed reinvestigation, and its validity and significance are uncertain.

Discussion

Whilst the evidence presented above indicates that the wastage of the last ice sheet in Wester Ross was interrupted by at least one widespread readvance (the Wester Ross Readvance) and by other readvances or stillstands of at least local importance, many uncertainties attend the correlation and interpretation of former ice-sheet readvance limits in this area. There appear to be four main possibilities.

1. Correlation of the Wester Ross Readvance with the Achnasheen Readvance and other former ice limits east of the present north-south watershed, particularly those of Strath Vaich, Strath Rannoch and Glen Mór. As noted earlier, this implies that the contemporaneous ice-sheet lay well to the west of the Fannich Mountains and thus conflicts with the evidence of striae, which indicate ice movement westwards from the Fannichs. If the former ice sheet remained in the vicinity of the Fannichs, as implied by striae, then the Achnasheen Readvance moraines apparently mark the margin of a much less extensive ice mass than that delimited by the Wester Ross Readvance moraines. The implication is that the Achnasheen Readvance post-dated the Wester Ross Readvance.

2. Interpretation of the available evidence in terms of two regional and several local readvances of the downwasting ice sheet. If it is accepted that the Fannichs continued to act as a major centre of ice dispersal during ice-sheet downwastage, the available evidence suggests that the Wester Ross Readvance must have pre-dated the Achnasheen Readvance. If this were the case, the eastern

margin of the Wester Ross Readvance may have lain in Easter Ross; the supposed lateral moraines on Ben Wyvis (Peach *et al.*, 1912) and the end moraines mentioned by Peach *et al.* (1913b, p.92) in the Cromarty Firth area may be significant in this respect. If the Achnasheen Readvance was also of regional significance, then it may correlate with the Strath Vaich, Strath Rannoch and Glen Mòr limits. The connection between these and the Achnasheen moraines is uncertain, however, as is the western extent of this later ice mass, though the Loch Achall and Slioch moraines may represent possible correlatives. The Gleann Méinich moraine and the ice limit identified by Reed at Little Gruinard River seem unlikely to be related to either readvance.

3. Perhaps the simplest interpretation of present evidence is that only the Wester Ross Readvance was of regional significance, and that the eastern margins of this readvance lay in Easter Ross or beyond, or indeed that the readvance affected only the western margin of the downwasting ice sheet. There is no positive evidence to indicate that any other readvance in the area was of more than local significance.

4. A more radical suggestion is that glacier ice was much more widespread in Wester Ross during the Loch Lomond Stadial than has hitherto been believed. The argument for the Achnasheen, Fannich, Strath Vaich, Strath Rannoch and Glen Mòr moraines being older than the Loch Lomond Stadial rests largely on the assumption that these represent ice masses of a size inconsistent with the dimensions of stadial glaciers in this area. This argument is circular. If it is accepted that Sissons' postulated Glascarnoch moraine (in Sutherland, 1984a, figure 10) does not exist (Reed, unpublished), then there is no stratigraphic or morphostratigraphic evidence to discount a stadial age for any of these ice limits [the position of the Glen Mòr moraine is incorrectly plotted in Sutherland's original map (1984a, figure 10); stadial corrie glaciers do not occur within this limit]. Moreover, Reed's remapping of the Fannich Mountains indicates that the last ice mass here was of entirely local origin, and of a form entirely consistent with the regeneration of ice during the Loch Lomond Stadial. Finally, it may be significant that Pennington *et al.* (1972; also Pennington, 1977a) failed to find organic Lateglacial sediment in Loch a'Chroisg, which lies immediately inside one of the Achnasheen moraine limits. Similarly, Sissons (pers. comm.) failed to find evidence of pre-stadial organic sediments by coring through peat inside the limit of the Achnasheen Readvance in Strath Bran. The absence of sediments of Lateglacial Interstadial age at these sites is consistent with interpretation of the moraines as Loch Lomond Readvance limits.

In sum, little of certainty emerges from present evidence concerning the ice-sheet readvances in Wester Ross; only the Wester Ross Readvance can be shown to

represent a large-scale ice-sheet readvance, albeit of uncertain age. All of the other documented ice limits may represent no more than local halts or readvances, and, as argued above, some of these may relate to the Loch Lomond Readvance rather than ice-sheet downwastage. If correct, this latter consideration implies that Sissons' reconstruction of Loch Lomond Readvance limits in this area is substantially in error, and that palaeoclimatic inferences based on this reconstruction may be invalid.

Although the age of the Wester Ross Readvance is unknown, it is notable that in this area high-level marine rock platforms occur only outside the readvance limit. Sissons (1981a, 1982b) has inferred from the restriction of high rock platform fragments in Scotland to areas west of a line drawn through Islay, Jura, Mull, Ardnamurchan, Central Skye and Applecross that throughout much of the later Devensian the western limit of the last Scottish ice sheet lay amongst the Inner Hebrides, so that platforms were formed under periglacial conditions beyond this limit, but not within it. If this is correct, the Wester Ross moraines appear to offer evidence for at least one position of the ice sheet during the period of platform formation. The restriction of rock platform fragments to areas outside the readvance limit also implies that significant coastal erosion of bedrock ended with ice-sheet retreat following the Wester Ross Readvance. As noted earlier, if Sissons' model of rock platform formation under periglacial conditions is correct, then these relationships suggest that the Wester Ross Readvance dates to c. 13,500-13,000 yr BP, when the oceanic polar front migrated north of the west coast of Scotland (Sutherland, in press).

Sissons (1981b) also suggested that the readvance may have resulted from reinvigoration of the wasting Late Devensian ice sheet as the average position of the atmospheric polar front moved northwards across the Scottish Highlands in the period immediately preceding the Lateglacial Interstadial. If this interpretation is correct, then the occurrence of later ice-sheet readvances or stillstands in Wester Ross may indicate that the northward movement of the average position of the front was not regular but oscillatory, resulting in periods of increased snowfall that briefly and perhaps only locally arrested the overall downwastage of ice in this area.

THE LOCH LOMOND READVANCE

During the Loch Lomond Readvance an extensive ice field developed in the Western Grampian Highlands of Scotland and in the North-West Highlands south of Loch Carron (Sissons, 1979, 1983; Thorp, 1986). Reconstructions of the extent of ice cover in Wester Ross and areas farther north, however, indicate much more restricted glaciation at

this time (Robinson, 1977; Sissons, 1977; Figure 1.4). Although it is unknown whether the Western Highlands were completely deglaciated during the preceding Lateglacial Interstadial of c. 13,000-11,000 B.P. (Sutherland, 1984a, p. 209-210), the relatively restricted extent of stadial glaciation in Wester Ross and the fact that the pattern of ice advance at this time was utterly different from (and in places cuts across) that which occurred during the Wester Ross Readvance supports interpretation of the Loch Lomond Stadial glaciation in this area in terms of renewed glaciation following complete deglaciation during the interstadial (Sissons, 1977, p.58; Robinson and Ballantyne, 1979; Ballantyne, 1986a, p.22). For this reason the term 'Loch Lomond Advance' (rather than 'readvance') has frequently been employed in the recent literature relating to this glacial event in Wester Ross. Palaeoclimatic considerations, however, suggest that glacier ice may have survived the Lateglacial Interstadial in some of the higher corries of Wester Ross (see below), and the traditional term 'Loch Lomond Readvance' first introduced by Simpson (1933) is therefore adhered to in this guide.

Field Evidence

Morphological evidence for expansion of glacier ice following the Lateglacial Interstadial is manifold in Wester Ross, and has been mapped by Sissons (1977) in the area north-west of Glen Torridon and north of Loch Fannich and by Robinson (1977) on the Applecross Peninsula and in the area between Glen Torridon and Strath Carron. Details of Sissons' mapping have subsequently been revised for the An Teallach area (Ballantyne, 1981, figure 4.5) and the area south-west of Loch Maree (Ballantyne 1986a), and revision of his mapping in the mountains north-east of Loch Maree and north of the Fannich ridge is currently in progress (W.J. Reed, unpublished). If, as noted earlier, certain 'ice-sheet readvance' moraines should prove to be of Loch Lomond Readvance age then further substantial revision of Sissons' mapped glacier limits is implied, particularly in areas immediately east of the north-south watershed.

The evidence that has been used to map the limits of glaciers of presumed Loch Lomond Stadial age in Wester Ross includes end and lateral moraines, boulder limits, drift limits, striae, the lower limits of certain relict periglacial features, and the distribution of areas of hummocky and fluted drift and certain fluvioglacial features. The termini of most Loch Lomond Readvance glaciers are marked by end moraines. Some of these are extremely large: the Gharbhrain moraine near Loch Glascarnoch (NH 285 756), for example, is up to 25 m high, over 200 m broad and about 800 m long, and the end moraines marking the limits of the glaciers that emanated from corries on Beinn Dearg Mòr (NH 045 802) and An Teallach (NH 092847) rise up to 40 m and 30 m respectively above the

adjacent terrain. Others, however, consist of little more than lines of large boulders, typical examples being the five moraines that mark successive positions of the former ice margin in a corrie north-west of the An Teallach plateau (NH 06 87).

An intriguing feature of the Loch Lomond Readvance glacier limits in Wester Ross is that many are marked by multiple end moraine ridges. Sissons (1977), for example, recorded three instances where the limits of corrie glaciers are marked by at least five successive and approximately parallel moraine ridges, and noted the occurrence elsewhere of double, triple and quadruple moraines. Similarly, many of the 23 glacial limits mapped by Robinson (1977) consist of more than one moraine, and she recorded four moraine ridges at five of these sites. In all cases the entire suite of inner moraines is developed within a few hundred metres of the outermost limit, and in most cases the outermost moraine is by far the largest. The implication of this evidence is that in the early stages of retreat the ice remained active and experienced at least brief periods of stillstand or readvance. An example of a possible ice-wedge cast reported in an exposure just *within* the limit of the Gleann na Muice glacier at NH 071 803 by Sissons (1977, p.56) may provide support for this interpretation; if the structure described by Sissons is a true ice-wedge cast, then it implies that following the retreat of ice from its maximal extent the climate remained sufficiently cold for the development of continuous permafrost at c. 100 m O.D. This interpretation may also help to account for the formation of massive moraines such as the Gharbhrainn moraine, which may reflect continued debris supply to the snout of a slowly-receding but active glacier over a considerable time period. The lack of recessional moraines farther inside the glacier limits, however, suggests that ice retreat from the terminal moraine belts was uninterrupted by further readvances or stillstands.

In some localities the termini of former glaciers are marked not by moraine ridges but by the limits of abundant glacially-transported boulders or thick (often hummocky) drift. A fine example of such a drift limit records the maximal extent of the glacier that was nourished in Coire Toll an Lochain, An Teallach (NH 095 838); inside the former glacial limit thick drift completely obscures the underlying bedrock, but beyond the limit drift is completely absent. Hummocky drift is particularly well represented inside certain Loch Lomond Readvance limits in Wester Ross. Coire a'Cheud-chnoic (the 'Valley of a Hundred Hills') in Glen Torridon is one of the finest areas of hummocky moraines in the Great Britain, and equally well-developed if less extensive areas of hummocks occur, for example, on the low ground immediately north of the Fannich ridge and in Strath Lungard, south of Loch Maree. Research by Hodgson (1982, 1986) on the characteristics of hummocky

and fluted drift in Wester Ross has shown that in most cases both types of landform were produced by subglacial deformation of pre-existing till, with only limited net downglacier movement of sediment. Both forms are much more abundant inside the Loch Lomond Readvance limits than outside [indeed, Sissons (1977) reported that in Wester Ross fluted drift is restricted entirely to areas glaciated during the Loch Lomond Readvance], and hummocky drift often extends to the edge of former ice margins as defined by end and lateral moraines. In areas where other ice-marginal evidence is lacking, the extent of hummocky drift has been used to provide a minimal estimate of the extent of former ice cover during the Loch Lomond Readvance. This criterion cannot be employed indiscriminately, however, as in some areas hummocky moraines also occur well beyond the known limits of the Loch Lomond Readvance.

Striae provide rather more certain evidence of the dimensions of Loch Lomond Readvance glaciers, particularly where the orientation of these is at variance with or cuts across earlier striae relating to the final movements of the last ice sheet, as occurs in the area between Liathach and Beinn Eighe and in Coire Làir near Strath Carron (Peach *et al.*, 1913b).

On higher ground occupied by Loch Lomond Readvance glaciers, lateral moraines, drift limits and boulder limits are rarely present, so that reconstruction of the position of the former glacier margins relies on establishing the position of periglacial 'trimlines' that mark the boundary between ice-scoured glaciated terrain and frost-weathered bedrock that supports certain relict periglacial landforms, particularly boulder lobes (Thorp, 1981, 1986; Ballantyne, 1984). On some well-jointed lithologies such as Cambrian Quartzite, *in situ* blockfields extend down to the Loch Lomond Readvance limit, but do not occur within it, but on many lithologies the contrast between terrain that was glaciated at this time and that which was not is more subtle, and evident only in slight frost modification of ice-scoured bedrock and widening of joints outside of the Loch Lomond Readvance limit (Ballantyne, 1982). On Torridon Sandstone terrain in particular, the 'trimline' representing the upper limit of Loch Lomond Readvance glaciers is much less well defined than the much higher and older trimline that apparently represents the limit of the last ice sheet in this area (W.J. Reed, unpublished).

Stratigraphy and chronology

The rather limited stratigraphic evidence that relates to the Lateglacial in Wester Ross is consistent with a Loch Lomond Stadial age for the final local expansion of glacier ice in this area. Cores taken by Robinson (1977) from a peat-filled kettle hole at Glassnock (NG 866 461), some 2 km outside a moraine of inferred Loch Lomond Readvance age, contained organic sediments relating to the Lateglacial

Interstadial; cores from a similar basin immediately inside the same moraine limit at Druim Dubh (NG 885 471) revealed only Flandrian sediments. Although radiocarbon dates obtained on samples of gyttja from the Glassnock site proved of dubious validity owing to contamination, the stratigraphic contrasts between these two sites are in accord with a Loch Lomond Readvance age for the Druim Dubh moraine and, by implication, all of the substantial icefield that Robinson mapped between Glen Torridon and Strath Carron (Figure 1.4).

Organic sediments of Lateglacial Interstadial age have not, however, been found in cores recovered from lake sediments at Loch Maree, Loch Clair and Loch a'Chroisg, all of which lie outside the mapped limits of the Loch Lomond Readvance in Wester Ross (Birks, 1972; Pennington *et al.*, 1972; Pennington, 1977a). In all cases this may be due to failure of the corers to penetrate minerogenic sediment of stadial age. At Loch Maree, however, the sub-Flandrian sediments consist of c. 0.7 m of laminated silts and clays, which appears to confirm that glacier ice was absent from the western part of the Loch Maree lake basin during the Loch Lomond Stadial (Birks, 1972). At Loch Clair, moreover, the limit of the Loch Lomond Readvance is uncertain. Hummocky moraines similar to those employed to establish the extent of Loch Lomond Stadial glaciation elsewhere in this area fringe the western shores of the loch, but Robinson (1977, p. 76) regarded this evidence as equivocal and placed a tentative limit to the readvance 1 km to the south-west of the loch. As noted earlier, the absence of Lateglacial Interstadial sediments in the Loch a'Chroisg core may suggest that the supposed Achnasheen Readvance ice limit immediately to the east could be of Loch Lomond Readvance age, but given the difficulties of penetrating minerogenic sediments on lake floors such a conclusion is premature on present evidence.

At Loch Droma (NH 253 754), Lateglacial Interstadial sediments underlie inorganic silts and demonstrate that this site escaped glaciation during the Loch Lomond Stadial. Kirk and Godwin (1963) were uncertain as to which part of the Lateglacial sequence was represented by their analyses of organic sediments from this site, as at the time of their work the pollen stratigraphy of Lateglacial Interstadial deposits in the Scottish Highlands was incompletely established. The regional pollen zonation of Pennington *et al.* (1972), however, makes it clear that an almost complete Lateglacial sequence is present and that the base of the *Artemisia* regional pollen zone (Loch Lomond Stadial) occurs in the laminated sediments above the organic-rich horizon. This is consistent with assigning a Loch Lomond Readvance age to the the nearby Gharbhrair moraine (Kirk *et al.*, 1966; Sissons, 1977) and to the limits of a large glacier that was nourished in the corries north-east of the Fannich Ridge and terminated on low ground between Loch Droma and Loch Glascarnoch (W.J. Reed,

unpublished). Indeed, the coarsening upwards of the Stadial lithostratigraphic sequence at Loch Droma is in accord with the approach of this glacier to the present site of Loch Droma. If this interpretation is correct, it suggests that the Loch Lomond Readvance glaciers reached their maximum in the latter part of the stadial.

In Loch Kishorn, site investigation boreholes immediately outside former glacier limits below Coire nan Arr and Coire na Bà revealed a very coarse bouldery horizon 12.8 m thick overlying shell-bearing marine sediments containing a fauna with Clyde Beds affinities (Robinson, 1977). The coarse overlying horizon has been interpreted by Robinson as being contemporaneous with the adjacent former glaciers, and the underlying Lateglacial Interstadial sediments therefore indicate a Loch Lomond Readvance age for these glaciers.

The available evidence thus suggests that subsequent to the retreat of the last ice sheet in Wester Ross there was only one period of expansion of valley and corrie glaciers [with the questionable exception of a small independent glacier that terminated in Strath Bran and was assigned to the Achnasheen Readvance by Sissons (1982a)] and that this glacial phase correlates with the Loch Lomond Readvance.

With the possible exception of Loch Droma, however, none of the above evidence permits accurate dating of the culmination of the Loch Lomond Readvance in Wester Ross. Precise dating of this event has proved elusive elsewhere in Scotland also, on account of the uncertainties associated with radiocarbon dating of organic sediments at the base of kettle holes within the limits of Loch Lomond Readvance glaciers (Sutherland, 1980). Dates presently available from shells over-ridden or transported by glacier ice and from basal organic deposits within the glacier limits suggest that the ice reached its greatest extent in the Southern and South-West Highlands during the first half of the Loch Lomond Stadial, that is between c. 11,000 B.P. and c. 10,500 B.P. (cf. Sutherland, 1984a, p. 214-6). It is not known whether the culmination of glaciation in Northern Scotland was synchronous with that farther south.

Distribution

The limits of the Loch Lomond Readvance as mapped by Robinson (1977) and Sissons (1977) show that, in general, glaciers were restricted to mountainous terrain and that ice cover was most widespread in the west of the area (Figure 1.4). All of the former glaciers mapped by Robinson and Sissons relate to one of seven centres of ice accumulation and dispersal, as follows.

1. The Applecross Hills, where Robinson (1977) mapped a small transection complex of four valley glaciers and seven

independent corrie glaciers. The termini of all of these descended below 300 m, and three extended below present sea-level into Loch Kishorn. The mean equilibrium line altitude (ELA) for the Applecross glaciers is given by Robinson as 409 m, or 394 m if an apparently 'anomalous' ice tongue is excluded.

2. The mountainous area between Glen Torridon and Strath Carron, much of which was covered by an icefield with several outlet glaciers but no independent glaciers. In the north the icefield was confluent with a glacier from north of Glen Torridon, and in the south with ice from south-east of Strath Carron, though the limits of the latter have not been determined. Robinson (1977) gives the mean ELA of the icefield as 474 m.

3. The Torridon Hills between Loch Maree and Loch Torridon, where Sissons (1977, figure 9) mapped a small former icefield and three small corrie glaciers. Ballantyne (1986a) subsequently remapped the limits of the outlet glaciers that flowed north-west from the icefield source on either side of Baosbheinn, and showed that these tongues extended 4-5 km farther than in Sissons' reconstruction. To the south one outlet glacier terminated below present sea level in Loch Torridon and another was confluent with ice from south of Glen Torridon. Sissons' (1977) reconstructed ELAs for this area range from 382 m to 652 m with a mean ELA of 552 m, but revised mapping gives a lower mean figure of 549 m.

4. The mountainous area between Loch Maree and Loch na Sealga (i.e. Letterewe Forest and Fisherfield Forest), where Sissons (1977, figure 6) mapped a small icefield or transection glacier complex and four small former corrie glaciers. He also recorded an isolated corrie glacier on Slioch, 5 km south of the icefield. The former glaciers mapped in this area by Sissons have termini at altitudes ranging from under 100 m to nearly 500 m, and reconstructed ELAs of 393-637 m (mean ELA: 519 m, or 502 m if the Slioch glacier is excluded). W.J. Reed (unpublished) has questioned the accuracy of some of Sissons' limits in this area.

5. The An Teallach massif, which nourished five or six small corrie glaciers, and the adjacent mountain of Sàil Mhór, which nourished two. Sissons (1977) gives the range of ELAs for these glaciers as 317-838 m, but remapping of the limits of a small glacier that formerly occupied Coire Mór on An Teallach (Ballantyne, 1981) suggests that the highest figure is an overestimate. The mean of Sissons' ELA values for this area is 585 m.

6. The Beinn Dearg massif and the mountains of Freevater Forest in the far north of Wester Ross and extending into Sutherland. The Beinn Dearg group, according to Sissons (1977), comprised five small corrie and valley glaciers and

the large valley glacier that flowed south-west to terminate at the Gharbhrain moraine, with reconstructed ELAs of 536-886m (mean 687 m). The Freevater Forest group in southern Sutherland consisted of seven small north or north-east facing corrie glaciers and a large ice tongue in Strath Mulzie, with reconstructed ELAs of 508-718m (mean 581 m).

7. The Fannich mountains, where Sissons (1977, figure 8) mapped the limits of a small north-facing corrie glacier with a reconstructed ELA of 847 m, an east-facing corrie glacier of similar size with a reconstructed ELA of 480 m, and a large intervening ice mass to the north-east of the Fannich Ridge formed by the coalescence of several corrie glaciers and with reconstructed ELAs of 675 m (west) and 490 m (east). The 'anomalously' low ELA values of 480 m and 490 m for former glaciers that developed in the eastern part of the Fannichs led Sissons (personal communication) to suggest that the limits of these glaciers represented an earlier glacial stage, possibly related to ice sheet deglaciation (Figure 1.4). Remapping of the Fannichs area by W.J. Reed (unpublished), however, appears to confirm the former presence of a large independent glacier that had its source in the north-eastern corries of the Fannichs and extended down to less than 300 m altitude between Loch Droma and Loch Glascarnoch, and another that formed in the corries north-east of Beinn Liath Mhór Fannich and covered the present site of Loch Sgeireach (NH 23 73). If correct, this mapping suggests that there is no reason to suppose that any of the glacier limits mapped by Sissons (1977) in the Fannichs pre-dates the Loch Lomond Readvance. Moreover, the presence of thick hummocky drift in valleys south of the Fannich ridge, around Loch a'Mhadaidh (Kirk *et al.*, 1966) and in the western part of the Fannich area suggests that the Loch Lomond Readvance may have been even more widespread in this area than Reed's revised mapping has indicated.

SEA-LEVEL CHANGE.

Prior to last ice sheet.

Two altitudinally distinct rock platforms that show signs of having been glaciated have been described from Wester Ross. The lower occurs at approximately 3 m O.D. (Sissons and Dawson, 1981). The platform has been observed at many localities around the coast and is typically several tens of metres wide but with a maximum recorded width of 150 m. The age of the platform is uncertain: it is ice-moulded and in places passes under glacial deposits. Sissons and Dawson (1981) suggested that it may have been formed during parts of interglacials when sea level was relatively stable.

The higher glaciated rock platform has been traced along parts of the west coast of the Applecross Peninsula (Robinson, 1977) as well as in fragmentary form along parts of the Wester Ross coast north of Loch Torridon (Sissons and Dawson, 1981). On the Applecross coast the platform ranges in altitude between 32 m and 37 m O.D. with a southward tilt (Robinson, 1977). Farther north, the platforms surveyed by Sissons and Dawson (1981) occur between 20 and 24 m O.D. They considered the altitude of some of the lower fragments to relate to retrimming of a pre-existing feature during ice-sheet retreat, as one of the platform fragments is continuous with a platform cut in drift and beach gravels rest upon another. However, even allowing for such an effect and taking the uppermost altitudes Sissons and Dawson (1981) assign to the platform, it is apparent that there is a significant drop in altitude northwards from Applecross. Such a drop, considered together with the southward tilt of the Applecross platform, indicates that the platform as a whole is either warped or dislocated between south of Cuaig (NG 705 574) on the Applecross Peninsula and Redpoint to the north of the mouth of Loch Torridon.

The platform has been shown to pre-date the last ice sheet by the occurrence of striations on its surface (Robinson, 1977) and by drift masking certain of the fragments farther north (Sissons and Dawson, 1981). It is similar to many of the 'high' rock platform fragments widely developed throughout the Inner Hebrides many of which also show evidence of having been glaciated. In the early part of this century, when a monoglacialisist view was widely held, such evidence of glaciation was considered to indicate a 'pre-glacial' age for the features (e.g. Wright, 1911). Later, however, formation in an interglacial (or interglacials) was considered most likely by many authors (e.g. McCann, 1968; Jardine, 1977; Sissons, 1976). More recently, a glacial age has been proposed for the various high platform fragments (Sutherland, 1981; Sissons, 1982b), their altitude being due to isostatic tilting and their limited distribution, particularly towards the Scottish mainland, being explained by former glacier occuppance of those areas from which the platforms are absent (Sissons, 1981a). Sissons (1982b; 1983) expanded this hypothesis to suggest that many of the platform fragments were eroded during the Devensian, particularly between c. 75,000 yr BP and the time of the Wester Ross Readvance. There is no independent evidence to support this chronology, however, and it must remain speculative until further evidence is available.

Lateglacial shorelines.

Early descriptions of the coastal areas of Wester Ross (Peach *et al.*, 1913a; b) only gave sparing descriptions of the raised shorelines. In particular they noted that correlatives of the highest shoreline features

on the outer coast (the so-called '100-ft raised beach') were apparently absent from the inner sea lochs where only the '50-ft raised beach' was present. From this distribution they inferred that the inner lochs were occupied by ice at the time of formation of the highest shorelines.

No further work was published on the shorelines of Wester Ross until the studies of Donner (1959) and McCann (1963) in both of which only a few features were surveyed as part of much larger projects. Donner (1959) noted the absence of the '100-ft raised beach' from the inner sea lochs occupied by ice during Wright's (1937) 'Highland Readvance', which coincided in places with the limit now mapped as the Wester Ross Readvance. By comparison with other areas of Scotland, Donner considered that this 'Highland Readvance' was of Pollen Zone III (i.e. Loch Lomond Stadial) age and that the (horizontal) '50-ft raised beach' was approximately contemporaneous with it. The (tilted) '100-ft beach', part of which Donner identified at Strome Ferry on Loch Carron, was considered to be equivalent in age to the 'Perth Readvance' of Simpson (1933).

More detail was given by Kirk *et al.* (1966) who recorded altitudes of Lateglacial shorelines at nine localities in the Loch Broom, Little Loch Broom and Gruinard Bay areas. Along Loch Broom they reported that the marine limit coincided with a particular shoreline that sloped to the NW at c. 0.24 m km^{-1} (0.8 ft mile^{-1}) and which they considered contemporaneous with ice margins at the heads of Loch Broom and Little Loch Broom and by Loch Achall. It was argued that this was equivalent in age to the '100-ft beach' at Oban, which on the basis of the evidence from Loch Droma, they dated to not later than 12,800 yr BP. The marine limit at the head of Loch Broom was placed at c. 19 m (63 feet) and in Little Loch Broom at c. 19 m (61 feet). A lower shoreline at about 13 m was also reported from inner Loch Broom.

It is apparent from the above that there was considerable confusion in the literature as to which raised shorelines correlated with which of the presumed ice margins, whether shorelines were tilted or horizontal and the chronology of shoreline formation. It part this was the product of the methodologies applied: apart from the early Geological Survey, the studies were not the result of a complete survey of the coast but were selective in recording only those features that were considered to be of significance. The first modern study in which all relevant raised shoreline features were mapped and surveyed to a common datum was that of Robinson (1977) along the coast from the head of Loch Torridon to the head of Loch Carron.

Robinson (1977) found that along the west coast of the Applecross Peninsula the marine limit declined

northwards along the coast from over 31 m O.D. around Applecross Bay to below 26 m O.D. north of Cuaig. Along this stretch of coast both depositional and erosional features comprise the marine limit. One particularly impressive platform fragment, cut principally in till but with occasional outcrops of planated bedrock, extends for four kilometres and has a width of up to 300 m. Of interest is that in the area to the south of Cuaig there is an apparent dislocation of c. 1.7 m in the highest shoreline. This dislocation is in the same general area as the warping or dislocation that may be inferred for the older rock platform as discussed above.

As well as declining northwards along the Applecross coast the altitude of the marine limit also declines up the sea lochs to approximately 26 m O.D. at the heads of lochs Carron and Kishorn and, along Loch Torridon, to c. 21 m O.D. at Shildaig and below 19 m O.D. at the loch head (Robinson, 1977). Systematic surveying of terraces allowed Robinson to demonstrate that certain features, (as at the head of Loch Torridon), which had previously been inferred to be marine, were in fact either outwash or kame terraces. Despite the detail of this survey, because of the fragmentary nature of the preserved evidence of former marine activity, Robinson could not identify any specific shorelines.

In a later study applying the same methodology, Sissons and Dawson (1981) worked around the coast between Redpoint at the mouth of Loch Torridon and the head of Little Loch Broom. They had the particular objective of establishing the relationship of the Wester Ross Readvance to the contemporaneous sea level, although many other raised marine, fluvio-glacial and fluvial landforms were surveyed at the same time. Sissons and Dawson (1981) confirmed a continuation northwards of the pattern established by Robinson (1977). The marine limit on the west coast continued to decline northwards from c. 23 m at Redpoint to c. 18 m at Greenstone Point and along this stretch of coast, outside the Wester Ross moraines, was comprised of both depositional and erosional features. The marine limit also was shown to decline along the sea lochs to below 19 m in Gairloch, to c. 13 m at the head of Loch Ewe and to c. 16 m at the head of Little Loch Broom. As in the Loch Torridon area, no marked break in the marine limit was apparent at the Wester Ross Readvance limit and it did not prove possible to establish a direct link between the moraines and particular marine or glacio-marine features. However, by considering the relationship of certain outwash terraces, fans and channels that occurred downstream of the moraines and that could be linked to particular shoreline features, the Wester Ross Readvance was correlated with a shoreline (termed the Main Wester Ross Shoreline) that was assigned a NNWly gradient of c. $0.33-0.39 \text{ m km}^{-1}$. This shoreline coincided with the marine limit on the outer coast and hence it was argued that this indicated its

origin following a transgression. The shoreline was also considered to coincide with the cessation of significant marine erosion during the deglacial sequence and, following Sissons (1981a) shoreline model, hence to correlate with the movement of the oceanic polar front to the north of Scotland.

Sissons and Dawson (1981) also suggested that another Lateglacial shoreline might be present 3-4 m below the Main Wester Ross Shoreline. The relationship of outwash terraces to contemporaneous sea-levels indicated that ice persisted in the valley at the head of Little Loch Broom whilst there was a theoretical relative sea-level fall of 4.5-8.5 m and in the Loch Maree basin whilst there was a theoretical relative sea-level fall of c. 11 m. These ice marginal positions, together with the regular decline in the marine limit up the sea lochs are indicative of progressive, possibly slow, ice retreat subsequent to the Wester Ross Readvance, at least until the ice was within the confines of the mountains.

Subsequent to ice retreat from the coastal zone, there is no available evidence as to the position of sea level. Robinson (1977) has shown that the glaciers of the Loch Lomond Readvance related to a sea level below that which obtained following the Main Postglacial Transgression but no specific shoreline features dated to the latter part of the Lateglacial have been identified. On the basis of the absence of a marked rock-cut platform and cliff similar to the Main Rock Platform found farther south (Gray, 1978), Sissons and Dawson (1981) concluded that the Main Lateglacial Shoreline (of probable late Lateglacial Interstadial and early Loch Lomond Stadial age (Sutherland, 1984a)), the presumed correlative of the Main Rock Platform (Sissons, 1974), was below present sea level off the Wester Ross coast.

Flandrian

The coast of much of Wester Ross is rather steep and accumulations of littoral sediments are confined to coastal re-entrants and the areas of lower ground where major valleys reach sea level. Along the margins of sea lochs, the Flandrian raised marine deposits occupy a narrow irregular belt 20-80 m wide, typically backed by a cliff cut into drift deposits where they occur. The stretches of this cliff cut in rock are apparently inherited from the lower rock-cut feature described earlier.

Studies of Flandrian sea-level change around the coast of Wester Ross have concentrated on their morphological expression as indicated by raised shingle ridges, beach terraces and minor deltas. Early work was hampered by the concepts of the '25 foot' and '15 foot' raised beaches which were considered to be horizontal

(Donner, 1959). Subsequently, it was appreciated that the raised shorelines were tilted. Kirk *et al.* (1966) recorded two shorelines beside Loch Broom they considered to be of Flandrian age. The upper sloped from c. 8.8 m (29 ft) at the head of Loch Broom to c. 6.4 m (21 ft) on the outer coast with a gradient of c. 0.076 m km^{-1} and the lower, less clear shoreline occurred at c. 5.8-5.2 m (19-17 ft). As part of a wider study, McCann (1966) incorporated 10 sites ranging in altitude from 8.2 m by Loch Carron to 4.0 m by Loch Broom into a first-order trend surface model of the 'Main Post-glacial Shoreline' along the west coast of Scotland from Loch Linnhe to Loch Broom. The shoreline in this model had an average gradient dipping towards the NW of 0.075 m km^{-1} . Despite the apparent agreement between the shoreline gradients of Kirk *et al.* (1966) and McCann (1966) it should be noted that McCann's shoreline includes data, such as at Ullapool, that Kirk *et al.* (1966) considered to be part of their lower shoreline.

The more detailed studies of Robinson (1977) and Sissons and Dawson (1981) emphasised the local variability in the altitude to which littoral deposits accumulated around the Wester Ross coast, due principally to differences in fetch. They did not identify specific shorelines, but indicated that the highest Flandrian marine deposits, considered to correlate with the Main Postglacial Shoreline, sloped from c. 9 m O.D. at the head of Loch Carron, to c. 6-7 m O.D. in northern Wester Ross.

The various correlations for the Flandrian shorelines in Wester Ross have been proposed in the absence of any direct dating evidence: further understanding of Flandrian sea-level change will be dependent upon the study of sites that permit dating.

PERIGLACIAL LANDFORMS AND DEPOSITS

Age

The mountains of Wester Ross support a wide range of periglacial phenomena, some of which are active at present whilst others are relict features formed under severe climatic conditions during the Devensian. On the basis of research carried out mainly on the mountains of Ross-shire, Ballantyne (1984) differentiated Devensian relicts from active Holocene features using four criteria: (i) the distribution of periglacial features in relation to the limits of Loch Lomond Readvance glaciers; (ii) radiocarbon dating and pollen analysis of organic horizons buried under periglacial deposits; (iii) measurement of present activity; and (iv) present appearance (many relict features support mature zonal soils or a virtually complete cover of vegetation and/or peat). The range of upland Devensian and

Holocene periglacial phenomena differentiated using these criteria is summarised in Table 1.2.

Assessment of the age of relict periglacial phenomena in Wester Ross depends largely on interpretation of the 'periglacial trimline' identified by W.J. Reed on the higher parts of many mountains. If this trimline does indeed delimit the upper surface of the last ice sheet at its maximal extent, then many relict features may have formed throughout the Devensian or longer on nunataks that protruded through the last and possibly earlier ice sheets. Conversely, if the last ice sheet extended over the mountain summits, most relict periglacial features are likely to have developed only since the ice sheet reached its maximal extent, though it is possible that some older plateau features may have survived intact under shallow, cold-based high-level ice caps (cf. Sugden, 1971). However, as many relict periglacial features descend right down to the limits of Loch Lomond Readvance glaciers, it is evident that most of the forms *now visible* were last active during the Loch Lomond Stadial, though some (particularly *in situ* frost-weathered detritus) may have begun to develop much earlier (Sissons, 1983). Certain valley-floor forms, such as relict talus, protalus ramparts and talus-foot rock glaciers can, however, be unequivocally attributed to the Lateglacial following ice sheet deglaciation.

Devensian periglacial features

The most widespread evidence of Devensian periglacial activity on the mountains of Wester Ross is the mantle of frost-weathered mountain-top detritus that covers almost all plateaux and moderate slopes above 800 m and descends to 600 m or lower on some well-jointed rocks. The contrast in the degree of frost-shattering and frost-wedging of bedrock inside and outside the limits of the Loch Lomond Readvance, for example in the Applecross Hills (Sissons, 1967, p. 224; Robinson, 1977, p. 94) and in the corries of An Teallach (Ballantyne, 1982) leaves little doubt that much of the clastic component of mountain-top detritus was produced by macrogelivation under severe periglacial conditions during the Devensian, and that Holocene frost-weathering has been of relatively limited importance.

Three types of mountain-top detritus have been identified on Scottish mountains (Ballantyne, 1984), and all are present in Wester Ross (Figure 1.6). Type 1, comprising openwork blockfields and blockslopes in which fine material is absent or confined to the base of the regolith, is best developed on well-jointed rocks that have resisted microgelivation. Such detritus usually exhibits vertical sorting (coarsening upwards) and often completely buries the underlying bedrock. In Wester Ross it is best developed on outliers of fine-grained Cambrian Quartzite, such as those of An Teallach and Beinn Eighe, though openwork blockfields are also found on Moine granulites and

Table 1.2

Late Devensian and Flandrian periglacial features on Scottish Mountains.*

| Category | Features of Late Devensian Age | Features of Holocene Age |
|-------------------------------------|--|---|
| Frost-weathered regolith | <ol style="list-style-type: none"> 1. Mountain-top detritus (blockfields, stone pavements and debris surfaces)† 2. Blockslopes and debris-mantled slopes‡ | |
| Rapid mass-movement features | <ol style="list-style-type: none"> 1. Most talus slopes (especially outside the limits of Loch Lomond Stadial glaciers) 2. Protalus ramparts 3. Avalanche boulder tongues (?) | <ol style="list-style-type: none"> 1. Some talus slopes (especially inside the limits of Loch Lomond Stadial glaciers) 2. Debris flows 3. Shallow translational slides 4. Avalanche boulder tongues |
| Slow mass-movement features | <ol style="list-style-type: none"> 1. Rock glaciers 2. Boulder sheets and lobes 3. Debris sheets and lobes‡ 4. Solifluction sheets and lobes | <ol style="list-style-type: none"> 1. Solifluction sheets and lobes 2. Ploughing boulders 3. Turf-banked terraces |
| Frost-sorting and mass-displacement | <ol style="list-style-type: none"> 1. Large sorted circles 2. Large sorted stripes 3. Earth hummocks 4. Nonsorted stripes | <ol style="list-style-type: none"> 1. Small sorted circles 2. Small sorted stripes 3. Earth hummocks (?) |
| Wind action features | | <ol style="list-style-type: none"> 1. Deflation surfaces 2. Wind stripes and crescents 3. Niveo-acolian sand deposits |
| Nival and fluvial landforms | <ol style="list-style-type: none"> 1. Nivation hollows 2. Colluvial cones (?) 3. Alluvial fans | <ol style="list-style-type: none"> 1. Nivation hollows 2. Colluvial cones 3. Alluvial fans |

Based on Ballantyne (1984) Table 1.

† Locally modified by Flandrian frost sorting

‡ Locally subject to intermittent movement under present-day conditions.

(?) Indicates uncertainty.

on some Torridon Sandstone peaks, such as the Applecross hills (Robinson, 1977).

Far more characteristic of Torridon Sandstone mountains, however, is the second type of regolith, which consists of clasts embedded in an abundant matrix of medium and coarse sand and grit. Typically, the structure of such deposits consists of a surface concentration of rounded, flat-lying slabs or boulders (sometimes interlocking to form a stone pavement) that overlies a shallow sand-rich zone with fewer and generally smaller clasts. This grades downwards to a concentration of angular blocks that increase in size with depth (Figure 1.6). Vegetation cover is often sparse, and organic soil development negligible. In contrast to the characteristically smooth profiles of true blockslopes, debris-mantled slopes of type 2 regolith may have very irregular profiles interrupted by rock steps, as debris cover is usually shallow (rarely > 0.7 m). This type of detritus is widespread on the upper slopes of most Torridon Sandstone mountains, for example on Sàil Mhór, Slioch, Beinn an Eòin, Beinn Bhan and the northern plateau of An Teallach. It is also developed on coarse-grained, conglomeratic basal Cambrian Quartzite on An Teallach and Beinn Eighe.

Type 3 regolith characteristically takes the form of a shallow diamicton in which angular (and often platy) frost-weathered clasts are embedded in a matrix that consists dominantly of fine to medium sand with an appreciable silt content. Vertical sorting is sometimes evident in the form of a surface or near-surface rubble layer (Figure 1.6). Such regolith forms the parent material for rankers and podzols and is normally carpeted by a complete cover of vegetation; it is by far the dominant type on Moine schist, and covers wide tracts of high-level terrain east of the Moine Thrust.

Developed on the mountain-top detritus of Wester Ross are relict patterned ground and periglacial mass-movement features. Inactive sorted circles up to 1 m in diameter occur on An Teallach and the Fannich Mountains (Ballantyne, 1981, p. 400) and spectacular examples exceeding 2 m in width occur on Lewisian Gneiss near the summit of A'Mhaighdean (NH 008 749). Relict sorted stripes have also been mapped by Robinson (1977) in the Applecross hills and occur on the summit plateau of Beinn Dearg above c. 1050 m. On the schist mountains east of the Moine Thrust, nonsorted patterned ground in the form of dome-like earth hummocks is more common, the relict nature of such features being evident in the development of mature podzolic soil horizons that follow the undulations of the surface microrelief (Ballantyne, 1984, 1986b).

The slow downslope movement of mountain-top detritus during the Devonian resulted in the formation of successive 'sheets' of moving debris that terminated

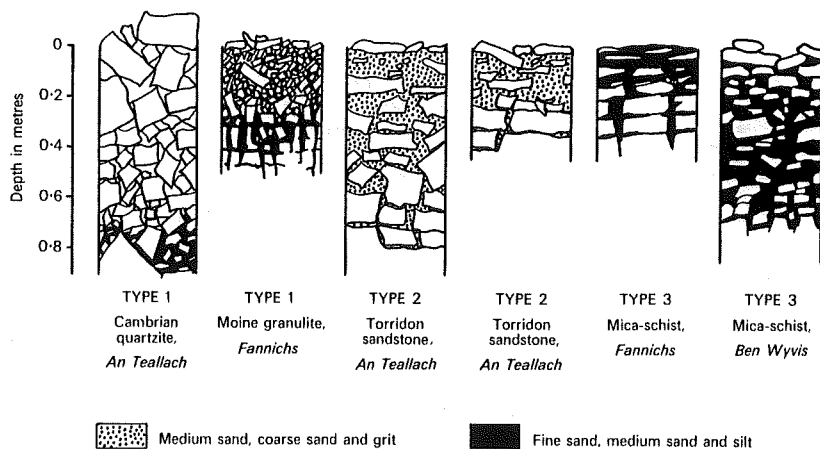


Figure 1.6. Types of frost-weathered detritus developed on different lithologies in Wester Ross (after Ballantyne (1981)).

downslope in long risers up to 4 m high. On gradients exceeding 10°, locally accelerated movement resulted in the formation of lobe-fronted sheets that over-rode each other on steep slopes to produce features that are often (and often incorrectly) referred to as 'solifluction lobes'. Each of the three types of relict sheets and associated lobes identified by Ballantyne (1984) is present in Wester Ross. Superb examples of large openwork boulder lobes with risers up to 4 m high occur at the foot of a quartzite blockslope on Maol Cheann-Dearg, between Glen Torridon and Strath Carron, and similar though smaller features with risers up to 2 m high occur on the Torridon Sandstone regolith of Beinn Damh (Robinson, 1977). Other examples on the Applecross hills and on a quartzite blockslope on An Teallach display pronounced lateral sorting, which suggests a genetic affiliation with large sorted circles and lends support to interpretation of these features as large-scale frost creep forms. Rather smaller vertically-sorted solifluction lobes, in which a rubble layer overlies a solifluction-susceptible diamicton, have been observed on the Fannichs, and relict nonsorted solifluction lobes with low-gradient, degraded risers are common on slopes underlain by Moinean mica-schists.

Distinct from the periglacial features found on plateaux and upper slope are those developed on valley floors below free faces. The most common are relict talus sheets that occur outside the limits of the Loch Lomond Readvance and appear to have accumulated in the interval between the retreat of the last ice sheet and the end of the Loch Lomond Stadial (Ballantyne and Eckford, 1984). Such taluses are usually mature features, are often completely vegetated, and frequently display evidence of recent erosion by debris flows, stream incision and shallow translational sliding. Examples occur not only on high ground (e.g. fringing Slioch and parts of An Teallach) but also near sea level (e.g. the quartzite talus flanking the Dundonnell River at NH 12 83).

Associated with relict talus slopes are two examples of Lateglacial protalus ramparts, one at 515 m on the western slopes of An Teallach (at NH 054 875; Ballantyne and Kirkbride, 1986) and a particularly spectacular feature nearly 500 m long at 470 m below the north-west slopes of Baosbheinn (NG 854 677). The latter was initially interpreted by Sissons (1976c) in terms of two distinct stages of accumulation, but Ballantyne (1986a) has demonstrated that the lower ridge mapped by Sissons is a Wester Ross Readvance lateral moraine and has suggested that the bouldery upper ridge formed when a massive rockslide or series of rockslides over-rode a former snowbed and partly buried the moraine. Landsliding on to glacier ice during the Loch Lomond Stadial was apparently responsible for producing two rock glacier-like features in Wester Ross, in a corrie on Beinn Alligin (NG 86 60) and in Coire Garbh, south-east of Maol Chean-Dearg (NG 93 49). The

former is 1.2 km long and 200-400 m wide, and consists of huge Torridon Sandstone boulders; it lies below a conspicuous landslide scar that represents the source of the debris (Sissons, 1975). The latter is a tongue-shaped deposit, approximately 500 m long and 500 m wide, composed mainly of quartzite boulders (Robinson, 1977, p.62). Both are sharply-defined features, but lack the steep, high frontal slope of true rock glaciers, though their form and location (well within the mapped limits of the Loch Lomond Readvance) accords with their interpretation as rockslide deposits transported downvalley by glacier ice.

Active periglacial features

Present-day periglacial weathering on the mountains of Wester Ross appears to be largely or entirely restricted to microgelivation (mechanically-induced granular disintegration and flaking of rock under cold conditions), the effects of which are highly discriminatory with respect to rock type. Judged in terms of the roundness of exposed rock surfaces and abundance of recent granular detritus, Torridon Sandstone appears to be most susceptible to granular disaggregation under present conditions, whilst Cambrian Quartzite and Lewisian Gneiss are least susceptible. Micaceous Moine schists occasionally show signs of recent flaking along cleavage planes, but siliceous (granulitic) schists reveal little recent modification apart from some surface rounding (Ballantyne, 1981, 1987). Marked contrasts in rounding between exposed and buried rock surfaces (Ballantyne, 1981, 1984) indicate that the effects of microgelivation are limited to exposed surfaces, so that the process is constrained by the cover of soil, peat and vegetation that mantles much high ground in Wester Ross, particularly on mountains east of the Moine Thrust.

Peat and vegetation cover probably also explain the apparent rarity of active sorted patterned ground features in Wester Ross. Small-scale active sorted circles and stripes are abundant elsewhere in upland Britain on 'type 3' regolith (Ballantyne, 1987), but in Wester Ross such regolith normally supports a complete vegetation cover so that evidence of recent frost-sorting is absent or obscured. Active solifluction features, however, are abundant on such regolith, particularly on mountains underlain by Moine schists. Superb examples of active solifluction sheets and lobes occur on the higher parts of the Fannich Mountains, for example above 900 m near the summits of Sgùrr Breac, A'Chailleach and Sgurr Mór (see Sissons, 1967, plate 13a). Such solifluction features are generally vegetation-covered, but differ from their Devensian counterparts in being smaller (generally 0.2-1.0 m thick) with steep, bulging risers. Excavation of active sheets and lobes generally reveals buried organic soil material. Five radiocarbon dates obtained by Ballantyne

(1986c) from a soil horizon buried by the downslope movement of a 0.4 m thick solifluction lobe at 840 m in the Fannich Mountains (at NH 186 722) yielded ages that range from 890 ± 120 yr BP to 530 ± 90 yr BP. As these radiocarbon ages are statistically indistinguishable from that of 660 ± 70 yr BP obtained for a sample from the same horizon immediately downslope of the lobe front, this evidence appears to indicate very rapid, very recent advance of the lobe over a distance of at least 3 m. The rapidity of lobe movement appears to reflect greatly accelerated recent activity, probably triggered either by climatic deterioration during the 'Little Ice Age' or by vegetation degradation caused by overgrazing.

Intimately associated with active solifluction features in the Fannichs and elsewhere in Wester Ross are ploughing boulders located at the downslope ends of vegetation-covered furrows. Such furrows, together with the 'bow-waves' of turf and soil pushed up downslope of the boulders, indicate downslope movement of the boulders at a rate exceeding that of the surrounding regolith. Six ploughing boulders monitored by Ballantyne (1981) at 800 m on Sgurr Breac in the western Fannichs (NH 164 711) were found to be moving downslope at rates averaging 6-34.5 mm y^{-1} , rate of movement being strongly related to gradient.

Wind erosion and niveo-aeolian deposition play an important rôle in the present-day periglaciation of the mountains of Wester Ross, particularly those underlain by rocks that have weathered to produce an abundance of cohesionless sand-rich 'type 2' regolith. On exposed Torridon Sandstone plateaux, such as those of Slioch, Baosbheinn and An Teallach, strong winds have stripped away virtually all vegetation cover and winnowed away all exposed sand-sized particles to create extensive deflation surfaces carpeted by a lag deposit of fine gravel. Complementing such extensive deflation is the accumulation of windblown sand deposits in the form of vegetation-covered 'sand sheets' on sheltered lee slopes (Peach *et al.*, 1913a; Godard, 1965). Deposits of windblown sand up to 4 m thick that flank the northern plateau of An Teallach have been shown by Ballantyne and Whittington (1987) to be of predominantly niveo-aeolian origin. Sand grains weathered from bedrock and from exposed clasts on plateau areas are blown on to the winter snowpack on surrounding slopes. When the snow melts, the grains are lowered on to the underlying vegetation, which grows through the accumulating deposit and thus stabilises it. Thufur-like 'sand hummocks' are sometimes developed on the surface of the accumulating sand as a result of selective wash between vegetation tussocks (Ballantyne, 1986b). Radiocarbon dating and pollen analyses of organic horizons within and at the base of the niveo-aeolian deposits on An Teallach have demonstrated that sand accumulation began in the early Flandrian before c. 7900 B.P., but was eventually much reduced by establishment of a stable vegetation cover over

the plateau source area. Recent disruption of this vegetation cover triggered either by increased storminess or overgrazing resulted in extensive erosion of sand deposits on the plateau and their redeposition on surrounding slopes. Present accumulation on lee slopes declines with distance downwind of the plateau source area and ranges from 10 to 300 g m⁻² y⁻¹, but this is balanced to some extent by retreat of the unvegetated margins of the sand sheets at rates averaging 25-30 mm y⁻¹.

Small-scale deflation features also occur on the plateaux of Wester Ross, particularly on Torridon Sandstone mountains, and include vegetation stripes and crescents on otherwise vegetated terrain and, more commonly, elongate scars of vegetation-free ground on vegetated surfaces (Ballantyne, 1981, p. 433-8). Closely related to these wind patterns are turf-banked terraces, which are step-like features with gently-sloping, largely unvegetated treads and steep, well-vegetated risers. Three types may be differentiated (Ballantyne 1987): (i) horizontal 'deflation terraces' aligned parallel to dominant wind direction and apparently formed by creep operating on the treads of deflation scars cut across vegetated slopes; (ii) other horizontal terraces formed on lee slopes, possibly by the accumulation of debris dammed behind vegetation 'crescents'; and (iii) oblique terraces that dip steeply upwind on otherwise vegetation-free slopes and which may reflect the progressive anchoring of creeping debris by vegetation sheltering in the lee of boulders (Ballantyne, 1981). Deflation terraces most commonly occur on the vegetated slopes of mountains underlain by Moine schist, the other two types on Torridon Sandstone mountains. Robinson (1977, p. 94), for example, noted abundant turf-banked terraces typically 10 m long and 0.5-1.0 m high on the Applecross hills, both inside and outside the Loch Lomond Readvance limits, and on An Teallach horizontal terraces range from 3 to 20 m in length and 0.1 to 1.2 m in riser height. Oblique terraces tend to be larger; the excellent examples that sweep across the steep (up to 36°) southern slope of Glas Mheall Mór on An Teallach (NH 07 85) are 5-45 m long with risers 0.8-3.4 m high. The two types often intersect near slope crests, and horizontal terraces on 'type 3' regolith sometimes merge laterally with with active solifluction sheets and lobes. On An Teallach, movement of debris on terrace treads and around relatively immobile risers seems to be dominated by superficial frost creep that averages a few millimetres per year at the surface and declines rapidly to zero at depths of 140 mm or less (Ballantyne, 1981).

Studies of present-day nivation in Wester Ross have been restricted to assessment of the geomorphic rôle of late-lying snow in hollows at the margins of niveo-aeolian sand sheets (Ballantyne, 1985). These observations indicate that current snowpatch erosion is largely restricted to redistribution of cohesionless sandy sediments by nival

meltwater, and that even this process is of only local significance and is ineffective in areas of complete vegetation cover.

Although present-day talus accumulation below rockwalls outside the limits of the Loch Lomond Readvance appears to be negligible (Ballantyne and Eckford, 1984), inside these limits talus cones that must have developed entirely during the Holocene often present a fresher and less 'mature' appearance. Such cones commonly occur below steep, high cliffs, particularly in corries, and recent debris is often strewn over their sparsely or incompletely vegetated slopes. At such sites, current rockfall activity appears to be much greater than that associated with relict talus outside the Loch Lomond Readvance limits. In a corrie on An Teallach (Glas Tholl, NH 08 84), Ballantyne and Eckford (1984) recorded 39 rockfalls in 58 hours. Although most were of very small magnitude, the size of lichen-free rockfall scars on the cliffs of Glas Tholl and the complete destruction of the apex of a talus cone during the winter of 1976-7 (Ballantyne, 1981, p.182) indicate that large-scale events are not infrequent. Such evidence suggests that talus accumulation may still be appreciable in Wester Ross, but only at favourable sites within the limits of the Loch Lomond Readvance.

Distribution

On a single mountain or massif of fairly uniform lithology, the distribution of upland periglacial features reflects five controls, namely former glacier limits, altitude, vegetation cover, aspect and gradient. All *in situ* Devensian features occur only outside the limits of the Loch Lomond Readvance, and most features on upper slopes (frost-weathered detritus and landforms developed on this detritus, such as large-scale patterned ground) generally occur only above the upper 'trimline' identified by Ballantyne (1984) and Reed (unpublished). Former glacier limits thus also dictate the altitudinal limits of relict periglacial phenomena on plateaux and upper slopes. Relict talus, however, descends in places to near sea level, and the altitude of Lateglacial protalus ramparts was apparently determined both by topographic circumstances and the by the level at which perennial snowbeds could survive without developing into glaciers (Ballantyne and Kirkbride, 1986).

The controls on the downslope limits of active periglacial phenomena in Wester Ross are incompletely understood. Freezing depth and wetness probably control the lower limits of active solifluction, but those of frost-sorted and wind-patterned ground appear to be related to the occurrence of vegetation-free ground and are thus controlled by exposure rather than temperature or precipitation regime (Ballantyne, 1987). The distribution of aeolian and niveo-aeolian features is also strongly

controlled by aspect, insofar as sand sheets and horizontal and oblique turf-banked terraces are predominantly developed on lee (easterly) slopes (Ballantyne, 1981; Ballantyne and Whittington, 1987). Gradient affects the distribution of both active and relict features in that most periglacial landforms on slopes exceeding a few degrees (sheets, lobes, terraces and stripes) have developed at least in part through slow mass-movement of regolith.

Detailed mapping of the periglacial features on An Teallach and the Fannichs (Ballantyne, 1981) has revealed that, despite similarities in altitude, topography, climate and climatic history, these massifs support rather different assemblages of periglacial phenomena, a difference attributable to differences in lithology or, more specifically, the response of different rocks to Devensian periglacial weathering. The cohesionless, sand-rich 'type 2' regolith developed on the Torridon Sandstone of An Teallach supports spectacular examples of aeolian features (deflation surfaces, niveo-aeolian deposits, horizontal and oblique turf-banked terraces), but true frost-action forms such as sorted patterned ground or solifluction features are rare or poorly developed. In contrast, the 'type 3' regolith developed on the Moine schists of the Fannichs supports sorted patterned ground, earth hummocks and excellent examples of active and relict solifluction features, but aeolian forms are limited to wind stripes and deflation terraces. The difference between the two massifs appears to be due first to the cohesionless nature of 'type 2' regolith, which allows ready entrainment of sediment by wind, and secondly to the frost-susceptible nature of the regolith developed on Moine schists, which permits the formation of patterned ground and solifluction features that are dependent on ice-segregation for their development (Ballantyne, 1984, 1987). The 'type 1' regolith of the Cambrian Quartzite blockfields supports, in general, only a very limited range of forms, including boulder lobes and large-scale sorted patterned ground.

OTHER ASPECTS OF LATEGLACIAL AND HOLOCENE LANDFORM DEVELOPMENT

Rock slope failures

Documented examples of rock slope failures are fairly numerous in Wester Ross (Figure 1.7), though the density of such failures is much less than, for example, in the mountains of western Inverness-shire or the South-West Highlands (Ballantyne, 1986d). A notable feature of their distribution is that the great majority are located on schist or gneiss and comparatively few on Torridon Sandstone, so that the density of rock slope failures is greater to the east of the Moine Thrust (Figure 1.7). The

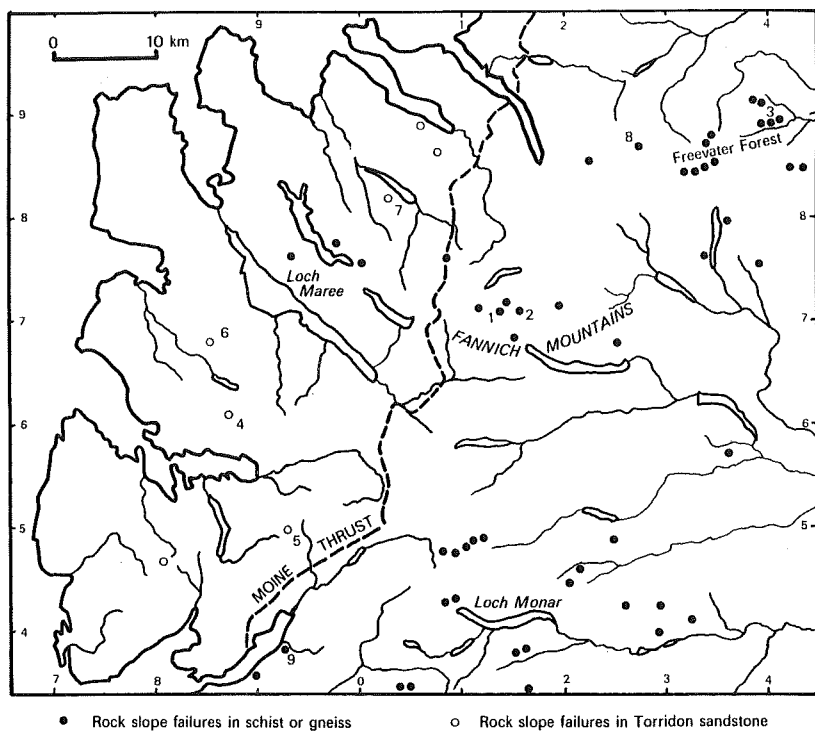


Figure 1.7. Distribution of documented rock-slope failures in Wester Ross.

association of non-rotational rock slope failures in the Scottish Highlands with schist and gneiss has been explained by Holmes (1984) in terms of two factors: first, schists in particular tend to have relatively low friction angles; secondly and more importantly, many gneisses and schists possess pronounced foliation planes that form potential shear surfaces where they dip valleywards.

Several of the documented rock slope failures in Wester Ross are of particular interest. In the Fannich Mountains, the large-scale slope deformations south-east of A'Chailleach (NH 137 712; 1 in Figure 1.7) and south-east of Sgùrr Breac (NH 150 705; 2 in Figure 1.7) have pronounced failure scarps upslope, but lack slide toes downslope. In a detailed analysis of these landslides, Holmes (1984) suggested that progressive failure along foliation planes, possibly exacerbated by high cleft-water pressures, may have accounted for the slope deformation. The absence of a slide toe suggests that these represent examples of rock sagging or 'Sackung' (large-scale deformation of rock slopes without a continuous failure plane necessarily forming), the first to be identified in Britain (Holmes, 1984, p. 173-4). Holmes also mentions a possible rock avalanche in Wester Ross, below Carn Alladale (NH 40 89; 3 in Figure 1.7), and Whalley (1976) suggested that the 'rock glacier' identified by Sissons (1975) below Beinn Alligin (NG 86 60; 4 in Figure 1.7) may represent another, though this has been disputed by Sissons (1976b).

The age of most of the rock slope failures in Wester Ross is unknown. The A'Chailleach (1) and Sgùrr Breac (2) failures have been assigned to the Lateglacial by Holmes (1984) on the grounds that relict solifluction features overlie the failure scarps. If the 'rock glaciers' at Beinn Alligin (4) and Maol Chead-Dearg (5) do indeed represent landsliding on to glacier ice, then a Loch Lomond Stadial age is implied for these failures (Sissons, 1975; Robinson, 1977), and a similar argument applies to the rock slide or rock slides (6) that produced the Baosbheinn protalus rampart (Ballantyne, 1986a). Other failures, for example on Beinn Dearg Mòr (7) and in upper Glen Douchary (8) deposited landslide debris within the limits of the Loch Lomond Readvance as mapped by Sissons (1977), hence must have occurred since the disappearance of these glaciers. For the Scottish Highlands as a whole, Holmes (1984) has suggested that the majority of rock-slope failures are approximately 5000-10,000 years old, and has explained this timing in terms of a 'delayed action' (progressive failure) response to initial rock slope weakening caused by fluctuating cleft-water pressures during glaciation and deglaciation. That many steep rock slopes remain in a state of critical conditional stability is illustrated by recent rock slope failures by Loch Carron (9) caused by excavation, blasting and heavy rainfall during the construction of the Strömeferry by-pass in 1968-71 (Ballantyne, 1986d).

Debris flows

The great majority of debris flows in Wester Ross are simple hillslope flows that take the form of paired levées aligned downslope and terminating on lower gradients in one or more lobes of debris. Occasional valley-confined flows also occur, however, which have built up substantial debris cones below gullies (e.g. at NH 085 859 on An Teallach). Although debris flows occur on steep mountain slopes throughout Wester Ross, they are much rarer on slopes underlain by schist or gneiss than on those underlain by Torridon Sandstone or basal conglomeratic Cambrian Quartzite. East of the Moine Thrust, hillslope debris flows are largely restricted to relict (Lateglacial) talus slopes, but on the Torridon Sandstone mountains west of the thrust they occur not only on talus, but also are abundant on steep slopes supporting a shallow mantle of frost-weathered regolith. On the south-west slope of Baosbheinn, for example, Strachan (1976) mapped some 58 individual flows over a distance of 4.5 km, and Ballantyne (1981) counted 45 flows on a kilometre-long slope on Glas Mheall Mór, An Teallach (NH 07 85). Impressive debris flows also sweep down from Cambrian Quartzite outliers over the underlying Torridon Sandstone on some mountains, and are particularly conspicuous on the southern slopes of Beinn Eighe above Glen Torridon. The high density of debris flows on sandstone and conglomeratic quartzite slopes probably reflects the high infiltration rates associated with sand-rich regolith. These permit a rapid rise in the water table during rainstorms, leading to increased pore-water pressures, reduction in effective normal stresses, failure (often initially in the form of translational sliding) and flow. The susceptibility of sandy regolith to debris flow activity is probably enhanced by the cohesionless nature of such soils and by the absence, particularly on high ground, of a complete vegetation cover on sandy soils.

Lichenometric measurements carried out by Innes (1982, 1983) on 70 debris flows in Coire Toll an Lochain, An Teallach (NH 07 83) suggested that most are less than a century old, and that all apparently post-date A.D. 1740. Innes attributed the apparent recency of debris flow activity here and elsewhere in the Scottish Highlands to destruction of vegetation cover by burning and overgrazing, but his results and conclusions have been challenged (Ballantyne, 1987) on the grounds that later flows often obscure earlier ones, thus introducing a bias into the lichenometric dating of such features, and that many of the flows he investigated (including those on An Teallach) emanate from rock gullies unlikely to have been affected by burning or overgrazing. The considerable size of some debris cones deposited by successive debris flows suggests a prolonged period of accumulation (cf. Brazier *et al.*, in press). Debris flow events nevertheless appear to be fairly common in Wester Ross under present-day conditions: eight separate flows were triggered by five different rainstorms

on An Teallach between 1975 and 1984 (Ballantyne, unpublished), and a severe rainstorm in 1968 caused several debris flows that closed the Kinlochewe-Achnasheen road in Glen Docherty (NH 05 60; Strachan, 1976).

Present rates of mass-transport activity

A comprehensive survey of present mass-transport rates on An Teallach, designed to establish both the relative importance of different mass-transport mechanisms and to allow comparison with other mountain environments, has been attempted by Ballantyne (1981). For comparative purposes the mass transport rates measured on An Teallach were converted to a common unit, watts per square kilometre ($W\ km^{-2}$). This unit represents potential energy loss over a uniform time interval and standard area of $1\ km^2$; details of the calculations are given in Ballantyne (1981).

The results (Table 1.3) must be treated with some caution, as An Teallach is a fairly high, steep mountain, exposed to high precipitation (c. $3,600\ mm\ y^{-1}$ at 670 m) and very strong winds that have stripped plateau areas and most upper slopes of all but a patchy vegetation cover. The rates measured (especially for wind action) are therefore likely to be above average for most mountains in Wester Ross and indeed elsewhere in Scotland. Four interesting features emerge from these data. First, rapid mass-transport processes (rockfall and debris flow) are clearly more effective than creep and solifluction. In part, however, this reflects the high relief of the massif, and the absence of solifluction *sensu stricto* on the 'type 2' regolith of An Teallach. On the Fannichs, solifluction appears to be at least locally much more rapid than current slow mass movement on An Teallach (cf. Ballantyne, 1986c). Secondly, the slower creep rates for slopes supporting turf-banked terraces confirm that such terraces (unlike solifluction lobes) reflect retardation rather than acceleration of slow mass movement. Thirdly, the figures highlight the importance of solute transport, even though the figure cited is certainly an overestimate, owing to the inclusion of dissolved salts introduced by precipitation. Finally, the effectiveness of aeolian transport is notable, though this clearly represents optimal circumstances. For all process sets except avalanches, the An Teallach rates are of the same order of magnitude as (and in some cases exceed) those measured by Rapp in northern Scandinavia. It is also notable that the relative effectiveness of different agents (i.e. solute transport > rapid mass movement > slow mass movement) is similar for An Teallach and Karkevagge.

The current rôle of high-magnitude 'catastrophic' events in shaping the landscape of Wester Ross is, however, largely unknown. Acreman (1983) has described the effects of an exceptional flood of Ardesie Burn, which drains the western slopes of An Teallach. The flood (in September

Table 1.3

Comparative rates of mass transport activity on An Teallach
and in Karkevagge, northern Scandinavia¹

| Process set | An Teallach (Ballantyne, 1987) | Karkevagge (Rapp, 1960) |
|---------------------------|-----------------------------------|----------------------------|
| Rockfall | 1.689 | 0.405 |
| Avalanches | 0.000 | 0.453 |
| Landslides & debris flows | 0.560 | 1.997 |
| Creep and solifluction | 0.175 | 0.166 |
| Creep on terraced slopes | 0.036 | - |
| Surface wash | localised | slight |
| Wind action | 0.394 | - |
| Solute transport | 9.017 ² | 2.828 |

¹ All values are expressed in $W \text{ km}^{-2}$

² Probably a considerable over-estimate, as it includes the solute input of incident precipitation.

1981) resulted from a fall of 140 mm of rain in 24 hours, an event with an estimated return period of 120 years. Owing to low antecedent moisture conditions, however, this rainstorm apparently resulted in only a single debris flow on the upper slopes of the mountain. A fan at the mouth of the river was extensively eroded and reworked, but the offshore discharge of non-dissolved load attributable to the flood was only c. 1040 tonnes, equivalent to c. 8.4 years average sediment discharge from the basin, and erosive effects in the higher parts of the catchment were negligible.

ENVIRONMENTAL CHANGE.

Lateglacial Interstadial

Only two pollen diagrams covering the whole of the Lateglacial Interstadial are available from Wester Ross: Loch Droma (Kirk and Godwin, 1963) and Glassnock (Robinson, 1977). Information from pollen, chemical and diatom studies of Lateglacial Interstadial sediments from areas to the north and to the south has also been published by Pennington *et al.* (1972) and Pennington (1977a) and a regional pollen zonation and Lateglacial chronostratigraphy have been proposed by Pennington (1975). Taken together, these studies provide a detailed and consistent picture of environmental change from the time of ice-sheet deglaciation of at least the lower ground to the onset of the Loch Lomond Stadial.

At the sites studied, the sediments deposited following deglaciation are uniform or weakly laminated silts. In the lowest horizons these contain very little carbon, few or no pollen grains, and show high levels of bases such as Ca, Na, K and Mg. Derivation from skeletal soils with virtually no plant cover has been inferred. The first sediments to provide countable numbers of pollen grains are also those in which chemical analyses are consistent with soil maturation, this being indicated by a diminution in K and Mg and a rise in N, I and carbon content. The local pollen assemblage zones are dominated by *Rumex*, *Salix herbacea* and/or *Lycopodium selago*, as well as, at certain sites, showing significant proportions of *Artemisia* and *Oxyria*, open habitat plants which are known colonisers of recently deglaciated terrain as well as being indicative of the presence of frequent snow patches.

On the evidence of a basal radiocarbon date from Cam Loch (NC 220 121) of $12,960 \pm 240$ yr BP (Pennington, 1975), it has been inferred that around 13,000 yr BP there was an expansion of woody plants, particularly *Empetrum* and, at some sites, *Juniperus*, although significant levels of *Rumex* pollen continued. These vegetational changes coincided with further increases in carbon content

(although absolute values remain low) and continuing decline in the concentration of Ca, Mg, Na and K. The diatom assemblages present have low species diversity and are typical of alkaline waters. Taken together, the evidence suggests succession of the pioneer vegetation with a more closed cover of dwarf shrub heath.

In the north of Scotland most Lateglacial pollen diagrams then record a period of reduction in the levels of woody taxa such as *Empetrum*, renewed expansion of *Artemisia* and continuing high levels or increases in *Rumex*. Pollen concentrations decline, as in some sites does the carbon content. At other sites an increase in K and Mg has been noted as well as the occurrence of sub-aerial diatom species, implying increased soil erosion. This evidence is suggestive of a weak climatic recession which, on the basis of the Cam Loch chronostratigraphy has been correlated with the Older Dryas (12,000 - 11,800 yr BP) of NW Europe. This event appears to have been insufficiently strong to be generally registered in pollen diagrams throughout Scotland (Walker, 1984).

Subsequently there was a renewed expansion of woody plants, in particular *Empetrum* and, at some sites, *Juniperus*. Tree birch pollen grains occur but these may be due to transport from birch copses farther to the south or east. Open habitat indicators decline whilst there is a marked increase in Cyperaceae. This period coincides with maximum pollen concentration values as well as maximum carbon content and high levels of N and I in the sediments. Diatom species diversity also increases at this time and the diatoms in the open lochs are typical of nutrient-rich alkaline waters. The environment therefore has been inferred to be one in which acid soils had developed under a cover of ericaceous dwarf shrub heath or tundra. The high representation of *Empetrum* has been considered to imply rather oceanic conditions.

The opening of this *Empetrum*-dominated phase and the coincidental decline in values for *Rumex* has been radiocarbon dated to c. 11,800 yr BP at Cam Loch (Pennington, 1975) and on Mull (Lowe and Walker, 1986) but it is this horizon to which the Loch Droma date of $12,810 \pm 155$ yr BP refers (Kirk and Godwin, 1963). Broadly similar dates for the close of the period with relatively high *Rumex* values to those from Cam Loch and Mull have been reported from sites elsewhere in the Scottish Highlands (e.g. Vasari, 1977; Birks and Mathewes, 1978; Lowe, 1978). The Loch Droma date is therefore approximately 1000 years to old by comparison with the pollen stratigraphy.

The close of this period and the onset of the cold conditions of the Loch Lomond Stadial is conventionally placed at 11,000 yr BP but is not well dated (Gray and Lowe, 1977). It is probable that this is partly due to a transitional period during which temperatures

declined and thresholds affecting both the vegetational cover and sediment production were crossed at different times in different places.

The lack of direct modern analogues for the vegetational communities that existed during the Lateglacial together with the relative slowness of response of vegetational change to improving climatic conditions make direct climatic inferences from the pollen data very difficult (Pennington, 1977b). Temperature changes can be much more readily inferred from Coleoptera (Atkinson *et al.*, 1987) but no such faunas from northern Scotland have been analysed. Coope (1977), however, has proposed a hypothetical July temperature curve for northern Scotland based on extrapolation of his results from England, Wales and southern Scotland. He suggests that around 13,000 yr BP July temperatures were approximately 11.5°C and thereafter they declined to around 9.5°C between 12,000 and 11,000 yr BP. These are equivalent to temperature reductions from the present day of around 2°C and 4°C respectively. The environment as inferred from pollen analyses gives broad qualitative support to these estimates.

The marine climate for the west coast of Scotland as inferred from mollusc and foraminiferal distributions (Peacock, 1981; 1983) in general supports the temperature variations proposed by Coope (1977). At around 13,000 yr BP there may have been a warm episode although marine temperatures apparently did not reach similar levels to those of the present. Subsequently there was a cooling and between 12,500 and 12,000 yr BP, while summer surface temperatures were perhaps only 1-2°C below those of today, the body of water was some 3°C lower in summer and 2-3°C lower in winter (i.e. near freezing). A possibly significant difference with the terrestrial temperature record is a brief period of surface water warming a little before 11,000 yr BP at a time when terrestrial temperatures were declining, a situation that would be particularly conducive to glacier growth during the early phase of the Loch Lomond Readvance. Only one site is known in Wester Ross from which a marine fauna of likely Lateglacial Interstadial age has been reported. This is from Loch Kishorn (Robinson, 1977) and the faunal assemblage indicates notably cooler conditions than those typical of the main part of the Interstadial succession farther south. In the absence of radiocarbon dating, however, the reasons for this difference cannot be established.

In the light of this palaeoclimatic background, the likelihood of the persistence of glacier ice throughout the Lateglacial Interstadial can be assessed. Glaciological considerations, relating mean ablation season temperature to accumulation at the equilibrium line, can be used to predict, given a particular temperature and a range of precipitation (accumulation) values, the

likelihood of glacier inception in a particular area. For instance, using data from modern Norwegian glaciers as a model (Sutherland, 1984b), and assuming precipitation values of a similar magnitude to those of today, it can be shown (Sutherland, unpublished) that in Scotland with a temperature fall from present day values of 2°C only the Ben Nevis range would be likely to support glacier formation (cf. Manley, 1949). However, a fall in temperature of 3°C would make, for example, the higher Fannichs, Ben Dearg, Ben Eighe and possibly An Teallach susceptible to glacierization. It therefore seems unlikely that, were Wester Ross very largely deglaciated by the time of the thermal maximum at the onset of the Lateglacial Interstadial, glaciers would not have survived at this time. However, the subsequent decline in temperatures implies that for the greater part of the interstadial glaciers could have existed in the higher mountains.

The extent of ice and timing of deglaciation during the early part of the Interstadial is not well known. As discussed above, the Loch Droma radiocarbon date is c. 1000 years too old relative to the pollen stratigraphy and does not therefore provide a critical limiting date on deglaciation. Sissons and Dawson (1981) have suggested that the Wester Ross Readvance culminated at the time when the oceanic polar front retreated north of Scotland. If correct, this implies a considerable ice mass in Wester Ross at this time and the regular decline of the marine limit towards the heads of the sea lochs inside the readvance limit is indicative of regular retreat rather than rapid disintegration of the ice. If the approximate dating of the Wester Ross Readvance suggested by Sissons and Dawson (1981) is correct, it therefore seems quite possible that glacier ice survived throughout the Lateglacial Interstadial, initially in the form of a retreating ice sheet and subsequently as climatically healthy corrie and valley glaciers in the higher mountains.

The Loch Droma site is of particular significance as the pollen stratigraphy establishes that throughout the Lateglacial Interstadial laminated sediments were deposited. In the studies of the Lateglacial sediments of sixteen lochs in Northern Scotland, Pennington (1977a) showed that the only lochs that contained laminated sediments during the Loch Lomond Stadial were also those that received meltwaters from Loch Lomond Readvance glaciers. This suggests that the rhythmic inorganic sedimentation in such lochs reflects the presence of glacier ice in the loch catchment. If this interpretation is applied to the Loch Droma lithostratigraphy, continued glaciation of the Fannichs throughout the Lateglacial Interstadial seems indicated.

Loch Lomond Stadial

The Loch Lomond Stadial was characterised by a very severe climate. Basin sedimentation during the stadial was almost entirely of non-organic silts and clays with occasional clasts. Pollen analyses of these sediments indicate a marked reduction (in comparison to the preceding, Interstadial) of woody plants such as *Empetrum* and *Juniperus* and a corresponding increase in open ground indicators such as *Lycopodium selago*, and pollen of the families Caryophyllaceae, Compositae and Cruciferae. The stadial has been particularly noted for the increase in values of *Artemisia* pollen throughout much of the Scottish Highlands but there is a marked regional differentiation in the representation of *Artemisia* during this period (Pennington *et al.*, 1972; Macpherson, 1980; Tipping, 1985). In the northern Highlands the available sites indicate low percentages of *Artemisia* to the west of the regional watershed with increased representation to the east. As certain species of *Artemisia* are chionophobic (see Lowe and Walker, 1986), the variations in its occurrence during the stadial have been related to the extent of snow cover and hence amount of precipitation, those areas with low *Artemisia* values (such as the Glassnock site in Torridon (Robinson, 1977)) being thought to be in areas of high precipitation. If this argument is correct, then the increased representation of *Artemisia* at Loch Droma (Kirk and Godwin, 1963) in comparison with Glassnock implies a north-eastwards decline in precipitation across Wester Ross during the stadial.

The distribution of Loch Lomond Readvance glaciers also provides information on the climate during the Stadial. Excepting those areas (such as the Fannichs) where there is uncertainty as to the extent of the readvance glaciers, data relating to glacier size, potential snow-blowing areas, potential avalanching areas, insolation receipt and equilibrium line altitudes (ELAs) (cf. Sissons and Sutherland (1976); Sutherland (1984b)) are available for 51 glaciers in Wester Ross (Sutherland, unpublished). These can be considered in three separate groups from west to east: Applecross-Torridon, Letterewe-An Teallach and Beinn Dearg-Freevater Forest.

Certain systematic changes are apparent between these groups. From west to east there is a general rise in the ELAs and a decrease in the intensity of glacierization. There is also a west to east increase in the average potential snow-blowing area relative to glacier area and an accompanying decrease in the potential receipt of solar radiation. With respect to the different quadrants, potential snow-blowing areas (relative to glacier size) are greatest to the SW for all areas but from west to east there are general increases in the SW, SE and NW quadrants. It is only in the easternmost area (i.e. Beinn Dearg-Freevater Forest) that NE snow-blowing areas attain any

significance. These relationships suggest that there was an overall climatic control on the glaciers such that those farther east increasingly occurred in particularly favourable topographic situations where the accumulation on the glacier was augmented by wind-blown snow and ablation diminished by increased shading. This pattern is consistent with a general eastwards decline in precipitation across Wester Ross during the stadial

The glacier source areas occupied by ice during the Loch Lomond Readvance imply, unless precipitation values were markedly higher than those of today, a fall in mean summer (May-September) temperature of at least 5 to 6°C from present values (Sutherland, unpublished). However, with temperatures towards the upper part of this range, unacceptably high accumulation totals are indicated for the lower western glaciers by comparison with data derived from modern glaciers. Similarly, unless precipitation was *very much* lower than today a mean summer temperature reduction of over 7°C would imply much more extensive glacier development than occurred during the Loch Lomond Readvance. The established distribution of Loch Lomond Readvance glaciers is therefore indicative of a mean summer temperature of c. 6°C in Wester Ross (present-day value, 12.5°C). This is equivalent to a July temperature of 7.5°C, a figure comparable to stadial temperatures inferred in other studies (e.g. Sissons and Sutherland, 1976; Sissons, 1980b; Atkinson *et al.*, 1987). Sissons (1977) has reported the occurrence of a fossil frost wedge inside the limit of the outer moraines of a Loch Lomond Readvance glacier south of An Teallach. There must be considerable uncertainty as to inferring the former presence of permafrost on the basis of a single wedge-like cast (Black, 1983) but if correct this would imply mean annual temperatures during the stadial of <-5°C (Ballantyne, 1984). Together with the summer temperature estimates the annual range of temperature may therefore have been in excess of 25°C.

Average accumulation on modern glaciers is known to be closely dependent upon mean summer temperature, but accumulation is also a function of the snow that falls, avalanches or is blown on to the glacier surface. Thus the accumulation figures that may be inferred for glaciers from knowledge of the mean summer temperature and of the ELA only in part reflect local precipitation. Ahlmann (1924), however, has studied the relationship of precipitation to mean summer temperature at the glaciation level, that is approximately 100-200 m above the regional ELA values. Ahlmann's relationship, appropriately adjusted to the ELA figures, can be used to indicate the likely precipitation in the various Wester Ross mountain groups during the Stadial. The figures derived indicate precipitation in the Torridon hills of around 3000 mm, of 2000-2500 mm in the An Teallach area and around 1500 mm on Beinn Dearg. These precipitation estimates are slightly lower than today's

values in the west (cf Ballantyne, 1983) but markedly lower than present in the east, thus implying a greater precipitation gradient from west to east than today.

Flandrian.

A limited amount of information from palynological studies is available from Wester Ross on vegetational changes during the Flandrian. At only two sites, Loch Clair (Pennington *et al.*, 1972) and Loch Maree (Birks, 1972) have complete sequences of Flandrian sediments been analysed. Other sites at which only parts of the Flandrian sequence have been studied are at Beinn Eighe (Durno and McVean, 1959), Loch Droma (Kirk and Godwin, 1963) and in the Torridon-Applecross area (Robinson, 1977).

At the sites where the earliest Flandrian sediments have been studied (Lochs Maree and Clair, Glassnock and Druim Dubh) the initial pollen rain representing a transition from the Loch Lomond Stadial apparently reflects an open dwarf shrub heath, the very earliest samples having significant values of Gramineae, *Rumex*, *Lycopodium selago*, *Salix* cf. *herbacea* and *Empetrum*. Shortly after this a rapid increase occurs in the *Juniperus* pollen values together with a decrease in *Empetrum*. This rise in the *Juniperus* values is attributed to either migration of the shrub into the area or to increased flowering, in response to climatic amelioration, of those junipers already present in the vegetation cover. Close dating of the earliest vegetational changes has not been attempted but at both Loch Clair and Loch Maree the early phase of juniper dominance ceased by c. 9000 yr BP. Extrapolation of the linear sedimentation rate in the Loch Maree core to the base of the Flandrian indicates a lower age of c. 9800 yr BP for these events: this suggests a relative young age for the juniper peak compared with sites farther south (Walker, 1984). Extrapolation of the Loch Clair sedimentation curve to the lowermost parts of that profile is of limited value because of the complicated sedimentary sequence in the earliest Flandrian sediments.

After c. 9000 yr BP there was a marked rise first in *Betula* and subsequently in *Corylus/Myrica* pollen values. In the Loch Maree core, *Betula* fruits occur indicating the presence of tree birch in the catchment and expansion of birch woodland with some hazel at lower levels at the expense of the juniper scrub has been inferred. The high values of fern spores suggest that this woodland had an understorey of ferns. In the Loch Maree core, pollen of *Quercus*, *Ulmus*, and *Sorbus aucuparia* together with spores of *Pteridium aquilinum* first appear or rise from low numbers at around 8800 yr BP. During this period spores and leaves of *Sphagnum*, *Juncus* seeds and *Calluna vulgaris*

pollen are also encountered, suggesting development of acidophilous mires in some localities.

The duration of this phase of birch woodland is markedly different at lochs Clair and Maree despite the two being only c. 5 km apart and c. 80 m different in altitude. At Loch Maree, *Pinus* pollen values increased rapidly at around 8250 yr BP, and migration of pine into the catchment within 100 years has been inferred. At Loch Clair, however, a marked rise in pollen values for *Pinus* did not occur until c. 6500 yr BP. By this time a decrease had started in the values for *Pinus* recorded at Loch Maree. In contrast to this diachroneity in forest development, the immigration of alder into the region appears to be registered synchronously at both sites: at Loch Maree *Alnus* pollen initially appeared in small quantities at about 6900 yr BP, with a rapid rise at c. 6500 yr BP, whilst in Loch Clair *Alnus* appeared by c. 6520 yr BP.

Fire may have been important in the ecology of the pine forests for charcoal occurs both in the lake sediments subsequent to the rise in *Pinus* pollen values as well as in distinct horizons associated with pine stumps in peat bogs in the Beinn Eighe area. Durno and McVean (1959) suggested widespread destruction of the pine forest by fire occurred on at least three occasions.

Low values of *Ulmus* pollen had been recorded at both Loch Clair and Loch Maree through the period of development of the pine forest. Both sites record a drop in *Ulmus* at approximately 5200 (± 100) yr BP but little other evidence for disturbance of the pine or birch woodlands at this time. Thus while local human activity cannot be ruled out as a cause of the decline of elm in Wester Ross, it is more likely that the decline in elm pollen is due to a reduction in long distance transfer reflecting events farther south.

The difference in the history of the pine forest neighbouring lochs Maree and Clair continues during the later Flandrian. Around Loch Maree there is a rapid decline in *Pinus* pollen values at c. 4200 yr BP with an accompanying increase in pollen representing bog and dwarf shrub communities. At Loch Clair there is no similar rapid fall in *Pinus* values, although after c. 2900 yr BP decline occurs with a corresponding rise in Gramineae and *Calluna* pollen, suggesting some replacement of the pine forest by heath and grassland.

At the sites studied, there are no changes in the vegetation during the Flandrian (until relatively modern times) that can be related to human activity with any degree of certainty. The presence of man, at least around the coast since Mesolithic times, is, however, indicated by the artefacts at Shieldaig and Redpoint (Clarke, this guide). Neolithic activity is also recorded in adjacent

areas (Birks, 1973) and some impact, at least locally, of prehistoric people on the vegetation may reasonably be expected to be found in the future.

C K Ballantyne

D G Sutherland

W J Reed

2. DAY 1: ACHNASHEEN.

ITINERARY

The first half-day is a walk around the upper part of Strath Bran, starting and finishing at the Ledgowan Lodge Hotel. The stopping points are as follows:

1. The edge of the thick drift sheet marking the limit of the ice lobe that blocked Strath Bran where lacustrine sediments occur below till (NH 198 578).
2. At the uppermost part of the former ice lobe where the ice-dammed lake drained submarginally (NH 220 585)
3. By the former ice margin in the valley bottom where cross-valley moraines and the ice marginal deposits are seen (NH 195 591)
4. On the terraces west of Achnasheen (NH 153 580 and NH 160 576).

Introduction

Since last century (e.g. Nicol, 1844; Lucy, 1886) the impressive sequence of terraces near the village of Achnaseen has interested geologists. Early accounts argued for fluvial, lacustrine or marine origins for the terraces but the essentials of their formation appear to have been first realised in 1895 during a visit to the area by 'Dr Penck of Berlin' in the company of Officers of the Geological Survey of Scotland. The results of this visit appeared first in print in Geikie (1901; p.294) who suggested that the terraces were deposited in a lake in Strath Bran dammed by ice flowing outwards from the Fannich mountains to the north. More details relating to this interpretation were supplied in the Geological Survey Memoir (Peach et al., 1913a) but it was not until the work of Sissons (1982a) that a sequence of events associated with the establishment and drainage of the ice-dammed lake was documented.

Glacial features

The most impressive glacial feature in Strath Bran is the massive westward thickening sheet of drift which terminates abruptly in a roughly north-south break of slope up to 20 m high crossing the full width of the valley approximately 2.5 km east of Achnasheen (Figure 2.1). Sissons (1982a) traced the margin of this drift sheet from an altitude of c. 245 m on the north valley slope, where it merged to the north-east with a belt of mounds, across the valley bottom and up to an altitude of c. 225 m on the southern side of the valley. To the east of there, the margin of the drift sheet is more typically a ridge to approximately 250 m upslope of which in an easterly direction it is succeeded by a series of large drift mounds that attain a maximum altitude of c. 275 m on the valley side. The large drift mounds on the southern flank of the valley are succeeded in a downslope direction to the ENE by a sequence of meltwater channels associated with areas of bedrock devoid of drift which Sissons considered to be the result of sub-marginal meltwater drainage. Farther down Strath Bran on the northern side of the valley around NH 255 618 Sissons recorded a linear belt of morainic mounds trending upslope from near the valley bottom towards the WNW. After a short gap these mounds were continued upslope by a lateral moraine up to 5 m high which Sissons traced to an altitude of over 220 m.

All these features Sissons (1982a) considered to mark the limit of a lobe of ice that had emerged from the col between Strath Bran and the Loch Fannich valley to the north and had flowed out to block the drainage along Strath Bran. The contemporaneity of this ice mass with a lake in upper Strath Bran is demonstrated by laminated lacustrine sediments underlying till deposited at the margin of the lobe at NH 198 578 as well as laminated sediments overlying

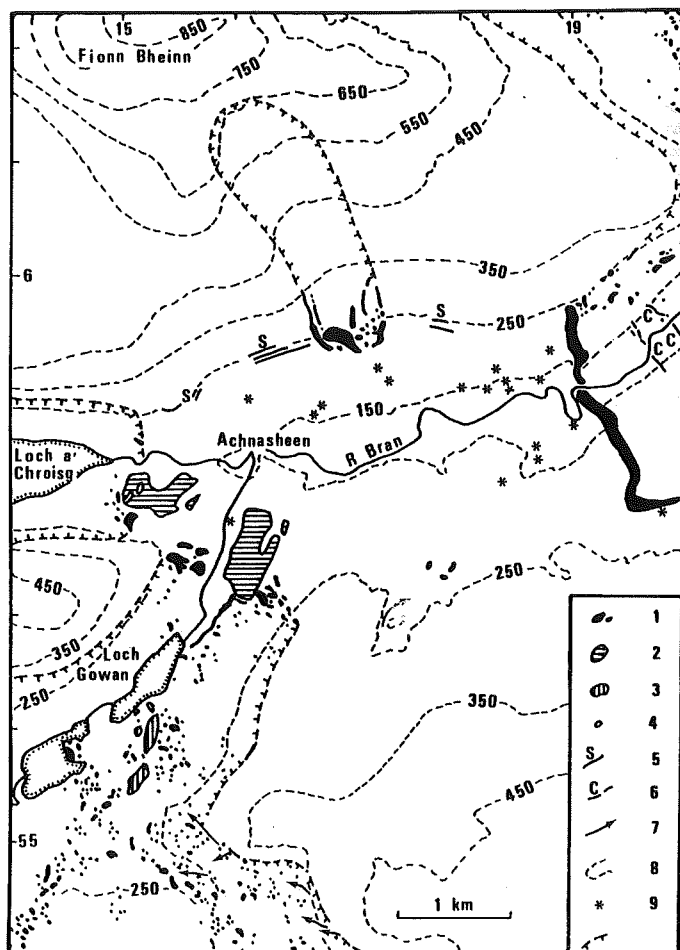


Figure 2.1. Ice limits around Achnasheen. 1. Drift mounds; 2. Major delta terrace; 3. Large kame terraces; 4. Kettles and groups of kettles; 5. Lake shorelines; 6. Cross-valley moraines; 7. Meltwater channels; 8. Contours, 50 m v.l.; 9. Exposures of fine laminated lake-floor sediments; 10. Inferred glacier limits.

the ice marginal deposits at NH 191 592.

As is discussed below, the western margin of the ice lobe defined by Sissons' evidence dammed a lake that was at least 125 m deep in the centre of the valley. Whilst the former ice lobe was responsible for the existence of the lake, the lake, in turn, appears to have controlled the actual position of the ice margin across the width of Strath Bran, for the uppermost levels reached by the abrupt margin of the drift sheet that trends approximately normal to the axis of Strath Bran accord closely with the maximum levels of the lake. (This also appears to have happened with the ice margins west of Achnasheen discussed below). Glacial sedimentation near the ice margin was also controlled by the lake. Sissons (1982a) noted a similarity in position and form between the wedge-like till sheet formed at the ice margin and the cross-valley moraines described by Andrews (1963). Smaller ridges also resembling cross-valley moraines were noted by Sissons around NH 198 595 having formed during initial ice retreat. Water depth relative to ice thickness was great enough to cause bouyancy at the ice margin (cf. Paterson, 1969) and increased ablation in the lake would have resulted in enhanced glacier flow towards the lake. These two factors would therefore explain the large volume of material in the terminal feature adjacent to the former lake (in contrast, for example, to the minor moraines marking the eastern, downvalley margin of the former lobe) as well as the form of the deposit.

The ice-contact nature of the up-valley ends of the major terraces west of Achnasheen at the mouths of the Loch a'Chroisg and Loch Gowan valleys imply that the terraces were formed when ice occupied these valleys. Sissons (1982a) demonstrated, however, that various fluvioglacial features as well as drift mounds which could be traced upslope from close to these terraces implied that glaciers had terminated slightly farther down both valleys than the ice-contact slopes. The evidence for this is best preserved in the Loch Gowan valley, particularly on the south-eastern flank. There Sissons traced drift mounds directly upslope to an altitude of c. 260 m. To the SSW Sissons noted a belt of boulders that merged into a lateral moraine 2-3 m high which is in turn followed by a marked drift limit to NH 158 551 where, at the junction with the valley to the SE, the drift limit swings in this direction to continue gently upslope. On the NW side of the Loch Gowan valley drift mounds were only noted by Sissons immediately upslope of the major terrace where they were traced to an altitude of c. 245 m.

The contemporaneity of the two ice limits west and SW of Achnasheen with lacustrine sedimentation in Strath Bran is demonstrated both by the terrace relationships discussed below and by the occurrence at the base of the terraces of bedded silts, sands and clays these

being overlain by sands and gravels showing foreset bedding (e.g. NH 159 577; NH 156 581). These sediments imply deposition into a standing water body (Lucy, 1886; Peach et al., 1913a; Sissons, 1982a).

One further ice limit was described by Peach et al. (1913a) and Sissons (1982a) near Achnaseen. This is a group of morainic mounds on the side of Strath Bran around NH 190 594 below a recess on the south-east side of Fionn Bheinn. Disrupted laminated sediments indicate that the former glacier that deposited the mounds was contemporaneous with or post-dated the deposition of lacustrine sediments in upper Strath Bran.

Ice-dammed lake and associated terraces

Direct evidence for a former lake in upper Strath Bran exists most abundantly in the numerous small exposures of laminated silts and clays with occasional drop stones which are found on the lower valley slopes up to a maximum recorded altitude of c. 250 m O.D. Sissons (1982a) also identified former lake shorelines along the northern flank of the valley. These he surveyed, establishing three separate lake levels at c. 255 m, c. 245 m and c. 237 m O.D. The lake had a maximum depth of at least 125 m adjacent to the ice lobe damming the lake to the east. Such a depth was insufficient to initiate subglacial drainage (cf Glen, 1954) and Sissons interpreted the sequence of submarginal channels and water-swept bedrock along the southern margin of this lobe as being the drainage ways that controlled the level of the lake. The separate lake levels indicated by the shorelines related to different stages of downcutting of the submarginal channels.

None of the major terraces to the west of Achnasheen relate to the uppermost lake levels. Sissons' surveying indicated that the highest terrace NE of Loch Gowan descends from 191 m to 175 m in c. 850 m (c. 18 m km⁻¹) and the highest terrace east of Loch a'Chroisg fell from 185 m to 176 m in c. 500 m (c. 18 m km⁻¹). The presence of foreset bedding in these features together with the common lowest altitude on both suggests deposition in a lake with a level of c. 175 m. Sissons was able to identify a meltwater channel farther downvalley to the east within the limits of the ice lobe from the Loch Fannich valley the intake of which is at c. 175 m, this apparently controlling the level of a lake during initial ice retreat.

Upon drainage of the 175 m lake rapid incision of the large terraces west of Achnasheen occurred, for while ice still occupied the areas of Loch a'Chroisg and Loch Gowan, a sequence of lower terraces, partly flanking the major ones, were formed, merging with the valley bottom and present floodplain in the area of the by now drained former lake. Sissons (1982a) suggested that a minor lake at c.

140 m was formed by the damming action of the drift associated with the easterly ice lobe, but there is little evidence that this was more than an very temporary event: the sands he suggested as having been deposited in that lake are apparently of Flandrian age.

Age

There is no evidence that bears directly on the dating of the events in the Achnasheen area. The distribution of the lake sediments in the bottom of Strath Bran implies that the valley was clear of glacier ice prior to the events described which, in turn, suggests a readvance origin for the glacial features. The occurrence of lacustrine sediments below glacial deposits also implies, at least locally, an ice readvance. Clapperton (1977) reproduced a map of the terraces west of Achnasheen by A M D Gemmell and suggested that they might mark the limits of 'the local ice cap during the Late-glacial' (p.31). However, Robinson (1977) and Sissons (1977) interpreted the limits of the Loch Lomond Readvance as occurring some distance to the west, suggesting an earlier age for the Achnasheen deposits (cf. Sutherland, 1984a). Sissons (1982a) was unable, however, to locate any evidence that would refute the hypothesis that the Achnasheen ice limits and terraces were related to the Loch Lomond Readvance. New evidence is therefore awaited before the place of the Achnasheen deposits in the glacial sequence is established.

D G Sutherland.

3. DAY 2: AN TEALLACH

ITINERARY

The party will travel directly to An Teallach and begin the ascent of the mountain from the car park at Corrie Hallie (NH 114 850). The walking will be strenuous and participants must be prepared for adverse weather. The route will cross the northern plateau of An Teallach from the quartzite escarpment in the south-east (NH 090 841) to rejoin the road at Ardessie in the north-west (NH 053 896). The following sites will be visited.

1. Quartzite Escarpment (NH 090 841): glacial limits, striae, view of corries and quartzite blockslopes.
2. Glas Tholl end moraine (NH 092 846)
3. Lateral limit of Glas Tholl glacier (NH 085 850): view of Holocene talus cones and debris flows.
4. NE slope of Glas Mheall Mór (NH 085 859): possible glacier limits, Holocene debris cone and debris flow.
5. Coire a'Mhuillin (NH 077 862): end moraine, periglacial features, relict talus slopes.
6. Mheall Garbh (NH 079 866 and 073 865): periglacial trimline.
7. An Teallach plateau (NH 069 861): deflation surface, niveo-aeolian sand deposits, high-level erratics.
8. An Teallach plateau (NH 062 865): Weathering, readvance limits.
9. Protalus rampart (NH 054 875): lateral moraines and relict talus slopes.
10. Mac is Màthair moraines (NH 059 878) and ice-sheet 'medial moraine'

The following sites will be visited on the return journey to Achnasheen:

11. Ardessie (NH 053 896): recent flood erosion and landslide.
12. Dundonnell (NH 090880): Lateglacial raised shorelines and outwash.
13. Corrieshalloch Gorge (NH 203 780): meltwater gorge.
14. Loch Droma (NH 253 756): Lateglacial pollen site.
15. Loch Glascarnoch (NH 277 743): periglacial trimlines and the Gharbhrain moraine.
16. Strath Vaich (NH 359 714): readvance moraines and outwash terraces.

3. AN TEALLACH

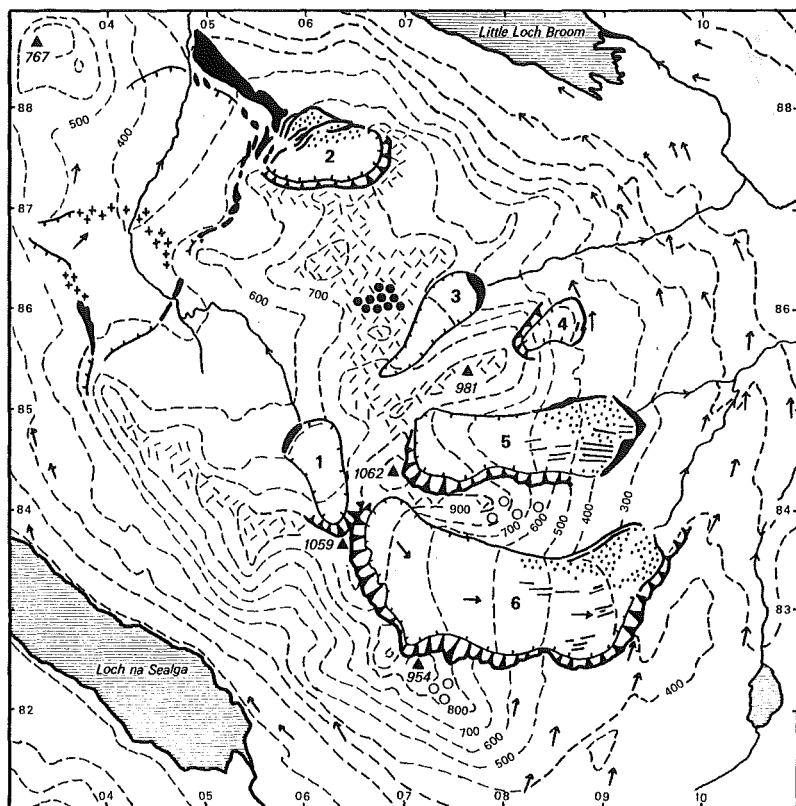
INTRODUCTION

The An Teallach Massif is located in the north-western part of Wester Ross at 57°49'N, 5°16'W. The northern part of An Teallach (Figure 3.1) consists of gently-rolling plateau between 730 m and 860 m, but farther south steep rocky arêtes rise above spectacular corries and culminate in the pyramidal summits of Bidean a'Ghlas Thuill (1062 m) and Sgùrr Fìona (1059 m). The massif is entirely composed of eastward-dipping Torridon Sandstones except for unconformable outliers of Cambrian Quartzite on each of its three eastern spurs. The present 'maritime periglacial' climate on the higher parts of An Teallach is dominated by high precipitation, prolonged snow-lie and strong winds rather than extremes of cold. Although mean monthly temperatures lie below 0°C for 4-5 months of the year, air temperatures rarely fall below -10°C; annual precipitation at 665 m averages 3577 mm; average snow-lie (>50% cover) on exposed ground increases from c. 120 d y^{-1} at 600 m to c. 190 d y^{-1} at 1000 m, but drifts in lee valleys are known to develop to depths exceeding 7m and usually survive for >200 d y^{-1} ; westerly winds are dominant and gusts >100 km h^{-1} are fairly common, particularly in winter (Ballantyne, 1981, 1983, 1985).

The massif is of interest to Quaternary scientists on account of the outstanding range of glacial and periglacial landforms that it supports (Ballantyne, 1977). Of particular interest is the evidence for at least four glacial stages on An Teallach, the earliest being represented by high-level erratics, the next by a high-level 'periglacial trimline', the penultimate stage by a sequence of moraines relating to readvances or stillstands that interrupted the retreat of the last ice sheet, and the final stage, the Loch Lomond Readvance, by exceptionally well-developed end moraines and drift limits. The periglacial features of An Teallach are dominated by wind-related forms (deflation surfaces, niveo-aeolian sand deposits and turf-banked terraces) characteristic of cohesionless, sand-rich frost-weathered regolith, though relict and active talus and related slope features are also represented.

Ice sheet glaciation

Erratics of 'thrust' Torridonian Sandstone at c. 900 m on Sàil Liath, the southernmost quartzite outlier, indicate former ice sheet glaciation to at least that altitude, though there is no evidence that the highest summits have ever been over-ridden by glacier ice (Peach *et al.*, 1913a, p. 105). A remarkable high-level train of quartzite erratics also crosses the northern plateau at 760 m (NH 068



- | | |
|----------------------------|---|
| Moraine ridges | Erratics of 'thrust' Torridon Sandstone |
| Hummocky drift | Erratic train of Cambrian Quartzite |
| Fluted moraines | Inferred glacial limit |
| Striae | In situ frost weathered detritus |
| Cliffs | Glacially deposited boulders |
| 767 Summits (m) | |
| Contours (100 m intervals) | |

0 2 km

Figure 3.1: The An Teallach massif, showing the limits of former glaciers and other glacial features.

860) and indicates former ice-sheet movement to the WNW across the plateau. Both sets of erratics, however, lie well above the altitude of the 'periglacial trimline' represented by the limits of *in situ* frost-weathered detritus, which occurs at c. 700 m around the northern plateau (Figure 3.2). If this trimline represents the upper limit of the last ice sheet at its maximal extent, then the high-level erratics must have been emplaced by an earlier, more extensive ice sheet.

A sequence of four former ice limits in the broad valley west of the massif provides evidence of local stillstands or readvances that interrupted the retreat of the last ice sheet in this area (Figure 3.1). At the north-east end of the valley there is a massive drift ridge over 1 km long that was interpreted by Robinson and Ballantyne (1979) as a form of medial moraine deposited when ice moving north down the valley parted from that moving WNW along the trough now occupied by Little Loch Broom. A second stage is represented by lateral moraines on the east side of the valley but extending north almost as far as the massive medial moraine. The third former glacier limit in the valley is marked by an 80 m wide arcuate spread of sandstone boulders that crosses the valley 1.6 km from the medial moraine and is continued to the south-west by a boulder-strewn lateral moraine 450 m long. The final former ice limit comprises a discontinuous line of low boulder-covered ridges that cross the south-west end of the valley and apparently mark the limit of the glacier that occupied the Loch na Sealga trough after the valley west of An Teallach had become ice-free. Robinson and Ballantyne (1979) suggested that this sequence of moraines probably relates to the Wester Ross Readvance, but noted that this correlation is uncertain.

The Loch Lomond Readvance

During the Loch Lomond Readvance, An Teallach supported a number of small corrie glaciers. Sissons (1977) mapped the limits of six such glaciers, but the evidence for one of these (4 in Figure 3.2) seems dubious, and the limits of another (1 in Figure 3.2) were subsequently re-mapped by Ballantyne (1981, p. 55) some 500 m outside Sissons' postulated limit. The evidence for local glaciation on An Teallach is as follows.

Glacier 1 : The lower limit is marked by an end moraine 2-3 m high and 210 m long. The downslope limit of relict boulder lobes defines the south-west margin of the former glacier for some distance upvalley.

Glacier 2 : A sequence of five end or lateral moraines mark former positions of the glacier margin. The outermost moraine is the largest and most continuous; some of the inner moraines are fragmentary and consist only of very low boulder ridges amongst an extensive spread of boulders that

terminates at the outermost moraine. This moraine truncates the ice sheet 'medial moraine' described by Robinson and Ballantyne (1979, p. 275).

Glacier 3 : A broad, arcuate end moraine c. 260 m long marks the former glacier terminus. The lateral limits have been obscured by mass-movement of frost-weathered detritus.

Glacier 4 : Although Sissons (1977) mapped a clear end-moraine at this site, the field evidence appears to consist only of some rather dubious drift mounds. Sissons himself (1977, p. 57) suggested that the 'glacier' may have been merely a perennial snowbed, but the supposed glacier limit has none of the characteristics of a proglacial rampart.

Glacier 5 : The former terminus of this glacier is marked by an impressive end moraine that rises up to 30 m above driftless ice-scoured rock on its distal side, but is typically only 1-3 m high on its proximal side, indicating the presence of a considerable thickness of drift. Broad fluted and hummocky moraines extend for some distance inside the former glacier limit, which is continued for c. 1 km by a lateral moraine on the north slope of the corrie. In the higher parts of the corrie joint depths are significantly greater on outcrops outside the former ice limit (Ballantyne, 1982).

Glacier 6 : A pronounced drift limit bounded by low lateral moraines defines the former glacier margin. The northern lateral moraine can be traced for almost 2 km into the corrie.

Relict periglacial phenomena

The most widespread manifestation of Devensian periglaciation on An Teallach is the mantle of frost-weathered detritus that covers the plateau and slopes of less than c. 35° above c. 700 m. Only on the southernmost two quartzite outliers are true blockfields developed; elsewhere frost-weathered clasts, generally slabby in form, are embedded in a sandy matrix. Apart from the blockfield areas, *in situ* detritus rarely exceeds 1.0 m in depth, and in places outcrops of frost-weathered sandstone rise through the debris mantle. The strong contrasts in the roundness of exposed (rounded) and buried (angular) clasts indicate that the debris mantle on plateau areas is essentially stable and has been unaffected by cryoturbation for a very long time, though superficial frost creep is still effective and has transported regolith to within the limits of the Loch Lomond Readvance glaciers in places. The regolith mantle supports few relict periglacial features, though boulder lobes are well-developed outside the Loch Lomond Readvance limit in the southern part of the massif (NH 060 842) and rather poor and possibly dubious examples of relict sorted circles occur at c. 750 m on the northern plateau (cf. Ballantyne, 1981, figure 10.5).

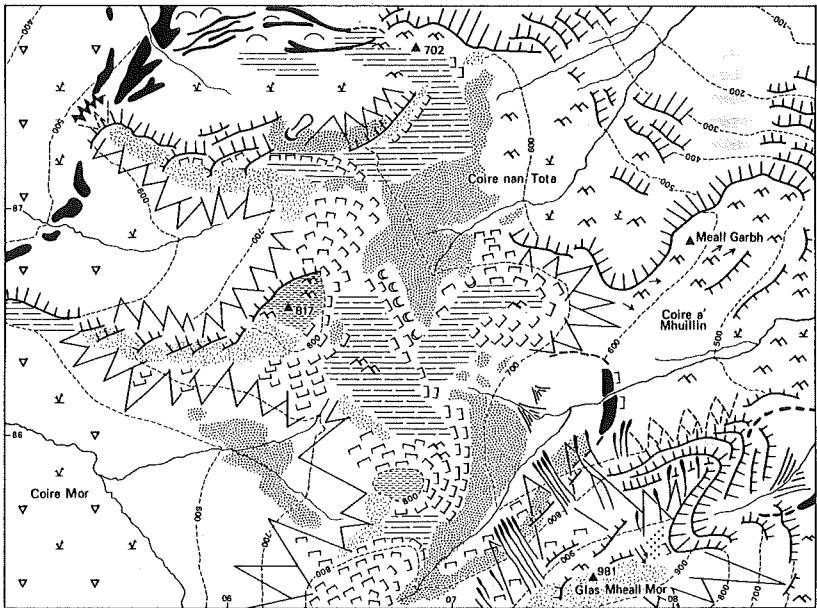
Relict talus of inferred Lateglacial age occurs at the foot of cliffs immediately outside the Loch Lomond Readvance end moraine in Coire a'Mhuillinn (NH 080 861; Ballantyne and Eckford, 1984), and a solitary example of a Loch Lomond Stadial protalus rampart occurs at the foot of another relict talus slope in the north-western part of the massif at NH 054 875 (Ballantyne and Kirkbride, 1986).

Active and Holocene periglacial features

An Teallach supports what is probably the finest assemblage of high-level aeolian and niveo-aeolian features in Great Britain. Much of the frost-weathered regolith on the plateau forms an extensive deflation surface, and the products of deflation have accumulated as niveo-aeolian sand sheets on the slopes flanking the plateau (Figure 3.2). Isolated 'islands' of sand also occur within cols on the plateau, and indicate formerly more widespread sand cover. The deposits reach a maximum thickness (up to 4 m) on lee (easterly) slopes downwind of such cols; elsewhere they rarely exceed 1.5 m in depth. Ballantyne and Whittington (1987) have demonstrated that the thickest deposits began to accumulate in the early Flandrian, but that accumulation virtually ceased following, they suggested, establishment of a stable unbroken vegetation cover over much of the plateau source area. Recent disruption of this cover and erosion of sand deposits that had accumulated in cols on the plateau led to renewed deposition of sand on lee slopes downwind of these cols. Niveo-aeolian sand deposition is active at present; Ballantyne and Whittington (1987) calculated that c. 9.3 t of sand were deposited in Coire nan Tota (Figure 3.2) during the winter of 1976-7, of which c. 3.2 t represented sand reworked from remnant 'islands' on the plateau and the remainder was apparently supplied by granular disintegration and deflation of particles derived from exposed clasts and bedrock on the vegetation-free plateau surface.

On some slopes (e.g. at NH 068 866) eluviation by nival meltwater between vegetation tussocks as sand accumulated has resulted in the formation of large, thufur-like sand hummocks (Ballantyne, 1986b). At the head of Coire nan Tota, a number of small nivation hollows have developed in the sand deposits through erosion of the unvegetated scarps at the margins of sand sheets and reworking and deposition of eroded sand by nival meltwater (Ballantyne, 1985).

Although wind-patterned ground in the form of deflation stripes and vegetation crescents is present on the plateau, the most impressive small-scale features reflecting the action of the wind are the flights of horizontal and oblique turf-banked terraces that have developed on frost-weathered regolith on slopes on and flanking the plateau (Figure 3.2). As their name suggests,



Late Devensian periglacial features

- Blockfield
- Debris surface
- Stone pavement
- Relict talus
- Debris mantled slope
- Blockslope
- Boulder sheets and lobes
- Sorted solifluction features
- Nonsorted solifluction features
- Large relict sorted circles
- Large relict sorted stripes
- Earth hummocks
- Hummock stripes
- Nivation hollows
- Protalus rampart

Holocene periglacial features

- Deflation surface
- Niveo-aeolian sand deposits
- Active talus
- Solifluction sheets and lobes
- Turf banked terraces
- Ploughing boulders
- Debris flows
- Translational slides
- Small active sorted circles
- Small active sorted stripes
- Wind stripes
- Nivation hollows
- Alluvial fan or cone

Miscellaneous

- Moraine ridge
- Drift limits
- Inferred glacier limit
- Hummocky drift
- Rock outcrops
- Hill peat
- Till sheet
- Free face
- Water bodies
- 890 Summits in metres
- 700 Contours at 100 m intervals

0 1000 m

Figure 3.2: Periglacial features on the northern plateau of An Teallach (Ballantyne, 1984).

turf-banked terraces have well-vegetated risers and sparsely-vegetated treads. The treads of horizontal terraces, which have a low (generally <10°) across-slope dip, often end in oblique ramps that connect treads at different levels. On some slopes these ramps approach or exceed the horizontal treads in size, giving rise to interconnecting (horizontal and oblique) terraces. On other slopes, turf-banked ramps dipping steeply across-slope are continuous for many metres, producing the impressive features here termed oblique terraces.

The alignment and location of turf-banked terraces is related to the survival of vegetation in the shelter (from westerly winds) offered by the terrace risers. Thus horizontal terraces tend to be best-developed on gentle to moderate lee slopes with easterly aspects ranging from 0° to 160°, but are rare or poorly developed on slopes with westerly aspects. Oblique terraces favour north- or south-facing slopes, and invariably dip upwind (westwards); those on the south slope of Glas Mheall Mór are particularly impressive.

Oblique terraces occur within the limits of the Loch Lomond Readvance glaciers on An Teallach, hence presumably developed during the Holocene. Horizontal terraces, however, rarely occur within these limits, although good examples occur on the lee slope of the end moraine in Coire a'Mhuillín. Present activity is limited to the superficial frost creep of debris across the treads; the risers appear to be essentially stable features that reflect retardation rather than acceleration of movement. The origin of the terraces remains rather enigmatic. One possibility is that the development of wind-patterned vegetation stripes and crescents on lee slopes effectively 'dammed' creeping debris, thus building the terraces which in turn provided sheltered sites that favoured vegetation growth. An alternative model for the development of horizontal terraces is that terrace development occurred first, and that vegetation colonisation of the risers enhanced the terrace form on lee slopes; there is evidence in support of this in the form of rather degraded unvegetated terraces on windward slopes at NH 065 852. Oblique terraces may also have developed through progressive anchoring of creeping debris by vegetation sheltering in the lee of boulders (Ballantyne, 1981).

Within the corries of An Teallach the most active processes operating at present are rockfall and debris flow. During the Holocene, talus cones have developed inside the limits of the Loch Lomond Readvance below the north-facing cliffs of Glas Tholl (NH 07 84) and Coire Toll an Lochain (NH 07 83), and considerable recent rockfall activity has been recorded at the former site (Ballantyne and Eckford, 1984). At the latter, Innes (1983) has demonstrated that many debris flows have occurred within the last century, and eight debris flows are known to have

occurred on the mountain between 1975 and 1984 (Ballantyne, unpublished).

THE QUARTZITE ESCARPMENT (NH 090 841)

Geology

The crest of the escarpment is composed of fine-grained Cambrian Quartzite 'pipe rock' that dips eastwards at 17°. About 1 km to the east the line of the Moine Thrust lies at the foot of the dip slope on the floor of Gleann Chaorachain, and can be seen in cross-profile across Strath Beag to the north. The westwards continuation of the unconformity between the Cambrian Quartzite and the underlying Torridon Sandstone can be seen some distance downslope of the three eastern summits of An Teallach (Sàil Liath, Glas Mheall Liath and Glas Mheall Mór).

Glacial landforms

The two corries facing the escarpment (Coire Toll an Lochain and Glas Tholl) are amongst the most impressive in Scotland. Both nourished glaciers during the Loch Lomond Stadial (Figure 3.1), that from Coire Toll an Lochain being delimited by low lateral moraines and that from Glas Tholl by a massive ramp-like moraine up to 30 m high on its distal side. A notable feature of both former ice margins is the contrast between a thick cover of drift inside the limits and the virtual absence of drift outside. The exposed Torridon Sandstone bedrock on the floor of the valley outside the limits of the Loch Lomond Readvance (Coir' a'Ghiubhsachain) is ice-scoured and in places striated. Striae and chattermarks are also well preserved on the fine-grained quartzite of the escarpment crest. All indicate a generally northwards movement of ice, and reflect deflection of the last ice sheet around the flanks of the An Teallach Massif, presumably during the Wester Ross Readvance and possibly earlier.

Periglacial landforms

The well-jointed Cambrian Quartzite of the outliers on Sàil Liath and Glas Mheall Liath forms impressive blockslopes that contrast markedly with the comparatively unweathered Torridon Sandstones which they overlie. That on Sàil Liath descends to below 600 m, much lower than the 'periglacial trimline' that marks the lower limit of frost-weathered Torridon Sandstone regolith elsewhere on the massif. This discrepancy suggests that, as in other periglacial environments, the quartzite has proved particularly susceptible to macrogelivation under severe periglacial conditions and that unlike the Torridon Sandstone it weathered to produce a thick cover of frost-shattered detritus in the comparatively short interval between the exposure of these slopes during the downwastage

of the last ice sheet and the end of the Loch Lomond Stadial. This explanation, however, fails to account for the unweathered nature of the quartzite on the escarpment itself. An alternative explanation is that blockslope deposits that originally formed above the level of the 'periglacial trimline' migrated downslope following ice-sheet downwastage. This view is supported by the fact that on Glas Mheall Liath the quartzite blockslope completely buries the underlying Torridon Sandstone for over 40 m downslope of the unconformity that separates the two rock types, and individual quartzite blocks extend even farther downslope (Ballantyne, 1981; Figure 3.3). The blockslope deposits are apparently inactive under present-day conditions.

THE GLAS THOLL END MORaine (NH 092 846)

The distal slope of this moraine is, according to Sissons (1977, p.46) up to 30 m high, but its inner slope, although approaching 10 m at one point, is typically only 1-3 m high. Outside of the moraine limit the ice-scoured Torridon Sandstone bedrock is virtually drift-free. This contrast implies the accumulation of c. 20-30 m of drift immediately inside the moraine, and suggests that this drift was *not* derived from re-working of pre-existing till (cf. Hodgson, 1982, 1986), but represents material eroded *ab initio* from the corrie upslope (Glas Tholl). Given the height and steepness of the north-facing rockwall in Glas Tholl and the rapid rates of rockfall known to have occurred during the Loch Lomond Stadial (Ballantyne and Kirkbride, 1987), glacially-transported rockfall detritus seems likely to have contributed substantially to this debris, and glacial erosion and transportation of talus formed in Glas Tholl before the onset of glacier advance appears another possible source. On level ground inside the moraine at NH 088 845 the till surface takes the form of regularly-spaced, low flutes nearly 20 m wide. Hummocky drift extends to the northern limit of the former glacier, which is marked by a lateral moraine and drift limit.

THE LATERAL LIMIT OF THE GLAS THOLL GLACIER (NH 085 850)

From the lateral limit of the former glacier at c. 500 m altitude there is an excellent view of the upper part of the corrie where high, gullied Torridon Sandstone cliffs overlook Holocene talus cones. Lichen-free scars on the cliffs and fresh spreads of boulders on the talus are indicative of recent rockfall (Ballantyne and Eckford, 1984), and some of the talus cones have been modified by debris flows.

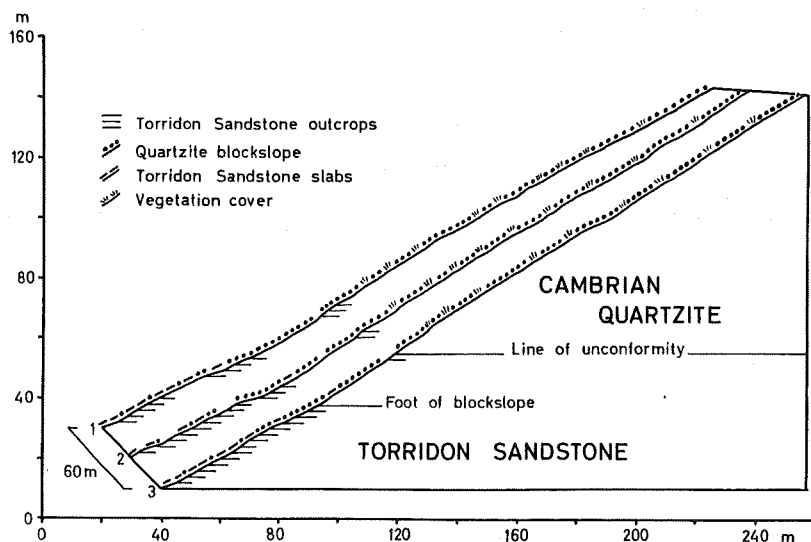


Figure 3.3: Extension of Cambrian Quartzite blockslope deposits over Torridon Sandstone bedrock as a result of mass-movement under severe periglacial conditions. Glas Mheall Liath, An Teallach (Ballantyne, 1981).

THE NORTH-EAST SLOPE OF GLAS MHEALL MÓR (NH 085 859)

On level ground downslope of a broad rocky cleft or embayment in the north-east slope of Glas Mheall Mór, Sissons (1977, Figure 3.1) mapped a moraine representing the limit of a small corrie glacier. The field evidence consists mainly of a few mounds of drift and appears equivocal, though the absence of talus development favours the occupation of this site by a glacier during the Loch Lomond Stadial. If so, then the large debris cone that has developed at the foot of the cleft is presumably of Holocene age. Such debris cones develop through the accumulation of sediment transported by repeated debris flows; the most recent flow at this site, however, merely redistributed sediment eroded from the cone apex. It is known to have occurred between 1979 and 1983, and may have been triggered by the exceptional rainstorm of September 1981 (Acreman, 1983).

COIRE A'MHUILLIN (NH 077 862)

Although not as impressive as the other eastern corries on An Teallach, Coire a'Mhuillin has proved a particularly useful site for the identification of morphostratigraphic relationships between periglacial features and former glacial limits (Figure 3.2). The most conspicuous glacial landform is a textbook example of an arcuate Loch Lomond Readvance end moraine (Sissons, 1977; Figure 3.1) that crosses the valley at NH 077 862 and provides an excellent viewpoint both upvalley and downvalley.

Talus slopes

Immediately outside the end moraine on the south side of the valley are extensive, vegetated relict talus slopes that have been surveyed and studied in detail by Ballantyne and Eckford (1984). Morphologically, these slopes display features characteristic of unmodified rockfall accumulations, namely an upper straight slope and basal concavity and maximum gradients of c. 36°. They are, however, much more 'mature' accumulations than the Holocene talus cones viewed in Glas Tholl, with a higher talus height to cliff height ratio (2:1 compared with 0.4:1 for the Glas Tholl talus). Moreover, the complete vegetation cover on these slopes and the fact that erosion (gullyng, shallow translational sliding and debris flow activity) has replaced rockfall accumulation as the dominant mode of geomorphic activity acting on these slopes indicates that they are essentially relict features, and Ballantyne and Eckford concluded that they probably developed in the interval between the retreat of the last ice sheet and the end of the Loch Lomond Stadial. This is supported by measurements that indicate a present-day rockwall retreat rate of only 0.015 mm y⁻¹, which is two orders of magnitude lower than rates calculated for the Loch Lomond Stadial

(Ballantyne and Kirkbride, 1987). Large boulders at the foot of the talus at NH 081 862 represent the products of a rockslide or rockfall of unknown age.

Debris-mantled slopes

Distinct from the talus slopes, which represent former rockfall accumulation, are the debris-mantled slopes upvalley from the moraine on the north-west slope of Glas Mheall Mór. These slopes are up to 600 m long, and extend from near the summit of Glas Mheall Mór (981 m) to the floor of Coire a'Mhuillín at 600-700 m. The modal gradient is 31°. Although from a distance these slopes appear to support a complete cover of frost-weathered debris, this impression is misleading: the slopes are essentially stepped Richter slopes mantled by a very thin (generally <1 m thick) cover of detritus through which numerous essentially unweathered outcrops of Torridon Sandstone protrude. The detritus cover is not *in situ* but has migrated downslope from the frost-shattered zone upslope, obscuring the lateral limits of the former glacier that terminated at the Coire a'Mhuillín moraine. The extent of debris transport down such slopes has been established through tracing quartzite boulders downslope from the outcrop near the summit of Glas Mheall Mór (Ballantyne, 1981): these are common nearly 300 m downslope of the outcrop on the south side of this summit, and occur up to 600 m downslope on the north side. Present creep rates of surface clasts on slopes of c. 30° at this site average c. 11 mm y⁻¹; if such rates are representative for creep throughout the Holocene, then a downslope movement of little more than 100 m is implied. The discrepancy may reflect much greater creep rates associated with severe periglacial conditions during the Lateglacial, though the picture is complicated by the fact that the debris-mantled slopes show abundant evidence for debris flow activity, both recent (5 flows occurred on this slope between 1975 and 1977) and ancient (in the form of degraded and vegetation-covered levées and terminal lobes), so it is conceivable that much of the frost-weathered regolith from upslope was transported by debris flow rather than creep. These observations highlight the dangers of employing apparently *in situ* frost-weathered regolith on steep slopes in delimiting Loch Lomond Readvance (and earlier) glacier margins, and demonstrate the effectiveness of Late Devensian and Holocene mass movement on unvegetated debris-mantled slopes.

Aeolian features

The slopes at the head of Coire a'Mhuillín are covered by well-vegetated sand deposits. Those near the crest of the slope consist of niveo-aeolian sand, but farther downslope reworking of the sand by nival meltwater is evident in the formation of alluvial cones and fans. Above the level of the vegetation and sand cover, turf-banked

terraces occupy frost-weathered regolith. Both *in situ* niveo-aeolian sand deposits and horizontal turf-banked terraces occur inside the limit of the Loch Lomond Readvance glacier that developed in Coire a'Mhuillin (Figure 3.2), which demonstrates formation since the glacier disappeared, presumably under the milder periglacial conditions of the Holocene. Good examples of horizontal turf-banked terraces actually occur on the distal slope of the Coire a'Mhuillin moraine, also demonstrating formation after the culmination of the Loch Lomond Readvance.

MHEALL GARBH (NH 079 866 and NH 073 865)

The spur that stretches north-eastwards from the An Teallach plateau to terminate at just over 600 m on the rocky summit of Mheall Garbh provides an excellent illustration of the high-level 'periglacial trimline' that occurs on mountains throughout Wester Ross and which may represent the surface of the last ice sheet at its maximal thickness. The small plateau of Mheall Garbh itself (NH 079 866) shows little sign of disruption by frost action: the bedrock is ice-scoured and littered with glacially-transported boulders. In contrast, an ascent of less than 100 m to the northern plateau proper (NH 073 865) reveals an area completely covered by frost-weathered regolith, with few rock outcrops and no evidence of former glacial activity. The difference in altitude is too slight to be responsible for the drastic increase in the degree of frost weathering, and indeed elsewhere in Wester Ross the dividing line occurs over much smaller vertical intervals (W.J. Reed, personal communication). Nor is the trimline at this site attributable to contrasts in weathering inside and outside the limits of the Loch Lomond Readvance, as both sites clearly lie well outside these limits (which are represented by the moraine in Coire a'Mhuillin).

Several inferences may be drawn from the contrast in the degree of frost-weathering between the two sites. First, it is apparent from the lower site that the effectiveness of macrogelivation since ice-sheet downwastage has been minimal, and largely restricted to the widening and deepening of joints and other discontinuities in the rock (cf. Ballantyne, 1982). This in turn suggests that the rock at the higher site must either have experienced weathering under a much more severe periglacial regime or, more likely, for a very much longer time period than that represented by the period of ice-sheet downwastage and the Loch Lomond Stadial combined. If the latter alternative is correct, it implies that the northern plateau of An Teallach must have been glacier-free throughout much of the Late Devensian or longer. As it is difficult to account for the comparative abruptness of the change between ice-scoured bedrock and frost-weathered regolith in any way other than exposure of the latter above a former ice mass, the simplest explanation is that the

trimline represents either the surface of the last ice sheet at its maximal extent or possibly the removal of periglacial debris from below a certain level by a relatively late thickening (readvance) of the ice sheet. As outlined in the introduction to this guide, however, it seems unlikely that removal of frost-weathered detritus by the Wester Ross Readvance was responsible for producing the trimline, as moraines associated with the readvance lie well below the trimline level (Figure 1.3). Unfortunately, the effectiveness of downslope movement of frost-weathered detritus during the Lateglacial and Holocene has obscured the location of the high-level trimline on all but gentle slopes and where, as at Mheall Garbh, plateaux capable of supporting *in situ* frost-weathered detritus occur on the same lithology both above and below the level of the trimline.

THE AN TEALLACH PLATEAU (NH 069 861)

High-level erratics

A remarkable train of high-level Cambrian Quartzite erratics crosses the plateau in a general east-west direction around NH 067 860 (Figure 3.1). Abundant boulders of fine-grained quartzite occur both on and within the Torridon Sandstone regolith. The southern margin of the erratic train is remarkably sharp, but the train fans out to the northwards and has no clear northern boundary. One possible source of the erratics is the Cambrian Quartzite escarpment to the east of An Teallach, which implies an upwards carry of erratics of c. 500 m over a distance of c. 4 km, but this interpretation requires a former westerly ice-movement that appears irreconcilable with striae indicating former northerly movement of ice down Coir a'Ghiubhsachan and along the escarpment itself, and seems tenable only if the erratics were emplaced by an earlier ice movement than that represented by the striae. An alternative source is the Cambrian Quartzite outcrop located above 940 m near the summit of Glas Mheall Mór at NH 079 855; if this were the erratic source it implies former movement in a WNWesterly direction of an ice mass exceeding that altitude. A possible objection to the second interpretation is that whereas the erratics are of fine-grained quartzite, the outcrop consists only of conglomeratic basal quartzite, but it is conceivable that the overlying fine-grained quartzite is no longer represented at the outcrop because it has been completely removed by glacial erosion. Whichever interpretation is correct, the erratics imply ice movement over the northern plateau at some time before the formation of the periglacial trimline on Mheall Garbh. The incorporation of quartzite erratics within the frost-weathered regolith is consistent with this interpretation. If the trimline represents the upper limit of the last ice sheet at its maximal thickness, then the erratic train was presumably

emplaced by a much thicker pre-Devensian ice mass that over-rode much or all of An Teallach.

Aeolian landforms

Much of the unvegetated regolith on the plateau forms an extensive deflation surface, armoured by boulders and carpeted with lag gravels. Particle-size analysis of the gravel lag (Ballantyne, 1981, figure 8.28) revealed that only 4% of the sample had intermediate axis lengths <6 mm, which implies that most smaller particles have been removed by wind. On gently-sloping ground the deflation surface merges with flights of horizontal turf-banked terraces. These are particularly well developed to the east of the plateau at the head of Coire a'Mhuillin and around the low hill at NH 068 858 (Figure 3.2).

Niveo-aeolian sand deposits

The products of deflation of the plateau have accumulated as niveo-aeolian sand deposits on the slopes flanking the plateau, and are particularly deep and extensive on lee (east-facing) slopes at the head of Coire a'Mhuillin and Coire nan Tota (Figure 3.2). The deposits are generally massive, poorly sorted, and coarser than most aeolian deposits, comprising mainly medium sand (212-600 μm) with a substantial proportion of coarse sand and even very small pebbles. The coarseness and poor sorting reflect the size of grains weathered from Torridon Sandstone clasts and bedrock, the strength of the wind, short transport distances and admixture of different grades of sand during niveo-aeolian deposition.

In a detailed study of the sedimentology, stratigraphy and history of the sand deposits, Ballantyne and Whittington (1987) logged and sampled several sections excavated in the unvegetated scarps that surround the sand sheets east of the plateau. All excavated sections revealed two distinct sand units, sometimes separated by an unconformity: an upper unit of up to 2 m of fresh, unweathered sand and a lower unit, also up to 2 m thick, of heavily weathered, leached and iron-stained sand with abundant manganese horizons. At two sites (NH 068 867 at the head of Coire nan Tota and NH 070 861 at the head of Coire a'Mhuillin) thick organic-rich horizons were found at the base of the lower sand unit and sampled for pollen analysis. As the stratigraphy of the two sites and the pollen stratigraphy of the organic-rich layers at these sites is almost identical, only that of the latter site ('site H') is illustrated here (Figures 3.4 and 3.5).

The pollen spectra at site H clearly indicate two major zones divided by a marked organic concentration midway up the column (Figure 3.5). Gramineae, *Calluna* and Coryloid pollen are generally much more strongly represented below this organic-rich band, Cyperaceae and

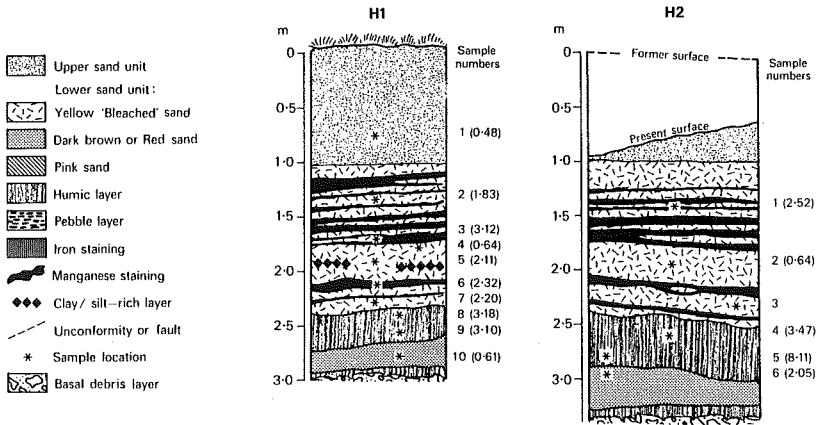


Figure 3.4: Stratigraphy of nivo-aeolian sand deposits at NH 070 861, near the head of Coire a'Mhuillin (Site H of Ballantyne and Whittington, 1987).

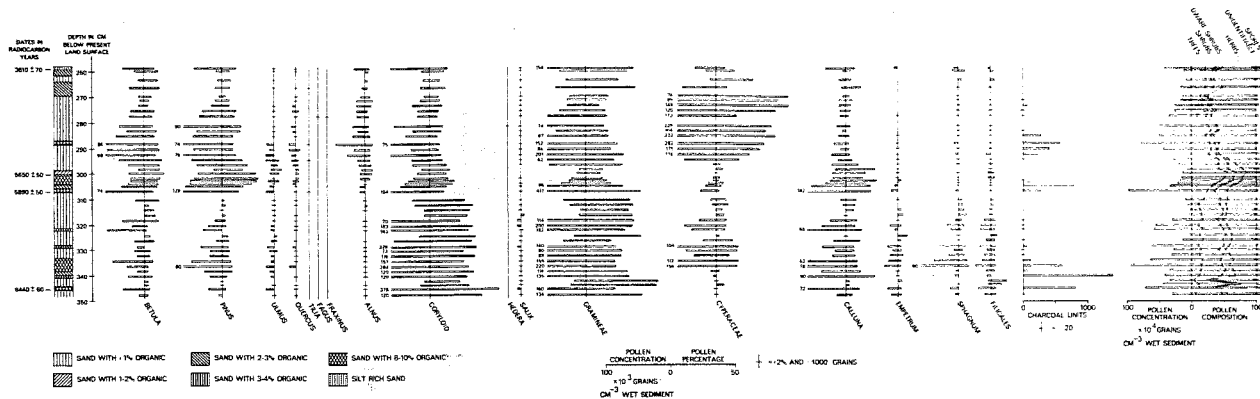


Figure 3.5. Pollen concentrations, relative pollen sums, charcoal units and radiocarbon dates for the organic-rich layer at the base of 'site H' (see text) in Coire a'Mhuilinn, An Teallach. Only the main taxa are depicted; one charcoal unit is a charcoal fragment of dimensions 20 x 20 μm .

arboreal pollen above. Replication of these patterns at the site at the head of Coire nan Tota suggests that the interpretation of this pattern may be assumed to have general rather than merely site-specific significance. A sample from 346 cm depth (near the base of the sand deposit; Figure 3.5) yielded a radiocarbon age of 6440 ± 60 yr BP; samples from the base (307 cm) and near the top (300 cm) of the organic-rich layer mid-way up the column gave radiocarbon ages of 5890 ± 50 yr BP and 5650 ± 50 yr BP respectively, and a sample from the very top of the organic-rich layer yielded a radiocarbon age of 3610 ± 70 yr BP.

At face value, these radiocarbon determinations suggest that the onset of sand accumulation may have coincided with general climatic deterioration early in the Atlantic period, but Ballantyne and Whittington (1987) have argued that they reflect contamination resulting from downwash of radiometrically young pollen, charcoal and other organic material through the permeable sand deposits, and considered that the onset of sand accumulation was much earlier than the ^{14}C dates suggest. The sudden rise in *Pinus* pollen and simultaneous sharp decline of Coryloid pollen midway up the profiles at both sites mirror similar changes at the upper limit of regional pollen zone NWS III (8900-7900 yr BP) of Pennington *et al.* (1972). Another feature of zone NWS III is a low concentration of both *Ulmus* and *Quercus* pollen, which is also characteristic of the lower zone in both pollen profiles from An Teallach. These comparisons strongly suggest that the organic-rich band mid-way up the profiles illustrated in Figure 3.5 occupies the boundary between zones NWS III and NWS IV of Pennington *et al.*, and therefore dates from c. 7900 yr BP. If this is correct, it implies that sand accumulation began much earlier in the Flandrian than the basal date of 6440 ± 60 B.P. would suggest, and that a thickness of c. 0.5 m of sand had accumulated at the head of lee valleys on An Teallach before c. 7900 yr BP.

Although the absence of pollen and organic-rich horizons above the basal 'humic' layers at site H (Figure 3.4) and at the similar site in Coire nan Tota make it impossible to infer how long the lower sand unit continued to accumulate, the marked weathering of this unit implies that sand accumulation must have virtually ceased long before the relatively fresh upper unit sand was deposited. Ballantyne and Whittington (1987) suggested that cessation of accumulation was probably due to the establishment of a complete and unbroken vegetation cover over much of the plateau, and inferred that the recent renewed deposition represented by the upper sand unit resulted from the breaking of this cover and reworking of sand deposits that had accumulated on cols on the plateau, deposits now represented only by remnant 'islands' of sand. They hypothesised that the breaking of the plateau vegetation cover that triggered erosion of sand on the plateau was

triggered either by increased storminess during the 'Little Ice Age' in the 17th and 18th centuries A.D., or by overgrazing by sheep introduced to the mountain in the 19th or late 18th centuries.

THE AN TEALLACH PLATEAU (NH 062 861)

The ascent to the highest point (826 m) on the northern part of the plateau provides good views of Coire nan Tota, the area of most widespread sand accumulation. If time permits, a brief detour will be made to a site of sand hummock development (NH 069 866), which is believed to reflect selective wash between vegetation tussocks by nival meltwater during niveo-aeolian sand accumulation (Ballantyne, 1986b), and to the small nivation hollows formed in the sand deposits by scarp erosion and redistribution of sediment by nival meltwater (NH 068 867; Ballantyne 1985).

At the highest point (NH 062 861), well-rounded outcrops of Torridon Sandstone provide evidence of the effectiveness of microgelivation on sandstone; this is also evident in the contrast between the exposed (rounded) and buried (angular) portions of clasts embedded in the plateau regolith.

From this point the party will descend westwards along a spur to a small peak at NH 050 866 (c. 620 m). From here may be viewed the evidence for former ice-margin positions relating to readvances or stillstands that interrupted the retreat of the last ice sheet in the valley to the west (Figure 3.1; Robinson and Ballantyne, 1979) and the end moraine that marks the limit of a Loch Lomond Readvance glacier at the head of Coire Mór (NH 059 848; glacier 1 in Figure 3.1). The party will then descend to a well-defined 'ice sheet' lateral moraine (NH 052 869) and follow this former ice limit to the next site.

THE AN TEALLACH PROTALUS RAMPART (NH 054 875)

The An Teallach protalus rampart is 120 m long, up to 34 m wide and consists of a ramp of rockfall debris at the foot of a vegetated relict talus slope. For part of its length it appears to rest directly on a lateral moraine that relates to one of the ice-sheet retreat stages in the valley west of An Teallach. Ballantyne and Kirkbride (1986) have argued that this and other relict protalus ramparts in upland Britain are of Loch Lomond Stadial age, on the grounds that rampart formation implies renewed cooling and the formation of perennial snowbeds some time after ice sheet retreat, and the Loch Lomond Stadial is the only period of pronounced renewed cooling for which there is evidence throughout upland Britain. The rampart is unusual in that it lacks the 'ridge and depression' profile exhibited by most ramparts illustrated in the literature, but this may simply reflect the failure of researchers to

identify protalus ramparts where an outer ridge and inner depression are absent. Comparison of the characteristics of rampart clasts with those of nearby Loch Lomond Readvance moraines (NH 060 877) revealed that the former are significantly larger, more angular and more 'slabby' in form (Ballantyne and Kirkbride, 1986).

The average amount of rockfall retreat implied by the volume of debris in the rampart is 1.27 m, which suggests that rockwall retreat rate during the Loch Lomond Stadial may have been of the order of $1.6\text{--}3.2 \text{ mm y}^{-1}$ (Ballantyne and Kirkbride, 1987), roughly 100-200 times greater than the present-day rate assessed for Coire a'Mhuillin. The high stadial rockfall rates indicated by the volumes of this and other relict protalus ramparts in upland Britain are comparable to those recorded in present-day alpine environments and suggest that, like present alpine environments, mountain rockwalls experienced a high frequency of effective freeze-thaw cycles during the stadial.

MAC IS MATHAIR MORAINES (NH 059 878)

During the Loch Lomond Readvance a small glacier formed in the shallow corrie at the north-western extremity of the An Teallach massif, below the peak of Mac is Mathair (702 m). The former glacier margin is of interest in that it comprises at least five distinct moraine ridges (Sissons, 1977; Figure 3.1). The outermost of these is the largest and most continuous; some of the inner moraines consist merely of low ridges of boulders on boulder-strewn terrain and are difficult to distinguish on the ground but stand out well on aerial photographs. This evidence indicates that during the early stages of retreat the ice remained active and experienced at least short-lived readvances or stillstands, though arguably the small dimensions and close spacing of some of the inner ridges suggests that these may represent annual moraines produced by winter advances during net retreat.

The outermost Loch Lomond Readvance moraine at this site is also of interest in that it appear to truncate the huge 'medial moraine' that Robinson and Ballantyne (1979) interpreted as marking the parting of ice in the valley west of An Teallach from that moving north-westwards down the trough now occupied by Little Loch Broom during ice sheet retreat. This suggests that the corrie below Mac is Mathair was already partly or entirely ice-free at the time the parting occurred. This site and others in Wester Ross (Ballantyne, 1986a) illustrate that the distribution of glacier ice during the Loch Lomond Readvance was, at least locally, very different from that during ice sheet retreat.

The 'medial moraine' takes the form of a massive drift ridge 1.2 km long and up to 20 m high and 120 m wide at its upper (south-eastern) end, but it broadens and flattens as

it descends to the north-west, finally taking the form of a spread of boulders nearly 300 m in width interrupted by low mounds and ridges. A meltwater channel cut northwards through the moraine near its highest point demonstrates that ice must have abutted against the moraine on its south-western side.

The route to Ardesie follows the crest of the 'medial moraine' as far as Ardesie Burn (Allt Airdeasaidh), whereafter the party will descend the well-marked path to the A 832 road at Ardesie. Two interesting features are encountered *en route*. Across the stream that flows along the south side of the moraine there are outcrops of deep-weathered Torridon Sandstone at NH 053 881, but the significance of these is unknown. Ardesie Burn itself flows for much of its lower course in an impressive, rock-cut meltwater gorge.

ARDESSIE (NH 053 896)

The raised fan at Ardesie represents the site of extensive erosion and damage to a croft and fish farm installations during an exceptional flood of Ardesie Burn in September 1981, which resulted from a fall of at least 140 mm of rain in 24 hours (Acreman, 1983). The flood resulted in considerable change in the course of the river downstream from the rock-cut channel at the road, with deposition of large gravel bars on the fan surface and loss of an estimated 1040 t of non-dissolved sediment (mostly eroded from the fan) which was deposited as a spread of sand offshore. Reconstruction of the fish farm installations has, however, obscured many of the effects of the flood.

From Ardesie may also be seen a rock-slope failure scar on the hillslope at NH 060 884. The absence of landslide debris downslope of this scar indicates either that the landslide represented by this scar pre-dated the last glacial occupation of the Little Loch Broom trough, or alternatively that it occurred on to the ice surface during the waning of the last ice sheet so that the debris was dispersed by glacier ice. The freshness of the scar suggests that the latter explanation is more likely.

C K Ballantyne

DUNDONNELL (NH 090 880)

The upper reaches of Little Loch Broom support various raised shoreline features that have a bearing on the extent of the Wester Ross Readvance in this area. At Dundonnell a major terrace fragment 700 m long ends near the head of the loch. The greater part of this terrace declines northwestwards from 23.0 m O.D. to 15.5 m O.D. at an

average gradient of 13 m km^{-1} , but the seaward part declines only 0.3 m in 120 m . The terrace has therefore been interpreted as representing outwash merging into a raised beach, the contemporary sea-level being placed at c. 15.5 m . (Sissons and Dawson, 1981).

An exposure on the northern side of Little Loch Broom showed till at least 2 m thick covered by $0.2\text{-}0.4 \text{ m}$ of manganese-cemented shingle and sand, this in turn being covered by 1 m of sediment that is interpreted as till that experienced solifluction during the Loch Lomond Stadial. The surface of the beach shingle occurs at 16.9 m O.D. , and in view of the limited fetch associated with this location suggests a former high water mark of c. 15 m . All of the Lateglacial raised beaches along the shores of Little Loch Broom occur between 14.9 and 17.0 m O.D. The projected altitudes of the Main Wester Ross Shoreline [which has been considered contemporaneous with the Wester Ross Readvance by Sissons and Dawson (1981)] range from 19 to 24 m for this area. The absence of raised beaches at these altitudes implies that Little Loch Broom was covered by glacier ice during the Wester Ross Readvance.

A G Dawson

BEINN NAM BAN VIEWPOINT (NH 105 900)

In clear weather, the road to Badralloch on the north side of Little Loch Broom affords excellent panoramic views of the An Teallach massif and surrounding area. Of particular interest is the extreme contrast between ice-scoured bedrock up to c. 700 m and *in situ* frost-weathered detritus above that altitude, a contrast that represents a 'periglacial trimline' which may define the upper limit of the last ice sheet at its greatest thickness. A good view is also obtained of the niveo-aeolian sand deposits that blanket much of Coire nan Tota on the north-eastern part of the massif (Figure 3.2), and of the ice-scoured Cambrian Quartzite escarpment to the east of the massif.

C K Ballantyne

CORRIESHALLOCH GORGE (NH 20 78).

The glacial breach of Dirrie More slopes gently westwards to terminate 'hanging' some 100 m above the Loch Broom glaciated trough. Into the step in the valley profile so formed has been cut the Corrieshalloch Gorge, one of the most impressive meltwater landforms in Britain. It is c. 1.25 km long, intakes at c. 170 m with an outflow at c. 70 m , is up to 60 m deep and in places only c. 10 m across at the lip. The long-profile is two-staged with the Falls of Measach occurring towards its head. Kirk *et al.* (1966) record that there is no evidence that it was re-

occupied by ice after its formation but it is difficult to envisage conditions being sufficiently unusual during or immediately after the last ice-sheet glaciation for there not to have been at least a significant pre-last glaciation channel cut into the valley shoulder at this locality. The present stream is manifestly underfit in such a major channel, but it has not been established whether the meltwaters that may be presumed to have cut the gorge were subglacial or pro-glacial. As there was likely to have been enhanced meltwater flow along the drainage during both ice-sheet decay and the Loch Lomond Readvance both types of meltwater activity may have contributed to the formation of the gorge.

D G Sutherland

LOCH DROMA (NH 253 753).

During the late 1950s excavations at Loch Droma, in connection with the construction of a hydro-electric power scheme, provided a so-far unique opportunity to examine in open section a full thickness of Lateglacial sediments derived from a lake basin that received meltwater drainage during the Loch Lomond Readvance. Loch Droma lies in the floor of the Dirrie More glacial breach immediately to the west of the main Atlantic-North Sea watershed at an altitude of approximately 270 m. It has a restricted catchment, but the low gradient floor of Dirrie More receives drainage from the Ben Dearg massif to the north and from the Fannichs range to the south. Both these mountain groups were source areas for Loch Lomond Readvance glaciers, drainage from certain of those glaciers in the Fannichs being into Dirrie More (Sissons, 1977; Reed, unpublished).

The stratigraphy of the site, as recorded by Kirk and Godwin (1963), is as follows:

8. *Peat*. Only the lower portion was seen but this contained lenses of coarse sand and *in situ* pine stumps.

7. *Coarse dark sand*. A discontinuous zone c. 30 cm thick and similar to the lenses in the overlying peat.

6. *Fine grey sands*. Characterised by cross-bedding and sharp discontinuities but finely laminated.

5. *Sand-silt*. Usually thicker than (6), with a banded appearance resulting from the rather regular intercalation of exceptionally fine light coloured material. Ripple-bedded.

4. *Grey silt*. Finely stratified or varved grey silt with laminations dipping towards the centre of the basin. Near the base a continuous zone of grey-brown silt occurred,

rich in organic material and macroscopic plant remains. A clay-rich dark horizon occurred c. 10 cm above the organic zone. The silts above the organic zone were more strongly varved than those below and showed no signs of disturbance.

3. *Moraine*. Angular and sub-angular locally derived material thinning towards the centre of the basin. On the southern flank of the basin it was contorted and showed signs of periglacial action.

2. *Grey-blue silt*. Highly contorted and sterile, preserved in a thin pocket below the moraine on the southern flank of the basin.

1. *Moine schist bedrock*.

A monolith was removed from the grey silts so placed as to include the organic horizon which was c. 15 cm thick at the locality sampled. Diatom and plant macrofossil identifications were carried out for the monolith as a whole and not placed in stratigraphic sequence although the bulk of the plant macrofossils were derived from the organic layer (Kirk and Godwin, 1963). Pollen analyses were carried out on a stratigraphic basis throughout the monolith.

The pollen analyses showed that there was an initial phase dominated by high values of *Lycopodium selago*, *Rumex* and *Artemisia*. This was followed by a notable expansion of *Empetrum* and a marked reduction of the initial dominants. There then occurs a reversal of this sequence with *Empetrum* falling and expansion of *Rumex* and *Lycopodium selago*. Subsequently the earlier pattern reasserts itself with *Rumex* falling to low values whilst *Empetrum* rises. This phase coincides with the beginning of the organic layer and throughout this horizon the pollen values show an irregular but slow decline in *Empetrum*, low levels of *Rumex* with initially fluctuating but latterly rising levels of *Lycopodium selago*. Finally, in the laminated silts above the organic layer, there is a marked increase in *Artemisia* as well as particularly high levels of *Lycopodium selago*. In the monolith this layer was also noted to contain occasional small pebbles.

Kirk and Godwin (1963) recognised that the sediments were of Lateglacial age, but, due to the lack of comparable sites in the Scottish Highlands, they were uncertain as to the precise age and correlation of the pollen sequence. With a much greater number of sites available for comparison, it is now apparent (Pennington et al., 1972) that almost the entire Lateglacial period is represented by the section pollen analysed and reported by Kirk and Godwin. The lowermost part of the sequence correlates with the *Rumex* regional pollen zone A; the middle section with the *Empetrum* regional pollen zone B; and the top part of the section pollen analysed with the

Artemisia regional pollen zone C (Loch Lomond Stadial) of Pennington et al. (1972). Within the *Rumex* pollen zone, the fluctuations in the relative values of *Rumex* and *Empetrum* at Loch Droma are also recognised regionally and have been correlated by Pennington (1975; 1977a) with the Bølling/Older Dryas oscillation of the NW European chronostratigraphic sequence. The radiocarbon date from Loch Droma of $12,810 \pm 155$ yr BP is from the pollen zone A/B boundary, which has been dated elsewhere (Pennington, 1975) as c. 11,800 yr BP. It would therefore appear that the Loch Droma date is c. 1000 years too old.

The Lateglacial environment as interpreted by Kirk and Godwin (1963) was essentially treeless with a strong oceanic influence (as indicated by the high levels of *Empetrum* and the common occurrence of macrofossils of the moss *Rhacomitrium lanuginosum*). Within a mosaic of different vegetation communities, there were large areas of acidic *Empetrum* heath but snow patches with their characteristic vegetation were also common together with stony areas of disturbed soils with a somewhat calcareous nature carrying a rich herbaceous cover. They drew frequent analogies with the low alpine zone of northern Scandinavia.

The occurrence of laminated silts throughout almost all of the Lateglacial sequence was considered by Kirk and Godwin (1963) to result from the continuing presence of glaciers in the Dirrie More drainage basin during this period. The inference of glacier presence solely from the occurrence of laminated inorganic sediments is inevitably tentative. However, the results of Pennington (1977a) are of relevance to this interpretation. Of sixteen lake basins cored in northern Scotland, nine were from drainage basins that were not glacierized during the Loch Lomond Readvance. In these nine lochs, the Loch Lomond Stadial sediments were unlaminated silty clays in eight and impenetrable sand and gravel in the ninth. Of the seven lochs in drainage basins that contained Loch Lomond Readvance glaciers, the stadial sediments could only be penetrated in one (Loch Stack) where a sequence of laminated sediments was encountered. Of the remaining six lochs, laminated sediments made up all or part of the stadial sediments of three whilst in two others sand and gravel were encountered and in the last, sandy silt. Thus, of the lacustrine sites examined, laminated sediments only occurred in those basins glacierized during the Loch Lomond Readvance. The evidence would thus tend to support the interpretation of Kirk and Godwin (1963) that the laminated sediments at Loch Droma are the result of glacierization of the drainage basin.

If this interpretation of the lithostratigraphy is correct, then it is apparent that glacier ice was present in the Loch Droma catchment throughout most, if not all, of the Lateglacial. The most likely glacier source is

in the Fannich Range at the head of the Ghiubhais Li valley which is susceptible to glaciation with only a 3°C fall in mean summer (May-September) temperature (Sutherland, unpublished). The pollen analyses on the Loch Droma section only continue into the base of the Loch Lomond Stadial sediments, but on lithostratigraphic grounds it seems likely that the junction of the Unit 7 coarse dark sands with the Unit 6 fine grey sands marks the upper boundary to the Stadial sediments. If so, this implies a coarsening-upwards sequence of Stadial sediments which would not be inconsistent with the approach of a glacier along the Ghiubhais Li valley to close to the site during the Loch Lomond Readvance (Reed, unpublished).

D G Sutherland

THE WESTERN END OF LOCH GLASCARNOCH (NH 277 743)

From this location there is an excellent view in clear weather of mountain-top detritus that may have developed on summits that formed nunataks rising above the last ice sheet at its maximal thickness. To the north-west, extensive debris-mantled slopes composed of large, frost-shattered boulders of Moine schist are clearly visible on the higher slopes of Am Faochagach (954 m; NH 303 794) and Tom Bàn Mór (742 m; NH 318 753). These deposits probably developed initially above the level of the last ice sheet and subsequently moved downslope during ice-sheet downwastage and the Loch Lomond Stadial, forming boulder sheets and lobes. Downslope from the area covered by mountain-top detritus, bedrock surfaces have been affected by frost weathering during ice-sheet downwastage and the Loch Lomond Stadial and a thin and localised cover of frost-weathered debris was formed. This can be seen on the slopes of Meallan a'Bhùtha (NH 290 765) below an altitude of c. 700 m. The lower slopes of these mountains are till-covered, and below Tom Bàn Mór erratics of Inchbae augen-gneiss have been identified, some 5 km north-west of the source outcrop (Peach *et al.*, 1912; W.J. Reed, unpublished). Mountain-top detritus and boulder lobes can also be seen on high ground to the south, near the summit of Beinn Liath Mhór a'Ghiubhais Li (766 m; NH 281 713).

From the car park at NH 288 737 an excellent view is obtained of the massive Garbhrainn moraine, which is up to 25 m high, over 200 m broad and about 800 m long. This moraine formed at the terminus of a valley glacier that occupied Glen Làir during the Loch Lomond Stadial, and which had its sources in the corries of Beinn Dearg (1084 m) and Cona Mheall (980 m) to the north (Sissons, 1977).

W J Reed

STRATH VAICH (NH 359 714)

Extensive moraine ridges and outwash terraces in Strath Vaich and neighbouring Strath Rannoch have been mapped by W.J. Reed (unpublished; Figure 3.6). On the west side of Strath Vaich a lateral moraine ascends northwestwards immediately above the treeline. The equivalent limit on the eastern side of the glen is marked by drift hummocks. Drift mounds also occur along the southern margin of the highest outwash terrace, which therefore appears to have developed inside the former ice limit. Extensive though lower outwash terraces also occur outside the former glacier terminus. The age of the moraines and associated outwash terraces in Strath Vaich and Strath Rannoch remains to be established. Although interpreted by Sissons (in Sutherland, 1984, figure 10; Figure 1.4) as pre-dating the Loch Lomond Readvance, a Loch Lomond Stadial age (as originally suggested by Kirk *et al.*, 1966) cannot be discounted on present evidence.

W J Reed

From Strath Vaich the party will return to Achnasheen via Strath Bran. Of interest *en route* is a possible lateral moraine that crosses the north-west slope of Ben Wyvis at an altitude of c. 580 m.

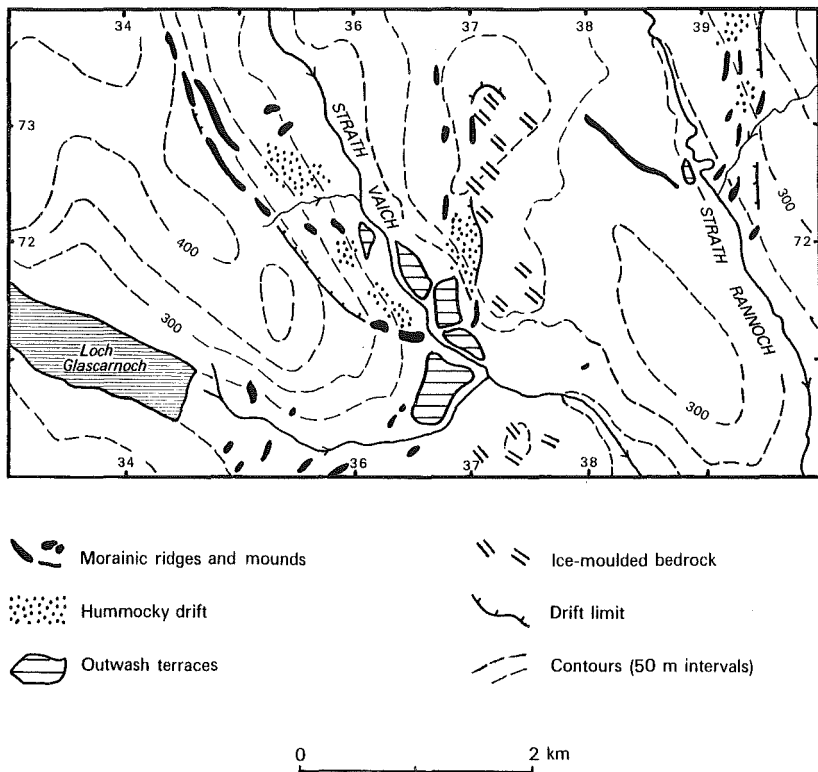


Figure 3.6: Former glacier limits and related features in Strath Vaich and Strath Rannoch (mapping by W.J. Reed, unpublished).

4. DAY 2 ALTERNATIVE EXCURSION: NORTHERN WESTER ROSS

ITINERARY

This excursion is offered as an alternative to the An Teallach excursion in event of poor weather.

The route follows the A 832 road in a clockwise circuit that starts and finishes at Achnasheen, with brief excursions along minor roads to view particular sites. The sites to be visited are as follows:

1. Glen Docherty (NH 072 589): debris flows, debris cones and alluvial fans.
2. Loch Bad an Sgalaig (NG 850 720): view of Baosbheinn protalus rampart.
3. South Erradale and Redpoint (NG 74 71): Lateglacial shorelines.
4. Poolewe (NG 85 80): outwash terraces and Lateglacial shorelines.
5. Cnoc nan Cullannan (NG 890 900): Wester Ross Readvance moraine.
6. Slaggan Bay (NG 84 94): Lateglacial shorelines and marine limit.
7. Gruinard Bay (NG 94 89): Lateglacial raised shorelines and gravel fan.
8. Gruinard River (NG 953 899): Lateglacial raised shorelines and fan.
9. Badcaul (NH 002 928): view of readvance moraines and ice limits.
10. Ardessie (NH 053 896): recent flood erosion and landslide.
11. Dundonnell (NH 090 880): Lateglacial raised shorelines and outwash terraces.
12. Beinn nam Ban (NH 105 900): View of An Teallach: periglacial trimlines and niveo-aeolian deposits.
13. Corrieshalloch Gorge (NH 203 780): meltwater gorge.
14. Loch Droma (NH 253 756): Lateglacial pollen site.
15. Loch Glascarnoch (NH 277 743): periglacial trimlines and the Gharbhrair moraine.
16. Strath Vaich (NH 359 714): readvance moraines and outwash terraces.

A description of sites 10-16 is given in the previous chapter. A possible alternative to this itinerary involves a visit to the Baosbheinn protalus rampart (NG 854 677; chapter 6) in the morning and exclusion of some later sites. A full description is given for the Baosbheinn protalus rampart in chapter 6.

INTRODUCTION

The main theme of the alternative excursion for day 2 is examination of the evidence linking the Wester Ross Readvance with a Lateglacial shoreline, the Main Wester Ross Shoreline proposed by Sissons and Dawson (1981). The route, however, also passes other sites of interest, mostly relating to former ice limits of various ages, and the opportunity is taken to examine these.

GLEN DOCHERTY (NH 072 589)

From the car park at the head of Glen Docherty a view is obtained of the debris fans that have developed north-east of the road. Spreads of boulders over the fan surfaces and fresh debris flow levées and lobes indicate recent activity, some of which is attributable to an intense rainstorm in 1968, when debris flows and torrential flood deposits blocked the road (Strachan, 1976).

C K Ballantyne

LOCH BAD AN SGALAIG (NG 850 720)

From the car park a view is obtained of the massive protalus rampart that lies at the foot of cliffs and talus slopes at the north-west end of Baosbheinn, just over 4 km to the south. The debris accumulation that can be seen from the road takes the form of a ridge c. 450 m long, that rises up to 55 m above the adjacent terrain on its distal side. This ridge is entirely composed of large boulders of Torridon Sandstone, and adjoins and partly buries a lower drift ridge with few large boulders. Sissons (1976c) interpreted both ridges as protalus ramparts of Loch Lomond Stadial age, and inferred that the development of the boulder ridge reflected increased climatic severity with the onset of full-stadial conditions. Ballantyne (1986a), however, has provided evidence that the lower ridge is a Wester Ross Readvance lateral moraine, and has suggested that the cliffs above the rampart form a rockslide scar and that the boulder ridge accumulated catastrophically as a result of landsliding rather than intermittent rockfall. Closed depressions within the boulder ridge appear to represent melt-out of buried ice, which raises the possibility that the deposit moved downslope as a protalus rock glacier due to deformation of ice under the weight of the debris. A fuller description and map of the rampart are provided in chapter 6.

C K Ballantyne

SOUTH ERRADALE AND REDPOINT (NG 74 71)

For a distance of 2 km from the coast, the River Erradale valley has a flat gravel floor several hundred metres in width. The gravel surface exhibits an overall seaward decline in altitude from 30.3 m to 20.9 m over 870 m and has an average gradient of 11m km^{-1} . West of South Erradale the seaward part of the gravel deposit has been built into a broad (200 m wide) flat-topped bar with an average crest altitude of 23.9 m. The gravel bar is continued to the south by a Lateglacial raised beach with an average altitude of 21.0 m. The raised beach and gravel bar are considered to be contemporaneous features, the 2.9 m difference in altitude between the two being the same as the difference between modern shingle ridge crests and high water mark spring tides on the outer coast of Wester Ross.

A lateral moraine marking the southern limit of the Wester Ross Readvance crosses the River Erradale valley, where it is associated with meltwater channels (Figure 4.1), which suggests that the large gravel spread at South Erradale is a contemporaneous deposit. The gravel bar at South Erradale is by far the largest such feature in Wester Ross. This may be accounted for by littoral bar formation being contemporaneous with outwash deposition, which would have permitted rapid progradation of the coastline. The Wester Ross Readvance moraine at South Erradale therefore appears to have been deposited when relative sea level stood at 21.0 m.

Approximately 2 km north of South Erradale, between Opinan and Port Henderson, a well-developed high rock platform backed by a degraded cliff extends for a distance of c. 700 m. The platform is here 300 m wide and has an average altitude of 22.4 m. Farther south at Redpoint there is a high rock platform over 1 km long and up to 200 m wide with an average altitude of 23.5 m. At both Redpoint and Opinan, the platform surfaces are mantled by Lateglacial marine gravels. The great width of these platforms makes it unlikely that they were eroded in the limited time likely to have been available during the Lateglacial. Sissons and Dawson (1981) have suggested that the Lateglacial sea modified pre-existing areas of rock platform and brought the altitude of the Lateglacial shoreline into altitudinal accord with the inner edges of pre-existing platforms. Evidence that the Lateglacial sea was capable of effecting significant erosion has been demonstrated for the Applecross area (Robinson 1977; see also chapter 5).

On the assumption that a pre-existing rock platform and cliff have been modified by Lateglacial marine action, it is reasonable to expect that at some other places such features remained above the marine limit and have not been so modified. One such feature has been described on the coast of Applecross (Robinson, 1977; see chapter 5). Within northern Wester Ross a well-marked raised platform and

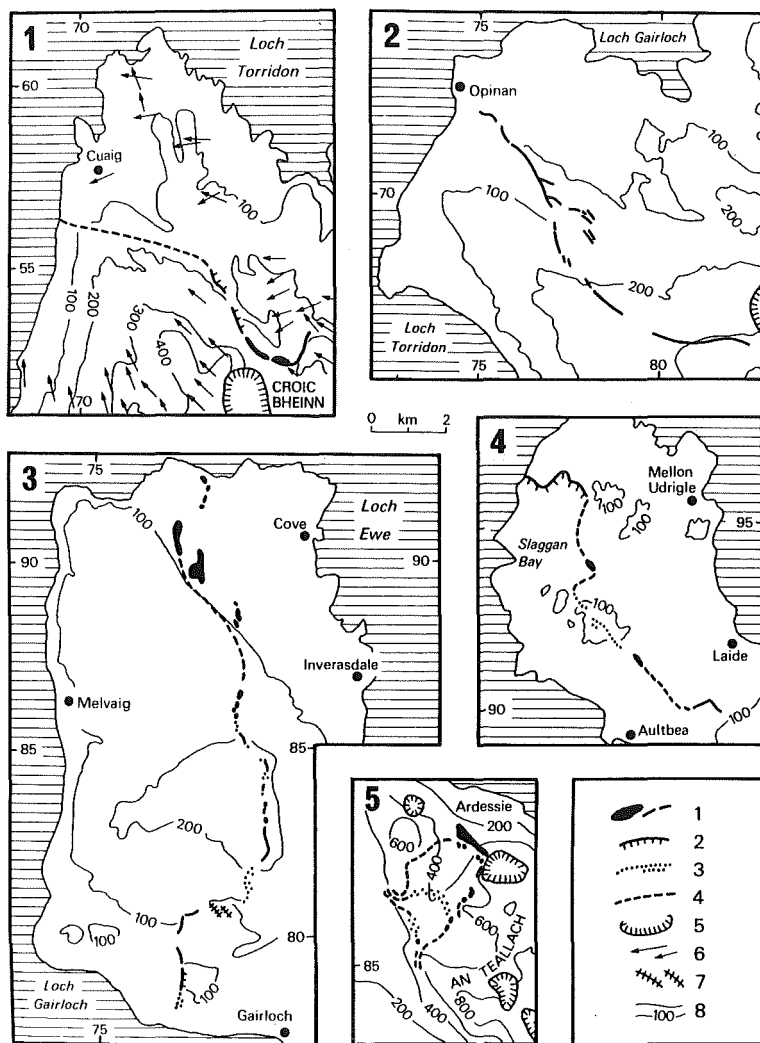


Figure 4.1: Ice limits associated with the Wester Ross Readvance, after Robinson and Ballantyne, 1979. Map 1: the Applecross moraine; Map 2: the Redpoint moraine; Map 3: The Gairloch moraine; Map 4: the Aultbea moraine; Map 5: the An Teallach moraines. Key: 1. moraine ridges; 2. drift limit; 3. belt of boulders; 4. interpolated glacier margin; 5. Loch Lomond Readvance glaciers; 6. striae; 7. esker; 8. contours at 100m or 200 m intervals.

cliff extend for 600 m along the coast near Melvaig (NG 737 882 to NG 737 888). The platform surface is mantled by drift and hence has not been surveyed, but is visible in the sides of geos. The platform surface lies above the 75' (22.9 m) contour, but the Lateglacial marine limit at this site is 20 m. It is therefore concluded that the pre-existing high rock platforms at Red Point and South Erradale (in contrast to the drift-covered high rock platforms elsewhere in northern Wester Ross at Melvaig, Greenstone Point (NG 850 970) and north of Slaggan Bay (NG 83 94)) owe their present form to modification by Lateglacial marine erosion. All of the fragments mentioned above may originally have formed in association with earlier periods of glaciation, which would imply formation by periglacial coastal processes (cf. Dawson, 1984; Sutherland, 1984a).

A G Dawson

POOLEWE (NG 85 80)

Between Lochs Maree and Ewe the River Ewe is bordered by gravel terraces. These rise up-valley but terminate downvalley from Loch Maree, thus indicating that they relate to a former ice margin located between Loch Maree and the coast. The highest terrace is very extensive, the largest fragment being 1300 m long and up to 500 m wide. This terrace begins just over 2 km inland, this being the approximate position of the former ice margin when the terrace ceased to be formed. Most of the terrace slopes seawards (from c. 25 m) at an average gradient of c. 9 m km⁻¹, and is interpreted as an outwash terrace. Over the last few hundred metres the gradient of the major fragment west of the River Ewe gradually diminishes, however, and for the last 125 m the terrace altitude is at 10.6-10.8 m. East of the River Ewe the highest terrace flattens out at the same altitude. Contemporary sea level is therefore placed at 10.8 m, and the extensive outwash terraces of the Ewe valley indicate occupation of Loch Maree by ice when relative sea level was at this altitude. Expressed in terms of the projection of the Main Wester Ross Shoreline, the total theoretical fall in sea level while the ice retreated c. 17 km from the Wester Ross Readvance limit near Slaggan Bay (NG 83 94) was c. 11 m (Figure 4.2).

A G Dawson

CNOC AN COLUMNAN (NG 890 900)

The direction indicator above the car park at this site sits on a lateral moraine (the Aultbea moraine of Robinson and Ballantyne, 1979) that defines the north-eastern margin of the Wester Ross Readvance in this area (Figures 4.1 and 4.2). The moraine fragment is c. 1 km

long, and runs north-east into the forest then ESE. Attempts to trace the former ice limit beyond Loch na Bà have proved fruitless, though Sissons and Dawson (1981) identified a boulder limit in the valley of Little Gruinard River (4 km to the ESE) that may represent the continuation of the Aultbea moraine. The moraine is largely composed of Torridon Sandstone boulders, and enclosed depressions within it indicate melt-out of buried ice. Three ridges of boulders and till at NG 893 894 may represent slightly later positions of the former ice margin.

SLAGGAN BAY (NG 84 94)

East of Slaggan ruins, the Wester Ross Readvance limit trends to the northwest (Figure 4.1). In the valley east of Slaggan Bay, a discontinuous line of boulders marks the descent of the limit on to low ground (Robinson and Ballantyne, 1979). North of Slaggan Bay is a zone 2.0-2.5 km wide crossed by many boulder or till ridges that are aligned west-east at the coast and NW-SE farther inland. The northern margin of this zone, beyond which drift ridges are absent, is interpreted as the former limit of the Wester Ross Readvance (Figures 4.1 and 4.2). The raised marine features that occur between Slaggan Bay and Greenstone Point demonstrate (i) the complexity of interpretation of Lateglacial relative shoreline changes in areas where raised beaches are fragmentary, (ii) the apparent absence of a fall in the Lateglacial marine limit at the Wester Ross Readvance limit north of Slaggan Bay, and (iii) the occurrence of a subsequent fall in sea level as ice retreated from this limit.

North of Slaggan Bay, Lateglacial marine activity is indicated by accumulations of rounded boulders within the belt of drift ridges. At one location (NG 839 953), beach ridge formation has resulted in the impounding of a small lake. In this area the marine limit as represented by the upper limit of rounded boulders occurs at 18.2 m. Farther north, beyond the Wester Ross Readvance limit on the exposed coastline south of Greenstone Point, the upper limit of marine activity is represented by two well-defined shingle ridges, the crests of which lie at 18.8 m and 19.3 m. This evidence indicates that there is no significant change in the level of the marine limit at the readvance limit. A subsequent fall in sea level as the ice retreated from the Wester Ross Readvance limit is, however, indicated by the outwash deposits of the River Ewe valley which are related to a shoreline at 10.8 m at Poolewe (Figure 4.3; see above).

On the northern coast of Slaggan Bay, an anomalous accumulation of raised beach deposits occurs at NG 835 947 (Figure 4.2, location A). The raised beach deposits in this area are cemented and occur up to 26.1 m, the highest altitude of raised beach sediments in northern Wester Ross.

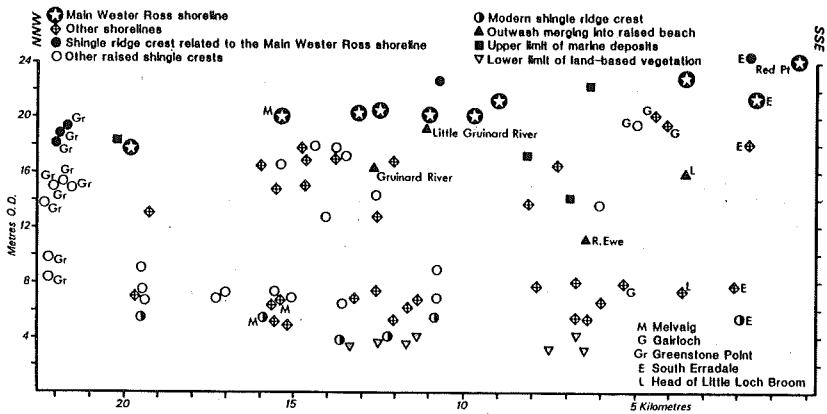


Figure 4.3: Height-distance diagram. 1. Main Wester Ross Shoreline. 2. Other shorelines. 3. Shingle ridge crest relating to the Main Wester Ross Shoreline. 4. Other raised shingle crests. 5. Modern shingle ridge crest. 6. Outwash merging into raised beach. 7. Upper limit of marine deposits. 8. Lower limit of land-based vegetation. (After Sissons and Dawson, 1981)..

At present there is no satisfactory explanation for the occurrence of these deposits at such a high altitude, although it is possible that wave funnelling may have been important in this particular area.

Immediately north of Slaggan Bay, bare outcrops of steeply-dipping Torridon Sandstone that rise to a fairly constant altitude (18-23 m) pass inland beneath till and peat, forming a marked step 150 m wide and 1 km long. The existence of a buried platform above the level of the Lateglacial marine limit at c. 18 m is suspected. In Wester Ross, steeply-dipping Torridon Sandstone beds underlie several areas of poorly-defined rock platform. High rock platform fragments are widespread near Greenstone Point (NG 850 870), for example, but here as elsewhere in Wester Ross the irregular surfaces of inclined Torridonian strata make the identification and measurement of platform inner edges difficult.

A G Dawson

GRUINARD BAY (NG 94 89)

The surface of a raised beach near Little Gruinard River lies at 18.4-18.9 m (NG 948 898; Sissons and Dawson, 1981). The shoreline itself is covered by the coast road but is considered to occur at c. 19 m. A raised beach at 20.2 m also occurs c. 1 km east of Little Gruinard, where it is partly obscured by blown sand (NG 953 898). Farther west, raised beaches occur at First Coast (NG 925 910) at 20.1 m and at Second Coast (NG 931 906) at 20.4 m.

The raised beach at Little Gruinard merges southwards with a prominent fan of very coarse gravel that rises to 28.6 m in 340 m, a gradient of 30 m km^{-1} . The fan cannot be traced farther upvalley on account of the lack of terrace development (the valley is steep-sided and narrow). Where the valley widens, however, c. 700 m inland from the fan apex, an ill-defined terrace-like deposit rises upvalley to a boulder limit that was interpreted by Sissons and Dawson (1981) as marking the limit of the Wester Ross Readvance. They inferred from this evidence that the readvance limit, the fan and the associated raised beach are contemporaneous features.

A G Dawson

GRUINARD RIVER (NH 961 919)

Although the boulder limit in the valley of the Little Gruinard River cannot be traced farther west on account of the irregularity of the Lewisian Gneiss terrain, there is evidence to suggest that at Gruinard River (3 km northwest of Little Gruinard; Figure 4.3) the Wester Ross Readvance

limit was beyond the present coastline. At the mouth of the river a raised fan of very coarse gravel merges laterally into a raised beach at NG 901 917. Raised shoreline measurements averaging 15.8 m have been generalised as 16 m owing to slight artificial modification. The fan is cut off seawards by a fossil cliff from which it rises inland to 21.0 m at an average gradient of 25 m km^{-1} . The fan cannot be traced farther inland because the Gruinard River flows in a rock gorge for the next 500 m upstream. Thereafter the valley widens markedly with ample space for terrace survival, but none exists even though the gradient of the valley floor is extremely gentle. The implication of this evidence is that when the fan and associated raised beach were formed, the contemporaneous ice margin was located at the rock-cut gorge, somewhere between the fan apex and the wide valley upstream. However, as the shoreline related to this ice margin is c. 4 m below the Main Wester Ross Shoreline around the head of Gruinard Bay, then the coast at the mouth of the Gruinard River must have been ice-covered at the maximum of the Wester Ross Readvance.

A G Dawson

BADCAUL VIEWPOINT (NH 002 928)

Three former ice limits of different age can be viewed from this point. Across Little Loch Broom the prominent peak of Beinn Ghobhlach (635 m; NH 056 943) is surrounded on all sides by ice-scoured Torridon Sandstone bedrock, but the summit area supports frost-weathered regolith indicative of prolonged exposure to severe periglacial conditions. The same is true of Sàil Mhór (767 m; NH 033 887; W.J. Reed, unpublished). This evidence indicates that at some time in the past, possibly when the last ice sheet reached its maximum thickness, the summit areas of both mountains were nunataks standing proud of the ice surface.

Six kilometres to the south-east of the viewpoint a broad drift ridge descends the north-western slopes of the An Teallach massif and terminates at the lip of a hanging valley above Ardesie (Figure 3.1). This ridge is 1.2 km long and up to 20 m high and 120 m wide at its upper end, but broadens and flattens as it descends to the north-west. A meltwater channel cut northwards through the ridge near its highest point demonstrates that glacier ice must have abutted the ridge on its south-western side, which precludes interpretation of this feature as a simple lateral moraine deposited at the margin of a glacier occupying the Little Loch Broom trough. Robinson and Ballantyne (1979) have suggested that the ridge represents a form of medial moraine deposited when the ice in the hanging valley parted from that in the trough, and have suggested that this and other former ice limits in the hanging valley correlate with the culmination of the Wester Ross Readvance. If correct, this implies that at the time

of the readvance ice occupied the trough but swept around the An Teallach massif.

Nearer to the viewpoint may be seen a well-defined moraine ridge at 200-250 m altitude which Sissons (1977) mapped as the limit of a small glacier that developed at the foot of the north-east facing cliffs of Sàil Bheag (409 m; NH 019 901) during the Loch Lomond Stadial. The limits of another small Loch Lomond Readvance glacier, which occupied a shallow corrie below Mac is Mhathair (702 m; NH 068 877), may also be seen upslope of the prominent drift ridge described above. At least five moraine ridges occur in this corrie, the outermost of which is the largest and truncates the drift ridge at its upper end.

C K Ballantyne

From the Badcaul viewpoint the party will proceed to Ardesie. Descriptions of this and other sites to be visited on the remainder of the excursion are given in the previous chapter, as the route to be followed is identical from Ardesie onwards.

5. DAY 3: TORRIDON AND APPECROSS

ITINERARY

The route is initially through Glen Docherty then across to and along Glen Torridon to Torridon House and hence on foot to Ben Alligin. Subsequently the south side of Loch Torridon is followed to the west coast of Applecross and thence to Bealach na Ba overlooking Loch Kishorn and finally up Strathcarron and Glen Carron to Achnasheen. The sites to be visited (some only briefly) are as follows:

1. Loch Clair (NH 00 57): Flandrian vegetational change and history of the pine forest;
2. Coire a'Cheud Cnoic (NG 95 55): 'hummocky moraine' genesis;
3. Ben Alligin (NG 86 60): glacially-transported landslide debris;
4. Coire Mhic Nobuil (NG 910 596): moraine genesis;
5. Lower Glen Torridon (NG 90 55): Loch Lomond Readvance end moraines, outwash terraces;
6. Shieldaig (NG 8161 5231): Mesolithic site;
7. Cuaig-Lonbain (NG 71 57)-(NG 68 53): Lateglacial shorelines;
8. Salacher (NG 683 510): high rock platform;
9. Bealach na Ba (NG 779 417): Loch Kishorn end moraines;
10. Strath Carron (NH 95 43): Loch Lomond Readvance end moraine, outwash terraces, Lateglacial shorelines.

LOCH CLAIR (NH 00 57).

The object of work at this site was to investigate, in a lake of moderate size, the record in allochthonous sediments of vegetation and soil history in a catchment on which native pine forest of the western type survives (Steven and Carlisle, 1959). The high concentration of pollen (cm^{-2}) found in the sediments raised some questions about pollen recruitment processes and particularly about the apparent predominance of pollen derived from the catchment by water transport (cf. the 'cpr' component of West's (1973) analysis). Full details of the work was described in Pennington et al. (1972) and Pennington (1973).

Site description.

The loch, altitude 92 m, has a roughly circular basin reaching a depth of 31 m in the centre, and a shallow north-western extension. The catchment is of high relief but not so rugged as the mountains of Torridon to the north: the bedrock is mainly sandstone and quartzite. The main inflow occupies a well-defined valley in which it flows through the shallow Loch Coulin (13 m) immediately above Loch Clair. The surviving patches of pine woods, called the Coulin Forest by Steven and Carlisle (1959), are mainly on well-drained drift in the upper valley around Loch Clair. There is much birch, as in most of the western pine woods.

The fact that no Lateglacial organic deposit was found in any of the 16 sediment cores taken in Loch Clair is consistent with the reconstruction of the limits of Loch Lomond Readvance glaciers (see Figure 1.4; Sissons, 1977; Robinson, 1977). This indicated that a glacier which emerged between Liathach and Beinn Eighe, and deposited the spread of hummocky moraine between Loch Clair and Glen Torridon, would be responsible for deposition of outwash material into Loch Clair - hence the presence in Loch Clair of thick barren mineral sediment, impenetrable to Mackereth corers, at the base of Flandrian organic muds.

The possible absence of large Loch Lomond Readvance glaciers from the catchment of the main inflow into Loch Clair suggested that Lateglacial organic sediment might be accessible to corers in Loch Coulin, but in this lake the Flandrian muds were found to be so silty that Mackereth corers would not penetrate them.

Sedimentary sequence.

(1) *Barren mineral sediment*, attributed to outwash from Loch Lomond Readvance glacier. This was encountered at 5 m below the mud surface in the central part of the lake, and at 3 m in shallower parts (water depth c. 6-10 m). It passes upwards via a transitional deposit into the

Flandrian organic muds. In the central parts, c. 1 m of barren sediment was found in the 6 m coring tube; here it showed a laminated structure with alternating layers of sand-sized and silt-sized particles. No graded bedding was observed - each lamination was a discrete layer and the structure differed from the varve couplets which make up the correlative sediments in the major Cumbrian lakes, e.g. Windermere. In those parts of the lake where water depths are less than 20 m, the barren mineral sediment was more sandy, less conspicuously laminated, and was not fully retained by Mackereth corers. In the northern part of the lake, beneath water less than 10 m in depth, the barren mineral sediment was not laminated - beneath c. 20 cm of silty clay it passed downwards into a thixotropic sand/silt/clay which flowed slowly when extruded from the coring tube - this resembled the correlative sediment in some lochs of the Great Glen.

The generally coarse-grained nature of these sediments made them unsuitable for the methods of geochemical analysis then in use by the Freshwater Biological Association. No organic particles of any kind could be found.

(ii) The *complex layered sediment*, transitional to Flandrian muds. This complex of more and less organic layers, with no regularity in the laminations, appeared lithologically transitional between Lateglacial and Flandrian deposition. The lowest sample from which pollen could be recovered contained only odd grains of *Artemisia*; it clearly post-dated the period of the Loch Lomond Readvance, and by comparison with the full profile from Loch Sionascaig, 60 km to the north-west, was allocated to the lowest pollen zone of the Flandrian. The sediment was interpreted as indicative of a particularly unstable land surface in the immediate catchment, following deglaciation.

(iii) The *Flandrian organic muds* are c. 5 m thick in the centre of the loch, and in this area the deposit between 5 m and 3 m below the mud surface includes thin brown/black colour laminations, c. 20 to 1 cm of mud. There was no evidence that these were annual rhythmites. These muds proved to be very rich in pollen. Their organic content of c. 10% carbon was rather lower than that of other lakes of North West Scotland. The irregular course of the curves for the elements sodium, potassium, calcium, iron, manganese and magnesium could not be interpreted in terms of the history of erosion on the catchment.

Radiocarbon dating.

The position and ^{14}C age of 6 dated samples from the central core used for pollen analysis are shown in Figure 5.1. No attempt was made to date the layered transitional deposit (ii) which was interpreted as the product of episodic deposition from an unstable land

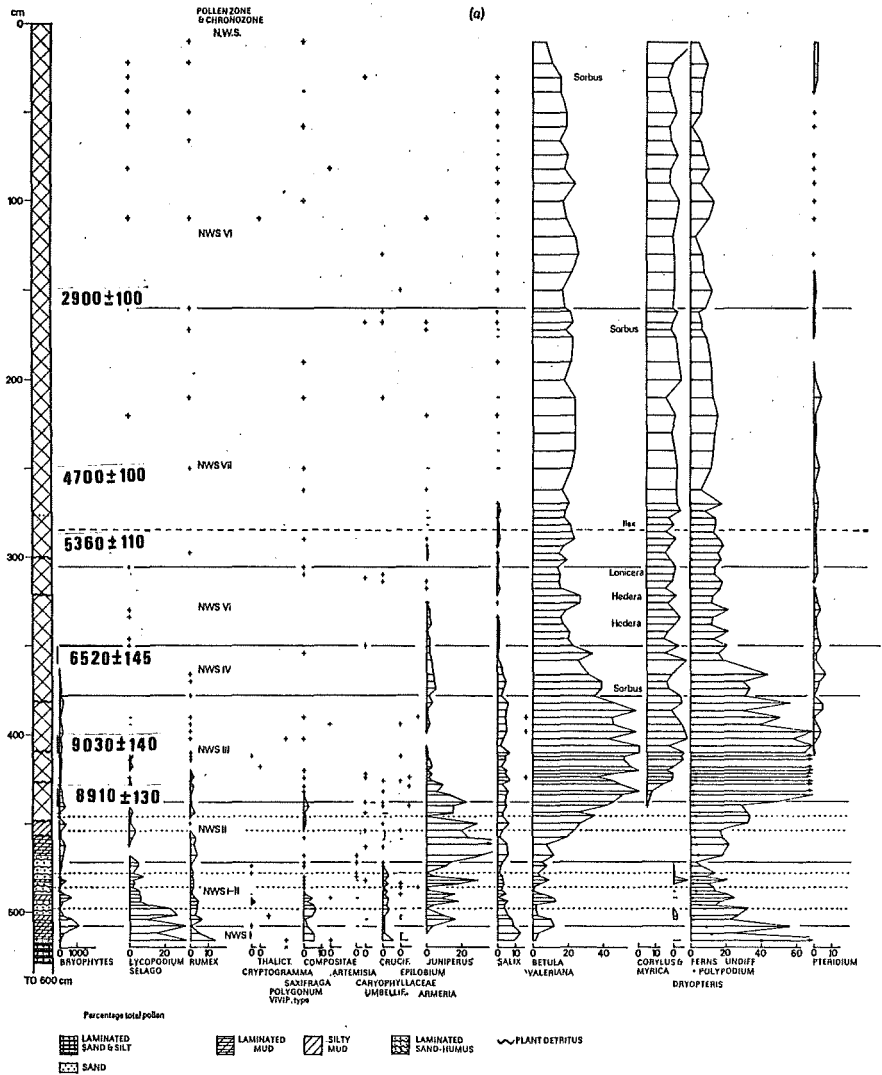
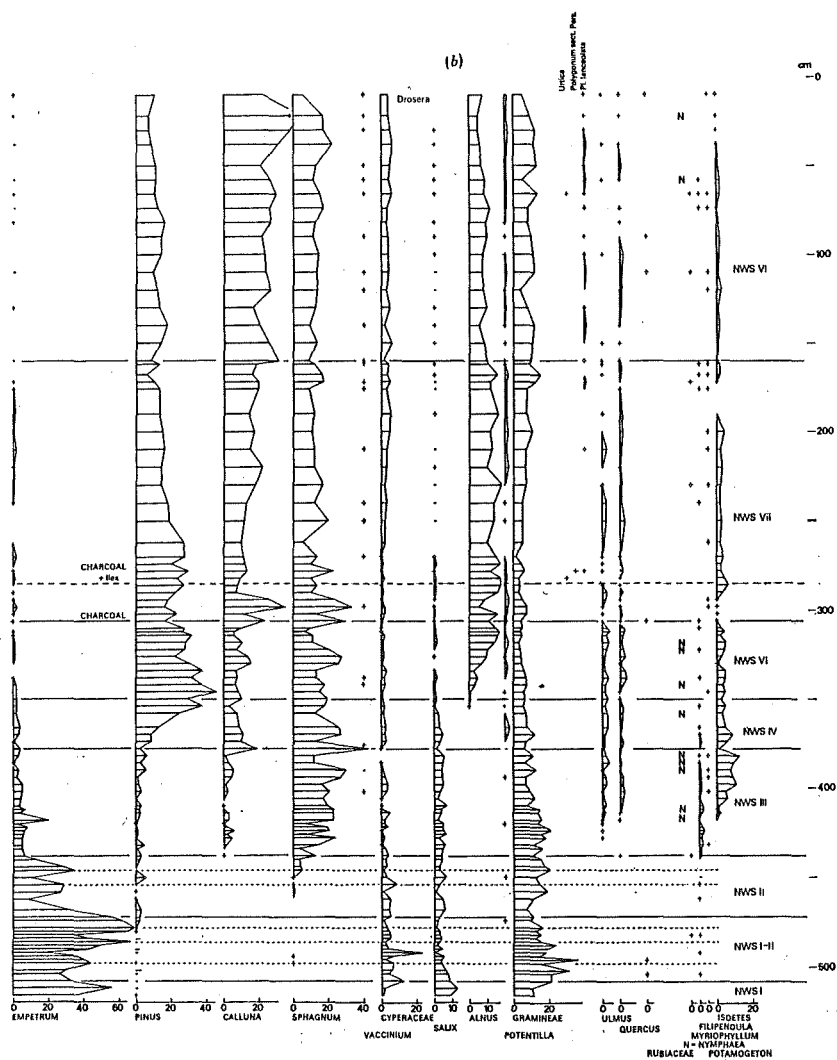


Figure 5.1. Loch Clair: complete pollen diagram. From Pennington et al. (1972).



surface, almost certain to produce an anomalous series of dates. The two lowest dates (from 4.0-4.4 m depth) were found to show overlapping uncertainties, but otherwise the dates formed a consistent series. Subsequent attempts to obtain a ^{14}C time-scale for the uppermost 1 m of sediment produced the same anomalies as are found in these recent sediments of a great many lakes.

Flandrian vegetation succession.

The lowest sample which contained countable quantities of pollen had a pollen spectrum containing 30% *Empetrum* (Figure 5.1), and by comparison with the pollen diagram from Loch Sionascaig this was placed in the lowest pollen zone of the Flandrian, post-dating the Transitional *Rumex-Lycopodium selago* zone allocated to the final part of the Loch Lomond Stadial. It was inferred that throughout the stadial, the catchment of Loch Clair was sufficiently subject to glacial and periglacial processes to dilute with very large amounts of mineral input the sparse production of pollen from the limited areas which were vegetated.

The vegetational history recorded in the dated core can be divided into four distinct periods:

1. From the undated lowest sample with 30% *Empetrum* until 8910 ± 130 yr BP, pollen spectra are dominated first by *Empetrum* and then by *Juniperus*, and *Betula* values remain low (<10%) until the steep rise to 50% at the top of this section. It is inferred that tree birches were not present in this catchment until shortly before 9000 yr BP, when they arrived by migration and rapidly expanded to form woodland which replaced a heath of *Empetrum* and juniper. Characteristic Lateglacial taxa such as *Lycopodium selago*, *Rumex acetosa/acetosella*, Compositae and Cruciferae persist until the expansion of the birches to form woodland.

This section of the pollen diagram corresponds with the complex layered transitional deposit, which is most readily explained as the product of episodic deposition in the lake from distinct sources, one rich in *Empetrum* pollen, fungal hyphae and dark coloured humus and intercalated with sand layers, the other rich in *Juniperus* pollen and producing grey-brown silty lake mud. Present evidence is not sufficient to show whether *Empetrum* and juniper co-existed - on a soil mosaic or at different altitudes - or were separated in time so that by the second part of this period, the peaks in *Empetrum* represented secondary deposition from a previous vegetation. Possibly these episodes of soil erosion and secondary deposition of pollen resulted from seasonal meltwater floods, from mountain snowfields which persisted after the end of the stadial.

2. From 8910 ± 130 yr BP to 6520 ± 145 yr BP, the pollen spectra indicate fern-rich birch woods with some hazel.

Corylus values increase from c. 8910 yr BP, but do not exceed 20% and there is no well-defined *Corylus* peak. *Empetrum* and *Juniperus* fall to low values, grasses and sedges fall towards minima for the profile. *Calluna* and *Sphagnum* appear. *Ulmus* and *Quercus* appear, but at such low values (1-2%) that they cannot be supposed to have been present in this catchment.

In the upper part of this section, *Pinus*, hitherto present as only odd grains, increases steeply, to reach 40% at 6520 yr BP. As pine increases, birch pollen and fern spores decrease. This change in forest composition at Loch Clair came nearly 2000 years later than the main expansion of *Pinus* recorded in the western part of Loch Maree (Birks, 1972) and illustrates the spatial and temporal complexity in the pine record which was noted by Birks (1977) for western Scotland.

3. From 6520 \pm 145 yr BP until 4700 \pm 100 yr BP was the period of maximum percentage values for *Pinus* and minima for grasses - possibly maximal tree canopy cover. *Alnus* appeared by 6520 yr BP, and apparently replaced *Salix*, occupying stream- and lake-side habitats. Percentage values for *Betula* and *Corylus* show little difference from 6520 yr BP to the surface.

Within this period of maximum pollen contribution from *Pinus*, an episode of vegetation disturbance was inferred from an interplay between the percentage curves for *Pinus* and *Calluna*, and the presence of two charcoal layers, c. 3 m below the mud surface. At the same horizon the *Ulmus* curve shows its first break, and the ^{14}C date of 5360 \pm 110 yr BP supported correlation of this with the Elm Decline of just before 5000 yr BP in northern England. It was inferred that the *Ulmus* pollen in Loch Clair originated from the 'regional' pollen rain over northern Britain, and that an absolute decrease in the annual deposition of elm pollen took place even in catchments where elms were not growing locally.

The diagrams showing pollen concentration and annual deposition rates over this horizon (Pennington, 1973; Fig. 10) demonstrate that the increased deposition rates shown by *Calluna*, *Corylus*+*Myrica*, and grasses, just above the break in the *Ulmus* curve, are not accompanied by any changes in these 'absolute' values for *Pinus* or *Betula*. It was therefore inferred that there was at this time no significant clearance of pine or pine-birch woodland round Loch Clair, but rather an episode of accelerated inwash of the pollen types and organic detritus characteristic of surface soils of damp pine woods. This material contained charcoal but the pollen curves do not suggest any extensive contemporaneous forest fire. The only pollen evidence for the presence of man was a single grain of *Plantago lanceolata* c. 20 cm above the *Calluna* peak, accompanied by *Rumex*, *Urtica* and *Polygonum* types. This is not conclusive

evidence for man being responsible for these changes, but establishes the possibility.

4. From 4700 ± 100 yr BP to the present, there is no sudden change in percentage pollen values, though originally a zone boundary was drawn at a horizon ^{14}C dated to 2900 ± 100 yr BP, from which percentage values of *Pinus* and *Alnus* are lower and those of *Calluna* and grasses higher, reflecting a decline in the areas of woodland. There is a great contrast with the diagrams from Loch Maree (Birks, 1972) and Loch Sionascaig (Pennington *et al.*, 1972), in both of which there is a sudden decline of pine to low values at c. 4000 yr BP with expansion of taxa characteristic of blanket bog. Pine forest appears to have survived on the area of the Coulin Forest. In the absence of any strong evidence for human pressure on the vegetation of this part of North West Scotland, it seems reasonable to suggest that soil drainage was an important factor in differentiating between sites with respect to the degree of replacement of forest by bog.

The absence from the pollen diagram of evidence for episodes of deforestation by man is consistent with the distribution pattern in Flandrian sediments of the elements carbon, iodine, iron, manganese, sodium, potassium, calcium and magnesium. In contrast with profiles from the Cumbrian lakes, the geochemical patterns show no evidence for episodes of accelerated erosional transport of soil material.

The Flandrian pollen diagram was originally divided into zones which were correlated to a sequence of Regional Pollen Assemblage Zones for North West Scotland (Pennington *et al.*, 1972, Table 3, pp203-207). The existence of so much spatial and temporal variation between sites, particularly in the history and composition of pine forests, has however raised doubts about the usefulness of regional syntheses except on the basis of ^{14}C dating.

The high concentration of pollen in the central sediments of Loch Clair - c. $3.3 \times 10^{15} \text{ cm}^{-3}$ - and the mean rate of sediment accumulation of 5 m in 10,000 years (1 cm in 20 years) lead to estimated rates of annual deposition of pollen which are c. 5 times those found in the larger Cumbrian lakes and in elongated Scottish lochs - Table 5.1. The pattern of sediment accumulation and the linear depth-time scale in the central core argue against this 'pollen-rich' nature of Loch Clair being attributable to any form of 'sediment focusing' (Likens and Davis, 1975). The effect of this high concentration of pollen is to give, for the period c. 5000 yr BP, higher rates of annual deposition of *Ulmus* pollen in Loch Clair - where the very low percentages cannot be reconciled with local presence of elms - than in Windermere, where percentage values of 10-15 must indicate that elms were locally present: Figure 5.2. These large quantities of pollen in the sediments of Loch

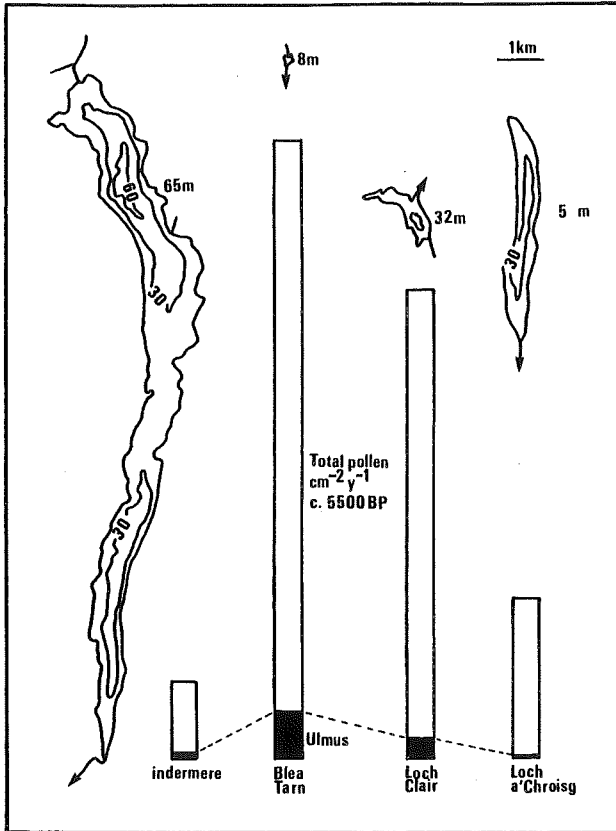


Figure 5.2. Comparative size of four Flandrian sites together with histograms representing (a) total pollen and (b) *Ulmus* pollen $\text{cm}^{-2} \text{y}^{-1}$, at c. 5500 yr BP (before the elm decline).

Table 5.1

Pollen deposition rates at elm decline compared.

| | | Total pollen (pollen cm ⁻² yr ⁻¹) | <i>Ulmus</i> pollen yr ⁻¹ |
|---|-----------------|--|--|
| <i>Before elm decline (c. 5500 yr BP)</i> | | | |
| Alder-oak-birch-elm zone | Windermere | 2,872 | 200 |
| <i>Ulmus</i> 10-15% A.P. | Blea Tarn | 23,215 | 1,716 |
| Pine-birch-alder zone | Loch Clair | 17,626 | 730 |
| <i>Ulmus</i> 2-5% A.P. | Loch a'Chroisg | 6,036 | 90 |
| <i>After elm decline (c. 5000 yr BP)</i> | | | |
| | Windermere | 4,750 | 50 |
| | Blea Tarn | 23,400 | 350 |
| | Loch Clair | 22,000 | 170 |
| | Loch a' Chroisg | 3,830 | 24 |

After Pennington (1973).

Clair must represent secondary deposition by inflowing streams from the surface of the catchment, since the estimated annual rates so greatly exceed amounts $\text{cm}^{-2}\text{y}^{-1}$ caught in traps in open situations. The excess compared with Windermere sediments may represent either a) superior sources of secondary pollen in the acid soils which have carried a Flandrian vegetation including much *Empetrum*, *Pinus* and *Calluna* (pollen is well preserved at pH 5.5 or below), or, b) a more complete sedimentation in Loch Clair of the suspended load of the inflows, including pollen, either because of the positions of inflow and outflow or of the presence in the suspended load of iron-silica-humic complexes; the presence of these was shown during unsuccessful attempts to isolate, identify and count the diatom frustules in the sediments.

Preliminary pollen counts on samples from streams in flood and from traps submerged in Loch Clair showed that there is a very large contribution of waterborne pollen to the lake, and that sediment-source material is as rich in pollen as are the sediments. It became obvious however that the intensive sampling required to obtain enough data to decide between alternatives (a) and (b) was not practical from a base at Windermere.

W Tutin

THE LOCH LOMOND READVANCE IN TORRIDON AND APPLECROSS

Evidence for Loch Lomond Readvance glaciers in the Applecross Peninsula and the area between Strath Carron and Glen Torridon exists abundantly in the form of clear terminal and lateral moraines and drift limits associated with these, hummocky and fluted moraines and fluvioglacial features related to the former glaciers (Figures 5.3 and 5.4). The general pattern of glaciation was one of valley glaciers descending several kilometres from centres of ice dispersal, e.g. from the dome which built up on the hills north of Strath Carron. Other glaciers were nourished in isolated corries (e.g. those on the eastern slopes of Beinn Bhan, Applecross), or in snow-gathering re-entrants on steep hillsides (e.g. Meall an Fhuaid, Applecross). Many glaciers were less than 5 km^2 at their maximal extent, the largest covered around 25 km^2 (e.g. the Coire Fionnaraich glacier) whilst the smallest was just over 0.25 km^2 (Coire Glas, above the Applecross River valley). At the maximum of the Readvance ice covered about 160 km^2 , the greatest extent being in the eastern part of the area between Glen Torridon and Strathcarron where the ice cap covered 108 km^2 and fed 9 outlet glaciers, the surface probably reaching over 800 m O.D. Firn-line altitudes calculated using reconstructed ice surfaces and contours (made possible by the clearly preserved glacial limits) show a rise from 409 m O.D. in the west to 474 m O.D. in the eastern area, those

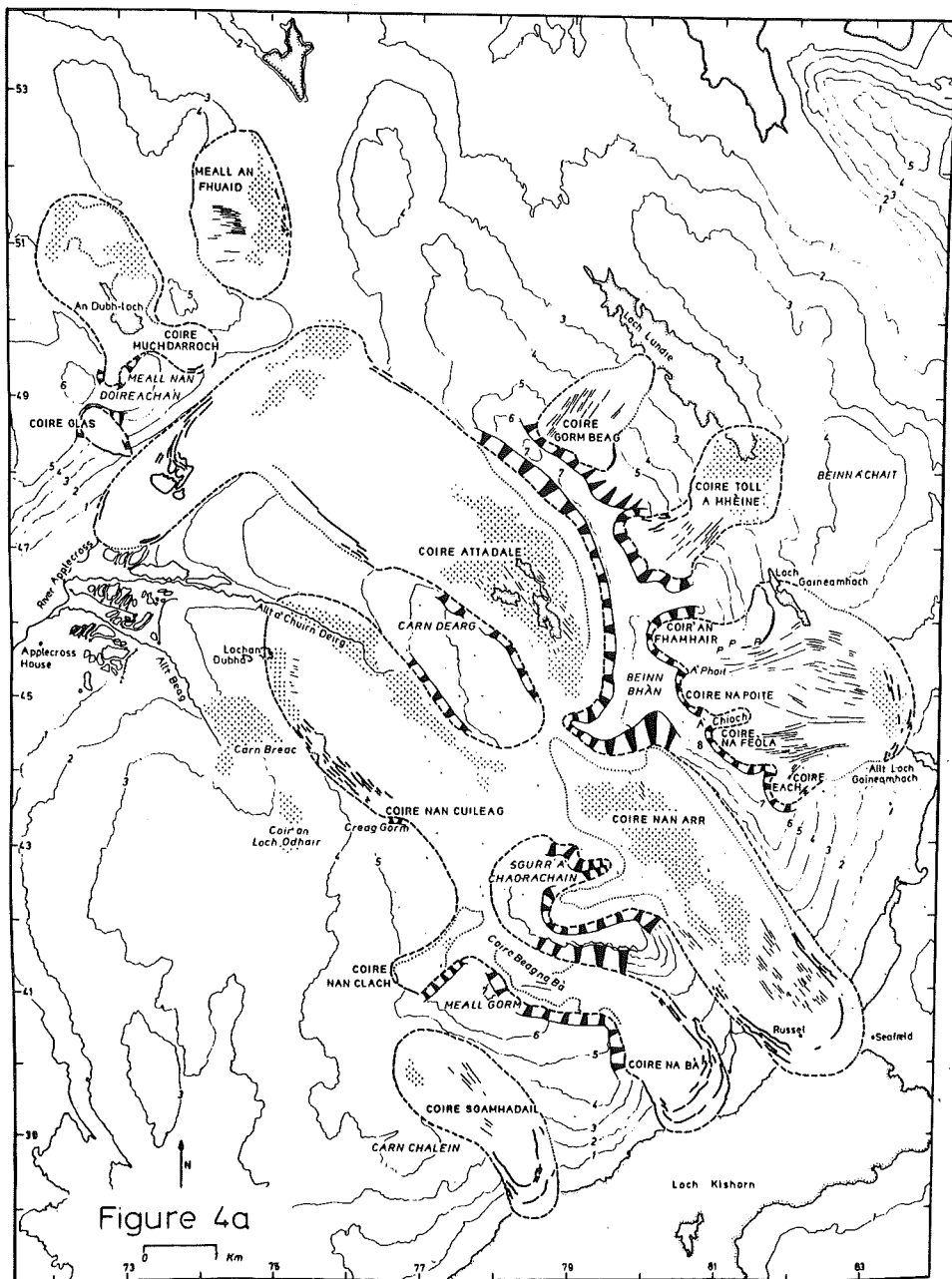


Figure 5.3. The Loch Lomond Readvance between Glen Torridon and Strath Carron.

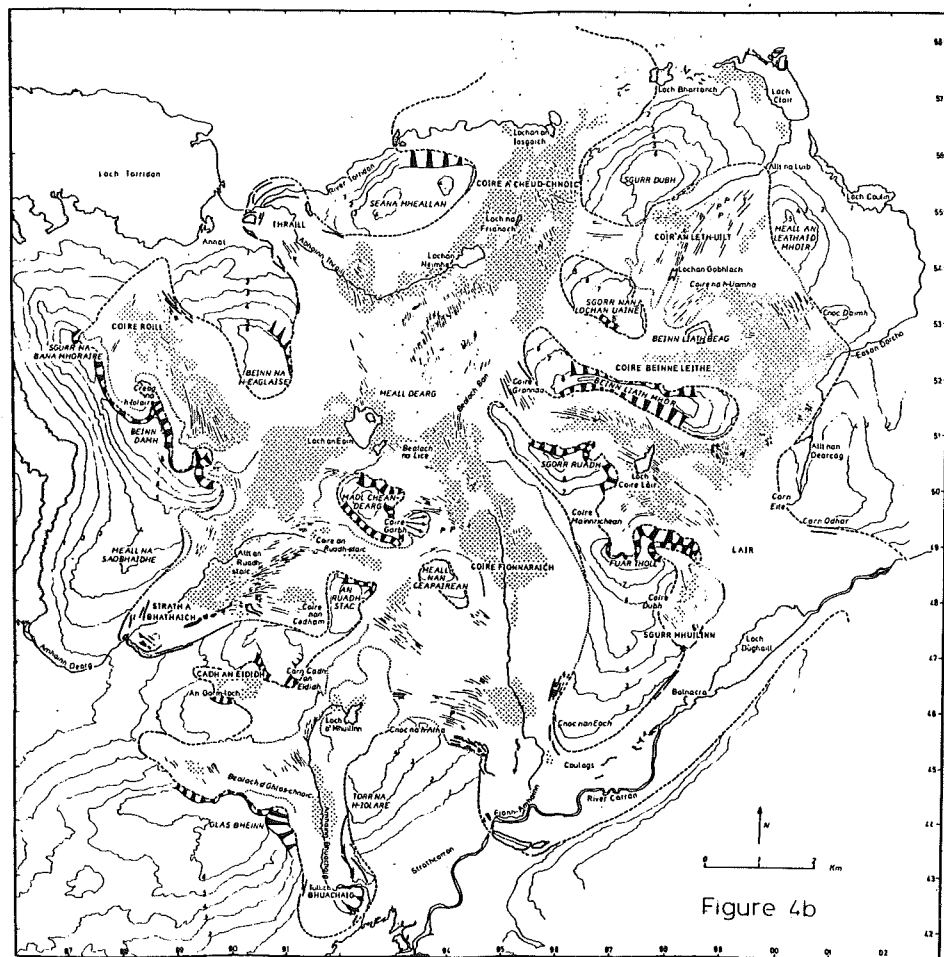


Figure 5.4. The Loch Lomond Readvance in Applecross.

glaciers on the southern margins of ice masses having the lowest firn lines.

Of the 23 glaciers mapped, 13 formed end moraines, 7 of these being multiple features, with four successive ridges being the most common pattern, e.g. the Thraill end moraines. Another 6 glaciers formed multiple lateral moraines (e.g. the features above Loch Kishorn). Despite this frequently-repeated number of stillstands or minor readvances during general glacier retreat there is no consistent pattern to the relative sizes of the moraines: at the Thraill terminus the largest ridge is the youngest one, whereas in Strath a' Bhathaich the oldest moraine is the major feature. In all cases the recessional ridges occur within several hundred metres of the outermost position.

Only one of the 10 glaciers that terminated between north and north-east left a well-defined end moraine and 6 formed none, whereas all except two of the remainder (those in small, steep, V-shaped valleys) terminating facing west and south, possess terminal features. It is possible that the orientation of the north and east facing termini increased their sensitivity to the climatic fluctuations which elsewhere produced multiple end moraines, curtailing still-stand of the ice and thus prohibiting moraine formation.

Fluted moraines are very common in the area and were formed by all except two of the mapped glaciers. Typically associated throughout Scotland with Loch Lomond Readvance glaciers, fluted moraines have been suggested to reflect rapid deglaciation (Sollid *et al.*, 1973). Steep down-glacier slopes are particularly favourable sites for fluted moraines, e.g. their extensive development on north-facing cliffs north of Meall Dearg, and on the rocky valley steps on Coire Roill, in the upper Lair valley and in the Beinn Bhan corries. The height and length of the flutes vary, in general the longest and highest being composed of coarser debris, e.g. in Coire Roill the longest fluted moraine stretches over 1 km downvalley from a rock projection, is a few tens of metres wide and the numerous moraine blocks in the vicinity reach 8 m in length. Derivation at vertical (e.g. corrie back walls) or steep rock faces (e.g. roches moutonnées) was apparently common in the area, and particularly dense concentrations of flutings are found below such favourable features.

In Coir Roill and many other localities flutings occur interspersed with or over-ride hummocky moraines. These moraines are also typically associated with the Loch Lomond Readvance limits and in this area are generally under 5 m high, densely covering valley sides and floors, though they also occur at high altitudes (e.g. at almost 500 m O.D. south of the An-Rhuadh-stac - Meall nan Ceapairean col). Their distribution is often apparently

random producing a disordered landscape but frequently alignments are evident in the crests of the mounds, e.g. obliquely downvalley in chevron pattern or directly downslope (e.g. the superb examples in upper Strath a'Bhathaich, west of Maol Chean-Dearg). Another area of hummocky moraines remarkable for their profusion and density is Coire a' Cheud Chnoic by Glen Torridon. Here the mounds are sharply defined, steep-sided, conical or elongated in their crests, reaching 15 m in height and with an oblique downslope alignment predominating.

Near the glaciers' termini fluvioglacial landforms record the decay of the Loch Lomond Readvance ice. The most frequent features in the area are kame terraces, the best examples being in Strath Carron, where they aid the interpretation of the adjoining Lair and Fionnaraich glacier snouts which downwasted together. Outwash fans are preserved where the glaciers terminated in relatively wide and shallow valleys e.g. in lower Strath Carron and lower Glen Torridon. The lower portions of the outwash fans have been altered by Flandrian marine activity below altitudes of c. 9 m O.D.

M Robinson

COIRE A'CHEUD CHNOIC (NG 95 55)

Coire a'Cheud Chnoic (the Valley of a Hundred Hills) drains into Glen Torridon from the SE. The area is underlain by Torridon Sandstone except where three sub-parallel thrusts aligned NE-SW have brought Cambrian Quartzite westwards (Figure 5.5). Much of the valley floor is covered by hummocky moraines which reach over 8 m in height. Occasionally bedrock crops out between moraines and in stream beds, indicating that there is no great thickness of till below the hummocks. Most of the till is contained in the moraines but this volume is estimated to be equivalent to a sheet about 2 m deep covering the area. There is therefore not an unusual accumulation of debris in the valley. To the south of the hummocky moraines, the floor of the valley is covered by a till sheet which incised stream courses show to be c. 3 m deep over much of this area. Its surface is featureless except for two groups of short but clear fluted moraines. Bedrock is exposed over much of the remaining glaciated area, the distribution of striae in Figure 5.5 being indicative of the area of exposure. In the lower part of the valley detailed mapping of the moraines indicates that the majority are elongate in a roughly N-S direction (Figure 5.6). Many are higher at their northern ends and this gives them a conical appearance when viewed from Glen Torridon.

Only three natural exposures were available for study in the moraines and all the remaining samples were recovered from pits dug to a depth of c. 1 m in the moraine

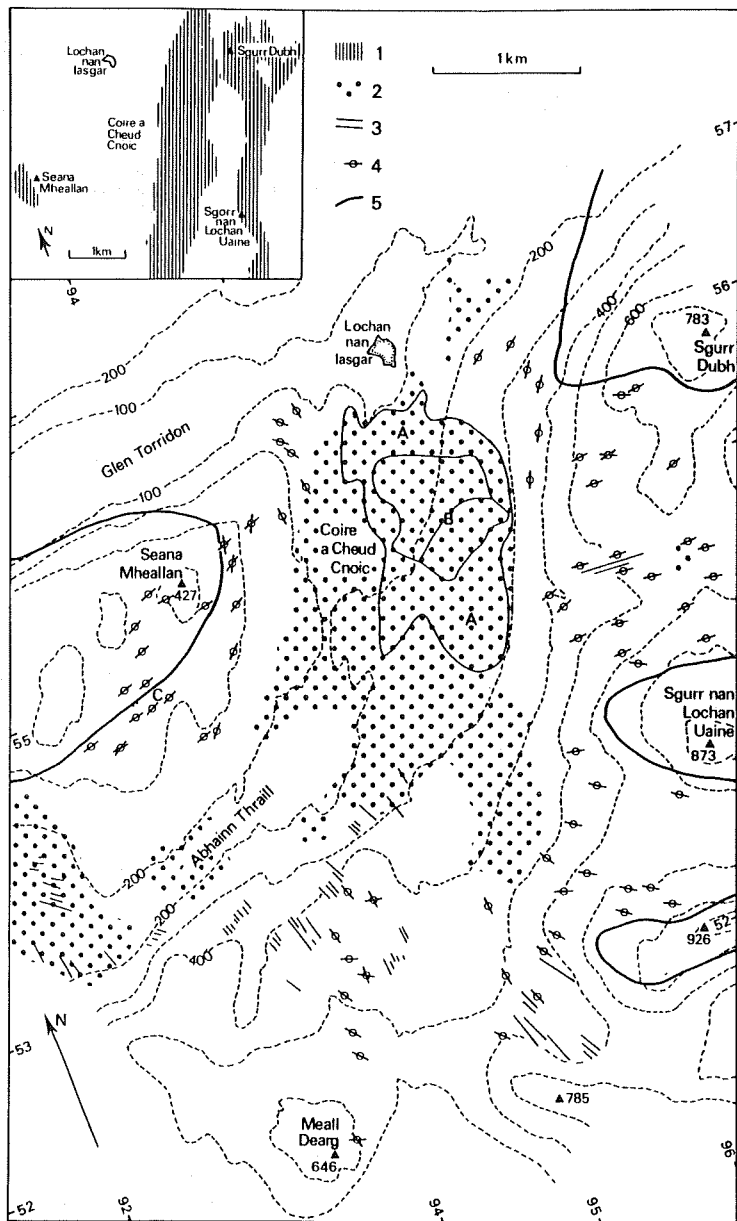


Figure 5.5. Coire a'Cheud Cnoic. 1. Quartzite; 2. Hummocky moraine; 3. Fluted moraines; 4. Striae; 5. Inferred glacier limits.

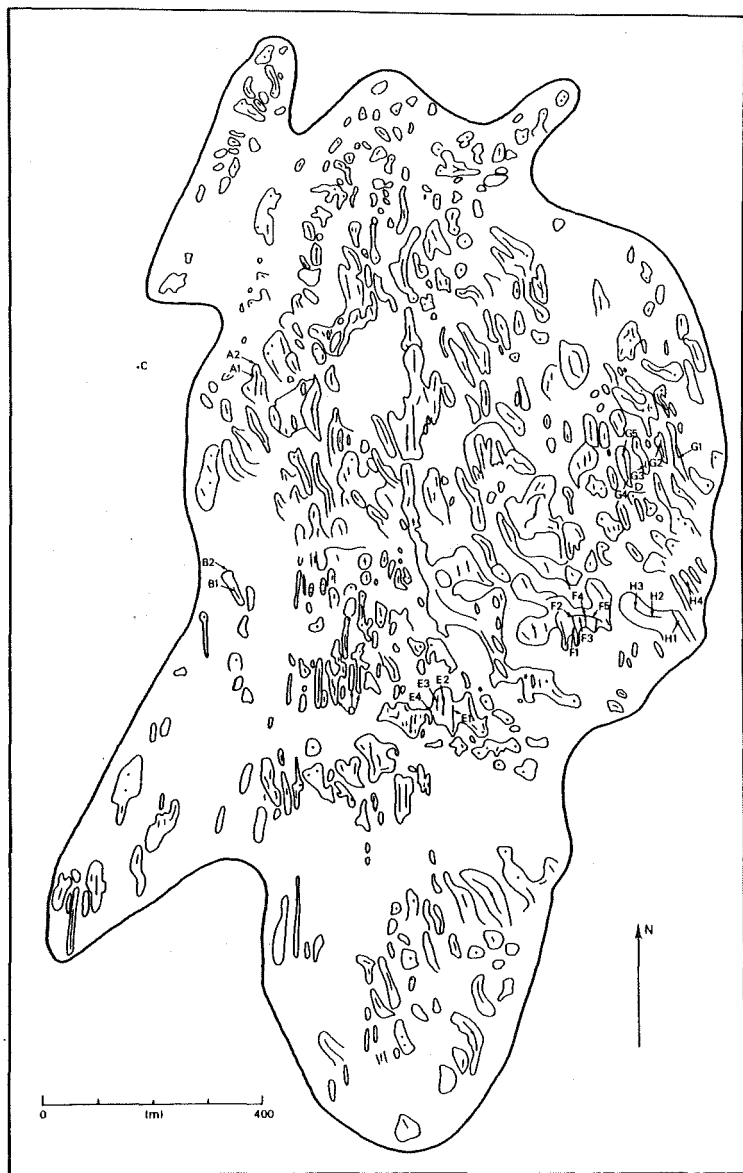


Figure 5.6. Hummocky moraines in Coire a'Cheud Cnoic. The figure shows breaks of slope and ridge crests. It also gives the sample locations. See Figure 5.5 for the location of the mapped area.

crests. Particle size analysis was carried out on 25 kg samples over the size range from -6ϕ to $<4\phi$. Lithological analysis concentrated on the proportions of Torridon Sandstone, Cambrian Quartzite and a category termed 'Ice Sheet Erratics' composed of Lewisian Gneiss, Moine Schist and Cambrian Fucoid Beds, all material that would have been transported into the area by ice moving to the west from east of the Moine Thrust. Clast form was recorded as the percentage of elongates (i.e. c:a axial ratio <0.5) in a sample of 25 and clast roundness was calculated as the mean of 25 or 50 clasts assigned to six roundness categories with numerical values ranging from 1 for very angular to 6 for well rounded. Till fabric analyses were carried out on 50 clasts with an a-axis >1 cm and an a:b axial ratio of >1.5 . (Hodgson, 1982).

Comparison of pairs of samples from the natural sections near bedrock and from neighbouring crests suggests broad similarities in particle size distributions, clast form and clast lithologies such that it was concluded that the near-surface samples from the ridge crests were representative of the material composing the moraines. This conclusion was also supported by sequential sampling of clast lithologies at 32 sites at 10-15 cm vertical intervals to c. 1 m depth. At 19 of these sites there was no significant variation with increasing depth whilst of the remaining 13, 7 showed a decrease and 5 an increase in sandstone clasts and three a decrease in ice-sheet erratics towards the surface. These results demonstrate a lack of any systematic variation with depth.

The particle size analyses indicate that the till is particularly coarse in this valley (34 samples, range of mean diameters (*sensu* McCammon, 1962) 0.34ϕ to -3.66ϕ). There are three reasons for supposing that there is a correspondence between moraine height and till coarseness: (i) the valley contains the highest features and, on average, the coarsest till sampled in the Torridon area; (ii) the correspondence is evident in local groups of features as well as throughout the valley; and (iii) correlation of moraine height against mean particle diameter for all sites in the valley yields a correlation coefficient of 0.36 which is significant at the 0.10 level. However, since there are many low moraines (2-3 m) it is possible that this result is unduly influenced by data from a few high moraines.

Till fabric analyses were carried out at 20 sites and the results are shown in Figure 5.7. The analyses show that 10 of the 20 sites exhibit primary modes parallel to the ridge crests and two of these have a secondary transverse peak. In another case a parallel and transverse mode are roughly the same magnitude, but a transverse mode was never dominant. Four fabrics showed dominant modes oblique to the ridge crests while two others have two oblique modes each and another has oblique and parallel

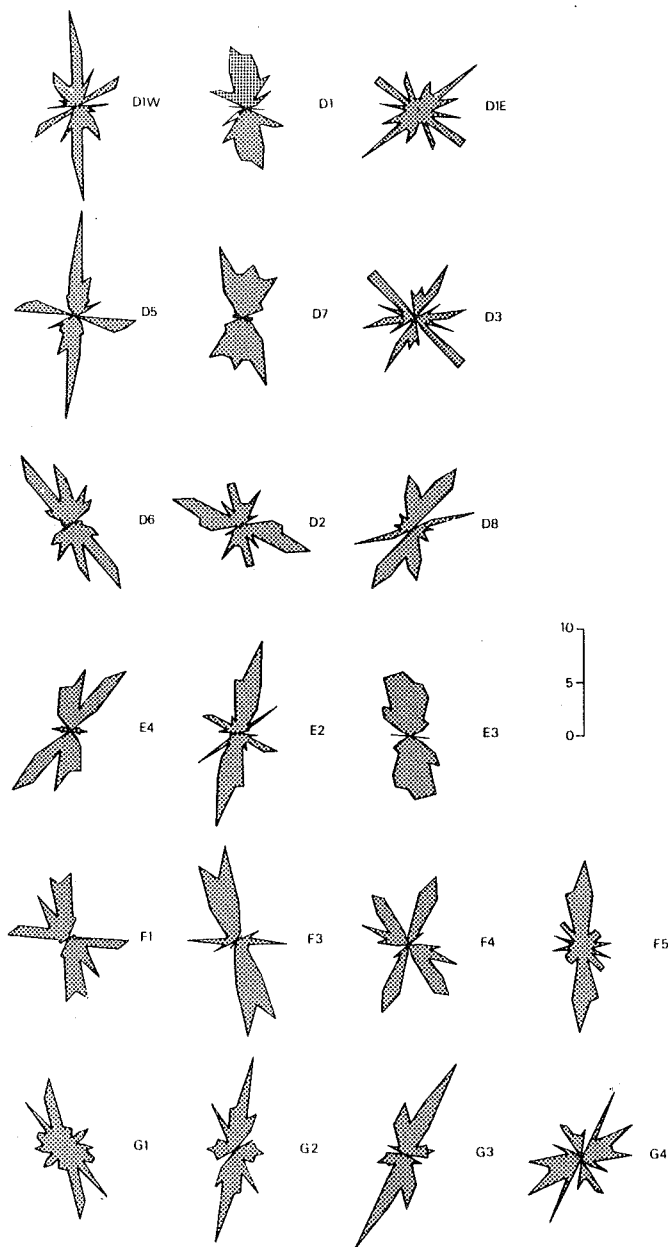


Figure 5.7. Till fabric analyses from Coire a'Cheud Cnoic. Ridge crest orientations are parallel to the long axis of the page. Sample locations given in Figure 5.6.

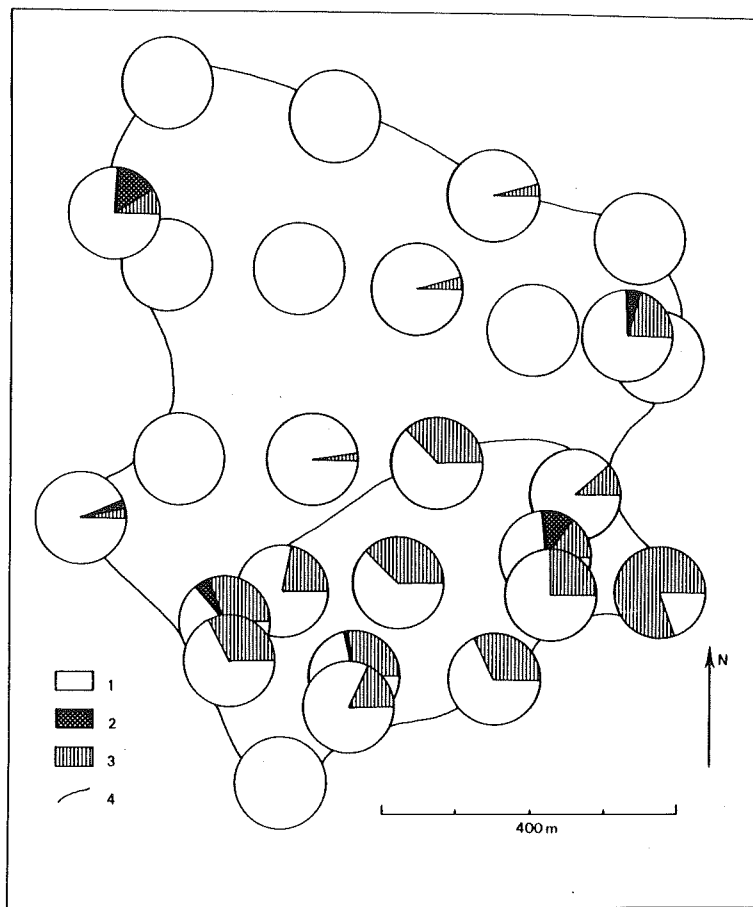


Figure 5.8. Pie diagrams of rock-type proportions in Coire a'Cheud Cnoic. 1. Sandstone; 2. Ice-sheet erratics (see text); 3. Quartzite; 4. Area limits (see Figure 5.5). The results are derived from counts of surface boulders and from groups of till samples. The area is subdivided on the basis of sites with a relatively high proportion of quartzite.

modes of equal magnitude. Only two analyses fail to display any modes. These results argue against the formation of the moraines as crevasse fillings and offer strong support to the suggestion that the moraines are a form of fluting.

The lithology of 100 boulders at 20 locations was counted and is shown in Figure 5.8 together with the averaged results of the lithological analyses of the till samples. A difference between these two groups of samples reflects the different size fractions - no ice-sheet erratic boulders were found in the valley. The most important finding is that quartzite accounts for only a small proportion of the surface boulders. Since all the steep ground overlooking the valley is underlain by quartzite and since supraglacial debris is characteristically bouldery and should be best represented at the surface of the till, it can be concluded that supraglacial debris, derived from the valley sides, does not constitute an important part of the accumulated debris in the valley.

Inspection of the pattern of the results of the lithological analyses shows that the highest quartzite contents occur in the south and SE parts of the area. This is unexpected because, with S-N ice-flow in Choire a'Cheud Cnoic any quartzite contribution, either as the load of the glaciers entering the valley from the east, or as rock-wall debris, would be streamed northwards along the east side of the valley. The quartzite-rich samples are situated below the mouth of the col between Sgurr Dubh and Sgurr nan Lochan Uaine so it can be tentatively suggested that the pattern reflects ice-flow down from this col at a time before it was deflected by stronger ice-flow in the main valley. Such a time may have occurred during the ice-sheet glaciation or early in the Loch Lomond Readvance.

The following explanation of the moraines is offered. As the main ice body advanced northwards along the valley, overwhelming whatever ice was flowing across its path from the east, much debris was available. This comprised till deposited by the Late Devensian ice sheet, the products of post-ice sheet pressure release and isostatic fracturing and the products of periglacial weathering at the start and end of the Lateglacial Interstadial. As the debris was overridden or entrained into the base of the ice it retarded the basal layers and was often formed into streamlined shapes. In this context it is relevant that the typical mound profile, described above, is analogous to a roche moutonnée and to those end moraines that have a shallow proximal and steep distal slope. Other similar features have been described by Donner and West (1955). They occur on Skye and are only 2-5 m high but have steep distal sides and till fabrics oriented parallel to elongate ridge crests. On this evidence Donner and West (1955) called them drumlins

although their profile is the reverse of the classic drumlin shape. It is interesting that they were originally interpreted as dead-ice topography by Clough and Harker (1904).

It is suggested that subsequent to the initial modelling the glacier had little erosive or transportational competence. Evidence for this suggestion includes the presence of a large volume of ice-sheet erratics and the distribution of quartzite boulders. In addition several factors favouring low competence can be invoked in this valley:

- (i) the interaction of this glacier with ice from the north of Glen Torridon (cf. Sissons, 1977) would have resulted in a slowing and a thickening of the ice;
- (ii) the coarseness of the material would have made it difficult to deform;
- (iii) the coarseness and permeability of the material would have ensured that pressure gradients were shallow and that water could escape down both valleys;
- (iv) Abhainn Thraillo to the west (Figure 5.5) would have provided an additional release for water pressure;
- (v) once stable moraines had formed they would have constituted a rough bed; and
- (vi) entrainment of debris by the ice would have initiated a negative feedback loop by reducing the mobility of the ice, hence its velocity and therefore its erosive competence.

It is concluded that the work in Coire a'Cheud Cnoic has been successful in disproving the explanation that the moraines resulted from the deposition of supraglacial morainic till from the surface of a down-wasting area of stagnant ice. Instead, several lines of evidence point to formation early in the Loch Lomond Readvance under active ice and several factors have been invoked to explain the subsequent preservation of the features in this area.

D Hodgson

THE BEINN ALLIGIN 'ROCK GLACIER' (NG 86 60)

On the floor of a deep, south-east facing corrie that lies to the south of the highest summit of Beinn Alligin (Sgurr Mhór, 985 m) there occurs a massive accumulation of coarse bouldery debris (Figure 5.9). The debris forms a continuous tongue-shaped deposit that rises to a maximum height of 12-15 m, is 1.2 km long and declines downslope in width from c. 400 m to c. 200m. It is composed of extremely large Torridon Sandstone boulders up to and occasionally exceeding 5 m in length, with no visible interstitial fine material. The deposit rests on a fairly gentle slope that falls from c. 400 m altitude to c. 260 m. The lateral margins of the deposit are sharply defined, and the surface

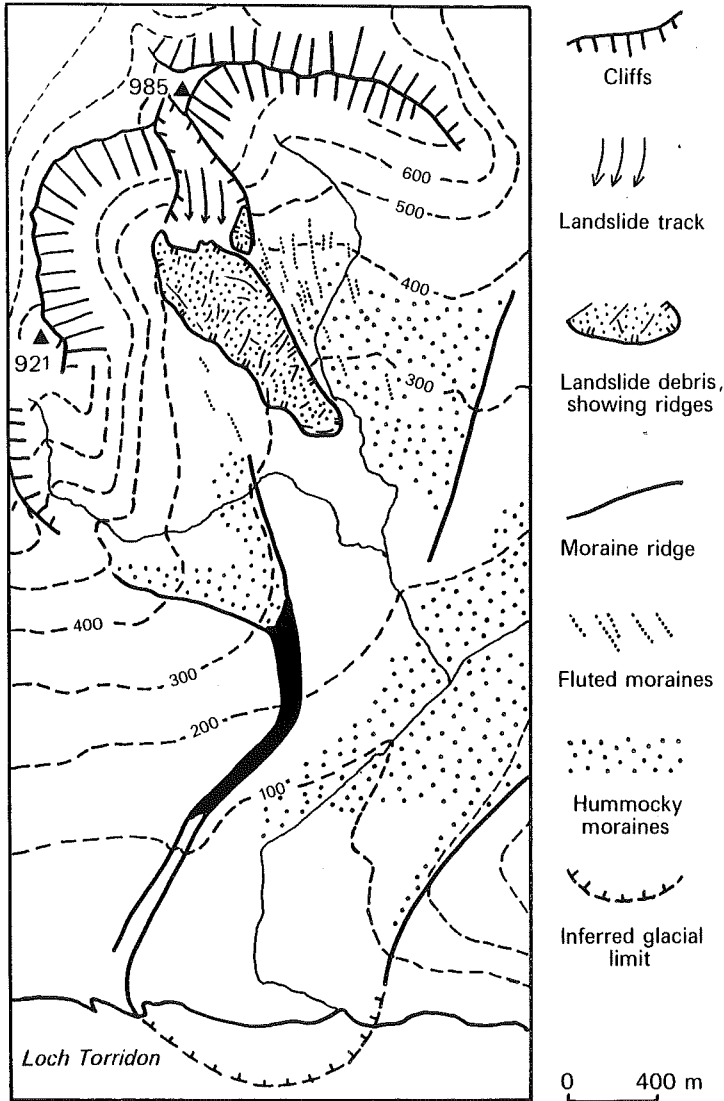


Figure 5.9. Former ice limits, glacial landforms and landslide scar and debris south of Beinn Alligin. Based on Sissons (1975; 1977).

relief consists of ridges and depressions. On the upslope part of the feature transverse ridges are poorly-defined and longitudinal ridges dominate, but farther downslope transverse ridges with steep distal slopes are better developed. The lowermost 300-400m of the deposit (below 300 m altitude) is, however, much lower and thinner than the remainder, and supports only small, poorly-defined and mainly transverse ridges separated by very shallow depressions. The entire deposit lies well within the limit of the Loch Lomond Readvance (Sissons, 1975, 1977; Figure 5.9).

The source of the debris was a large rockslide or rock avalanche that left a huge triangular failure scar on the steep cliffs south of Sgurr Mhór (Figure 5.9). On either side of the scar, near-vertical fault- (or joint-) controlled cliffs taper upwards to intersect near the summit of the mountain, and between these cliffs the failure plane is fairly smooth and lacks the distinctive stepped profile characteristic of the Torridon Sandstone cliffs on either side. In a paper devoted to interpretation of the debris accumulation, however, Sissons (1975) has argued that it does not represent a simple rockslide deposit in view of the fact that the debris is not merely banked against the foot of the cliff (as with many other landslides in Scotland) but extends 1.2 km down the gently-sloping valley floor. He proposed instead that the debris accumulation is a rock glacier, formed by the reactivation of a remnant of decaying glacier ice under the weight of rockslide debris near the end of the Loch Lomond Stadial.

An alternative explanation of the debris accumulation has been outlined by Whalley (1976), who noted that Sissons' explanation appears to require rock failure when the former glacier had shrunk to very limited dimensions, and who believed that 'the potential for the formation of a rock glacier by a very small amount of ice for a large volume of debris is low' (p. 176). Whalley suggested that the boulder accumulation may represent a form of flowslide or 'sturzstrom' deposit. He envisaged that the rockslide debris had moved away from the source area either over a 'cushion' of compressed air which would have allowed the debris to move at great speed with very low friction values (cf. Schreve, 1968), or as a flow of colliding blocks as advocated by Hsü (1975). In reply to Whalley's suggestions, Sissons (1976b) rejected his alternative interpretation on four counts: (i) the planar surface of the failure scar appears to indicate that the slide debris remained in contact with the rock wall, and not supported by an air cushion; (ii) Shreve (1968) emphasised the importance of a shelf of rock in 'launching' the landslide debris to create a trapped 'cushion' of air, but no such projection exists at the Beinn Alligin site; (iii) flowslide deposits are characterised by abrupt margins, yet the lower part of the Beinn Alligin debris mass is much lower than the remainder; and (iv) flowslide debris masses typically have steep

scarp-like edges surmounted by levée-like ridges, yet such features are absent from the margins of the Beinn Alligin deposit. Another possible argument against the interpretation of the feature as a form of flowslide is that though the failed rock mass must initially have moved southwards from the failure scar, there is no indication that it moved any distance up the opposite side of the corrie before being deflected by the slope of the corrie floor in a southeasterly direction.

Sissons' original interpretation of the debris accumulation in terms of glacial transportation of rockslide debris is strengthened by later reports of landslides associated with glacier ice during the Loch Lomond Readvance (Ballantyne, 1986d, p.148), including one of a similar though smaller feature on the floor of Coire Garbh (NG 93 49), 13 km south-east of Beinn Alligin (Robinson, 1977, p. 62). Holmes (1984), moreover, has established that the great majority of rock-slope failures in the Scottish Highlands occur within a short distance of the former limits of Loch Lomond Readvance glaciers, a fact that he attributed to rock-slope weakening as a result of fluctuating cleft-water pressures during glaciation and deglaciation. He has also shown that the majority of such landslides occurred during or after deglaciation, which implies that failure on to the surface of a decaying glacier is by no means as unlikely as Whalley (1976) seemed to envisage.

In one respect, however, Sissons' interpretation appears dubious. The termini of both fossil and active rock glaciers of all types invariably take the form of steep (>35°), high outer ridges, within which pronounced secondary ridges parallel to the outer ridge are often present. The Beinn Alligin feature lacks both of these features, and indeed, as Sissons observed, is much thinner (and less well-defined) at its lower end; in places it literally peters out downslope. This suggests that although the deposit may indeed represent glacially-transported rockfall debris, as Sissons suggested, the waning glacier that transported the debris may have been rather larger than he envisaged, so that although the debris was spread downvalley by reactivation of the ice, no 'true' rock glacier was formed.

C K Ballantyne

COIRE MHAIC NOBUIL. (NG 910 596).

Coire Mhaic Nobuil is a deep, U-shaped valley between Beinn Dearg (914 m) and Liathach (1023 m) (Figure 5.10). It drains to the west although the deeply breached watershed at its eastern end rises to only 360 m. The geology is rather simple: a small inlier of Lewisian Gneiss underlies the floor of the valley, the remainder of

Gneiss underlies the floor of the valley, the remainder of the area being Torridon Sandstone with the exception of two very small outcrops of Cambrian Quartzite on the highest part of the Liathach ridge.

The direction of flow of the Loch Lomond Readvance glacier which last occupied the valley is indicated by the widespread fluted moraine below the corries on the north of Liathach and on the valley floor. The margin of this westerly flowing glacier is indicated by a double lateral moraine on the NW flank of Liathach which descends westwards from an altitude of just below 500 m.

Most of the valley floor is occupied by hummocky moraines that can be divided into two areas with distinctive characteristics. The eastern group are massive mounds up to 8 m high, with smooth convex profiles (except where interrupted by small, steep-sided kettle holes) and a general lack of surface boulders. Some of these features are elongate and other have corrugated surfaces: since the resulting lineations are parallel to one another and conform to the general pattern of ice flow, they are considered to be a form of fluted moraine.

To the west the features appear chaotic, being a mixture of large and small mounds, sometimes distinct and separate and sometimes forming massive conglomerations. However they all have steep slopes and sharp crests and are littered with massive sandstone boulders. To the west of this area the drift in the valley floor has a much more subdued relief with occasional mounds.

At nine localities (Figure 5.10) on the valley floor, the proportions of Torridon Sandstone and Lewisian Gneiss were ascertained on the basis of counts of 200-300 clasts in the -4 ϕ to -3 ϕ size fraction. The sites were closely spaced and aligned in the direction of ice flow across the geological contacts in order to monitor the compositional changes of the till. The sequence of samples could not be continued beyond Site 9 because another glacier had become confluent with the Coire Mhic Nobuil ice (Sissons, 1977) thus complicating the pattern of deposition. Few erratics related to ice-sheet flow (i.e. from east of the Moine Thrust some 10 km to the west) were encountered in this valley. The results are given in Table 5.2.

Table 5.2.

Till compositional changes in Coire Mhic Nobuil.

| Site | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|--------------|-----|------|------|------|------|------|------|------|------|
| Sandstone(%) | 100 | 95.3 | 81.1 | 62.4 | 29.5 | 23.2 | 32.0 | 56.3 | 77.8 |
| Gneiss(%) | 0 | 4.7 | 18.9 | 37.6 | 70.5 | 76.8 | 68.0 | 43.7 | 22.2 |

>>> ice flow direction >>>

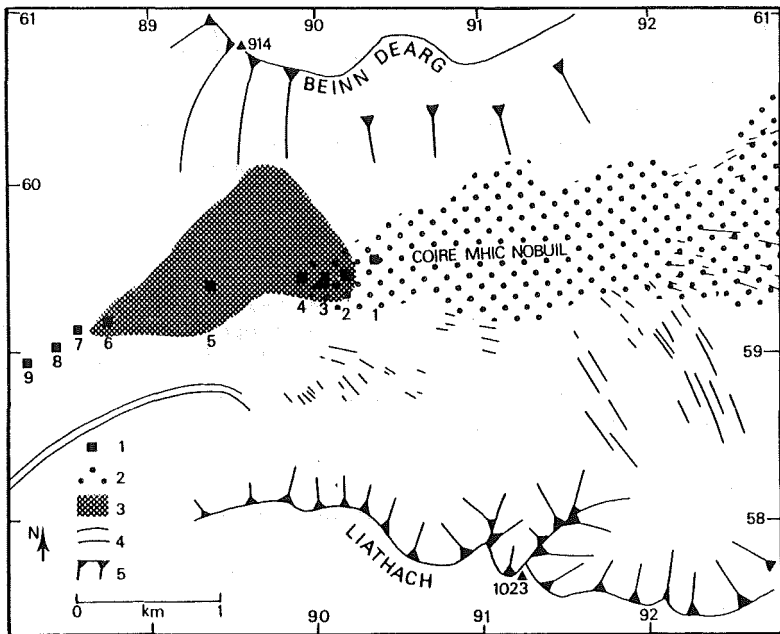


Figure 5.10. Coire Mhic Nobuil. 1. Sample locations; 2. Hummocky moraines; 3. Lewisian Gneiss; 4. Moraine ridges; 5. Steep hill slopes.

The figures indicate that the composition of the till changes quickly down-ice of the start of the inlier but that a significant percentage of sandstone (>20%) survives in the till to the end of the gneiss outcrop. On returning to sandstone bedrock the sandstone content of the till rises quickly.

A related observation is that, as shown in Figure 5.10, the hummocky moraines terminate shortly after the start of the gneiss but that on the last of these features over 50% of the surface boulders (some of them up to 2 m long) are of gneiss.

Discussion

It may be expected that the steep-sided, chaotic moraines of Coire Mhic Nobuil developed below high steep valley sides would be of supraglacial origin. However, the rapid inclusion of gneiss boulders and pebbles in response to the change in bedrock shows that the till was derived subglacially.

Paucity of till on Lewisian Gneiss bedrock is a widespread characteristic that indicates that the rock is very resistant to glacial erosion. This valley conforms to this generalisation since the volume of till is greatly reduced a short distance down-valley of the start of the gneiss bedrock (as the limit of hummocky moraines and the increased frequency of bedrock exposure in the stream bed show).

The observed rapid increase in the proportion of gneiss in the till and among the surface boulders is made more impressive by the resistant nature of the rock type. The reduction in the overall volume of the till shows that, in this example, the change in composition cannot be attributed to incorporation of vast volumes of gneiss, hence it must result from the early deposition of sandstone debris. This conclusion rules out the possibility of elevation of the debris to the glacier surface between its erosion and deposition as this process would require considerable down-valley movement.

The compositional changes at the sites across the downvalley gneiss-sandstone contact provide complementary evidence of the dependence of the till on the local bedrock.

The mechanism proposed to account for the valley-bottom derivation, limited transport and rapid deposition of the debris, together with the evidence for glacier over-ridding of at least some of the moraines, is incorporation of the debris in the glacier near its snout by pushing, over-ridding and shearing during glacier advance. As conditions favourable to lodgement rather than erosion pertained (coarse debris, rough valley floor, low water

pressure, small horizontal shear stress due to slow glacier flow and large pressure normal to the glacier bed) the incorporated debris was relatively stable at the base of the glacier for the remainder of the Loch Lomond Readvance.

D M Hodgson.

LOWER GLEN TORRIDON (NG 19 55)

Two Loch Lomond Readvance glaciers flowed north on the north-west edge of the ice cap that stretched from Glas Beinn to the slopes of Fuar Tholl (Figure 5.3) to terminate near the head of Loch Torridon: the Thraill glacier and the Coire Roill glacier. In common with most of the glaciers that terminated facing between north and north-east in this area there is no clear end moraine for the Coire Roill glacier. Steep terrain in this locality may explain this absence but the reason for the general pattern is not known.

The Thraill glacier flowed north-west to terminate in Glen Torridon, depositing a clear multiple arcuate ridge. South of the River Torridon the moraine forms a complex of mounds and ridges, the distal slope of the main outer ridge being c. 10 m high. East of the Abhainn Thraill the innermost ridge is a major feature, curving upvalley for nearly 1 km. Three moraine ridges mark successive limits on the north side of the River Torridon: the highest is the inner feature, reaching 7 to 10 m high. The outermost limit falls c. 4 m to the peat-covered outwash fan that slopes seaward from the moraine.

The outwash fan is limited at its west end by the Flandrian beach ridges at 7 and 8 m O.D. A narrow terrace skirts the northern edge of this fan, along the break of slope at the valley edge. It has a similar slope to the outwash fan but its surface lies about 5 m higher. The lithologies present in the terrace include a high percentage of non-local Moinian clasts, unlike the Loch Lomond Readvance deposits which largely comprise Torridon Sandstone and Cambrian Quartzite. A pre-Lateglacial Interstadial age is therefore implied for this feature: it may be a kame terrace or the eroded remnant of an earlier outwash fan related presumably to the ice retreat following the last glacial episode in this area, the Wester Ross Readvance. The lowest point levelled is 18.8 m O.D., implying a sea level below this altitude at the time of formation of the terrace.

M Robinson

SHIELDSAIG (NG 8161 5231) and REDPOINT (NG 726 685).

Relatively little is known about the Mesolithic occupation of the western coast of Scotland. Recent excavations at Kinloch on the island of Rhum have shown the presence of human activity from 8,500 yr BP through the Neolithic and Bronze Age periods (Wickham-Jones and Pollock, 1986). In addition to this site being the earliest dated settlement in Scotland, further interest is provided by the extensive exploitation for the manufacture of artefacts of bloodstone, a hydrothermal chalcedony, which crops out at Bloodstone Hill on the west coast of Rhum.

Worked bloodstone has been recorded from other archaeological sites along the west coast from Ardnamurchan to Redpoint and from other islands such as Glenbrittle on Skye and South Uist. On such sites the amounts used are very small, just a few flakes incorporated into larger worked stone assemblages. A particular problem represented by the occurrence of bloodstone artefacts at these sites is whether they are derived from Rhum and represent transport and/or trading by prehistoric people or whether they are derived from separate sources and only utilised locally.

At present, in addition to local geological investigations for bloodstone sources close to known sites, electron spin resonance is being used to characterize the bloodstone from the sites both on and off Rhum. As yet there are no firm results to link the sites away from Rhum with Bloodstone Hill as the variety of material within the term 'bloodstone' provides a wide range of character traces. However, given the archaeological evidence and the almost exclusive concentration of bloodstone pebbles at Bloodstone Hill, it would appear that some exploitation of this source was continuous throughout the prehistoric period.

The two archaeological sites reported here are represented by flaked stone assemblages in which a variety of raw materials have been used: flint, quartz, chalcedonies and indurated mudstones as well as bloodstone. This wide selection of materials for working is not uncommon in Scottish prehistoric sites as flint is found only in some gravel or beach sources (Wickham-Jones and Collins, 1978). Most of the stone would have been selected from local sources.

Shieldsaig.

The site lies by a pit from which gravel was extracted for road construction. It is located on a terrace at c. 16 m O.D. slightly below the altitude of the raised shoreline on which the village of Shieldsaig stands which represents the local marine limit at c. 21 m O.D. (Robinson, 1977).

An 8 m-long section in the pit revealed a surface layer of peat resting on a thin (3-6 cm) bed of aeolian sand which in turn overlay interstratified rounded gravels and bedded sands. Only flaked stone artefacts were found during excavation. Most were located at the junction between the aeolian sand and the overlying peat.

Of the 6,000 lithics, over 90% were made of quartz. Less than 1% of the assemblage is retouched into formal tool types. These include scrapers, microliths, awls and two small oval points. The assemblage is diagnostic of a Mesolithic 'hunter-gatherer' community.

Dating of the site is problematical. A ^{14}C date of 3720 ± 525 yr BP from charcoal immediately underlying the surface peat would appear to be quite late for Mesolithic activity, even in Scotland. However, there is slight evidence from work on Jura that the Mesolithic culture on the west coast extended into the period of Neolithic farming elsewhere in Scotland (Mercer, 1970). A later age may also be indicated by the underlying wind-blown sand which probably post-dated the Main Postglacial Shoreline of c. 6,000-7,000 yr BP.

Redpoint.

This is an unexcavated site, the presence of which is indicated by the occurrence of flaked lithics in eroding sand dunes (Gray, 1960).

There are two machair systems, one on either side of the rock outcrop of Redpoint. The main flake scatter lies south of the stream at c. 10 m O.D. where a blow-out has revealed a dark organic layer in loose sand and abundant gravel. Sand dunes rising behind this flattish area or erosion show dark horizons well above the flake scatter.

The collection of 1300 pieces includes mainly quartz with smaller amounts of bloodstone, flint and indurated mudstone. There is a small microlithic element in the retouched pieces which may indicate a Mesolithic age. However this dating is only tentative and would need to be confirmed by proper excavation.

A Clarke

NORTH-WEST APPLECROSS PENINSULA

Glaciation

This area is particularly interesting because of evidence of two distinct directions of ice movement prior to the Loch Lomond Readvance (Figure 5.11). As in the entire Applecross Peninsula and area to the east, there is

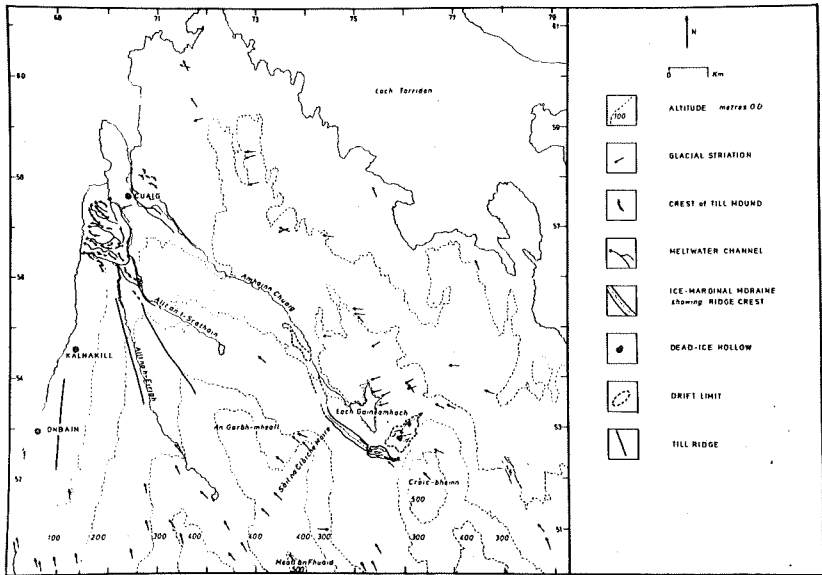


Figure 5.11. Glacial features of the north-west Applecross Peninsula.

a predominant direction of striae from SE to NW at high and low altitudes (Horne, 1899). In western Applecross, a marked swing toward NNW may have been due to deflection by ice moving out from Skye, a local centre of ice dispersal. Three long till ridges or 'drums' in the area run parallel with these striae and confirm a major movement of ice almost parallel to the coast. It is assumed that all these features belong to the Late Devensian maximum stage of glaciation. The easternmost till ridge forms a boundary between the smooth till-mantled slopes to the south and west and a much barer, rugged and moraine-strewn landscape on the north east side. The ridge itself is c. 2 km long, straight, even-crested, and 20 to 30 m wide, on the north east side falling up to 30 m to the adjacent land. This and the neighbouring till ridge run NNW towards an area of morainic mounds south of Cuaig (Figure 5.11), in the vicinity of which the ridges terminate.

In the north-west corner of the Applecross Peninsula striae indicate a predominantly westerly direction of ice movement. A large ice-marginal moraine north west of Croic-bheinn (Figure 5.11) and its continuation to the north west, the marked drift limit referred to above, and the moraine mounds at Cuaig together with the westerly orientation of striae, imply a separate and later phase of glaciation for this northern part of the Applecross Peninsula. Evidence for this phase, the Wester Ross Readvance, has been described from elsewhere in Wester Ross (Robinson and Ballantyne, 1979). The glacial limit at Croic-bheinn is a steep-sided, complex feature almost 2 km long, reaching 200 m in width and over 15 m in height. Dead ice hollows occur in the moraine, and it has four subsidiary ridges on its crest at the eastern end. Boulders are common all over the moraine: Torridon Sandstone predominates but Lewisian Gneiss boulders also occur (both rock types are present locally). Sections in the feature showed sub-angular to sub-rounded boulders densely packed in a sparse gritty matrix. The relationship of the moraine to the adjacent high ground, the predominance of glacial drift on its eastern side and the disposition of the local striae all confirm that glacial ice lay on the east side of the moraine, and the logical conclusion is that it is a lateral moraine formed by a very large valley glacier moving westward along the Loch Torridon trough.

To the north-west the moraine is continued as a low broad ridge of boulders which tails off after several hundred metres into undulating boulder-strewn country. Some 5 km farther to the north west and in line with the former ice margin, lies the group of morainic mounds at Cuaig referred to above. These mounds are irregularly shaped, sharp-crested, reach several hundred metres in length and up to 10 m in height and are aligned approximately to the north west. Dissecting them is a network of large meltwater channels some tens of metres

deep, draining to the north-west or west-north-west to the coast, where they emerge high up on the coastal cliffs. Where utilised by present-day streams the channels are graded to sea level. Sections in the mounds show a fairly coarse matrix containing large cobbles and small boulders mainly of Torridon Sandstone. The morphological alignment of these features implies association with the Wester Ross Readvance ice rather than Late Devensian ice-sheet maximum ice particularly as they apparently truncate the long till ridges associated with the previous phase of glaciation. This suggestion of a second, more limited glacial episode is in keeping with the evidence from raised shoreline fragments discussed below where a lower Lateglacial marine limit at Cuaig occurs well inside the Wester Ross Readvance limit.

Raised shorelines

A well-developed former shoreline occurs between Cuaig and Lonbain, where a wide platform cut into till stretches continuously for almost 4 km, reaching a maximum width of 0.3 km (Figure 5.12). The platform is backed by a sloping cliff in the till-mantled hillside; bedrock is visible at one locality in the cliff and in several small planated outcrops on the platform itself. The frontal cliff is generally a steep or vertical drop to the present shore and in places till has slumped over it. Shelving rock is common on the shore and low-level raised beaches largely absent.

Beach deposits are present in places on the till platform, notably where rivers and streams debouch on to it: a large beach ridge or spit occurs at the former mouth of the Allt na Moine. Between this river and Kalnakill, the beach deposits are commonly under 1 m thick, and range from fairly pure coarse sands to rounded cobbles and small boulders. Other stretches of the platform seem to be till with or without a peat covering. It is possible that peat was originally present everywhere, but has been cleared for crofting purposes on the formerly cultivated land.

Though morphologically the platform appears to be a continuous feature, levelling revealed a division into two sections. Between Lonbain and Kalnakill the mean altitude measured over more than 1.5 km is 27.9 m O.D., whereas for the 1 km stretch north of Kalnakill the mean altitude is 29.6 m O.D. This discontinuity coincides with a general narrowing of the platform northwards, and a change in surficial deposits from apparently widespread beach deposits to peat-covered till. The cause of this apparent height discrepancy is not known, but dislocation subsequent to formation of the feature is possible. Proximity to the Wester Ross Readvance limit (approximately coincidental with the Allt na h-Eirigh near the coast) may be significant in this respect.

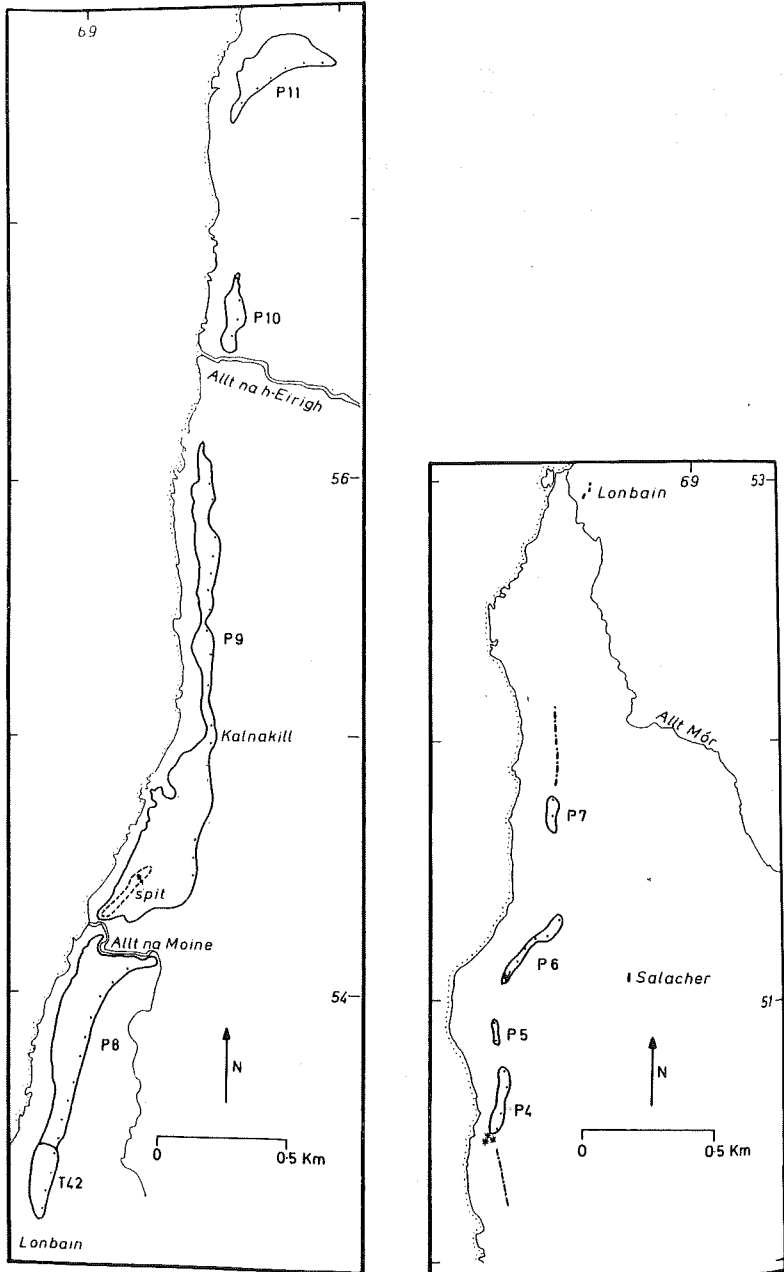


Figure 5.12. Raised shorelines along the Salacher - Lonbain - Kalnakill stretch of the west coast of Applecross. Asterisks represent sea stacks associated with the high rock platform.

Two further stretches of the till platform occur to the north of this stretch. At the same altitude as the platform north from Kalnakill, P10 (Figures 5.12 and 5.13) lies just within the Wester Ross Readvance limit which crosses the coast there. P11 at Cuaig is well within the glacial limit and its lower altitude (26.8 m O.D.) implies later formation, subsequent to ice wastage.

Sissons and Dawson (1981) investigated the relationship between the Wester Ross Readvance moraines and sea level in the area north of the Applecross Peninsula, from south of Gairloch to Little Loch Broom. They interpreted the relationship between ice-marginal positions (at the maximum and retreat stages) and shoreline features to show that in that area the maximum of the Wester Ross Readvance was associated with the local marine limit outside the end moraines. The marine limit is thus an approximately synchronous shoreline, the Main Wester Ross Shoreline.

North of Lonbain in western Applecross, the large platform described above constitutes the marine limit. It is crossed at its northern end (P10, Figure 5.12) by the Wester Ross Readvance limit, here presumably the southern margin of the outlet glacier that occupied the Loch Torridon trough. The west to north-westerly orientation of the meltwater channels near Cuaig implies a westerly destination of the meltwater, i.e. a shore to the west of the present one and a sea level below the level of the adjacent till platform. If when at its maximum the Wester Ross Readvance ice stood at (and beyond) Cuaig, sea level had coincided with the till platform, some evidence should exist such as deltaic structures, outwash grading into the shoreline, marine alteration of the moraines, or a more southerly orientation of the channels as they debouched at the coast that would directly link the moraine to sea level. Such evidence has not been observed. Rather, the impression given is of superimposition of the ice-marginal features upon a fossil shoreline, with sea level already below the level of the till platform. The till platform therefore does not appear to be part of the Main Wester Ross Shoreline and may have formed earlier, during decay of the Late Devensian maximum ice.

When ice wastage allowed formation of P11 (Figure 5.12) within the Wester Ross Readvance limit at Cuaig, sea level stood at c. 26.8 m O.D. The foregoing arguments, however, suggested that at the maximum of the Wester Ross Readvance sea level stood below (possibly well below) 27 m O.D. This implies that following erosion of the till platform relative sea level initially fell and subsequently rose again, thereafter to fall with continued ice decay. Unfortunately there is no stratigraphic evidence for this possible regressive-transgressive sea-level movement apparently associated with the Wester Ross Readvance.

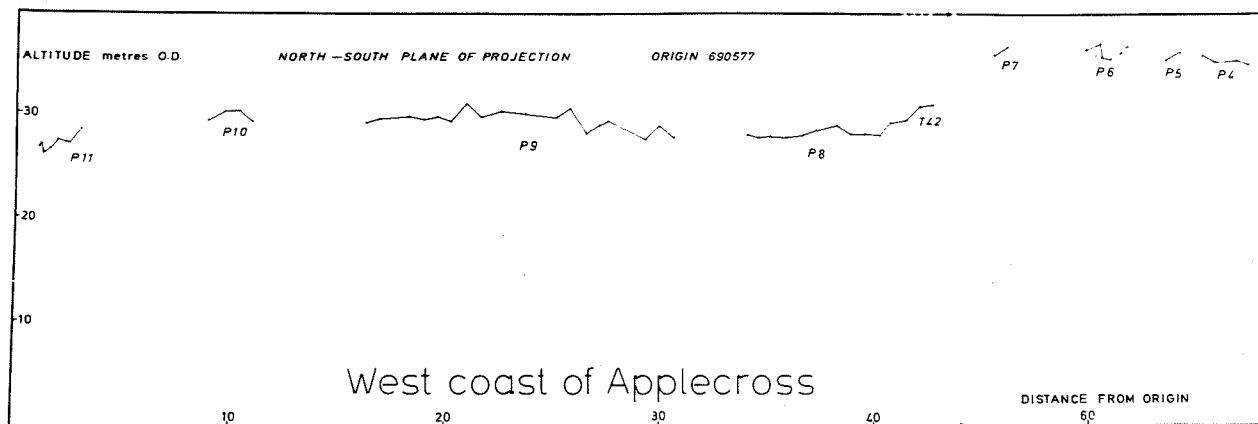


Figure 5.13. Height-distance diagram for raised shorelines shown in Figure 5.12.

The marine limit declines eastward up Loch Torridon to c. 21 m O.D. at Shieldaig, implying progressive ice retreat.

M Robinson

SALACHER (NG 683 510).

The highest shoreline on the west coast of Applecross is a rock platform which stretches intermittently for about 7 km from near Lonbain (Figure 5.12). This platform is generally between 25 and 75 m wide and backed by a rock cliff. It is followed by the new road where the coast trends east-west in to Applecross Bay, hence the loss of some field evidence in this part. The platform there is a well-marked feature fronted by precipitous slopes to the sea and backed by a steep vertical cliff with some rock debris along the break in slope. The gradients of frontal and rear cliffs associated with the platform tend to diminish along the west-facing coast, where the strike of the Torridon Sandstone bedrock is followed and the rear cliff is lower there. At its northern extremity the rear cliff appears very degraded and the platform itself is a gently inclined shelf dipping in steps seawards. Near Salacher rock stacks are preserved on the platform and narrow winding clefts in bedrock probably represent incipient stacks, marine erosion having ceased before they were isolated.

Levelling of the best-developed stretches of platform reveals a pronounced dip to the south, from 36 m to 34 m O.D. over 1.3 km (Figure 5.13). Approximate heights extracted from the surveyor's road plans mostly fall between 29 and 32 m O.D. for the section of platform affected by the new road, confirming continuation of this gradient. This dip is opposed to the expected gradient due to isostatic recovery, and along with the rather degraded and 'old' appearance of the feature, the reported occurrence of striae on the platform (Horne, on original 1:10,560 Geological Survey Field Slip) a pre-Lateglacial age is implied for this feature.

The abundance of till in the northern part of coastal Applecross, and the predominance of thinly-covered or bare rock in the south is believed to explain the distribution of the two shoreline features described above. The rock platform may be present and buried beneath till upslope from the till platform, but it appears that Lateglacial marine erosion, so effective in the north, made no impression on the rocky coastline to the south.

M Robinson

LOCH KISHORN (NG 81 39).

Three corrie glaciers flowed south-eastwards from the high Applecross plateau and terminated near the present shore of Loch Kishorn (Coire nan Arr, Coire na Ba, Coire Sgamhadail; Figure 5.4). Multiple end moraines indicate up to four fluctuations of the glaciers near their maximal positions. The clearly defined lateral and arcuate terminal moraine ridges reach several metres in height and frequently consist of strings of Torridon Sandstone boulders up to 5 m across, the moraines in places running uninterrupted for hundreds of metres. The former terminii in two cases reached below present sea level and in one (Coire nan Arr) across to the farther (eastern) shore of Loch Kishorn where numerous erratic blocks of sandstone are scattered on the Cambrian limestone rock platform and the shore. An inner ice limit for this glacier comprises an arc of boulders on the intertidal mud flats of the present River Kishorn estuary.

Between the end moraines of the Coire nan Arr and Coire na Ba glaciers, Howard Doris built an oil platform construction site in the mid-1970s: this destroyed some field evidence but produced interesting borehole data from offshore boreholes (Figure 5.14). Five borehole records show bedrock at c. 21 to 30 m below sea level overlain in four cases by silt and clay with some sand and gravel, then by much coarser deposits of sand with cobbles and boulders. In one borehole the finer stratum contained shells, of which samples were obtained. In view of the position of the boreholes, the coarse material is interpreted as outwash debris from one or both of the adjacent glaciers, overlying a marine deposit from a lower-energy environment of the early Loch Lomond Stadial or the Lateglacial Interstadial.

Further information about this Lateglacial marine environment was provided by identification of the shells (by Dr S Smith, Royal Scottish Museum, Edinburgh), part of a detrital deposit contained in the grey sandy silt layer 5 m above rock head (Table 5.3). The sediment resembles typical Lateglacial marine sediment of the 'Clyde Beds' type (Peacock, 1975). The wide variety of genera present implies that the assemblage belongs to the 'Clyde Beds' but apparently the warmer indicators usually found in these deposits are missing (Dr J D Peacock, pers. comm.). The relationship of the shell deposit to former sea level is not known, neither is the age of the shells, only that they grew in open water sometime after general deglaciation and prior to the Loch Lomond Readvance.

M Robinson

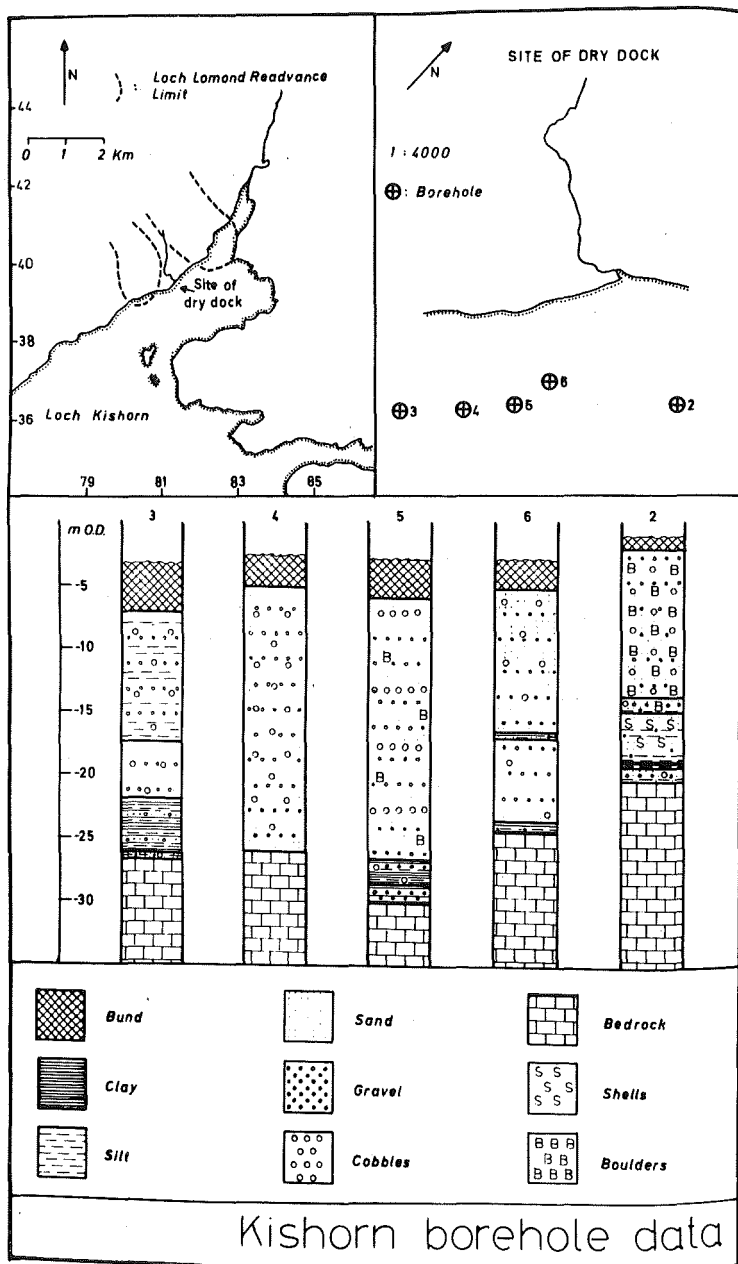


Figure 5.14. Details of boreholes in Loch Kishorn.

Table 5.3

Molluscs recovered from Lateglacial sediments in Loch
Kishorn.

Astarte borealis (Schumacher)
Astarte montagui (Dillwyn)
Astarte sulcata (da Costa)
Balanus cf. balanus (L)
Buccinum cf. tenue (Gray)
Chlamys islandica (Müller)
Cingula sp.
Crenella decussata (Montagu)
Echinoderm spines
Gibbula cineraria (L)
Littorina saxatilis agg. (Olivi)
Lora decussata agg. (Couthouy)
Macoma calcarea (L)
Margarites costulata (Möller)
Natica sp.
Nuculana pernula (Müller)
Parvicardium scabrum (Philippi)
Rissoa sp.
Yoldiella ambliia
Yoldiella fraterna.

(Identified by Dr S. Smith, Royal Scottish Museum,
Edinburgh).

GLASSCNOCK (NG 8670 4610) and DRUIM DUBH (NG 8845 4720).

Glassnock lies at 75 m O.D., 2 km downvalley from the well-developed outer terminal moraine of a presumed Loch Lomond Readvance glacier in Strath a'Bhathaich (Figure 5.3). Druim Dubh lies at 152 m O.D. between the second and third end moraine ridges of that former glacier, the moraines marking successive still-stands or minor readvances of the ice after it had reached its maximum extent. The stratigraphies of those sections analysed are as follows:

Glassnock.

| depth (m) | stratigraphy |
|------------|--|
| 4.99-5.245 | brown gyttja, abundant fine macrofossils. <i>Potamogeton</i> drupes present 5.14 to 5.17 m. Large leaf fragments present at 4.99 m |
| 5.245-5.41 | thixotropic pale grey clay and silt, very few macrofossils. |
| 5.41-5.48 | clay gyttja, few macrofossils. Sand present at 5.42 m. |
| 5.48-5.60 | greenish brown gyttja, moss macrofossils abundant at 5.52 to 5.50 m. Infrequent fine gravel at 5.51 m. |
| 5.60-5.61 | clay gyttja |
| 5.61-5.62 | white clay. |

Druim Dubh.

| depth (m) | stratigraphy |
|-----------|---|
| 6.11-6.12 | brown clay gyttja with fine macrofossils. |
| 6.12-6.16 | greenish brown clay gyttja. |
| 6.16-6.17 | grey-green clay gyttja. |

The lithological and biostratigraphical records from the two sites are presented in Figures 5.15, 5.16 and 5.17, the pollen data being in concentration values, i.e. thousands of grains per cubic centimetre of sediment.

The Lateglacial: Glassnock.

The lithostratigraphy corresponds markedly with the changes in total fossil concentration and individual taxon curves (Figures 5.15 and 5.16). The outstanding feature is the relatively low concentration values present through zone G-3, which covers most of the clay and silt stratum. Below this, 20 cm of gyttja and clay gyttja contain much fossil pollen and spores, and the overlying

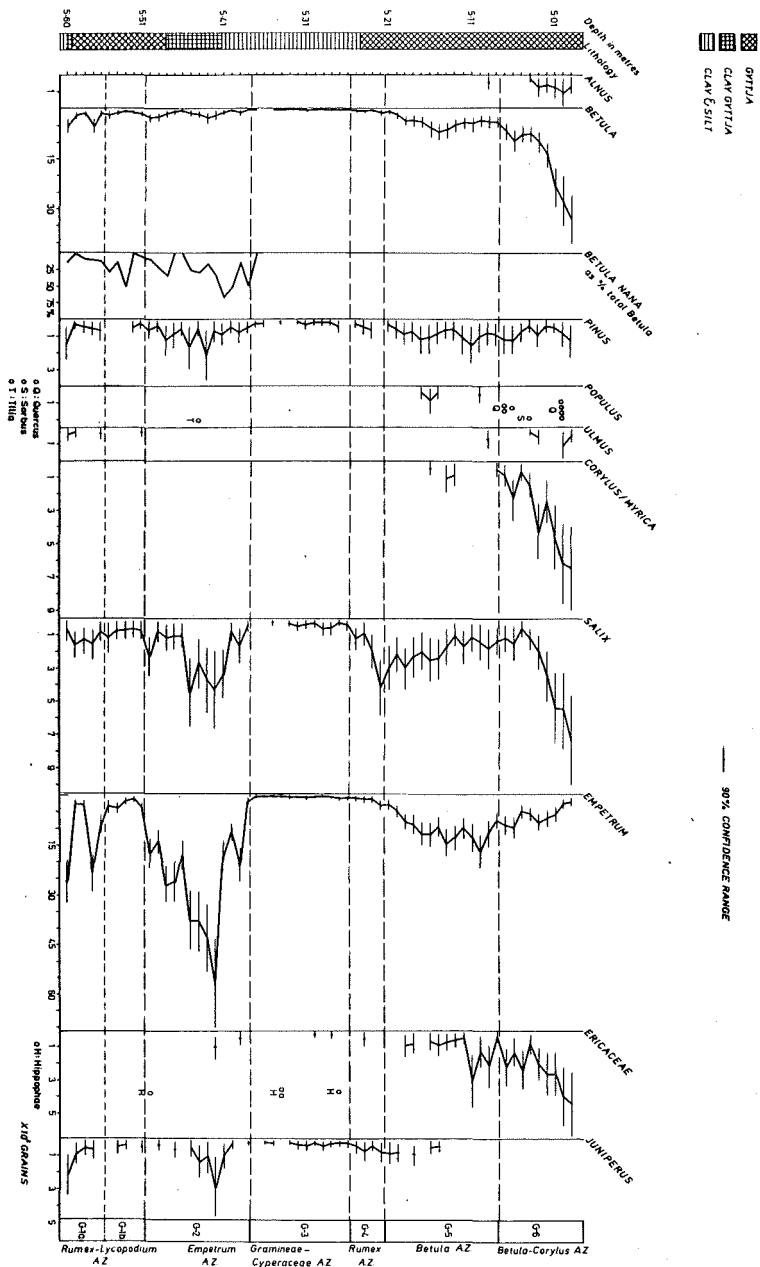


Figure 5.15. Glasscock: Trees and shrubs pollen diagram for the Lateglacial and early Flandrian.

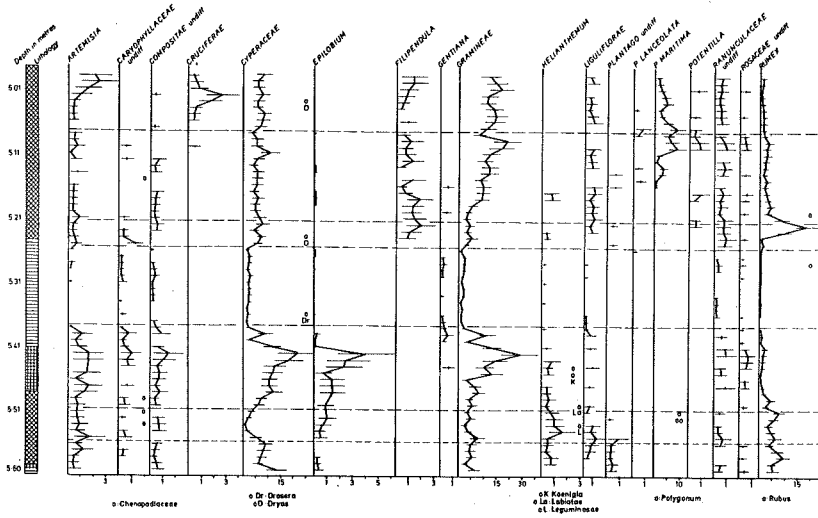
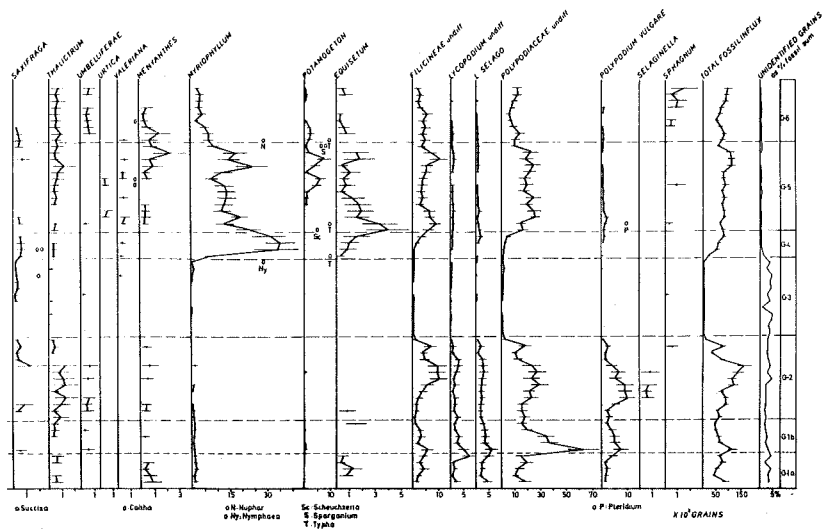


Figure 5.16. Glasscock: herbs, aquatics and spores diagram for the Lateglacial and early Flandrian.



gyttja which grades upward into fibrous peat (at c. 4.86 m) is similarly rich in pollen. The organic sediments represent the biogenic products of the kettle hole basin with open water.

The pollen spectra confirm the Lateglacial character of the basal organic and minerogenic sediments: well-known heliophilous ruderals and 'opportunistic' taxa such as *Rumex*, *Artemisia*, *Heliathemum* and *Thalictrum* are abundantly represented whereas the thermophilous types do not appear until later, above the isolated minerogenic layer. Some tree pollen is present: *Pinus* being almost continuous, and *Tilia* and *Ulmus* occur sporadically. Evidence from other pollen diagrams suggests immigration of *Pinus* into the area after 8000 yr BP and the absence of *Tilia* and meagre development of *Ulmus* at any time in North West Scotland (Birks, 1977). The source(s) of the thermophilous arboreal pollen may be local, i.e. till or other slope deposits which incorporated pollen from a previous interstadial/interglacial, subsequently washed into the basin under periglacial conditions. If this was the case, however, a greater representation of such pollen should occur in those strata most affected by solifluction, i.e. basal sediments and the Stadial minerogenic layer. The marked decline in *Pinus* values through zone G-3 implies that this was not the case, and a non-local source and long-distance transport are inferred. The presence of *Ulmus* in the two lowest levels and a fairly high representation of *Pinus* in the basal level may indicate that some inwashing of secondary grains did occur, but the relative importance of these two sources is impossible to assess. The occasional grains of *Hippophae rhamnoides* (Birks, 1973), and those grains of *Ambrosia/Xanthium* type (classified under Compositae undiff. here) which were noted by R Andrew (pers. comm.) are also believed to be of secondary origin.

Alongside the herbs, dwarf woody shrubs were obviously present in the Lateglacial vegetation, being most abundant in zone G-2. A low scrub including *Betula nana*, *Salix* spp., *Empetrum* (most likely *E. nigrum* cf. Godwin, 1975), and *Juniperus communis* probably dominated areas of relatively stable substrate, *Empetrum* possibly acting as a pioneer shrub on mineral soils (Gimingham, 1972). Its apparent abundance at this time implies the prevalence of cool oceanic conditions (Brown, 1971).

Within the lower predominantly organic horizon, the total fossil concentration curve has two main peaks, one in early zone G-1b and the second in zone G-2. The intervening trough occupies most of zone G-1b and reflects low values of many taxa, especially *Empetrum* and Cyperaceae, while *Rumex* has slightly increased values. In view of the apparently homogeneous lithology in this section of the core it is most likely that a climatic change affecting plant growth caused the slight negative

oscillation, some critical threshold (e.g. of temperature or precipitation) having been crossed and having initiated the registered succession. Such oscillations in the pollen spectra of Lateglacial Interstadial diagrams are widely reported in the literature from North West Europe and the British Isles. The nearest sites recording such oscillations are in Sutherland and the Great Glen (Pennington et al., 1972; Pennington, 1975; Haworth, 1976), Mull (Lowe and Walker, 1986a), and the Grampian region (Donner, 1957; Vasari and Vasari, 1968). Where climatic conditions are invoked to explain the reversals in pollen curves from this period, reference is usually made to the Older Dryas episode (c. 12,000-11,800 yr BP, Pennington, 1975). If a genuine climatic fluctuation is recorded here in the early Lateglacial in Wester Ross, it seems logical to correlate it with the event which differentially affected all of North West Europe. At Glassnock the event caused a general reduction in pollen production, particularly in the dwarf shrubs. Influx of *Artemisia*, *Rumex* and *Heliathemum* pollen was maintained or exceeded previous levels. The implications are that most plants did not flower so freely or that their numbers were reduced in this period, while taxa known to thrive in open and disturbed conditions were less severely affected.

The pollen data from Glassnock register this climatic oscillation as a very minor event. Lowe and Walker (1986a) found tentative suggestions of such an Interstadial fluctuation at one Lateglacial site on Mull but not at another less than 40 km away: they inferred either purely local causal factors, or a very low-key climatic oscillation affecting only those communities existing near a critical threshold. Upland sites such as Glassnock, close to where 1000 years later extensive glacier ice built up to form an ice cap, might be expected to have been especially sensitive to such minor fluctuations in climate.

If an Older Dryas oscillation at Glassnock is reflected in the pollen curves, no corresponding lithological effect is noticeable in the lithostratigraphy. Throughout zone G-2, however, the minerogenic content gradually increases to almost 100% at 5.4 m. The decline of *Myricophyllum* (almost entirely *M. alterniflorum*) might imply a corresponding reduction in clear open water, but may also have been related to declining temperatures. Increased inwash of fine minerogenic material to create the clay gyttja could have resulted from diversion of a single stream or more widespread slope-wash into the basin: in either case a noted increase in the incidence of extremely shrunken *Empetrum* tetrads between 5.47 and 5.41 m (as initially at 5.61 m) is explicable as the result of grains lodged in soil particles of the catchment being redeposited in the basin. Similarly affected *Empetrum* and other pollen types were found in considerable quantities in the Lateglacial sediments of the Mull sites (Lowe and Walker,

1986a), but unlike Glassnock, this redeposition continued throughout the Stadial. An unknown proportion of the increase in all taxon concentration in zone G-2 could be similarly attributable to such secondary deposition.

Organic production in the kettle hole ceased at 5.41 m, being superseded by minerogenic sedimentation during the Loch Lomond Stadial. It is probable that the silts and silty-clays of the mineral stratum were derived from inwash of the surface of unconsolidated mineral soils on the slopes surrounding the basin. Microscopic examination of the sand grains from this layer (where the sand fraction constituted under 5% of the samples analysed) did not indicate aeolian transport, but some of the finer debris may have been derived from sources beyond the catchment of the kettle hole. Solifluction and wind transport of silt were both likely to have operated during the cold phase when glacier ice approached to within 2 km of the site. The resulting poorly-polleniferous stratum probably contains many redeposited fossils, but from the pollen record it appears that the dwarf shrubs with grasses, sedges, *Rumex*, and latterly *Saxifraga* provided such vegetation cover as existed at the time.

Artemisia pollen is notably lacking throughout almost all of G-3, and this pattern would accord with the inverse relationship inferred between *Artemisia* representation and contemporaneous snow cover (Walker, 1975; Birks and Mathewes, 1978; Lowe and Walker, 1986a). The known preference of many *Artemisia* species for relatively dry and continental conditions (Iversen, 1954; Berglund, 1966) suggests that such conditions did not exist in this area at any time during the Stadial. At sites elsewhere in both western and eastern Scotland the Stadial can be divided into an earlier, wetter period and a succeeding drier more 'continental' phase because of low *Artemisia* values followed by an increased representation. At Glassnock conditions were presumably so snowy during the entire Stadial, when the Strath a' Bhathaich glacier approached the site, that production of *Artemisia* pollen more or less ceased until organic deposition was resumed in the early Flandrian.

The lithological and biostratigraphical evidence presented on the pollen diagram and described above indicates that the Lateglacial Interstadial and Loch Lomond Stadial represented by zones G-1 to G-2 and G-3 respectively. Radiocarbon dating was carried out on four critical levels using bulked samples from cores adjacent to the analysed sequence, but the results unfortunately did not provide a credible chronological sequence and nothing is gained by their inclusion. Radiocarbon dating of the major events in the Scottish Lateglacial and early Flandrian is now well established (Walker, 1984) and it would be possible because of the clear changes in lithologies and pollen curves at Glassnock to assign

approximate dates to the episodes and events in vegetational succession, hence allowing estimation of sediment accumulation rates and pollen influx values instead of pollen concentration data (cf. Lowe and Walker, 1986b).

The Early Flandrian: Glassnock and Druim Dubh.

Minerogenic sedimentation in zone G-3 was followed by an abrupt resumption of organic production within the basin. Zone G-4 includes taxa common in the interstadial, with aquatic plants becoming abundant again and new thermophilous taxa, such as *Filipendula* and *Typha*, appearing. The latter suggests July temperatures at that time of above 14°C (Iversen, 1954). Pollen influxes from the dwarf-shrubs increase through zone G-4, *Salix* reaching dominance at the top of the zone. *Rumex* flourished for a relatively brief period: until this point the early Flandrian vegetation probably resembled that at the height of the Lateglacial Interstadial. Thereafter, continued climatic amelioration allowed immigration and succession to proceed beyond the stage previously reached.

Evidence of vegetational succession from a landscape initially dominated by dwarf-shrubs to one dominated by birch and hazel woodland is contained within about 18 cm of gyttja at Glassnock and 6 cm in the Druim Dubh basin. *Juniperus* and *Empetrum* declined as taller species arrived, eventually shading out the dwarf-shrubs and heliophilous herbs. The appearance and establishment of Ericaceae were possibly connected with the immigration of birch trees, since at least some of the taxon is believed to be attributable to *Vaccinium*, which may have formed an understorey in birch copses as occurs today in the Scottish uplands (Burnett, 1964). Alongside the first patches of woodland it is probable that tall herb meadow vegetation flourished: this is indicated (zones G-5, early G-6, DD-2a) by the relatively abundant *Filipendula*, the presence of *Urtica* and *Valeriana*, and the many other herbaceous taxa represented in these zones. Near the tops of the analysed core sections the rapidly increasing values of *Betula*, *Corylus/Myrica*, (and *Salix* at Glassnock) imply the imminent arrival of a closed woodland in which the pioneer trees aspen and rowan were also present. The steady *Pinus* concentrations indicate that coniferous woodland was still at some distance, and oak and elm were unlikely to have been local at this time. *Alnus* poses a problem: the continuous representation over 6 cm in upper zone G-6 may indicate its first appearance in the area, although this seems somewhat premature by comparison with other diagrams from North West Scotland (Birks, 1977) and with the diagrams from Mull where *Alnus* is believed to have been present in low quantities from about 7000 yr BP.

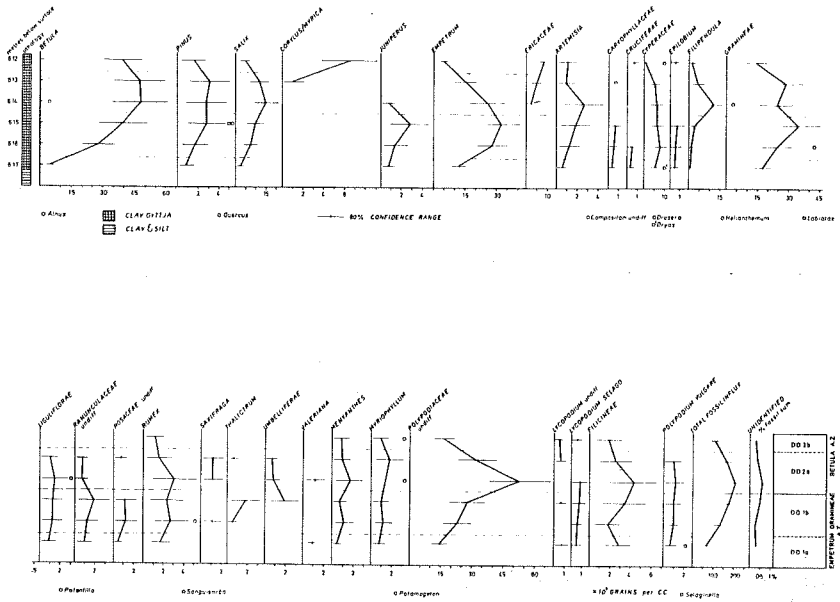


Figure 5.17. Druim Dubh. Early Flandrian complete pollen diagram.

Regional comparisons

A comparison of the vegetational succession described here with sequences from other sites in North West Scotland demonstrates both similarities and differences.

A Lateglacial sequence similar to the lower Glassnock diagram was recorded at Loch Droma (Kirk and Godwin, 1963), with *Empetrum* gaining dominance over *Rumex*, *Lycopodium*, and other pioneer taxa, while the top of the diagram indicates reversion to the earlier assemblage with much-increased *Artemisia*.

Pennington *et al.* (1972) and Pennington (1975) defined three Lateglacial zones and Flandrian Regional Assemblage Zones (NSI to NSVI) and chronozones (NWSI to NWSVI) for northern Scotland. Of the former, the earlier two (A and B) correspond well with zones G-1 and G-2, being dominated by *Rumex* and *Empetrum* respectively. Zone C is an *Artemisia* zone, but since this taxon is most frequent in the more easterly sites, the term is less appropriate in the west. The writer's transitional Flandrian zones G-4 and DD-1a correspond to NSI, and although *Juniperus* has no striking peak at Glassnock or Druim Dubh, Pennington *et al.*'s zone NSII is clearly the same phase preceding the arrival of closed woodland. NSIII can be equated with zone G-6 and upper zone DD-2 as it is at all sites the period of *Betula-Corylus* woodland.

At Loch Maree, an early Flandrian zone with high *Juniperus* and rising *Betula* (Zone LME-1, Birks, 1972) is followed by one showing joint dominance of birch and hazel.

This rather consistent pattern of Lateglacial and early Flandrian vegetational development indicates broadly uniform trends from Wester Ross and Sutherland. Interesting differences are evident, however, between this mainland pattern and that of the neighbouring Isle of Skye (Vasari and Vasari, 1968; Birks, 1973). In the Lateglacial there *Empetrum* was relatively unimportant and pollen percentages of *Rumex* are also decidedly lower than in mainland sites. The establishment of tree birch in the Sleat peninsula of Skye in the Lateglacial Interstadial preceded by probably over 1000 years the arrival of trees in the adjacent mainland. An implication might be that in the Interstadial climatic conditions on Skye were in general less severe than on the neighbouring land, with tall herb assemblages and localised birch copses instead of the dwarf-shrub heath which predominated elsewhere. Differences in edaphic conditions may also help explain these contrasts in vegetation, as base-rich soils were probably more common in at least parts of the island. A similar contrast in development of vegetation also applies in the very early Flandrian, but it ceases with the spread of mixed deciduous woodland on Skye and the mainland.

Conclusions

Interpretation of the litho- and biostratigraphy of the two basins supports the hypothesis that the end moraine lying between them was formed during the Loch Lomond Readvance. The development of vegetation throughout the Lateglacial and early Flandrian largely follows the trends established already for the north west mainland of Scotland. It is suggested that evidence exists of a minor climatic recession in the early Lateglacial Interstadial, sufficient to affect plant communities, but not severe enough to induce slope-wash at this site.

M Robinson

LOWER STRATHCARRON.

Two Loch Lomond Readvance glaciers terminated near the present head of Loch Carron, comprising the southern outlet glaciers of a large apron of ice, part of the ice cap that stretched from Glas Beinn to the slopes of Fuar Tholl. Two minor tongues of ice flowed north-west from the same source (Figure 5.3). At Tullich House (NG 918 428) near Loch Carron, a large complex mound of till marks the former snout of the Bhuachaig glacier. In plan, the deposit is arcuate with its western part missing and replaced by as true outwash fan that slopes seaward from near Tullich House. The distal slopes of the moraine have undergone trimming by the river and possibly, in part, by the Main Postglacial sea. The moraine margin is cut by two meltwater channels. From the front of the feature (14 m maximum height) the surface rises in four uneven steps; at the back, two 4 m high ridges trend east-west over the surface. A river-cut section here shows 3 m of till overlying c. 4 m of fluvioglacial strata, implying ice advance over outwash. A small till ridge exists beyond the steep front of this moraine complex and presumably marks the glacial limit. Clear lateral moraine ridges lead up-valley from the terminus.

The second moraine at the head of Loch Carron, i.e. that of the glacier which emerged from Coire Fionnaraich, is a long terminal ridge best preserved on the east side of the River Carron: this reaches 15 m in height with a broad undulating crest, and associated subsidiary mounds and ridges. The limit continues up the eastern valley side as a wide system of linear mounds. From the moraine an extensive peat-covered outwash fan stretches down-valley to the Flandrian raised beaches (Flandrian marine limit here being approximately 9 m O.D.). Up-valley from the end moraine are many fluvioglacial features typical of decaying ice - kames, kettles, kame terraces and eskers: these continue for 4 km and imply that the Fionnaraich glacier coalesced at its terminus with the Lair glacier, creating a large area of stagnant ice. A

spectacular belt of lateral moraine marks the limit on the north side of Strath Carron: this reaches c. 75 m in width and comprises multiple ridges under 5 m in height which trend sub-parallel, in its upper reaches bordering areas of fluted moraine.

Raised beaches in lower Strath Carron are relatively minor features, small beach ridges, sand spits, etc. with an obvious grouping at 7 to 7.5 m O.D. Two breaks of slope in the long profile of the Strathcarron outwash indicate the Main Postglacial limit (9.1 m O.D.) and a second period of marine activity when sea level lay between 6 and 7 m O.D.

On the south-east shore of Loch Carron at Achintee (NG 942 417), a very distinct terrace skirts the valley edge for 2.5 km. Levelling showed it to comprise a linked series of cones, some of the apices of which coincide with river/stream channels. The morphology and the deltaic bedding revealed in sections suggest formation by a series of streams depositing deltas which merged laterally. The mean height of this composite feature (23.7 m O.D.) suggests formation when the sea in Loch Carron stood near the Lateglacial marine limit (26 m O.D. here), and when large quantities of alluvial material were available.

On the north shore of lower Loch Carron large fluvioglacial features far outside Loch Lomond Readvance limits record the former existence there of a down-wasting ice lobe, related presumably to the last phase of glaciation prior to the Lateglacial, the Wester Ross Readvance (though no moraines belonging to this phase are presently known in this area). At North Strome (NG 858 354) two terraces interpreted as a kame terrace and an ice-marginal delta (at c. 34 m O.D. and 16 m O.D. respectively) are associated with small meltwater channels, the delta showing foreset bedding dipping landwards from a source lying to the south. At Ardaneaskan (NG 835 353) 2 km to the west of Strome, a large terrace slopes from over 30 m O.D. (eastern end) to 25 m O.D. in c. 0.5 km. Coarse pebbles and cobbles comprise much of this feature but massive, convoluted silty sands fining upwards into clays are also present in the terrace front (NG 838 354). This feature is interpreted as a kame terrace and it is probable that it is contemporaneous with the even larger terrace on the south shore of Loch Carron near Achmore (NG 855 336) of approximately the same altitude.

M Robinson.

6. OTHER SITES OF QUATERNARY INTEREST IN WESTER ROSS

THE BAOSBHEINN PROTALUS RAMPART (NG 854 677)

By far the most impressive protalus rampart hitherto described in Great Britain is located at 450 m altitude downslope of Torridon Sandstone cliffs and talus at the north-west end of the Baosbheinn ridge in the Torridon hills 6 km south-west of Loch Maree. In a paper devoted to interpretation of this feature, Sissons (1976c) noted that the rampart apparently comprises two distinct ridges: an openwork, unvegetated upper ridge (AB in Figure 6.1) composed of large Torridon Sandstone boulders, and a lower ridge (CD in Figure 6.1) with few large boulders and covered by vegetation and peaty soil. He described the combined length of the two ridges as exactly 1 km and noted that the distal slope reaches a height of 55 m, dimensions which imply that the Baosbheinn rampart is the largest yet described anywhere in the world (Washburn, 1979, p. 234). Sissons interpreted both ridges as a protalus rampart 'complex' of Loch Lomond Stadial age, arguing that the formation of the feature must have occurred under periglacial conditions that prevailed after ice-sheet deglaciation but before the onset of the relatively mild conditions of the Flandrian. He inferred that the lower ridge formed under cool cloudy conditions dominated by southeasterly snow-bearing winds early in the stadial, and that the subsequent formation of the upper boulder ridge (AB) reflected an abrupt drop in temperature and reduction of cloud cover with the onset of full-stadial conditions.

Ballantyne (1986a), however, has outlined various inconsistencies in Sissons' interpretation, in particular (i) the restriction of large boulders to the boulder ridge (these are absent from surrounding talus slopes), (ii) the lack of rockfall source areas above the lower ridge, (iii) the presence of Cambrian Quartzite erratics in the lower ridge, and (iv) the presence of a further lower ridge (EF in Figure 6.1) that is not mentioned by Sissons. He demonstrated that the sedimentological characteristics of the lower ridge are almost identical to those of a Wester Ross Readvance lateral moraine mapped by Robinson and Ballantyne (1979) c. 4 km south-west of the rampart, and are utterly different from those of the boulder ridge. Geomorphological mapping of the area established that the two lower ridges CD and EF are apparently also lateral moraines that define the southern margin of a former ice mass that moved westwards from the Loch Maree trough at the culmination of the Wester Ross Readvance. The readvance limit cannot, however, be traced across the intervening ground as the lateral moraines marking the southern limit of the Wester Ross Readvance have apparently been removed by the later north-westwards advance of a glacier along the

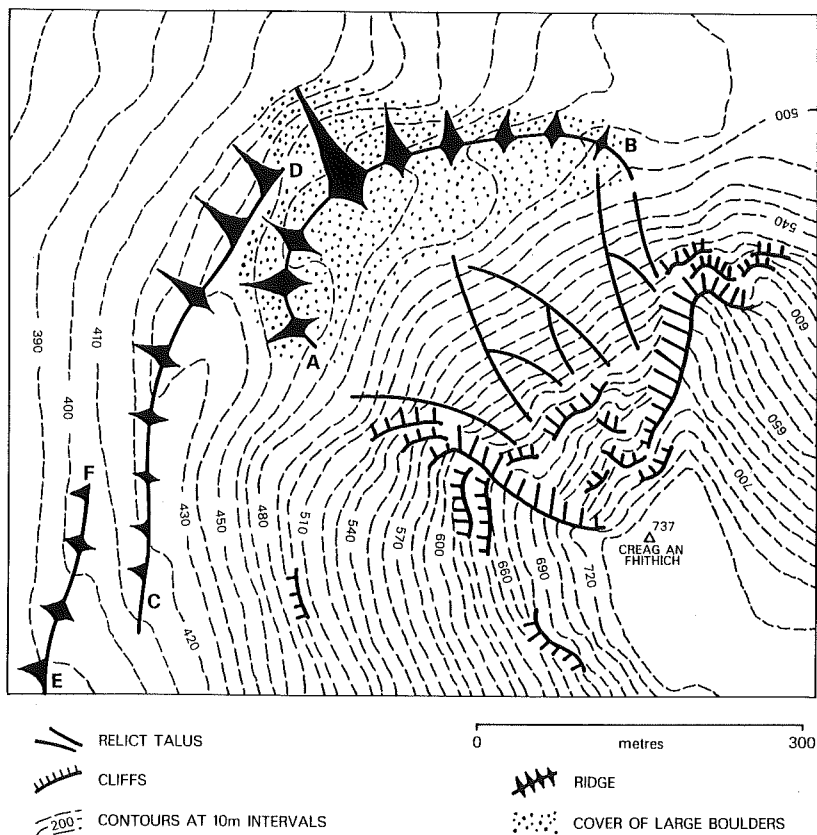


Figure 6.1: Plan of the Baosbheinn protalus rampart, showing the boulder ridge (AB), the lower ridges (CD and EF), and the distribution of cliffs, relict talus and the cover of large boulders (from Ballantyne, 1986a).

south-west flank of Baosbheinn during the Loch Lomond Stadial (Figure 6.2).

The interpretation of the upper boulder ridge as a 'conventional' protalus rampart also seems questionable: not only is the ridge unusually large for a protalus rampart (cf. Ballantyne and Kirkbride, 1986), but also the volume of rock it contains implies c. 14.3 m of rockwall retreat during the stadial, which is an order of magnitude greater than that implied by other ramparts of similar age (Ballantyne and Kirkbride, 1987). Ballantyne (1986a) has suggested that the massive size of this ridge and its constituent debris may be accounted for in terms of a major rockslide or series of rockslides over a former snowbed, pointing out (i) that this would account for the restricted distribution of large boulders (Figure 6.1), (ii) that the configuration of the slopes above the rampart resembles a major rockslide scar, and (iii) that the most extensive rockwall areas overlook the flanks of the ridge, not its centre, yet the ridge is thickest in the centre, an anomaly that is difficult to explain in terms of accumulation through discrete rockfall events but which is readily accounted for in terms of a single slope failure or series of such failures.

Interestingly, Sissons (1976c) noted the presence of a depression containing two closed hollows near the centre of the boulder ridge and suggested that these were produced by the melting of underlying snow, névé or ice. These may also be explained by the almost instantaneous burial and subsequent melting of firn or ice under rockslide debris. The burial of ice of whatever form suggests the possibility that the 'rampart' may have experienced some forward movement through deformation of buried ice, in which case it may be more properly classified as a protalus (talus-foot or valley-wall) rock glacier. Such rock glaciers with rather similar morphology have been described elsewhere in Scotland (e.g. Dawson, 1977). It is also notable that several protalus rock glaciers in Scotland, such as those in Strath Nethy and elsewhere in the Cairngorms, are also associated with rock-slope failure scars upslope (A.F. Maclean, personal communication).

Other features of interest in the Baosbheinn area

Below a small cliff at NG 830 660 a double lateral moraine marking the limit of the Loch Lomond Readvance glacier that occupied the trough south-west of Baosbheinn truncates a boulder-strewn triple lateral moraine that marks the limit of the Wester Ross Readvance (Figure 6.2). This site illustrates *par excellence* the differences in the configuration and distribution of glacier ice of the two readvances, the Wester Ross Readvance representing an interruption in overall ice-sheet retreat and the Loch Lomond Readvance representing partially or totally renewed glaciation with source areas on high ground. It reveals

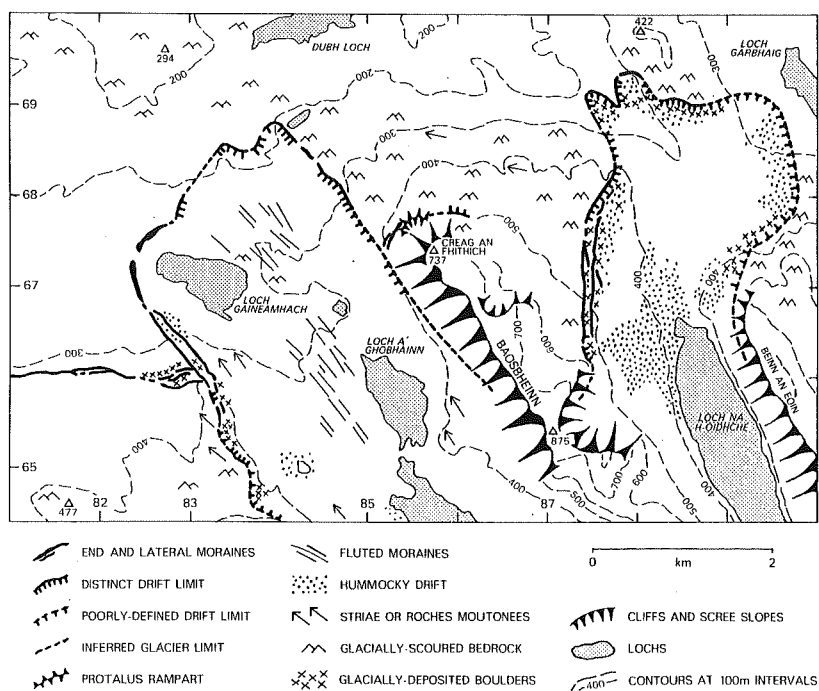


Figure 6.2: The limits of former glaciers and associated landforms in the vicinity of Baosbheinn (from Ballantyne, 1986a).

that terrain which escaped glaciation during the Wester Ross Readvance was in places ice-covered during the much more restricted Loch Lomond Readvance.

To the east of Baosbheinn a double lateral moraine and excellent drift limit mark the limit of the Loch Lomond Readvance in the Loch na h-Oidhche trough; thick hummocky drift is widespread inside this limit, but outside it drift is sparse and there are broad outcrops of ice-scoured bedrock. The lateral moraine terminates northwards in an area of hummocks, ridges and ice-transported boulders that define a former double terminal lobe (Figure 6.2) that is bisected by a steep rock knoll at NG 879 690.

The Torridon Sandstone summit ridge of Baosbheinn supports a cover of frost-shattered mountain-top detritus flanked by thin niveo-aeolian sand deposits above c. 700 m altitude. Interestingly, the northern part of Beinn an Eòin, 4 km to the south-east, exhibits ice-scoured Torridon Sandstone bedrock to an altitude of 715 m (NG 897 660), though the summit ridge of Beinn an Eòin above c. 800 m also supports deep *in situ* frost-weathered regolith. These relationships imply that a high-level periglacial trimline descends in a north-westerly direction across the northern Torridon hills, and suggest that the ice mass responsible for cutting this trimline moved over the northern part of Beinn an Eòin, but that the higher southern part of this mountain and all of Baosbheinn remained as nunataks above the ice at its greatest thickness. They also reveal that the trimline in this area represents a much thicker ice mass than that represented by the Wester Ross Readvance moraines (Figure 1.3).

The south-east slope of Baosbheinn supports a fine assemblage of debris flows and related features, including extensive debris cones produced by repeated accumulation of debris flow deposits at the foot of the slope (Strachan, 1976). As these cones lie within the limits of the Loch Lomond Readvance (Figure 6.2), they must have developed since final deglaciation. Many of the debris flows are recent.

THE SOLIFLUCTION FEATURES OF THE FANNICH MOUNTAINS

The Fannich Mountains support some of the finest active solifluction features in Great Britain. Active solifluction sheets and lobes occupy gentle and moderate gradients along the entire length of the Fannich ridge above 800-900 m altitude, the presence of such features here being favoured by the frost-susceptible 'type 3' regolith on which they are developed (Ballantyne, 1987). Morphologically, the most impressive forms comprise a great 'stairway' of solifluction sheets that occupy gradients of 6-18° between 950 m and 1050 m immediately south of the summit of Sgurr Mòr (1110 m; NH 203 719). Individual sheets range in length

from 25 m to well over 100 m, with treads 6-12 m wide and risers 0.4-1.4 m high. Vegetation cover is virtually complete, but eastwards the solifluction sheets merge with large turf-banked terraces or sheets with relatively unvegetated treads. On the steeper slopes to the west the terraces become progressively more lobate in form (Ballantyne, 1981).

Recent movement of most of the solifluction features is evident in steep and often bulging risers, and excavation of these frequently reveals buried soils and plant matter. A buried podzol was traced for over 3 m upslope under a lobe at c. 840 m altitude on the slopes of Sgurr nan Clach Geala at NH 186 722 by Ballantyne (1986c). A series of radiocarbon dates obtained on samples from the very top of an intact B horizon at various distances upslope from the lobe snout proved statistically indistinguishable from a date on a sample from the top of the same horizon immediately downslope (Figure 6.3), which indicates very rapid, very recent downslope movement of the lobe over a distance of at least 3 m.

Ploughing boulders are widespread on areas supporting active solifluction sheets and lobes, but rare elsewhere. Those on the Fannichs occur on gradients of 10-34°; boulder widths generally fall in the range 0.3-2.0 m, furrow depths within the range 0.1-0.4 m, and although furrow lengths of up to 19 m have been measured, most furrows are less than 6 m long. Present-day rates of boulder movement average a few millimetres to a few centimetres per year, and are strongly controlled by gradient. Study of the characteristics of the Fannich ploughing boulders led Ballantyne (1981) to propose that boulder movement accompanies the thawing of ice lenses under boulders during thaw of the surrounding frost-susceptible sediments, an explanation that accounts for the close association ploughing boulders with active solifluction features and their rarity in upland areas that do not support such features.

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