Quaternary of Scotland

Edited by

J. E. Gordon

Scottish Natural Heritage
Edinburgh, Scotland.

and

D. G. Sutherland

Edinburgh, Scotland.

GCR Editor: W. A. Wimbledon

JOINT NATURE CONSERVATION COMMITTEE

CHAPMAN & HALL

London · Glasgow · New York · Tokyo · Melbourne · Madras

Chapter 7

Inverness area

INTRODUCTION

D. G. Sutherland and J. E. Gordon

The Inverness area comprises the lowlands along the Moray Firth coast from the Dornoch Firth to east of Nairn, the upland areas of the hinterland and the glaciated valleys extending to the west and south-west, including the Great Glen (Figure 7.1). The principal focus of research on this area has centred on the evidence for the last ice-sheet, the pattern of deglaciation and the changes in relative sea level that both accompanied and followed the ice wastage (Auton, 1990a; Firth, 1990a). Until recently, only one deposit was known to pre-date the Late Devensian, the high-level shelly clay at Clava. However, the discovery of possible Hoxnian deposits at Dalcharn and probable Early Devensian interstadial deposits at a site on the Allt Odhar, both associated with multiple till successions, together with detailed reinvestigation of the Clava succession, has enabled the development of a provisional stratigraphy extending back to the Anglian (Merritt, 1990a).

The Inverness area was glaciated during the Pleistocene by one of the major ice streams flowing out from the Highlands, receiving ice from the mountains both to the north and the south of the Great Glen. The pattern of striations indicates that the ice generally moved towards the north-east during the later phases of glaciation (Merritt, 1990a) and was channelled into the inner Moray Firth, beyond which it diverged and flowed back on to the land in both Caithness (Chapter 5) and in Buchan (Chapter 8). As discussed for other regions, such an ice-flow pattern may have occurred on more than one occasion during the Pleistocene. On the higher ground between the Rivers Nairn and Findhorn, there is evidence for an earlier southwards ice-movement in the form of striations aligned north–south and the transport of Middle Old Red Sandstone erratics from source areas around Loch Ness and the inner Moray Firth (Horne, 1923; Merritt, 1990a).

Early work in the area recorded the presence of many glacial features including striations, erratics, moraines, glaciofluvial deposits and terraces (Jamieson, 1865, 1874, 1882b, 1906; Fraser, 1877, 1880; Aitken, 1880; Milne Home, 1880a; MacDonald, 1881; Cameron, 1882a, 1882b; MacDonald and Fraser, 1881; Wallace, 1883, 1898, 1901, 1906; Mackie, 1901; Peach *et al.*, 1912; Horne and Hinxman, 1914; Hinxman and Anderson, 1915; Horne, 1923), as well as a high-level (*c.* 150 m OD), shelly clay at Clava (Fraser, 1882a, 1882b; Horne *et al.*, 1894). In the Geological Survey Memoirs (Peach *et al.*, 1912; Horne and Hinxman, 1914; Hinxman and Anderson, 1915; Horne, 1923), three phases of glaciation were recognized: a period of maximum glaciation in which the whole landscape was covered by ice moving out from the mountains to the west and south, a period of confluent valley glaciers as the higher hills became ice-free and a final valley-glacier period accompanied by the formation of moraines. In the area south of the Moray Firth, ice-dammed lakes formed as the ice retreated (Horne, 1923). Later, Bremner (1934a, 1939c) and Charlesworth (1956) developed similar ideas on ice recession and glacial lakes. The effects of glacial erosion have been variable across the area, generally being greater in the west than in the east. To the east of the Great Glen, pockets of deeply weathered bedrock have survived glaciation, as at Clunas, providing a link with the more extensive occurrences of this phenomenon in north-east Scotland (see Chapter 8). More recent studies of glaciofluvial landforms in mid-Strathdearn (Young, 1980) and in the adjacent Dulnain and Spey valleys (Young, 1977b, 1978) indicate that the ice-sheet wasted largely *in situ*. The pattern locally, however, may be quite complex. In the middle Findhorn valley (see below), Auton (1990b) identified six stages involving both downwasting and recession and also the formation of an ice-dammed lake.

In the inner Moray Firth area and in the valleys to the west, a series of ice-sheet recessional stages was proposed by Kirk *et al.* (1966), J. S. Smith (1966, 1968, 1977) and Synge and Smith (1980). Readvances or stillstands were recognized at Ardersier, Alturlie, Kessock, Englishton, Muir of Ord, Balblair-Contin and Garve. However, reassessment of the evidence by Firth (1984, 1989a, 1989b, 1990a) led him to propose an alternative model of progressive ice recession without significant interruptions.

Evidence for pre-Late Devensian deposits occurs at three sites in the Inverness area. At Dalcharn, an organic deposit containing pollen of interglacial affinity forms part of a complex glacigenic succession observed in two separate exposures (Merritt and Auton, 1990; Walker *et al.*, 1992). The organic deposit, which contains lenses of compressed peat of infinite radiocarbon age and appears to have been cryoturbated and glaciotectonically disturbed, overlies weathered outwash

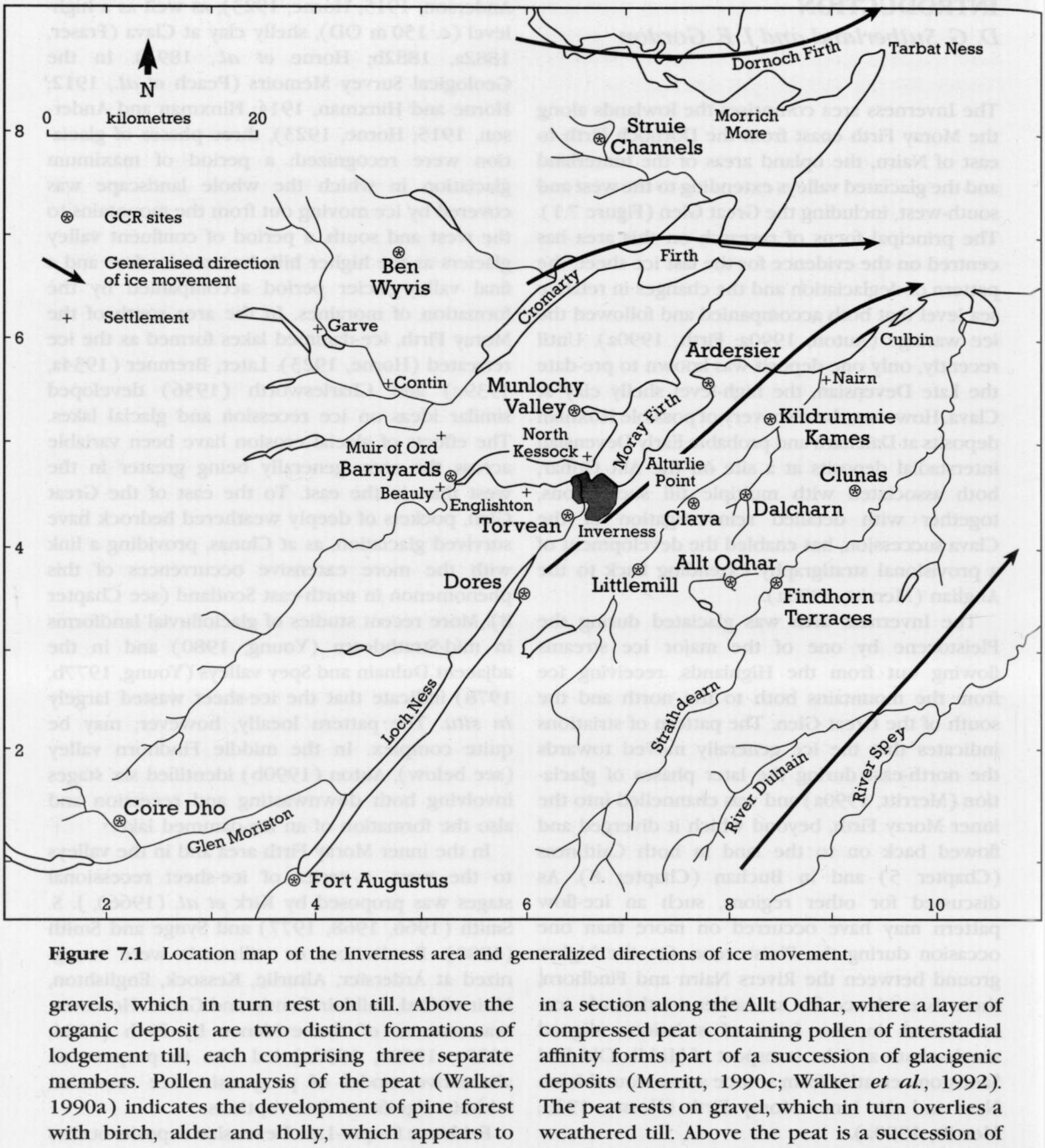


Figure 7.1 Location map of the Inverness area and generalized directions of ice movement.

gravels, which in turn rest on till. Above the organic deposit are two distinct formations of lodgement till, each comprising three separate members. Pollen analysis of the peat (Walker, 1990a) indicates the development of pine forest with birch, alder and holly, which appears to reflect an interglacial episode. The pollen record is similar to that from Fugla Ness in Shetland, which has been assigned to the Hoxnian, although such a correlation is now considered insecure (Lowe, 1984). At present, therefore, it is not possible to provide a firm age for the Dalcharn deposits (Walker, 1990a; Whittington, 1990; Walker *et al.*, 1992).

The second pre-Late Devensian deposit occurs in a section along the Allt Odhar, where a layer of compressed peat containing pollen of interstadial affinity forms part of a succession of glacigenic deposits (Merritt, 1990c; Walker *et al.*, 1992). The peat rests on gravel, which in turn overlies a weathered till. Above the peat is a succession of interbedded paraglacial deposits and till. Pollen analysis (Walker, 1990b) indicates a vegetation–climate cycle involving a succession from birch woodland with juniper and willow, through a phase of expansion of grassland and heathland, to an open landscape of species-poor grass and sedge communities. The peat has yielded an infinite radiocarbon date (Harkness, 1990) and a uranium series date of 106 ka +11/−10 ka, the latter placing the deposit in Oxygen Isotope Substage 5c (Walker *et al.*, 1992). The pollen and insect evidence also support an interstadial rather than an interglacial origin for the deposit (Walker *et al.*, 1992).

At Clava there is a high-level shelly clay. Originally discovered by Fraser (1882a, 1882b), this deposit was subsequently examined in detail by a committee of the British Association (Horne *et al.*, 1894) in the context of the debate about the existence of a major interglacial submergence of the British Isles. The majority of the committee considered the deposit to be in place and to result from such a submergence, but this was disputed (Bell, 1895a, 1897a). Later publications tended to emphasize the likelihood of the shell bed being a glacial erratic (Sissons, 1967a; Peacock, 1975b). More recently Sutherland (1981a) has suggested that the deposit is indeed *in situ* and results from a marine transgression consequent upon isostatic depression in front of an expanding Scottish ice-sheet. However, re-investigation of the site led Merritt (1990b) to conclude that the deposit is an erratic of marine sediments, transported by the Late Devensian ice-sheet from the Loch Ness basin.

The direction of movement of the last ice-sheet is well-illustrated by the transport of erratics from within the Highlands to the lower ground of the shores of the Moray Firth (Horne, 1923; Sissons, 1967a; Smith, 1977; Synge and Smith, 1980). Notable among these is the Inchbae augen-gneiss, fragments of which can be traced eastwards from its outcrop to the north-west of Ben Wyvis across the Black Isle and into the coastlands of Moray (Mackie, 1901; Peach *et al.*, 1912; Sutherland, 1984a). It is of interest that there is a distinct upper limit to these erratics on Ben Wyvis (Peach *et al.*, 1912), raising the possibility that the summit of this mountain was ice-free at the time of the maximum extent of the last ice-sheet. The major flow of ice emerging from the Great Glen is also reflected in the transport of erratics in an easterly direction (Horne and Hinxman, 1914; Horne, 1923; Bremner, 1934a; Peacock *et al.*, 1968).

The most striking landforms in the Inverness area relate to the period of deglaciation of the last ice-sheet. Particularly notable in this connection are the deposits at Ardersier and the sequence of glaciofluvial sediments that extends from Torvean at the mouth of the Great Glen at Inverness, through Littlemill to Kildrummie (Harris and Peacock, 1969; Smith, 1977; Synge and Smith, 1980; Firth, 1984). The deposits at Ardersier have been associated with a readvance of the last ice-sheet (J. S. Smith, 1968, 1977; Synge, 1977b; Synge and Smith, 1980), but this interpretation has been questioned by Firth (1984, 1989b). The esker and kame terraces at Torvean are outstanding landforms, among the largest examples of their type of Scotland, whilst the Flemington Esker at Kildrummie is one of the longest continuous such features in Scotland. Associated with such glaciofluvial deposits are meltwater channel systems, particularly on the higher ground and across spurs and interfluves. Young (1977b, 1980) has mapped the intricate sequences of channels in the valleys and hills to the south of Inverness, and a complex sequence of channels crosses the watershed between the Dornoch Firth and Cromarty Firth in upper Strathrory. Further elements in the suite of glaciofluvial deposits that resulted from the last deglaciation are outwash terraces, which are found in many of the valleys of the region. Along the River Findhorn, near the Streens Gorge, there is an extremely complex sequence of terraces (Young, 1980). This sequence was initiated during deglaciation and evolved still further during the Lateglacial and Holocene (Auton, 1990b).

Around the coasts the progressive ice wastage resulted in the formation of a series of raised shorelines (see Ardersier and Munlochy Valley). These are isostatically tilted towards the north-east, each successively younger shoreline extending farther west and having a lower gradient than its predecessor (Synge and Smith, 1980; Firth, 1984, 1989a). Shorelines also formed around Loch Ness at this time (see Dores and Fort Augustus), and were considered by Synge (1977b) and Synge and Smith (1980) to be marine, and part of the coastal sequence of shorelines. Firth (1984, 1986) has re-mapped these features and considers that there was no connection with the sea and that the shorelines are lacustrine in origin. As such, they are among the clearest former lake shoreline deposits in Scotland.

At the time of deglaciation, and continuing into the Lateglacial Interstadial, fossiliferous marine sediments were laid down in the sea lochs and along the coastal fringe. These have been studied in boreholes (Peacock, 1974a, 1977a; Peacock *et al.*, 1980) and, to date, no equivalents of the Errol beds (see Chapter 15 below), otherwise widely distributed on the east coast of Scotland, have been found in the inner firths of the Inverness area (Peacock, 1975c). This may suggest relatively late deglaciation of this area, although there is no dating evidence available to support such an idea.

There has been little investigation in the Inverness area of the Lateglacial Interstadial terrestrial environment. Pennington *et al.* (1972) and Pennington (1977a) provided details of pollen and other analyses carried out at Loch Tarff in the extreme south-west of the region. Following an initial phase of pioneer vegetation with species such as *Rumex* and *Lycopodium selago*, which are characteristic of disturbed, skeletal soils, there occurred a period of dwarf-shrub tundra with increased representation of *Empetrum*. A brief period of reduced *Empetrum* values then occurred, which may be correlated with the Older Dryas period of increased climatic severity between 12,000 and 11,800 BP. Thereafter there was a marked expansion of *Empetrum*, which was accompanied immediately prior to the onset of the Loch Lomond Stadial by a peak in juniper pollen. This period of *Empetrum* dominance corresponds to the major part of the Lateglacial Interstadial and represents a time of soil stability and increasing acidity as is also confirmed by the diatom assemblages contained in the sediments.

The events of the Loch Lomond Stadial left a strong imprint on the scenery of this area, most particularly in the south-west, which was invaded by glaciers flowing out from the ice-field of the western Highlands. Major outlet glaciers flowed along the Great Glen to terminate near Fort Augustus (see below) and along lower Glen Moriston. This latter glacier flowed across the exit to Coire Dho (see below) damming a lake and resulting in the production of an outstanding suite of landforms relating both to the ice-dammed lake (shorelines and cross-valley moraines) and to the drainage of the lake (water-swept bedrock and meltwater channels) (Sissons, 1977b).

Sissons (1979c) also suggested that certain of the deposits at Fort Augustus related to a *jökulhlaup*, when the ice-dammed lake in Glen Spean and Glen Roy (see Chapter 10) drained catastrophically during the decay phase of the Loch Lomond Readvance. He suggested that this raised the level of Loch Ness several metres and that the resultant flood and corresponding erosion of the glaciofluvial sediments in the Ness valley resulted in the construction of a major fan at Inverness, producing the narrows between Inverness and Kessock (Sissons, 1981c). Firth (1984, 1986) accepted the broad outline of Sissons' hypothesis, although he suggested modifications to details, such as the position of the ice front at the time of the supposed *jökulhlaup* and the precise nature of the changes in the level of Loch Ness accompanying the flood. In proposing this dramatic sequence of events, Sissons (1981c) also suggested that a marine erosion surface, which he identified underlying Holocene deposits at the head of the Beauly Firth and reaching an altitude a few metres above present sea level, was the equivalent of the Main Lateglacial Shoreline of the Forth valley.

Periglacial processes would have been active, particularly on the mountains during the Loch Lomond Stadial, and the large-scale, sorted ground features on Ben Wyvis may have received their final fashioning at this time, although the cover of frost-weathered debris on the summit area of that mountain may date from the early phases of deglaciation or, if the mountain was not in fact covered by the last ice-sheet, from the fully glacial part of the Late Devensian and earlier (Ballantyne, 1984; Ballantyne *et al.*, 1987).

There has been little study of the changes in the Holocene terrestrial environment of this region, although considerable work has been done on the evolution of the coastline. In the inner firths, Haggart (1982, 1986, 1987, 1988b) and Firth and Haggart (1989, 1990) have shown, by study of sites such as that at Barnyards, that during the early Holocene sea level initially fell, reaching a low some time after 9000 BP, then subsequently rose during the Main Postglacial Transgression to culminate, between 7100 BP and 5800 BP, in the formation of the Main Postglacial Shoreline. The subsequent fall in sea level to its present level is not securely dated, but several distinct shorelines were formed during this period, as is illustrated by the sequence of estuarine flats at Munlochy Valley (Firth, 1984). Elsewhere in the area, Holocene raised shoreline features are well-developed (Ogilvie, 1914, 1923; J.S. Smith, 1968, 1977; Comber, 1991; Hansom, 1991) and include shingle ridges (Dornoch Firth, Tarbat Ness, Spey Bay and Culbin) and sand beach ridges (Morrich More).

CLUNAS
A. M. Hall

Highlights

The stream section at Clunas illustrates the effects of differential weathering processes in a Devonian conglomerate. The survival of the weathered bedrock also highlights the relatively low intensity of glacial erosion in this area.

Introduction

The site at Clunas (NH 907446) is a stream exposure of weathered conglomerate at an altitude of 210 m OD on the Muckle Burn, 12.5 km south of Nairn. It is important for studies of deeply weathered bedrock, which is unusually widespread in both sedimentary and crystalline rocks to the east of Inverness and more especially in north-east Scotland (FitzPatrick, 1963; Hall, 1985, 1986; Hall *et al.*, 1989a). In particular, Clunas is a good example of deep weathering of a Devonian conglomerate, which is part of a small outlier of Middle Old Red Sandstone age (Horne, 1923). The site also gives important insights into the processes of differential weathering. The conglomerate contains large boulders of a variety of rock types and allows study of the chemical alteration of different rock types under identical environmental conditions. The only detailed study of the site is by Wilson *et al.* (1971).

Description

The conglomerate is exposed to a depth of up to 5 m and is overlain by up to 2 m of glaciofluvial gravel of probable Devensian age. The conglomerate contains large rounded boulders up to 1 m in diameter in various stages of weathering. Boulders of banded metaquartzite, metamorphosed grit and silicified volcanic rocks remain fresh, whereas boulders of granite and quartz–biotite-granulite are more or less decomposed to a clayey gritty sand.

The clay mineralogy of the weathered boulders has been studied in detail by Wilson *et al.* (1971). Feldspars, with the exception of microcline, are altered to montmorillonite. Kaolinite, derived from muscovite, is also present in smaller amounts. The presence of carbonate minerals lining microfractures in the weathered boulders indicates that these transformations occurred under a relatively closed, alkaline weathering system.

Interpretation

Chemically weathered rock is preserved at many sites in north-east Scotland and this reflects the relatively low degree of glacial erosion in the region. Deep weathering of Devonian sedimentary rocks is relatively rare (Hall, 1986), although several sites do occur around Elgin (Peacock *et al.*, 1968), Turriff (Hall, 1983) and between New Aberdour and Pennan (J. D. Peacock, unpublished data). At Clunas, the low degree of chemical alteration of the granite and granulite boulders is characteristic of the grus weathering type recognized by Hall (1985), which developed under humid temperate environments prior to the first regional glaciation, as well as during interglacial periods. The precise age of the weathering at Clunas, however, is presently unknown. The possibility that weathering of the boulders may have started soon after deposition in the Devonian has not yet been investigated, but is suggested by the presence of carbonate minerals infilling microfractures.

The site has interest for both regional pre-Pleistocene and Pleistocene geomorphology and also for its clay mineralogy. The survival of weathered bedrock demonstrates that the last, and probably the earlier, ice-sheets have failed significantly to lower the bedrock surface in the Clunas area. If the weathering is of pre-Pleistocene age, then minimal Pleistocene erosion has occurred (see Pittodrie) and the form of the pre-glacial landsurface can be reconstructed. The dominance of montmorillonite and the evidence of a relatively closed weathering system suggests that only the poorly drained base of the former weathering profile has been preserved. Elsewhere in north-east Scotland alteration of feldspars in granitic rocks generally gives kaolinitic clays (see Hill of Longhaven and Pittodrie) (Hall, 1983; Hall *et al.*, 1989a) and the abundance of montmorillonite at Clunas is therefore unusual. Its coexistence with small amounts of kaolinite, derived from alteration of muscovite, is also noteworthy as it demonstrates the importance of small-scale equilibria in clay mineral genesis (Wilson *et al.*, 1971).

Conclusion

Clunas forms part of a network of sites showing deeply weathered bedrock, one of the principal features of the geomorphology of north-eastern

Scotland. The example at Clunas is particularly interesting as the bedrock is a conglomerate in which pebbles of different lithologies show different degrees of alteration. Not only does the site provide insights into the processes of rock weathering, it also indicates minimal erosion by ice, a characteristic of this area during the Quaternary glaciations.

DALCHARN

C. A. Auton

Highlights

The sequence of sediments exposed in the stream sections at this site includes interglacial organic deposits which are both underlain and overlain by till. Although the deposits are undated, the sequence is remarkable for the detail of information it has yielded on the Quaternary history of the Inverness area and the potential it holds for providing further elaboration of this record.

Introduction

Sediments containing compressed and disseminated biogenic matter are exposed beneath a thick sequence of tills in a river cliff of the Allt Dearg at Dalcharn (NH 815452), some 6 km south-west of the village of Cawdor, near Nairn. The organic deposits, which lie at an altitude of *c.* 200 m OD, have been cryogenically and glaciotectonically disturbed, but contain pollen of full interglacial affinity reflecting the middle and later stages of an interglacial cycle. The overlying till sequence provides evidence of at least two separate glacial episodes, and although the age of the interglacial material cannot be firmly established at present it is probable that it pre-dates the Ipswichian.

The organic deposits occur near the bleached top of a deeply weathered gravel. The base of the gravel is not exposed at the section containing the organic material, but the gravel can be seen to overlie an older till at the base of another cliff section some 200 m to the north-east. Various aspects of these sections have been described by Bloodworth (1990), Merritt and Auton (1990), Walker (1990a), Whittington (1990) and Walker *et al.* (1992). Dalcharn provides the first evidence that the northern Grampian Highlands were covered by pine forest during at least one interglacial stage of the Middle or Late Quaternary.

Description

Exposures in the cliffs of the Allt Dearg, east of Dalcharn Cottages, display a succession of Quaternary sediments *c.* 25 m in thickness (Figure 7.2). The lithological subdivisions used in this account follow those of Merritt and Auton (1990) and Walker *et al.* (1992), and are based on a composite log of three sections: Dalcharn East (NH 81574537), Dalcharn West–Section A (NH 81464521) and Dalcharn West–Section B (NH 81434516), shown in Figure 7.3. The recognized sequence is as follows:

7.	Humic soil	*c.* 0.3 m
6.	Glaciofluvial gravel	up to 2.5 m
5.	Dalcharn 'upper till formation'	8.5–10.0 m
4.	Dalcharn 'lower till formation'	8.5–9.5 m
3.	Dalcharn 'biogenic formation'	1.3–1.6 m
2.	Dalcharn 'gravel formation'	up to 3.0 m
1.	Dearg 'till formation'	at least 1.0 m

The Dearg 'till formation' (unit 1) is a moderate yellowish brown, very stiff, massive diamicton, with abundant clasts of Devonian sandstone and is exposed beneath the Dalcharn 'gravel formation' at the Dalcharn East Section.

The Dalcharn 'gravel formation' (unit 2) is a poorly sorted, matrix-rich gravel, bleached in its upper part, containing a high proportion of decomposed and unsound clasts. The clay mineralogy of the matrix of this deposit, in which vermiculite occurs as a product of subaerial weathering, has been described by Bloodworth (1990).

The Dalcharn 'biogenic formation' (unit 3) is subdivided into an upper unit, the Dalcharn 'biogenic member' (0.5–0.6 m) and a lower unit, the Dalcharn 'cryoturbate member' (0.8–1.0 m). The uppermost 0.1–0.2 m of the 'biogenic member' comprises compact, laminated olive grey sandy and clayey silt with discontinuous wisps of pebbly sand and disseminated peaty matter. This overlies compact carbonaceous sandy silt and diamicton containing fibres and lumps of dark peaty material as well as discrete lenses, up to 0.05 by 0.01 m, of compressed sandy peat; an infinite radiocarbon date (>41,300 BP (GU–2340)) has been obtained from compressed peat close to the base of the 'biogenic member'.

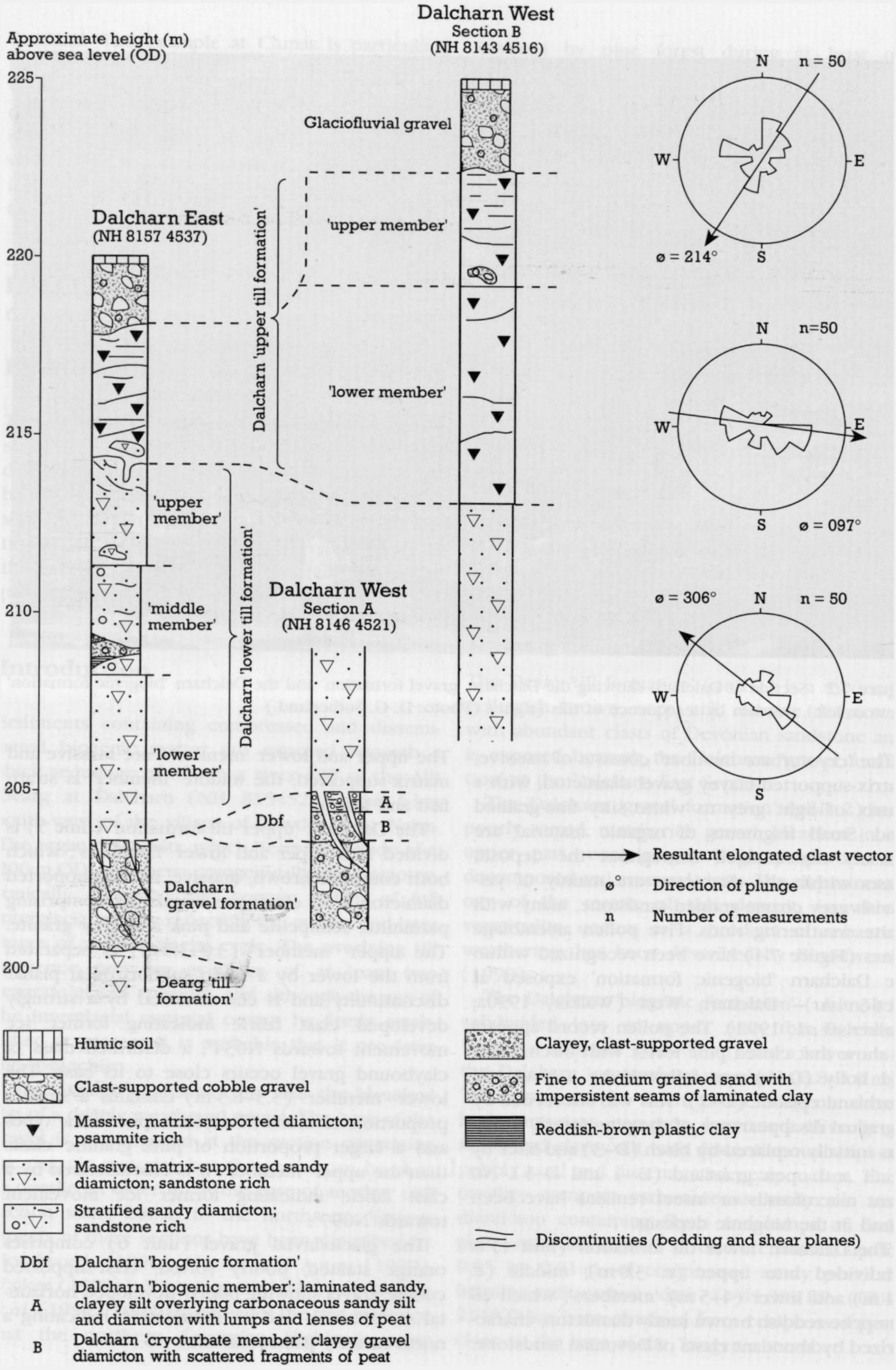
Figure 7.2 Section at Dalcharn showing the Dalcharn 'gravel formation' and the Dalcharn 'biogenic formation' (bottom left), overlain by a sequence of tills (right). (Photo: D. G. Sutherland.)

The 'cryoturbate member' consists of massive, matrix-supported clayey gravel diamicton, with a matrix of light grey to white silty fine-grained sand. Small fragments of organic material are sparsely disseminated throughout the deposit. Clasts within the diamicton are mainly of yellowish grey coarse-grained sandstone, many with white weathering rinds. Five pollen assemblage zones (Figure 7.4) have been recognized within the Dalcharn 'biogenic formation' exposed at Section A – Dalcharn West (Walker, 1990a; Walker *et al.*, 1992). The pollen record appears to show that closed pine forest with birch, alder and holly (D–1) was followed by a pine and heathland episode (D–2). This was succeeded by a gradual disappearance of the pine forest, which was initially replaced by birch (D–3) and later by heath and open grassland (D–4 and D–5). No plant macrofossils or insect remains have been found in the biogenic deposits.

The Dalcharn 'lower till formation' (unit 4) is subdivided into upper (*c.* 3.0 m), middle (*c.* 3.1 m) and lower (4–5 m) 'members', which all comprise reddish brown sandy diamicton, characterized by abundant clasts of Devonian sandstone. The upper and lower 'members' are massive and matrix-supported; the middle 'member' is stratified and friable.

The Dalcharn 'upper till formation' (unit 5) is divided into upper and lower 'members', which both comprise brown, massive, matrix-supported diamicton with clasts predominantly comprising psammite, semipelite and pink and grey granite. The upper 'member' (3.0–3.5 m) is separated from the lower by a sharp subhorizontal planar discontinuity and is characterized by a strongly developed clast fabric indicating former ice movement towards N034°; a deformed mass of claybound gravel occurs close to its base. The lower 'member' (5.5–6.5 m) contains a smaller proportion of clasts of metamorphic rock types and a larger proportion of pink granitic clasts than the upper 'member'; it is characterized by a clast fabric indicating former ice movement towards N097°.

The glaciofluvial gravel (unit 6) comprises orange stained, poorly sorted, clast-supported cobble gravel showing poorly developed horizontal stratification and an imbrication indicating a north-easterly palaeocurrent.



Dalcharn West
Section B
(NH 8143 4516)
Approximate height (m)
above sea level (OD)
225
220
215
210
205
200
Glaciofluvial gravel
'upper member'
'lower member'
Dalcharn 'upper till formation'
Dalcharn East
(NH 8157 4537)
'upper
member'
'middle
member'
'lower
member'
Dalcharn 'lower till formation'
Dalcharn West
Section A
(NH 8146 4521)
A
B
Dbf
Dalcharn
'gravel formation'
Dearg 'till
formation'
N
S
W
E
n = 50
ø = 214°
n=50
ø = 097°
ø = 306°
n = 50
Resultant elongated clast vector
ø° Direction of plunge
n Number of measurements
Humic soil
Clast-supported cobble gravel
Massive, matrix-supported diamicton; psammite rich
Massive, matrix-supported sandy diamicton; sandstone rich
Stratified sandy diamicton; sandstone rich
Clayey, clast-supported gravel
Fine to medium grained sand with impersistent seams of laminated clay
Reddish-brown plastic clay
Discontinuities (bedding and shear planes)
Dbf Dalcharn 'biogenic formation'
A Dalcharn 'biogenic member': laminated sandy, clayey silt overlying carbonaceous sandy silt and diamicton with lumps and lenses of peat
B Dalcharn 'cryoturbate member': clayey gravel diamicton with scattered fragments of peat

Interpretation

The occurrence of brown till with few sandstone erratics, overlying reddish brown till with abundant sandstone clasts is a common feature of many of the sequences of Quaternary deposits which mantle the high ground flanking the coastal lowlands of the Moray Firth between Inverness and Nairn. This stratigraphic relationship, which was first recognized by Fraser (1880) in Strathnairn and subsequently by Horne and Hinxman (1914) and Horne (1923) during the primary geological surveys of the surrounding districts, is clearly seen in the cliffs of the Allt Dearg and those of its tributaries. At Dalcharn, the recognition of discontinuities between the various tills, the change in composition of their clasts and in the orientation of their fabrics support the contention that the two till formations, which overlie the organic sediments and weathered gravel, are the products of at least two distinct glacial episodes.

Both 'members' of the Dalcharn 'upper till' formation contain flat-iron shaped cobbles and elongate clasts with striations parallel to their longer axes, and the matrices of both units are penetrated by subhorizontal fissures and sharp concavo-convex discontinuities. These features, together with the very poor sorting and overconsolidation of the diamictons, are considered to be characteristic attributes of lodgement tills (Dreimanis, 1989). The clast fabric of the upper 'member' indicates former ice movement towards the north-east, which is parallel to the general alignment of glacially streamlined features near the Dalcharn site. The fabric of the lower 'member' indicates former ice movement towards the east.

The relative abundance of clasts of Devonian sandstone, together with a weakly developed fabric suggesting former ice movement towards the south-east, serves to distinguish the Dalcharn 'lower till formation' from the overlying diamictons. This south-eastward direction of ice movement corresponds to the orientation of some striae on bedrock observed at a few sites on the high ground between Loch Moy and Loch Ness (see Merritt 1990a, fig. 1). The poorly sorted and overconsolidated nature of the upper 'member' of the 'lower till formation', the presence of striated cobbles and discontinuity surfaces suggest that it is probably a lodgement till, whereas the presence of winnowed horizons and discrete lenses of sand and gravel, particularly within the middle 'member' of the 'lower formation', suggests that these lower parts of the deposit may have been formed by basal meltout rather than by lodgement processes.

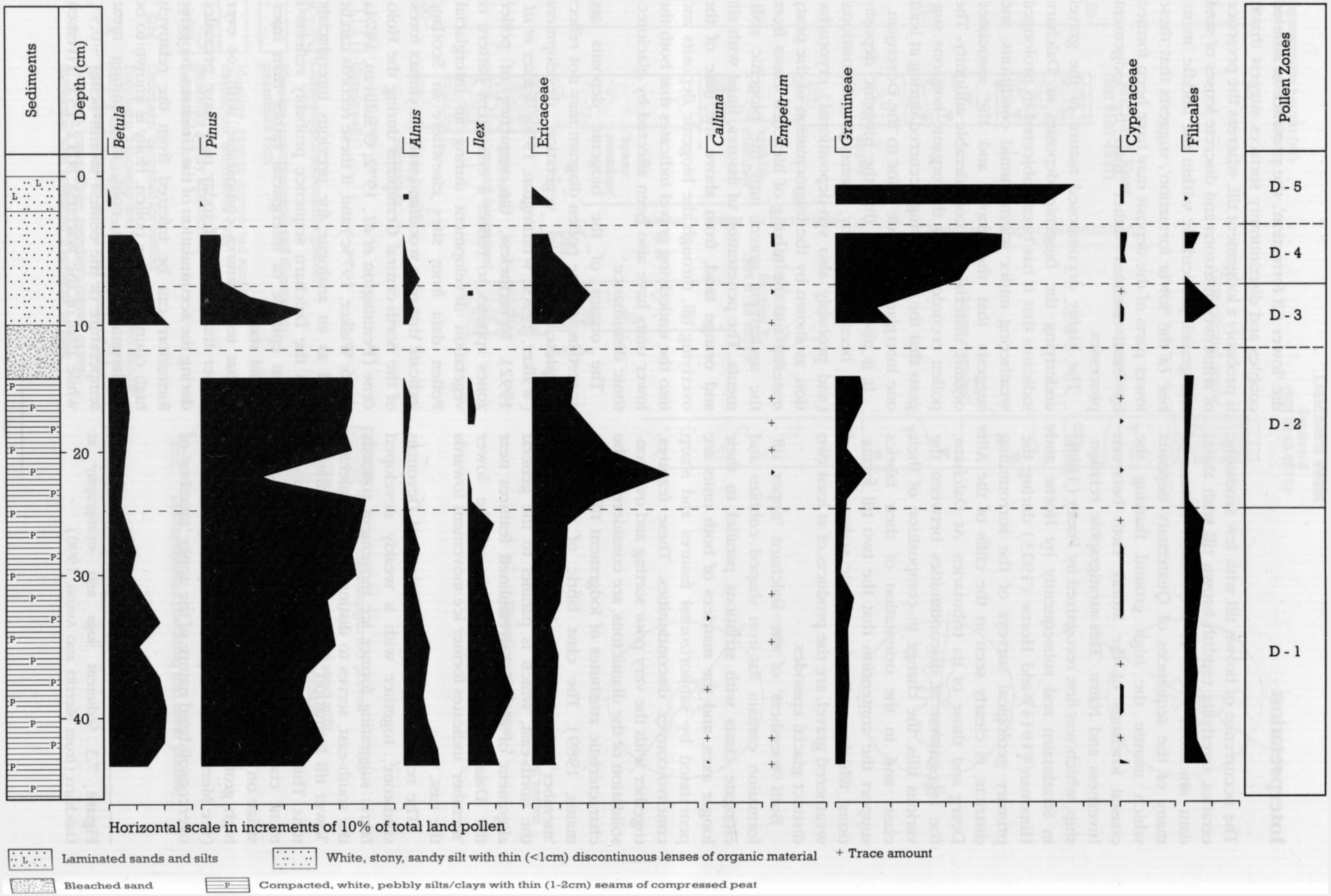
The highly decomposed nature of the gravel underlying the biogenic deposits at Dalcharn indicates that it has been subjected to prolonged weathering under warm humid conditions, and suggests that the gravel and the associated organic material is of considerable antiquity. The pollen recorded from the organic horizons suggests that the weathering occurred during at least one interglacial episode prior to the Devensian.

It is also apparent that the biogenic deposits have been affected by severe post-depositional (and probably also syn-depositional) cryoturbation, as shown by the fragmentation of the peaty material and the mixing of bleached clasts from the underlying gravel into the biogenic sediments. The penetration of fissures, lined with silt and orange sand, from above the base of the overlying till, through the biogenic deposits and into the underlying gravel indicates that both the lower units have also been affected by glaciotectonic disturbance.

The origins of the biogenic deposits are uncertain and the pollen diagram may not reflect complete sequential vegetation development (Walker, 1990a; Whittington, 1990; Walker *et al.*, 1992). Nevertheless, the sequence of pollen zones appears to reflect a consistent pattern of vegetation development during an interglacial. Pollen data from sites elsewhere in Scotland indicate that pine woodland was the climax forest of the north-central Grampians during the Holocene (Pennington *et al.*, 1972; O'Sullivan, 1974a, 1976; Walker, 1975c) and, if these records can be used as an analogue for previous interglacials, then the Dalcharn sequence probably reflects a warm episode of interglacial rather than interstadial status.

That temperatures comparable with, or even higher than, those of today may have prevailed during the accumulation of the Dalcharn 'biogenic formation' can be inferred from the relatively high counts for *Ilex* pollen. Holly is known to be intolerant of winter cold, the limiting mean temperature of the coldest month being −0.5°C while that of the warmest is 12–13°C (Iversen,

Figure 7.3 Sediment logs and stratigraphy at Dalcharn (from Merritt and Auton, 1990).



Sediments
Depth (cm)
Betula
Pinus
Alnus
Ilex
Ericaceae
Calluna
Empetrum
Gramineae
Cyperaceae
Filicales
Pollen Zones
D - 5
D - 4
D - 3
D - 2
D - 1
0
10
20
30
40
Horizontal scale in increments of 10% of total land pollen
Laminated sands and silts
White, stony, sandy silt with thin (<1cm) discontinuous lenses of organic material
+ Trace amount
Bleached sand
Compacted, white, pebbly silts/clays with thin (1-2cm) seams of compressed peat

1944). The Dalcharn site lies near to the present northern limit of *Ilex* in Britain (Godwin, 1975), and hence the relative abundance of *Ilex* pollen in Zone D–1 of the Dalcharn profile almost certainly reflects a climate somewhat warmer than that of today. The decline in *Ilex* at the D–1/D–2 boundary and its subsequent disappearance from the pollen record may therefore be seen as a response to deteriorating climatic conditions. Overall, the pollen record may represent the middle and later phases of an interglacial vegetation cycle, corresponding with the mesocratic, oligocratic and initial cryocratic phases of Iversen (1958) and Andersen (1966) (see also Birks, 1986).

The pollen assemblage from Dalcharn is similar in some respects to that described from Fugla Ness on Shetland by Birks and Ransom (1969), who equated the latter with the Gortian of Ireland, and hence the Hoxnian of southern England; although a Cromerian origin for the Fugla Ness record was not excluded. However, on present evidence it is not possible to firmly attribute either the Dalcharn or the Fugla Ness record to a particular interglacial within the Middle or Late Quaternary. Similarly, correlations with other interglacial or interglacial/interstadial sites in Scotland cannot be made. The pollen records from Sel Ayre on Shetland (Birks and Peglar, 1979), Toa Galson in north-west Lewis (Sutherland and Walker, 1984) and Abhainn Ruaival on St Kilda (Sutherland *et al.*, 1984) are characterized by open grassland or heathland vegetation, and there are difficulties in establishing correlations with the palaeosols at Teindland (Edwards *et al.*, 1976) and Kirkhill (Connell *et al.*, 1982) in north-east Scotland (Lowe, 1984; Walker, 1984b).

The pollen assemblage at Dalcharn represents the first record of an undoubted interglacial deposit beneath tills in the Moray Firth area, and is the first to provide unequivocal evidence of interglacial pine forest and its history. The presence of till beneath the weathered gravel at Dalcharn is also the first reported occurrence of a glacial deposit formed prior to at least one interglacial of the Middle or Late Quaternary on this part of the Scottish mainland. This recognition of pre-Late Devensian glacial and interglacial sediments has critical implications for the interpretation of multiple till sequences throughout northern Britain, which have hitherto been attributed to variations in the direction of movement within a single Late Devensian ice-sheet, but which may in fact represent successive earlier glacial episodes.

Conclusion

The sequence of deposits at Dalcharn is of considerable importance for the evidence it provides for the climatic and glacial history during the Quaternary. Although dating has yet to be firmly established, the length and detail of the record are exceptional, including evidence for an interglacial (temperate climate) and episodes of multiple glaciation and periglacial conditions. The interglacial deposits are significant in providing the first clear record of interglacial pine forest development in Scotland. The site has outstanding potential for elucidating further the glacial history of Scotland.

ALLT ODHAR

J. W. Merritt

Highlights

The stream section at Allt Odhar contains a bed of peat preserved within a sequence of glacial deposits. Analysis of pollen, plant-macrofossil and beetle remains, preserved in the peat, has allowed a detailed reconstruction of environmental conditions during an Early Devensian interstadial, the only one so far in Scotland to be unequivocally dated. The deposits also have significant potential for establishing a detailed glacial history of the area.

Introduction

The site (NJ 798368) is a river cliff located 16 km south-east of Inverness. It lies at *c.* 370 m OD immediately upstream of the confluence of the Allt Odhar and the Caochan nan Suidheig. A deposit of compressed peat was found towards the base of the section in 1988, during the systematic resurvey of Sheet 84 (Fortrose) by the

Figure 7.4 Relative pollen diagram for the Dalcharn 'biogenic formation', showing selected taxa only as percentage of total land pollen (from Walker, 1990a).

British Geological Survey. The peat, which contains pollen, insect remains and plant macrofossils of interstadial affinity, occurs above a weathered till and there is at least one till higher in the sequence (Merritt, 1990c). The precise age of the peat is in some doubt, but there is a convergence of evidence suggesting that it accumulated during an Early Devensian interstadial. The close proximity of this site to the Dalcharn interglacial site (see above) is of major significance in Scottish Quaternary research. They are the first sites from the mainland of Scotland to provide evidence of wooded conditions during both an interstadial and an interglacial period of the Middle or Late Quaternary. The Allt Odhar deposits provide the most detailed record yet published from a Scottish site of vegetational change during a pre-Late Devensian interstadial (Walker, 1990b; Walker *et al.*, 1992).

Description

The lithostratigraphy in the vicinity of the Allt Odhar site, given below, is that established by Merritt (1990c), with minor modifications after Walker *et al.* (1992):

6.	Blanket Peat	up to 2 m
5b.	Sheet-wash Gravel	up to 1.5 m
5a.	Carn Monadh Gravel	up to 10 m
4.	Moy Formation:	
c	Upper Till Member	up to 10 m
b	Lower Till Member	up to 6 m
a	Paraglacial Member	up to 2.2 m
3.	Odhar Peat	up to 0.6 m
2.	Odhar Gravel	up to 1.5 m
1.	Suidheig Till	at least 1.5 m

The lithostratigraphy is based on several sections because no single exposure reveals the complete sequence. At the Allt Odhar section (Figure 7.5) only units 1 to 4b are present.

The Suidheig Till (bed 1) is only recognized unequivocally at the type section, where it comprises a very stiff, light brown to moderate yellowish brown, massive, matrix-supported diamicton. Many of the clasts are decomposed and have orange weathering rinds. The nature and composition of the diamicton is similar to that of the lower till member (bed 4b) of the Moy Formation, but it is more deeply weathered.

The Odhar Gravel (bed 2) is a dense, poorly sorted, cobble gravel with a ferruginous pan towards the base. Pink granite is the dominant lithology, many clasts being unsound. The less abundant clasts of gneiss and schist are commonly decomposed. The deposit is fluvial in origin, possibly glaciofluvial.

The Odhar Peat (bed 3) (Figure 7.6) lies within a shallow depression at the top of the underlying gravel. Four distinct beds are apparent:

(i)	pebbly, peaty sand	0.2–0.3 m
(ii)	black amorphous peat with sand wisps	0.15–0.3 m
(iii)	compressed, felted, fibrous peat	0.35 m
(iv)	interlaminated sand and peat	0.2 m

The sand is generally bleached and the deposit as a whole most probably accumulated in a soligenous mire (Walker, 1990b). The results of pollen analysis on the Odhar Peat are reported by Walker (1990b) and Walker *et al.* (1992). Three pollen assemblage zones are recognized (Figure 7.7). A small number of plant macrofossil types were also recovered (cf. *Campanula* sp. (p), *Carex* sp. (p), *Cenococcum geophilum* (Fr.), *Montia fontana* ssp. *fontana* L., *Selaginella selaginoides* (L.) Link and *Viola* sp. (p.) (Walker *et al.*, 1992).

The lower part of the deposit (beds iii and iv) has yielded the remains of 31 taxa (23 species) of fossil insect (Coleoptera) (Walker *et al.*, 1992). The species generally show a preference for humus-rich or peaty soils or damp habitats (e.g. *Patrobus assimilis* Chaud., *Pterostichus diligens* (Sturm) and *Diacheila polita* Fald.), including deciduous woodland (*Pterostichus niger* (Schall.)) and thinly wooded environments with drier soils (*Calathus melanocephalus* (L.)). Five are no longer present in Britain (*Diacheila polita* Fald., *Helophorus* cf. *glacialis* Villa, *Olophrum boreale* (Payk.), *Euconecosum norvegicum* Munst. and *Boreaphilus henningianus* Sahlb.) but occur today in Fennoscandia. *Diacheila polita* Fald. is characteristic of tundra environments, but also occurs on the northern margins of the boreal forest.

Radiocarbon dating of samples from near the base of bed (iii) and from near the top of bed (ii) in both cases gave age estimates >51,100 BP (SSR–3677 and SSR–3678), indicating that the materials are older than the upper limit of radiocarbon dating (Harkness, 1990). A uranium-series disequilibrium age estimate of 124 ka ± 13 ka was initially obtained on a sample of peat from bed (iii) (Heijnis, 1990). Subsequently, based on additional measurements, a revised

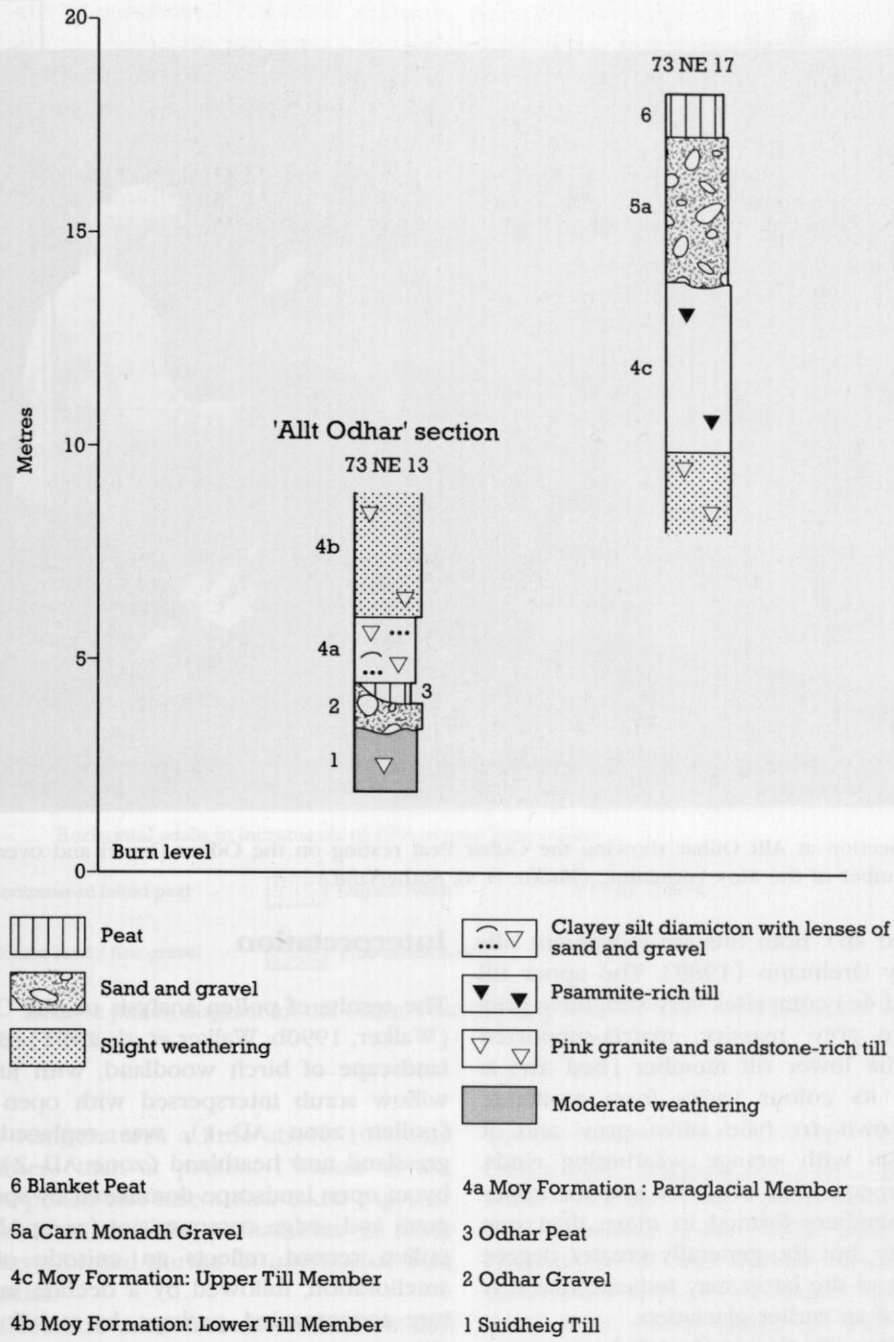


Figure 7.5 Sediment logs of the Allt Odhar and adjacent sections (from Merritt, 1990c).

estimate of 106 ka +11/−10 ka was obtained (Walker *et al.*, 1992).

The Moy Formation comprises two till members and a paraglacial member. The paraglacial member (bed 4a) is an extremely compact unit of pebbly clayey silt diamicton and silty sand with lenses of sand and gravel. The upper and lower contacts of the member are gradational, and there is evidence that the deposits have been consolidated and sheared subglacially. The unit was probably originally deposited by debris-flow processes, either proglacially or in periglacial conditions prior to the arrival of glacier ice.

Throughout the area, a psammite-rich till (bed 4c) overlies a pink granite-rich and sandstone-

Figure 7.6 Section at Allt Odhar showing the Odhar Peat resting on the Odhar Gravel and overlain by the Paraglacial Member of the Moy Formation. (Photo: D. G. Sutherland.)

rich one (bed 4b). Both tills are lodgement tills as defined by Dreimanis (1989). The upper till member (bed 4c) comprises very stiff, olive grey to pale olive grey, massive, matrix-supported diamicton. The lower till member (bed 4b) is more sandy, its colour varies from moderate yellowish brown to pale olive grey and it contains clasts with orange weathering rinds. There is no unequivocal evidence that the upper and lower members formed in more than one glacial episode, but the generally greater degree of weathering of the latter may indicate that it is the product of an earlier glaciation.

The Carn Monadh Gravel (bed 5a) appears to be restricted to the valley of the Allt Odhar. It mainly comprises thinly bedded silty sandy gravel with distinct planar subhorizontal stratification and it was probably deposited in ice-marginal fans as the higher ground became free of ice during deglaciation. The Sheet-wash Gravel (bed 5b) is a coarse, poorly sorted deposit that caps most of the river cliffs in the area. The overlying blanket peat (bed 6) contains pine stumps near the base.

Interpretation

The results of pollen analysis on the Odhar Peat (Walker, 1990b; Walker *et al.*, 1992) reveal that a landscape of birch woodland, with juniper and willow scrub interspersed with open grassland (pollen zone AD–1), was replaced first by grassland and heathland (zone AD–2) and then by an open landscape dominated by species-poor grass and sedge communities (zone AD–3). The pollen record reflects an episode of climatic amelioration, followed by a decline in temperature accompanied, perhaps, by a shift to wetter climatic conditions, and finally to a markedly more severe climatic regime. The scarcity of pine pollen, relatively low arboreal pollen counts, the absence of thermophilous taxa and the presence of herbaceous taxa with northern or montane affinities all indicate a climatic regime markedly cooler than that of a full interglacial. This conclusion is strongly supported by analysis of the fossil Coleoptera, which suggests a cool to cold climate similar to that occurring today in the birch zone of the Scandinavian mountains, with

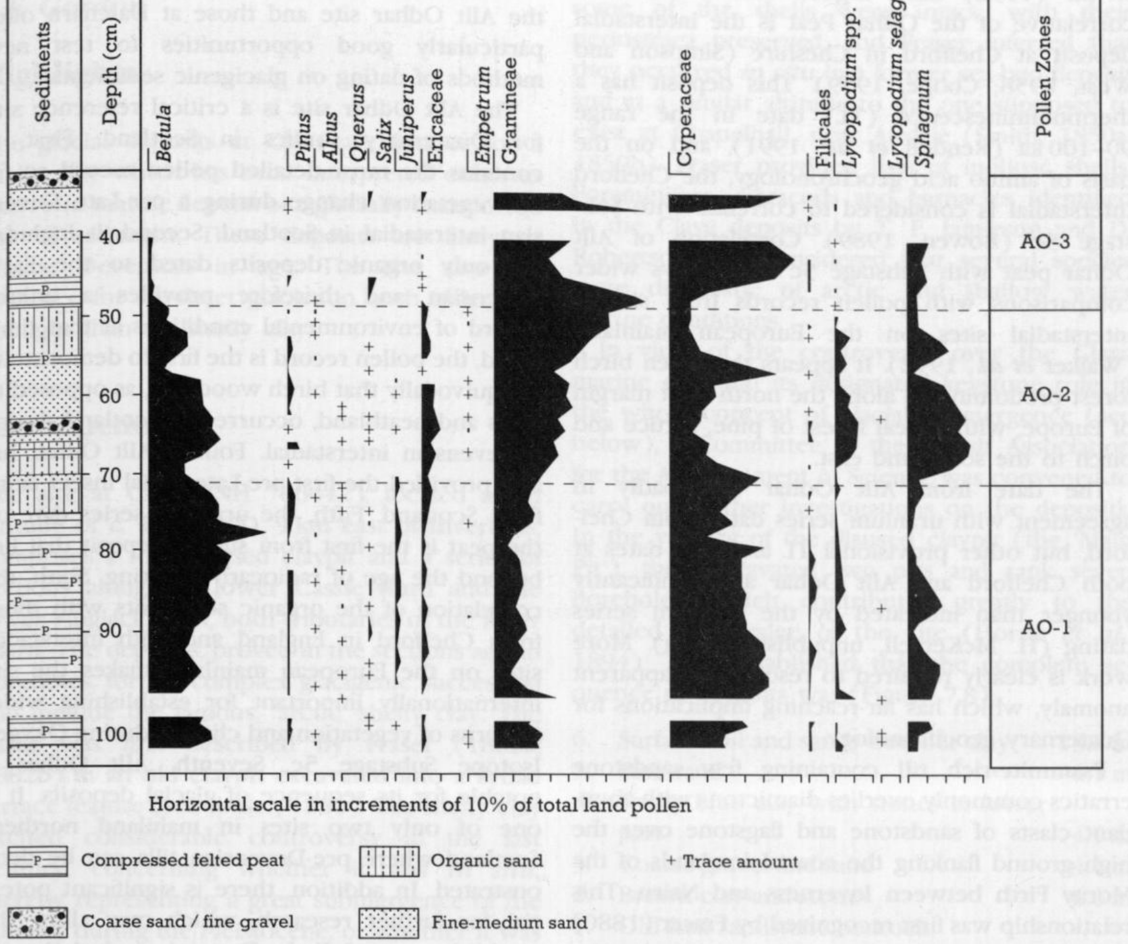


Figure 7.7 Relative pollen diagram for the Odhar Peat, showing selected taxa as percentages of total land pollen (from Walker, 1990b).

mean July temperatures a little above 10°C and colder winters than at present (Walker *et al.*, 1992). The pollen and insect data taken together strongly indicate that the Odhar Peat is more likely to have formed during an interstadial than an interglacial.

The radiocarbon dates from near the base and the top of the Odhar Peat indicate that the deposit is older than Middle Devensian (Harkness, 1990). Hence, it pre-dates organic remains from a number of previously published Scottish Devensian interstadial sites, including Tolsta Head on Lewis (von Weymarn and Edwards, 1973), Sourlie near Glasgow (Jardine *et al.*, 1988) and Crossbrae Farm near Turriff in north-east Scotland (Hall, 1984b; Hall and Connell, 1991), from which finite dates in the range 22,000–29,000 BP have been obtained. The relatively high frequencies of birch pollen in the spectra from Allt Odhar also suggest that the Odhar Peat is different in age from organic horizons at Teindland (Edwards *et al.*, 1976), Burn of Benholm (Donner, 1979) and Abhainn Ruaival on St Kilda (Sutherland *et al.*, 1984), where the radiocarbon dates were either infinite or best regarded as minimal (Sutherland, 1984a), and where the pollen shows evidence only of open grassland.

The uranium series date of *c.* 106 ka on the Odhar Peat places it firmly in the Early Devensian (Walker *et al.*, 1992). The interstadial episode may therefore be the terrestrial equivalent of Oxygen Isotope Substage 5c of the ocean record which has been dated using the technique of 'orbital tuning' to 103.29 ± 3.41 ka (Martinson *et al.*, 1987). On the basis of the uranium series date and the pollen and insect evidence, Walker *et al.* (1992) have argued that the nearest correlative of the Odhar Peat is the interstadial deposit at Chelford in Cheshire (Simpson and West, 1958; Coope, 1959). This deposit has a thermoluminescence (TL) date in the range 90–100 ka (Rendell *et al.*, 1991), and on the basis of amino acid geochronology, the Chelford Interstadial is considered to correlate with Substage 5c (Bowen, 1989). Correlation of Allt Odhar peat with Substage 5c also allows wider comparisons with pollen records from similar interstadial sites on the European mainland (Walker *et al.*, 1992). It appears that open birch forest predominated along the north-west margin of Europe, with boreal forest of pine, spruce and birch to the south and east.

The date from Allt Odhar is broadly in agreement with uranium series dates from Chelford, but other provisional TL and OSL dates at both Chelford and Allt Odhar are significantly younger than indicated by the uranium series dating (H. McKerrell, unpublished data). More work is clearly required to resolve this apparent anomaly, which has far-reaching implications for Quaternary geochronology.

Psammite-rich till containing few sandstone erratics commonly overlies diamictons with abundant clasts of sandstone and flagstone over the high ground flanking the coastal lowlands of the Moray Firth between Inverness and Nairn. This relationship was first recognized by Fraser (1880) in Strathnairn and it was substantiated during the primary geological survey of the Inverness area (Horne, 1923). It is clear that material derived from outcrops of Old Red Sandstone along the Moray Firth coast and around Loch Ness was transported eastwards and upwards on to the highest ground in the area (Sissons, 1967a). The final movement of ice, however, was towards the north-east, as indicated by the orientation of glacial striae, streamlined landforms and the clast composition of the youngest, psammite-rich tills (Merritt, 1990a). The precise ages and interrelationship of the psammite-rich and sandstone-rich tills are still unclear, but it is now certain at the Allt Odhar site that both are Devensian in age. The greater degree of weathering of the sandstone-rich till suggests that it could be an Early Devensian deposit, and the psammite-rich till a Late Devensian deposit. The Suidheig Till is almost certainly pre-Devensian in age. The Suidheig Till, together with the Dearg Till (?Anglian) at Dalcharn, are the only definite pre-Devensian tills known in mainland northern Scotland (cf. Worsley, 1991). The sections in the vicinity of the Allt Odhar site and those at Dalcharn offer particularly good opportunities to test new methods of dating on glacigenic sediments.

The Allt Odhar site is a critical reference site for Quaternary studies in Scotland. First, it contains the most detailed pollen record so far for vegetation change during a pre-Late Devensian interstadial in Scotland. Second, it includes the only organic deposits dated to the Early Devensian and therefore provides a unique record of environmental conditions at that time. Third, the pollen record is the first to demonstrate unequivocally that birch woodland, as opposed to grass and heathland, occurred in Scotland during a Devensian interstadial. Fourth, Allt Odhar has also provided the first pre-Lateglacial insect fauna from Scotland. Fifth, the uranium series date on the peat is the first from such a deposit that lies beyond the age of radiocarbon dating. Sixth, the correlation of the organic sediments with those from Chelford in England and with interstadial sites on the European mainland makes the site internationally important for establishing wider patterns of vegetation and climate during Oxygen Isotope Substage 5c. Seventh, Allt Odhar is notable for its sequence of glacial deposits. It is one of only two sites in mainland northern Scotland where pre-Devensian tills can be demonstrated. In addition, there is significant potential for further research, which may allow the establishment of Early Devensian glaciation in northern Scotland.

Conclusion

Allt Odhar is a site of great importance for Quaternary studies in Scotland. A bed of peat within a sequence of glacial deposits has yielded pollen and beetle remains that provide, so far, unique evidence for environmental conditions during the Early Devensian (around 106,000 years ago). They show a climatic deterioration and also that a landscape of birch woodland gave way to a more barren one with grass and sedge communities as the climate deteriorated. The site is also notable for older, pre-Devensian, glacial deposits, one of only two sites in northern Scotland where such deposits are known, and also a further till at the locality may be of Early Devensian origin.

CLAVA
J. E. Gordon

Highlights

The glacial deposits at Clava are famous for a shelly clay which has been interpreted either as an *in situ* marine deposit or a glacially transported raft of sediment. These deposits are Early or Middle Devensian in age. The site also has evidence for ice-sheet glaciation both older and younger than the shelly clay.

Introduction

The site at Clava (NH 766442), located at an altitude of *c.* 150 m OD, 9 km east of Inverness, comprises a long-disused claypit and a series of sections along the lower Cassie Burn and the lower Finglack Burn, both tributaries of the River Nairn. The deposits, proved in the sections and in boreholes, form a complex glacigenic succession and include the famous, 'arctic' shelly clay. The latter was first described by Fraser (1882a, 1882b) in an old claypit excavated into a broad terrace feature (see Fraser, 1880). The shelly clay excited considerable controversy in the last century, concerning whether it was *in situ*, thereby representing a great submergence of the country during the Pleistocene, or whether it was transported by ice from offshore. This controversy was recently revived (Sutherland, 1981a), but subsequent detailed investigation by Merritt (1990b) has provided support for a glacially transported origin for the deposit. The site and its significance have been widely discussed in the literature, but the principal references are by Fraser (1882a, 1882b), Horne *et al.* (1894), Sissons (1967a), Peacock (1975b), Holden (1977a), Sutherland (1981a) and Merritt (1990b, in press).

Description

Fraser (1882a, 1882b) noted shelly clay at the bottom of the claypit (now disused and overgrown), where it was overlain by fine, stratified sand, which was, in turn, overlain by boulder clay, soil and gravel. Chemical analysis of the shelly clay by W. I. Macadam showed it to be similar to clays derived from 'mixed gneiss and schist districts in the Highlands'. Although fragile, some of the shells were intact, with their periostraca preserved, and Fraser inferred that they occurred *in situ* in a former sea-bed deposit and at a similar altitude to the one supposed to exist at Chapelhall, near Airdrie (Smith, 1850a, 1850b). Fraser provided lists of mollusc shells, Foraminifera, ostracods and barnacles identified in the Clava deposits by T. F. Jamieson and D. Robertson, and considered that several species were diagnostic of arctic and shallow water marine conditions.

In view of the controversy over the Clava marine clay and its designated keystone role in the whole concept of glacial submergence (see below), a Committee of the British Association for the Advancement of Science was convened to carry out further investigations on the deposits. In the vicinity of the disused claypit (the 'Main Pit'), they excavated two pits and sank seven boreholes, which contributed greatly to the detailed knowledge of the site (Horne *et al.*, 1894). They established that the complete sequence of deposits was (Figure 7.8):

6.	Surface soil and sandy boulder clay	13.1 m
5.	Fine sand	6.1 m
4.	Shelly blue clay with stones in lower part	4.9 m
3.	Coarse gravel and sand	4.6 m
2.	Brown clay and stones	6.6 m
1.	Old Red Sandstone bedrock	—

Bed 4 was confirmed to be a marine deposit extending for at least 170 m and reaching a maximum thickness of 4.9 m. It was essentially horizontal and had well-defined contacts with the adjacent beds above and below. There was little sign of disturbance, although cracks and fissures were noted. Silt and clay were the main constituents, with a small number of clasts at the base. Of the latter, 59% comprised micaceous gneiss and 17% only of the local Old Red Sandstone. One piece of supposed Jurassic grit was found, the nearest source being *c.* 20 km to the north. Organic remains in the deposit were identified by D. Robertson, supplementing Fraser's original faunal list. They were shallow-water species representing an arctic or sub-arctic faunal assemblage. However, the variety of species was poorer than that recorded in the Lateglacial marine clays of the Clyde estuary or the east coast. The shells were not striated and were generally well-preserved with the periostraca intact, although some were partially crushed.

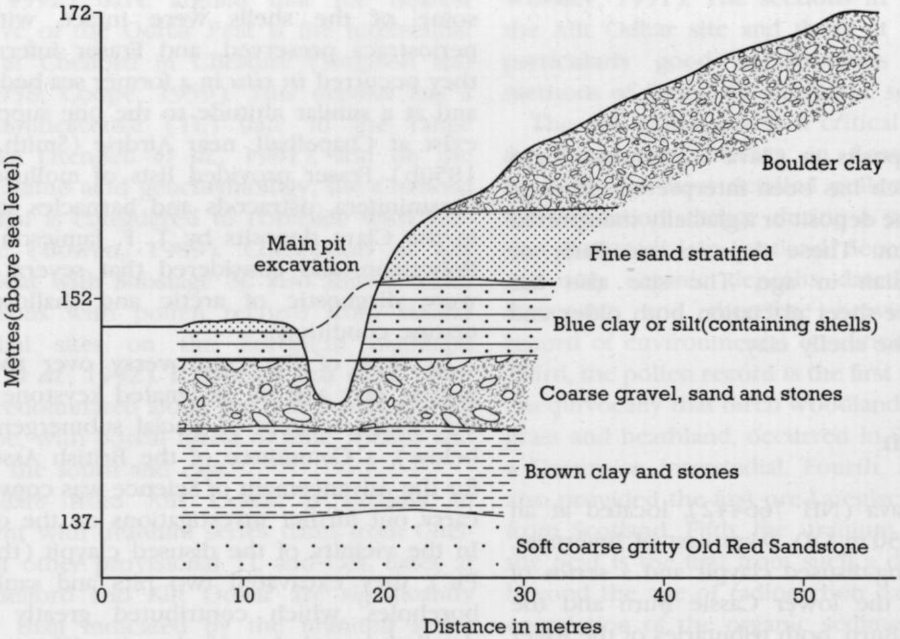


Figure 7.8 Clava: lithological succession at the 'Main Pit' (from Horne *et al.*, 1894).

Compressed annelid burrows were also observed in the marine clay. Clasts in beds 3 and 6 were predominantly derived from the local bedrock, up to 76% in the case of the latter.

Subsequently the deposits were reinvestigated by Peacock (1975b). Although the original sections were no longer exposed, fresh ones had appeared along the Cassie Burn a few hundred metres to the south-west. Here, Peacock described three main sedimentary units. At the base was a till varying in composition from a stiff, silty till to almost stoneless soft sand and silt, and with marine shells, including *Portlandia arctica* (Gray), which had not previously been recorded at Clava. Above the till was a bed of poorly sorted sand and gravel, and on top a bed of silty till interbedded with discontinuous layers and streaks of finely laminated silt, sand and fine-grained gravel.

By interpolation, Peacock correlated these beds with beds 4, 5 and 6 respectively in the succession reported by Horne *et al.* (1894), although he did not relocate the shelly clay of Horne *et al.* (1894). Subsequently, from a detailed reinvestigation of the various sections along the Cassie Burn and the Finglack Burn, Merritt (1990b, in press) has proposed a composite succession. The full lithostratigraphy recognized by him and the provisional correlations with the successions of the British Association Committee (Horne *et al.*, 1894) are as follows:

	British Association bed numbers
12. Diamictic gravel	–
11. Finglack Till (flow-till facies)	–
10. Finglack Till (melt-out facies)	
9. Finglack Till (lodgement facies)	6
8. Finglack Till (resedimented)	–
7. Glaciofluvial Ice-contact Deposits	–
6. Clava Sand	5
5. Clava Shelly Clay	4
4. Clava Shelly Till	
3. Drummore Gravel	3
2. Cassie Till	2
1. Bedrock	1

Merritt interpreted the Cassie Till (bed 2), known only from the British Association boreholes, as a lodgement or basal melt-out till. The

Drummore Gravel (Cassie Gravel of Merritt, 1990b) is exposed along the lower Finglack Burn, where it comprises principally a stratified, matrix-supported, gravelly, silty sand diamicton with a gravel composition of mainly sandstone and flagstone, with some metamorphic clasts; many of the gneiss and schist clasts are weathered. Merritt interpreted this unit as comprising subaerial sediment gravity flows that accumulated in an ice-marginal or supraglacial environment. From the relatively greater degree of weathering of this deposit, compared with the overlying bed, he inferred that it formed during an earlier glacial episode.

The Clava Shelly Till is exposed on the west side of the Cassie Burn and is described by Peacock (1975b) and Merritt (1990b). It comprises a stiff, matrix-supported diamicton with a matrix of silty, fine-sandy clay and contains clasts mainly of metamorphic rocks, but with some of granite and sandstone. Graham (1990) has confirmed the presence of *Portlandia arctica* in the deposit and listed a sparse microfossil assemblage. The presence of this bivalve provides evidence for a fully arctic environment (Peacock, 1975b; Graham, 1990) in contrast to the Clava Shelly Clay.

The Clava Shelly Clay is not presently exposed, and the main source of information has therefore been from the British Association investigation. Re-excavation of a temporary section at the site of the Main Pit, for a Quaternary Research Association field meeting in 1990, confirmed the principal findings, with particular attention drawn to the heavily sheared nature of the sediments. Graham (1990) has recently updated the taxonomic lists of the macrofauna and microfauna of the shelly clay (Table 7.1). He noted the absence of exclusively arctic forms and concluded that the assemblage was indicative of a high-boreal or colder environment. Amino acid analysis of museum specimens of *Littorina littorea* (L.) yielded a mean ratio (D-alloisoleucine: L-isoleucine) of 0.04, suggesting that the shells may be Middle Devensian in age (D. Q. Bowen, unpublished data). Radiocarbon dating of a museum specimen of *Littorina littorea* also has yielded a Middle Devensian age (43,800 ± 3,300 BP, OxA–2483), but this date should be regarded as a minimum age, being so close to the limit of radiocarbon dating. Further radiocarbon dating of field specimens collected in 1990 has yielded infinite age estimates: *Astarte sulcata* (da Costa), >41,200 (OxA–2483) and *Littorina littorea*,

Table 7.1 The macrofauna of the Clava Shelly Clay (from Graham, 1990)

Gastropoda
- *Boreotrophon clathratus* (Ström)
- *Buccinum undatum* Linné
- *Littorina littorea* Linné
- *Littorina* sp.
- *Littorina saxatilis* (Olivi) *rudis* (Maton)
- *Lunatia pallida* (Broderip and Sowerby)
- *Lunatia* sp.
- *Margarites helicinus* (Fabricius)
- *Margarites groenlandicus* (Gmelin)
- *Neptunea antiqua* (Linné)
- *Oenopota scalaris* (Moeller)
- *Oenopota trevelliana* (Turton)
- *Oenopota turricula nobilis* (Moeller)
- *Oenopota turricula* (Montagu)
- *Oenopota* sp.
- *Omalogyra atomus* (Philippi)
- *Rissoa parva?* (da Costa)

Bivalvia
- *Astarte sulcata* (da Costa)
- *Cerastoderma edule* (Linné)
- *Lepton nitidum* Turton
- *Macoma balthica* (Linné)
- *Macoma calcarea* (Gmelin)
- *Macoma* sp.
- *Mytilus edulis* (Linné)
- *Nicania montagui* (Dillwyn)
- *Nucula* sp.
- *Nuculoma tenuis* (Montagu)
- *Nuculana pernula* (Müller)
- *Nuculana* sp.
- *Thyasira flexuosa* (Montagu)*
- *Tridonta elliptica* (Brown)
- *Tridonta* sp.
- *Yoldiella lenticula* s.l. (Müller)
- *Yoldiella* sp.
- bivalve indet.
- mytilacean fragments
- unidentifiable bivalve fragments

Cirripedia
- *Balanus balanoides* Linné
- *Balanus crenatus*? Bruguière
- *Balanus* sp. plates

Decapoda
- crustacean claw

* probably a misidentification of one of the colder water species *Thyasira gouldi* (Philippi) or *Thyasira sarsi* (Philippi).

>43,000 (OxA–2876) (Merritt, in press).

The Clava Sand at the Main Pit shows poorly defined subhorizontal lamination and a well-developed system of clastic veins, which Merritt (1990b) has interpreted as the product of brittle fracture while the material was frozen and either overridden by, or transported within, glacial ice. Evidence of shearing of the deposit is also present near the junction with the overlying till. Clava Sand is also found overlying Clava Shelly Till in the Cassie Burn section (Merritt, 1990b), where it is folded as well as being cut by microfaults and shear planes. The Clava Shelly Till has been folded also.

The Glaciofluvial Ice-contact Deposits unit (bed 7), exposed on the west bank of the Cassie Burn, is a part waterlain and part mass-flow deposit, which is cut by a series of shear planes (Merritt, 1990b).

The Finglack Till is exposed in sections along the lower Finglack Burn and on the west side of the Cassie Burn (Peacock, 1975b; Merritt, 1990b). The clasts consist mainly of sandstone and flagstone, and the unit comprises a succession of lodgement, melt-out and flow-till facies. The origin of the overlying Diamictic gravel is uncertain (Merritt, 1990b).

Interpretation

In the period following its discovery, the significance of the Clava Shelly Clay was considered by both protagonists and antagonists of the glacial submergence theory of the time (cf. Davies, 1968a). Richardson (1882) referred to Clava as one of a number of high-level arctic shell beds in the British Isles indicating an extensive submergence during the glacial period. He also correlated these high-level deposits with shelly clays at many lower-level sites around the coast of Scotland.

Jamieson (1882b) thought the Clava deposit implied a similar amount of submergence to that which he inferred from the quartz and flint gravels at Windy Hills. Wilson (1886) associated the shelly clay at Clava with the so-called interglacial beds of Aberdeenshire (for example at Kippet Hills) and ascribed them to the same submergence. Crosskey (1887) re-examined the Clava shell-bed and supported Fraser's conclusion that it was a true *in situ* sea-bed deposit, citing its lack of disturbance and mixing with other debris, its sharp junction with the overlying sands and the preservation of the distinctive arctic shell assemblage.

Bell (1893a, 1893b, 1895a), however, argued that because of their limited extent and the lack of marine organisms in the overlying deposits, both the Clava and Chapelhall shell beds had been transported to their present positions by land ice. He considered that if subsequent glaciation had removed all traces of high-level marine deposits except at a few localities, it was difficult to explain why there were no marine remains in the overlying till. Significantly, also, clasts in the marine clay at Clava were not derived from local Old Red Sandstone rocks. In the case of Clava, Bell suggested that ice issuing from the Great Glen was deflected eastwards by an ice barrier in the Moray Firth and that it crossed part of the sea floor before reaching Clava. He also argued that the high-level shelly deposits in North Wales, Ireland and at Chapelhall did not provide substantive evidence for a 'great submergence' during the glacial period (Bell, 1891a, 1893b).

The majority of the British Association Committee concluded that the marine deposits were *in situ*, indicating former submergence of the land up to about 150 m OD. As evidence they cited the assemblage of organic remains, their mode of occurrence, the extent of the deposits and their apparently undisturbed character. A minority of the Committee (Bell and Kendall), however, argued that there was insufficient evidence to reach a firm conclusion and, moreover, doubted that there was any substantial evidence at all in Scotland for a great submergence. They questioned the widespread absence of shell beds and other traces of submergence and the lack of marine organisms in the overlying till. Although acknowledging certain difficulties, notably the extent of the deposit and the good preservation of the shells, they favoured an ice-rafted origin for the shelly clay, with a source area in Loch Ness, judging from ice-movement patterns inferred from striae and erratics.

In view of the lack of unanimity on the conclusions to the British Association Report, it was not surprising that debate on the origin and implications of the Clava shell bed continued. Indeed, Clava assumed even greater significance following the failure of a similar British Association Committee to relocate the shell bed at Chapelhall (Horne *et al.*, 1895). Further shell beds, however, were found in Kintyre (Horne *et al.*, 1897). In the years immediately following the

British Association investigations, Bell (1896a, 1897a, 1897b) continued to argue against the Clava and other similar deposits being *in situ* and resulting from an extensive marine submergence. He received support from Lamplugh (1906). In contrast, Reade (1896), Smith (1896a) and Jamieson (1906) maintained the view that the deposits were the product of a major marine submergence.

In the Geological Survey Memoir for the area, Horne (1923) summarized the findings of the British Association Committee, but produced no new evidence. Later, Bremner (1934a) speculated that the Clava marine beds might be preglacial, since there was no boulder clay beneath them. Bourcart (1938), however, suggested a possible correlation of the Clava marine clays with the Tyrrhenian marine transgression (Mindel–Riss interglacial). Charlesworth (1956) also favoured the view that the deposits were *in situ*, representing an interglacial submergence.

In contrast, Sissons (1967a) considered that the Jurassic erratic, the low content of local rocks and the marine fossils themselves all suggested that the material had been ice-rafted from the north prior to the last ice movement, from south-west to north-east.

Despite the inconclusiveness of the British Association Report and the significant implications for the Pleistocene history of Scotland if the deposits were *in situ*, there was no reinvestigation of the area until the work of Peacock (1975b). He argued that the shelly clay at Clava was part of a till unit comprising reworked sea-floor material. It was probably an autochthonous melt-out till (cf. Boulton, 1968) rather than a lodgement or flow till, since the preservation of annelid burrows precludes resedimentation. The existence of such intact erratics of marine sediments, often with well-preserved fossils and structures, has been widely documented (Jamieson *et al.*, 1898; Lamplugh, 1911; Debenham, 1919; Read, 1923; Eyles *et al.*, 1949; Peacock, 1966, 1971a), and possible mechanisms of entrainment have been proposed (Moran, 1971; Boulton, 1972a; Banham, 1975). Peacock related the characteristics of the sand and gravel bed (bed 5 in the succession of Horne *et al.*, 1894) along the Cassie Burn to deposition in a high-energy, fluvial environment and he explained the overlying beds (see above) as a succession of flow tills deposited in an environment similar to that of modern ice margins in Svalbard (Boulton, 1968).

Holden (1977a) considered that the last ice movement in the area was from the Great Glen and that it was moving, therefore, in the wrong direction to transport sea-floor materials inland. He argued that the Clava Shelly Clay was similar in characteristics and location to those at Tangy Glen in Kintyre and at Afton Lodge in Ayrshire. From his investigation of the Afton Lodge deposits, and in view of the apparent problems entailed in the ice-rafting explanation at Clava and Kintyre, he concluded that all three were *in situ* and represented a pre-Devensian sea-level stand at between 115 m and 150 m OD. Sutherland (1981a) also accepted an *in situ* origin for the high-level shell beds and presented a model relating these deposits to glacio-isostatically induced submergence in front of an expanding ice-sheet. However, the deposits at Clava fit only partly into the overall distribution pattern of the high-level shell beds and are apparently at too great an altitude to be fully explained by the model.

More recently, the detailed work of Merritt (1990b) has provided a significant advance in resolving the origin of what has been one of the most enigmatic Pleistocene deposits in Scotland. He summarizes the evidence for and against the shelly clay being *in situ*. The arguments in support have included the good state of preservation of the shells, the large size of the bed and its near horizontal form; counter arguments have included the occurrence elsewhere of large ice-rafted deposits with well-preserved shell contents, the lack of other evidence of sea levels at a comparable altitude to the Clava deposits and the distinctive composition of the shelly clay compared with the overlying and underlying deposits. In considering the evidence, Merritt (1990b) noted similarities with large, glacially transported rafts or 'megablocks' in North America (Moran *et al.*, 1980; Aber, 1985, 1989), particularly concerning the presence of glaciotectonic deformations. He correlated the Clava Sand overlying the Clava Shelly Clay at the Main Pit with lithologically similar sand overlying the Clava Shelly Till in the Cassie Burn sections, the latter in turn overlain unconformably by the glaciofluvial sand and gravel unit described by Peacock (1975b). He interpreted the deformation structures in the shelly till and the overlying sands, not simply as the result of overriding by the ice that deposited the Finglack Till, but as structures that were already in place and therefore formed as part of the transport and emplacement processes of these deposits. Peacock (1975b) considered that shelly clay graded into the shelly till, in a similar manner to the rafts of marine clay in the till at Boyne Quarry, near Portsoy (see below); such a pattern would conform with glaciotectonic deformation of megablocks during transportation (cf. Aber, 1985). However, as the shelly till contains a fauna indicative of colder conditions than the main raft of shelly clay, the two formations are not simply derived one from the other; the till is formed from a part of the sequence not preserved at the Main Pit (Merritt, in press). The reconstructed pattern of ice movement suggested that the source of the shelly clay was the Loch Ness Basin, which was inferred to have been an arm of the sea prior to the ice advance. The process of rafting involved the development of high pore-water pressures within interbedded sands and clays within the semi-enclosed basin of Loch Ness. The results of amino acid analysis and radiocarbon dating indicate that the shelly clay is Middle or Early Devensian in age and that it was transported by the Late Devensian ice-sheet.

Conclusion

Clava is best known for a bed of shelly clay that has had a significant bearing on interpretations of the Pleistocene history of Scotland. Although it has been suggested that the deposit is an *in situ* marine clay and reflects a phase of high sea level, either before or at the time of the build-up of the last (Late Devensian) ice-sheet, current interpretations indicate that it was transported *en masse* to its present location by the last ice-sheet (approximately 18,000 years ago). Clava is not only a site of historical importance, but is also recognized to be significant for studies of glacial sedimentation.

ARDERSIER

J. E. Gordon and J. W. Merritt

Highlights

The interest at Ardersier comprises ice-contact deposits of glaciomarine origin and a sequence of Lateglacial and Holocene raised shorelines. These features provide important evidence for interpreting the pattern of wastage of the Late Devensian ice-sheet, including a possible re-advance, and the changes in relative sea level that both accompanied and followed the period of ice-melting.

Introduction

The site (NH 780562) is located on the Ardersier peninsula on the east coast of the Moray Firth, between Inverness and Nairn. It forms part of a suite of glaciomarine ice-contact deposits and raised shorelines and includes an area of high ground consisting of contorted silts, sands and clays, trimmed on the north and west sides by a series of Lateglacial and Holocene raised shorelines. These features provide significant evidence for interpreting both the pattern of ice-sheet deglaciation during the Late Devensian and subsequent changes in relative sea level. The landforms and deposits at Ardersier have been described by Jamieson (1874), Wallace (1883), Ogilvie (1914), Horne (1923), J.S. Smith (1968, 1977), Small and Smith (1971), Synge (1977b), Synge and Smith (1980) and Firth (1984, 1989b, 1990b) and have featured in most reconstructions of the Pleistocene history of the area. They have been interpreted as demonstrating a major readvance of the Late Devensian ice-sheet ('Ardersier Readvance') (J.S. Smith, 1968, 1977; Synge, 1977b; Synge and Smith, 1980), although this interpretation has recently been challenged (Firth, 1984, 1989b).

Description

The deposits at Ardersier (Figure 7.9) were first described by Jamieson (1874), who recorded, near Kirkton, a small exposure (NH 793561) of grey clay containing shells of arctic molluscs, which was either overlain by, or incorporated within a brownish deposit of gravel and silt. Wallace (1883) later reported further details of the shelly deposit and noted that specimens examined by Jamieson included *Nuculana pernula* (Müller), *Macoma calcarea* (Gmelin) and *Tridonta elliptica* (Brown). Robertson (in Wallace, 1883) identified *Astarte sulcata* (da Costa) and several species of ostracod and Foraminifera. An updated and corrected faunal list by D. K. Graham is presented in Firth (1990b). Although the shells were largely fragmented, Robertson noted that many of the pieces were in a natural position. Horne (1923) subsequently provided additional information on the stratigraphy of the

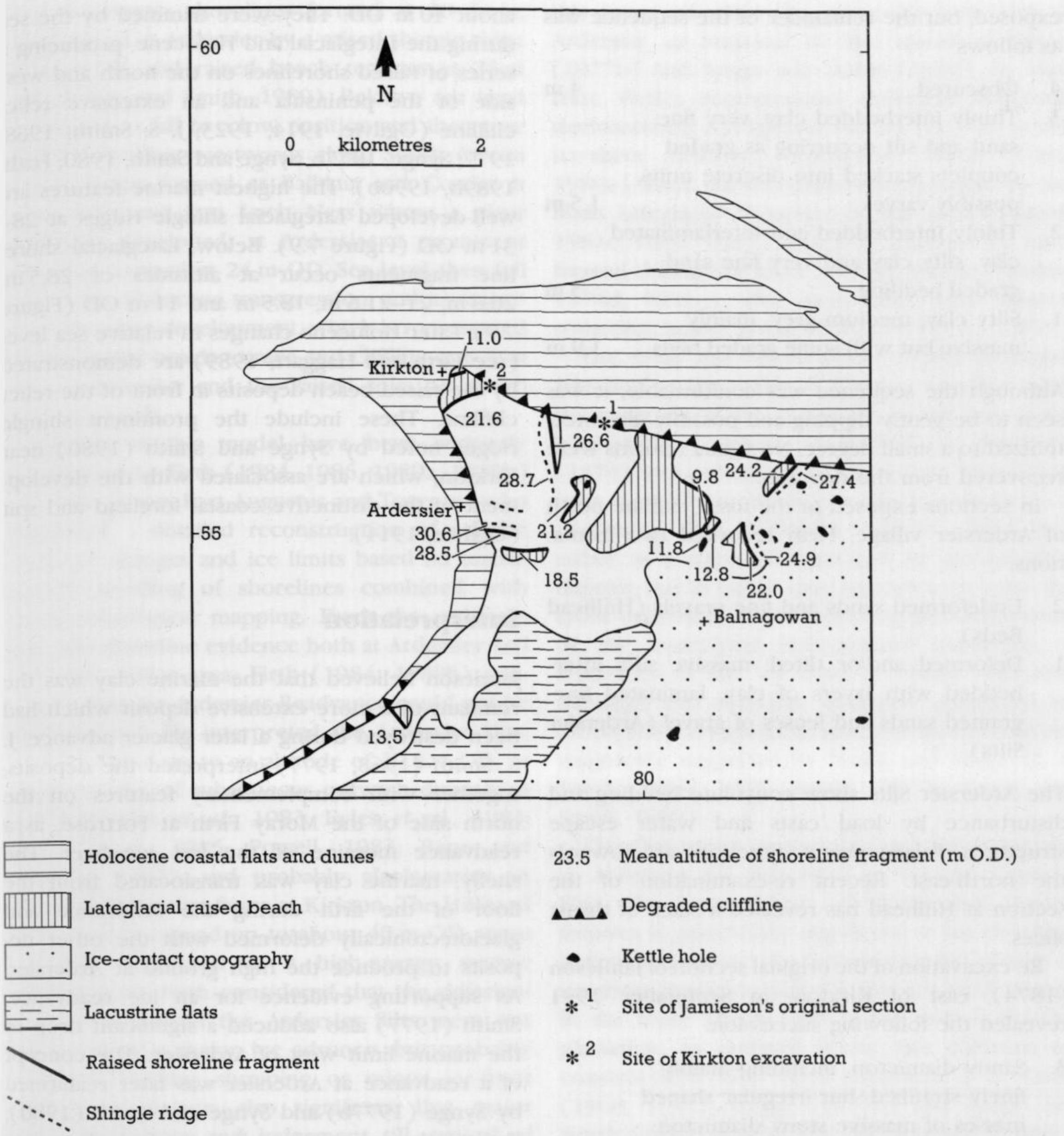


Figure 7.9 Geomorphology of the Ardersier area (from Firth, 1989b).

Kirkton section:

3.	Sand and clay deposit with some stones	1.2 m
2.	Stratified sand	1.8 m
1.	Grey, shelly clay	—

J.S. Smith (1968, 1977) referred to additional sections in the bluff behind the Ardersier village, which 'revealed beds of sand and silt which were folded, faulted and thrust, with inliers of blue clays' (Smith, 1977, p. 74).

Firth (1984, 1989b) described the following sequence in the bluff (NH 783565) east of Kirkton, but not, as he records, at the site of Jamieson's original section:

3. Horizontally bedded sands with well-rounded clasts.
2. Finely laminated sands interbedded with massively bedded silts.
1. Massively bedded, grey clay.

This section was re-exposed in September 1990. The uppermost bed of pebbly sand was not exposed, but the remainder of the sequence was as follows:

4.	Obscured	4 m
3.	Thinly interbedded clay, very fine sand and silt occurring as graded couplets stacked into discrete units, possibly varves	1.5 m
2.	Thinly interbedded and interlaminated clay, silty clay and very fine sand; graded bedding	5 m
1.	Silty clay, medium grey, mainly massive but with some graded beds	1.9 m

Although the sequence was conformable, it was seen to be gently dipping and possibly glaciotectonized to a small degree. No faunal remains were recovered from the deposits.

In sections exposed in the fossil cliffline north of Ardersier village, Firth recorded two formations:

2. Undeformed sands and fine gravels (Hillhead Beds).
1. Deformed and/or tilted, massive silts interbedded with layers of clay, laminated fine-grained sands and lenses of gravel (Ardersier Silts).

The Ardersier Silts show convolute bedding and disturbance by load casts and water escape structures. Palaeocurrent directions are towards the north-east. Recent re-examination of the section at Hillhead has revealed a stack of thrust slices.

Re-excavation of the original section of Jamieson (1874), east of Kirkton, in September 1991 revealed the following succession:

3.	Sandy diamicton, including mainly finely stratified, but irregular shaped masses of massive stony diamicton; clasts up to 0.5 m size; laminated sand, silt and clay at base above planar contact with bed 2	2.0 m
2.	Sand, comprising a stack of thrust-bound slices (0.2–0.4 m thick), intercalated with thin (<0.15 m), sheared silty clay seams	3.2 m
1.	Sand, poorly bedded, with steeply dipping thrusts lined by sheared silty clay and folded seams of silty clay <0.2 m thick	3.4 m

No shells were recovered in any of the beds.

The deposits at Ardersier rise to an altitude of about 40 m OD. They were trimmed by the sea during the Lateglacial and Holocene, producing a series of raised shorelines on the north and west side of the peninsula and an extensive relict cliffline (Ogilvie, 1914, 1923; J. S. Smith, 1968, 1977; Synge, 1977b; Synge and Smith, 1980; Firth, 1989b, 1990b). The highest marine features are well-developed Lateglacial shingle ridges at 28–31 m OD (Figure 7.9). Below, Lateglacial shoreline fragments occur at altitudes of 28.5 m, 26.6 m, 21–21.6 m, 18.5 m and 11 m OD (Figure 7.9). Later Holocene changes in relative sea level (see Firth and Haggart, 1989) are demonstrated by the raised beach deposits in front of the relict cliffline. These include the prominent shingle ridges noted by Synge and Smith (1980) near Kirkton, which are associated with the development of the distinctive coastal foreland and spit (Ogilvie, 1914).

Interpretation

Jamieson believed that the marine clay was the remnant of a more extensive deposit which had been destroyed during a later glacier advance. J. S. Smith (1968, 1977) interpreted the deposits, together with complementary features on the north side of the Moray Firth at Fortrose, as a readvance moraine of the last ice-sheet. The shelly, marine clay was translocated from the floor of the firth during the readvance and glaciotectonically deformed with the other deposits to produce the high ground at Ardersier. As supporting evidence for an ice readvance, Smith (1977) also adduced a significant drop in the marine limit west of Ardersier. The concept of a readvance at Ardersier was later reaffirmed by Synge (1977b) and Synge and Smith (1980); these authors recognized it as the first of a series of retreat stages or readvances in their model of deglaciation of the inner Moray Firth and its hinterland.

Synge (1977b) and Synge and Smith (1980) integrated the Ardersier evidence into a general model of Lateglacial shoreline changes and ice-sheet retreat stages in the Moray Firth and Loch Ness areas. Briefly, deglaciation of the area was accompanied by high relative sea level at about 38–42 m OD as the ice retreated from near Nairn to Inverness. Subsequently the ice readvanced to Ardersier, and deglaciation was interrupted by further halt stages (see Chapter 6, Introduction). As ice recession continued west and south-west from Inverness, shorelines formed at 28–34 m, represented at Ardersier by a raised shingle ridge at 28–31 m and raised beach terraces at 28 m OD (Synge and Smith, 1980). Relative sea level continued to fall to a low position and then rose again, extending westwards along Strath Conon where deltas formed at Balblair and Contin at 26 m OD, and into Loch Ness where a clear shoreline developed; at Ardersier a prominent shoreline formed at 24 m OD. Sea level then fell before the Holocene transgression, and its associated shoreline development, which is represented by the raised beach terrace and cliffline at 8–9 m OD at Ardersier and the raised spits on which Kirkton stands.

Aspects of this model have been seriously questioned by Firth (1984, 1986, 1989a, 1989b) (see also Dores, Fort Augustus and Torvean) who presented a detailed reconstruction of relative sea-level changes and ice limits based on instrumental levelling of shorelines combined with geomorphological mapping. From the sedimentary and shoreline evidence both at Ardersier and over the wider area, Firth (1984, 1989b) concluded that the Ardersier Readvance could not be substantiated. He interpreted the Ardersier Silts, which extend up to an altitude of 37.8 m OD, as characteristic of subaqueous outwash deposition (cf. Anderson *et al.*, 1983; Eyles *et al.*, 1983; Eyles *et al.*, 1985; Powell, 1983; Benn and Dawson, 1987), and probably glaciomarine in view of the marine fauna at Kirkton. The Hillhead Beds, which extend up to about 40 m OD, were probably deposited in a high-energy marine environment. Firth considered that the deformation structures in the Ardersier Silts were not indicative of a major ice advance, but probably reflected loading, slumping or minor ice-front movement. It was also significant that major thrust structures and lodgement till, typical of large-scale glaciotectonics (cf. Moran, 1971; Banham, 1975), were apparently absent. Furthermore, analysis of the shoreline data showed no significant drop in the marine limit at Ardersier. The highest in the sequence of ten Lateglacial shorelines identified by Firth includes the highest shingle ridges at Ardersier (30.6 m OD) and is associated with an ice limit near Inverness. The glaciomarine sediments at Ardersier indicate relatively higher sea level when they were deposited at an ice margin at Ardersier, so that sea level dropped from at least 37.8 m to about 30 m OD while the ice retreated from Ardersier to Inverness. However, there is no evidence that this occurred while the active ice front was at Ardersier, as required by the model of Synge (1977b) and Synge and Smith (1980). In contrast, Firth's reconstructed shoreline sequence demonstrated a progressive fall in sea level as the ice-sheet retreated westwards (Firth, 1984, 1989a). Since the shorelines are truncated by the Main Lateglacial Shoreline in the area (Sissons, 1981c; Firth, 1984), which is believed to have formed during the Loch Lomond Stadial (Sissons, 1974d, 1981c), they must have been formed sometime before about 11,000 BP (Firth, 1989a).

The folds and thrust planes in the Ardersier Silts and in the sands at Kirkton, together with the presence of the diamicton at the top of the succession, originally described by Jamieson (1874) and confirmed in the recent excavation, have a significant bearing on the question of ice readvance. The diamicton may be interpreted either as a subaerial mass-flow or glaciomarine deposit, but in either case appears to require the close proximity of ice following glaciotectonism of the underlying finer-grained sediments. A readvance of the ice front is clearly indicated, although the shoreline evidence presented by Firth (1989b) appears to preclude an event of the magnitude suggested by Smith and Synge (J. S. Smith, 1968, 1977; Synge, 1977b; Synge and Smith, 1980).

The Quaternary geomorphology and sediments at Ardersier are important in several respects. First, the juxtaposition of glacial and marine features is particularly significant; it has provided important evidence for interpreting the pattern of ice-sheet recession and relative sea-level change in the inner Moray Firth at the end of the last glaciation. As outlined above, two different reconstructions have been proposed. J. S. Smith (1968, 1977), Synge (1977b) and Synge and Smith (1980) believe that the deposits at Ardersier represent a readvance of the last ice-sheet. Elsewhere in eastern Scotland similar readvances are now largely discounted (Sissons, 1974c; Sutherland, 1984a), apart from the Elgin Oscillation (Peacock *et al.*, 1968), although in north-west Scotland the Wester Ross Readvance is based on clear geomorphological evidence (Robinson and Ballantyne, 1979) (see Gairloch Moraine). The work of Firth (1984, 1989b), however, suggests a different interpretation for the Ardersier evidence, which does not require a major ice readvance but rather progressive ice recession. Ardersier is therefore one of a number of key sites in Scotland for interpreting the mode of deglaciation of the last ice-sheet.

Second, Ardersier is important for the sediments that comprise the core of the higher ground. These have a significant bearing on the interpretation of the mode of deglaciation and the contemporary sedimentary processes and environments. In the model of J.S. Smith (1968, 1977), Synge (1977b) and Synge and Smith (1980) these sediments represent ice-transported and deformed marine deposits; in the model of Firth (1984, 1989b), they represent a glaciomarine sequence deposited in front of a stationary ice margin. The Ardersier deposits therefore provide key evidence for reconstructing deglacial events in the inner Moray Firth and have significant potential for further sedimentological investigation, particularly at the original section described by Jamieson (1874) at Kirkton.

Third, Ardersier is notable for its shell-bearing deposits (Jamieson, 1874; Wallace, 1883). Although these have not been relocated, they nevertheless offer significant potential for establishing firm dating control on the deglaciation of the inner Moray Firth for the first time.

Fourth, Ardersier provides important morphological and stratigraphic evidence for relative sea-level changes during deglaciation. The Ardersier shorelines provide important datum points on the shoreline diagram constructed by Firth (1984, 1989a) for the Lateglacial Interstadial, complementing the evidence from Munlochy Valley and Barnyards. According to Firth (1984, 1989b) the deposits indicate that relative sea level attained an altitude of about 40 m OD at Ardersier and that it subsequently fell from at least 37.8 m to about 30 m OD as the ice retreated to Inverness. As the ice retreated farther west, the progressive fall in relative sea level continued.

Fifth, the assemblage of features at Ardersier is completed by Holocene raised beach deposits, including raised shingle ridges. Although these add to the diversity of interests of the site, the Holocene sequence in the area is better demonstrated at Barnyards and Munlochy Valley, and raised shingle ridges, both Lateglacial and Holocene, are most spectacularly developed at Tarbat Ness and Spey Bay (Ogilvie, 1923; Smith, 1977).

Conclusion

The landforms and deposits at Ardersier are important for interpreting the pattern of wastage of the last (Late Devensian) ice-sheet (about 14,000–13,000 years ago) and the changes in the relative position of sea level that accompanied and followed deglaciation. The deposits may represent a readvance of the last ice-sheet, although such an event and its magnitude are still a matter of debate. Beach deposits and shorelines show that relative sea level was as high as 40 m above present as the ice melted, and their presence has contributed towards understanding the wider regional patterns of sea-level changes during the Devensian (Lateglacial) and the Holocene (approximately the last 13,000 years).

STRUIE CHANNELS

J. E. Gordon

Highlights

This site provides a good example of a meltwater channel system formed during the melting of the Late Devensian ice-sheet; such systems are relatively rare in northern Scotland.

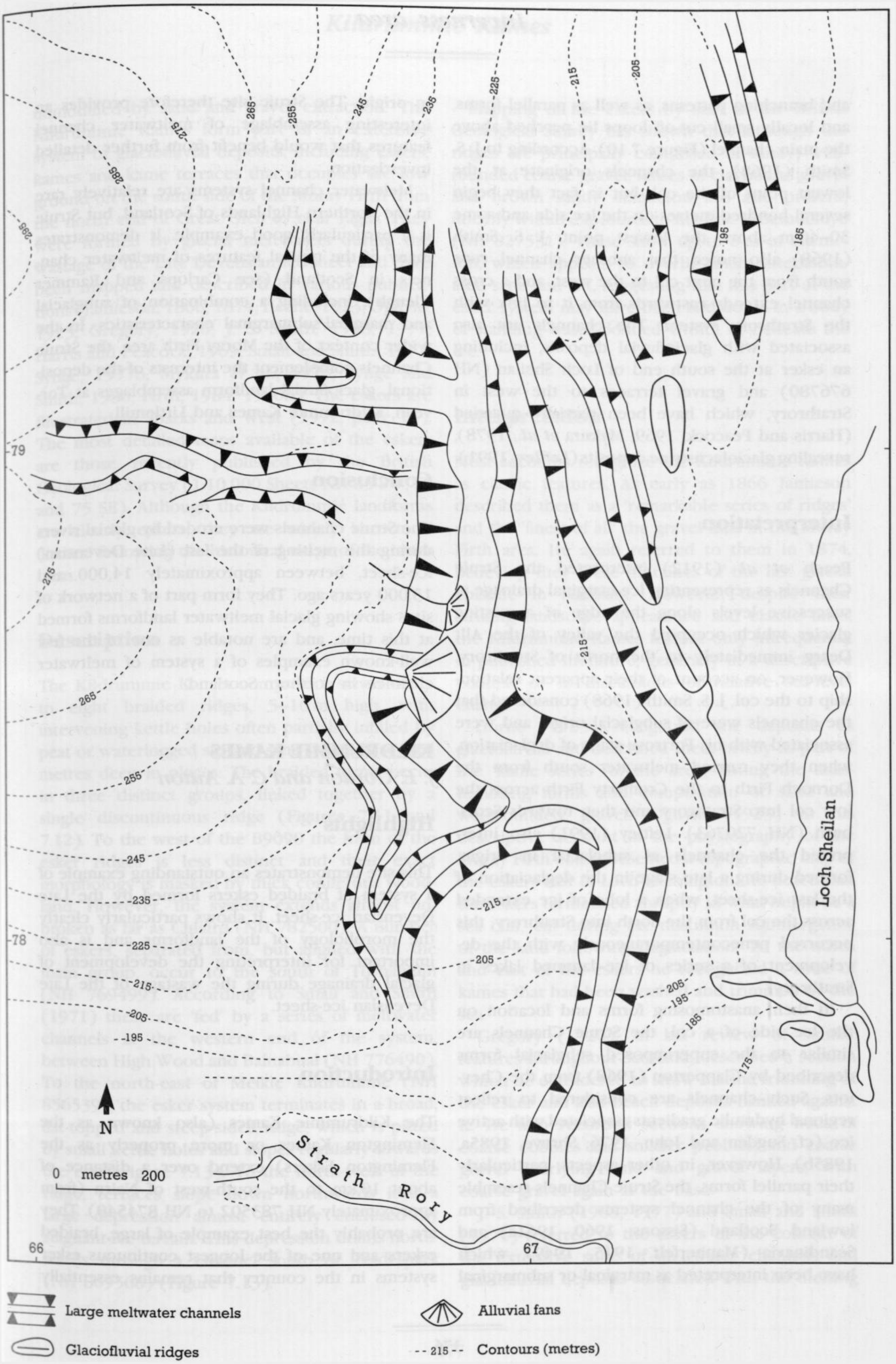
Introduction

The site (NH 670790) is located in Strathrory on the south side of a col at *c.* 208 m OD between the Dornoch Firth to the north and the Cromarty Firth to the south. It provides a good example of a glacial meltwater channel system in the northern Highlands. The Struie Channels were first recorded by Peach *et al.* (1912) and subsequently have been mapped and described by J. S. Smith (1968) and Leftley (1991); otherwise they have attracted little published comment despite the relative scarcity of well-developed meltwater channel systems north of the Great Glen.

Description

The interest comprises a series of subparallel meltwater channels. The largest is up to 33 m deep, 89 m wide and 2.5 km long (Figure 7.10). In plan form, the channels show anastomosing

Figure 7.10 Geomorphology of the Struie meltwater channels, Strathrory (from J. S. Smith, 1968; Leftley, 1991).



Loch Sheilan
Strath Rory
N
0 metres 200
79
78
66
67
Large meltwater channels
Alluvial fans
Glaciofluvial ridges
215 Contours (metres)

and branching patterns, as well as parallel forms, and locally small cut-off loops lie perched above the main channel (Figure 7.10). According to J. S. Smith (1968), the channels originate at the lowest point of the col, but in fact they begin several hundred metres on the lee side and some 30–40 m above the lowest point. J. S. Smith (1968) also noted that another channel runs south from the next col to the west, and a cross channel extends eastwards from it to link with the Strathrory system. The channels are also associated with glaciofluvial deposits, including an esker at the south end of Loch Sheilan (NH 676780) and gravel terraces to the west in Strathrory, which have been partially quarried (Harris and Peacock, 1969; Mykura *et al.*, 1978), revealing glaciolacustrine deposits (Leftley, 1991).

Interpretation

Peach *et al.* (1912) interpreted the Struie Channels as representing ice-marginal drainage at successive levels along the edge of a wasting glacier which occupied the valley of the Allt Dearg immediately to the north of Strathrory. However, on account of their apparent relationship to the col, J. S. Smith (1968) considered that the channels were of subglacial origin and were associated with his Fortrose stage of deglaciation, when they carried meltwater south from the Dornoch Firth to the Cromarty Firth across the low col into Strathrory and then towards Scotsburn (NH 720763). Leftley (1991) also interpreted the channels as subglacial in origin, formed during a late stage in the deglaciation of the last ice-sheet, when a lobe of ice extended across the col from the north into Strathrory; this occurred penecontemporaneously with the development of a series of ice-dammed lakes in Strathrory.

In their anastomosing forms and location on the lee side of a col, the Struie Channels are similar to the superimposed subglacial forms described by Clapperton (1968) from the Cheviots. Such channels are considered to reflect regional hydraulic gradients associated with active ice (cf. Sugden and John, 1976; Shreve, 1985a, 1985b). However, in other aspects, particularly their parallel forms, the Struie Channels resemble many of the channel systems described from lowland Scotland (Sissons, 1960, 1961a) and Scandinavia (Mannerfelt, 1945, 1949), which have been interpreted as marginal or submarginal in origin. The Struie site therefore provides an interesting assemblage of meltwater channel features that would benefit from further detailed investigation.

Meltwater channel systems are relatively rare in the northern Highlands of Scotland, but Struie is a particularly good example. It demonstrates many of the typical features of meltwater channels in Scotland (see Carlops and Rammer Cleugh), including a combination of subglacial and marginal/submarginal characteristics. In the wider context of the Moray Firth area, the Struie Channels complement the interests of the depositional, glaciofluvial landform assemblages at Torvean, Kildrummie Kames and Littlemill.

Conclusion

The Struie channels were eroded by glacial rivers during the melting of the last (Late Devensian) ice-sheet, between approximately 14,000 and 13,000 years ago. They form part of a network of sites showing glacial meltwater landforms formed at this time, and are notable as one of the few well-known examples of a system of meltwater channels in northern Scotland.

KILDRUMMIE KAMES

J. E. Gordon and C. A. Auton

Highlights

This site demonstrates an outstanding example of a system of braided eskers formed by the Late Devensian ice-sheet. It shows particularly clearly the morphology of the landforms and is also important for interpreting the development of glacial drainage during the wastage of the Late Devensian ice-sheet.

Introduction

The Kildrummie Kames (also known as the Flemington Kames or more properly as the Flemington Eskers) extend over a distance of about 10 km to the south-west of Nairn (from approximately NH 783502 to NH 874540). They are probably the best example of large, braided eskers and one of the longest continuous esker systems in the country that remains essentially unmodified by sand and gravel extraction. The Kildrummie Kames form part of an extensive system of glaciofluvial deposits, including eskers, kames and kame terraces that occupies the low ground on the south side of the Moray Firth from the north end of Great Glen to near Elgin. They were formed by glacial meltwaters during the wastage of the Late Devensian ice-sheet and have been mapped and described in various publications (Jamieson, 1866, 1874; Horne, 1923; Ogilvie, 1923; Gregory, 1926; J. S. Smith, 1968, 1977; Harris and Peacock, 1969; Small and Smith, 1971; Synge, 1977b; Mykura *et al.*, 1978; Synge and Smith, 1980; Firth, 1984, 1990b). The eskers are illustrated in Sparks and West (1972, plate 15). The most detailed maps available of the eskers are those recently published by the British Geological Survey (1:10,000 Sheets NH 85 SW, SE and 75 SE). Although the Kildrummie landforms are clearly eskers, they are widely known as 'kames' following the historical usage of the latter term.

Description

The Kildrummie Kames comprise a series of up to eight braided ridges, 5–10 m high, with intervening kettle holes often partially infilled by peat or waterlogged silt and sand which is several metres deep in places. The braided forms occur in three distinct groups, linked together by a single discontinuous ridge (Figures 7.11 and 7.12). To the west of the B9090 the form of the esker ridges is less distinct and their exact morphology is masked by thick coniferous woodland. However, the system extends almost unbroken as far as Culaird (NH 782500). A number of eskers, separated from, but aligned with the main group, occur to the south of Tornagrain (NH 769499). According to Small and Smith (1971) these are 'fed' by a series of meltwater channels at the western end of the system, between High Wood and Balnabual (NH 776490). To the north-east of Meikle Kildrummie (NH 856539), the esker system terminates in a broad, flat-topped and steep-sided ridge, which is pitted by small kettle holes and slopes regularly towards the east (Figure 7.13). To the north-west of the ridge, terraces slope down northwards into a large depression almost entirely enclosed by stagnant-ice terrain. This depression drains northwards through a channel south of Tradespark (NH 869568) (Figure 7.13).

Mapping of the eskers by staff of the British Geological Survey has shown that although the ridges are principally composed of sandy, well-rounded coarse gravel, lenses of claybound gravel and brown sandy diamicton are also present, notably within exposures to the east of Bemuchlye (NH 827531). These show up to 8 m of diamicton, which appears to overlie finely interlaminated sand and silt, suggesting that this part of the esker system may have been laid down in a body of standing water ponded within or beneath the ice.

Interpretation

Most accounts recognize the Kildrummie Kames as classic features. As early as 1866 Jamieson described them as a 'remarkable series of ridges' and the 'finest of all' the gravel hills in the Moray Firth area. He again referred to them in 1874, believing they were moraines of the last glacial episode in Scotland. However, despite their striking landscape appearance and classic lines, the Kildrummie Kames feature only infrequently in published literature, generally in a descriptive context or in discussions of relative sea-level change.

Horne (1923) recognized the deposits as glaciofluvial and described them briefly as part of the 'kame series' of the area, noting the anastomosing forms and composition of sand and well-rounded gravel. Ogilvie (1923) in his descriptive account of the physiography of the Moray Firth coast presented a topographic map of the eskers east of Loch Flemington. He noted that the eskers terminated abruptly in what might be a sea cliff, cut during the maximum submergence of the land following deglaciation. To the north and east of the eskers he recognized a zone of kames that had been washed and trimmed by the sea.

Gregory (1926), in his review of similar features throughout Scotland, described a section which he considered to show marine trimming of the esker and also beach deposits banked against it. He also recorded sections showing beds of coarse cobbles and smaller pebbles, and coarse gravel overlying sand and gravel layers, with coarse gravel again at the base.

J. S. Smith (1968, 1977) and Small and Smith (1971) referred to the eskers in the context of the extensive suite of meltwater channels and glaciofluvial deposits associated with the melting

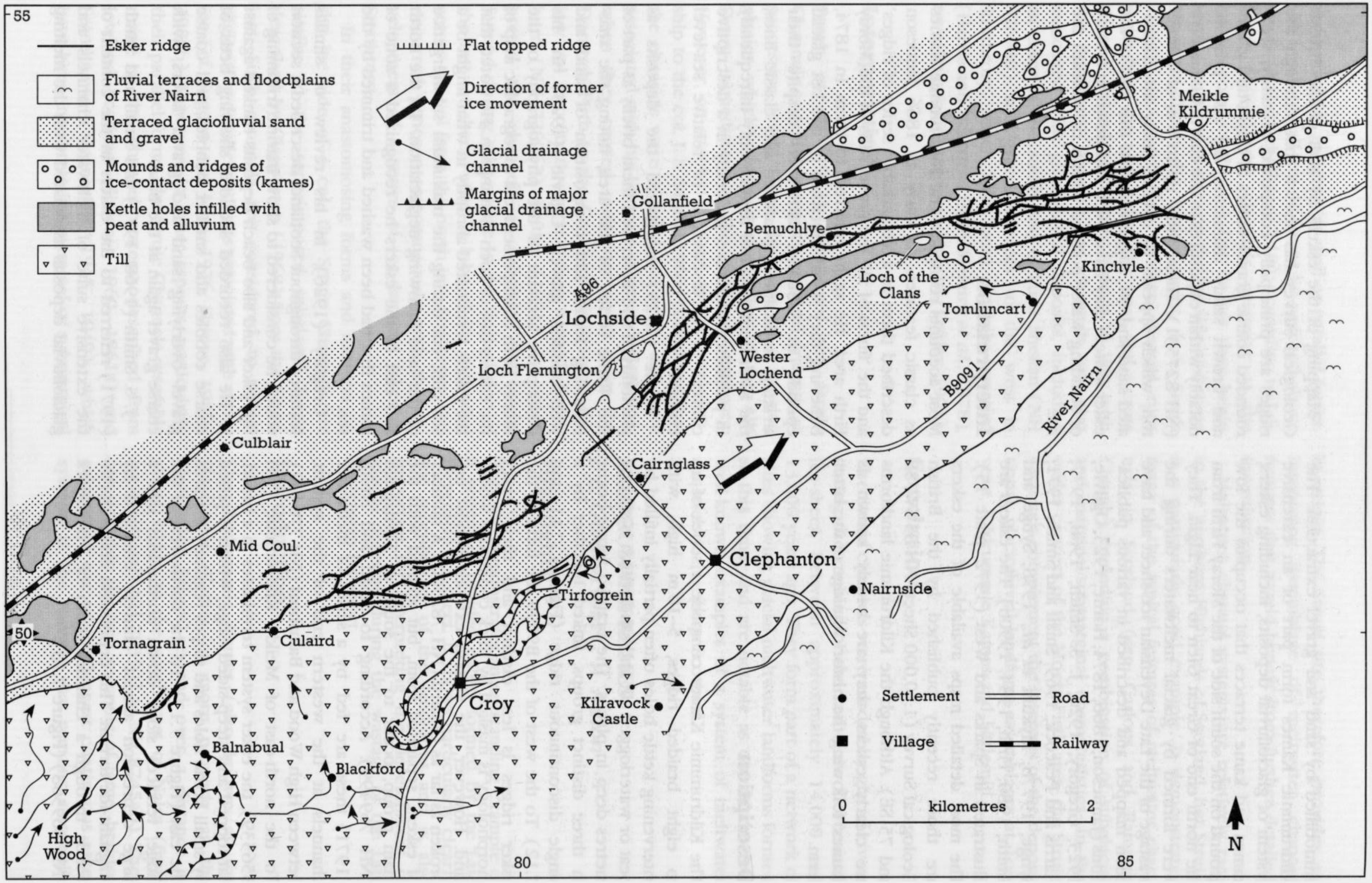
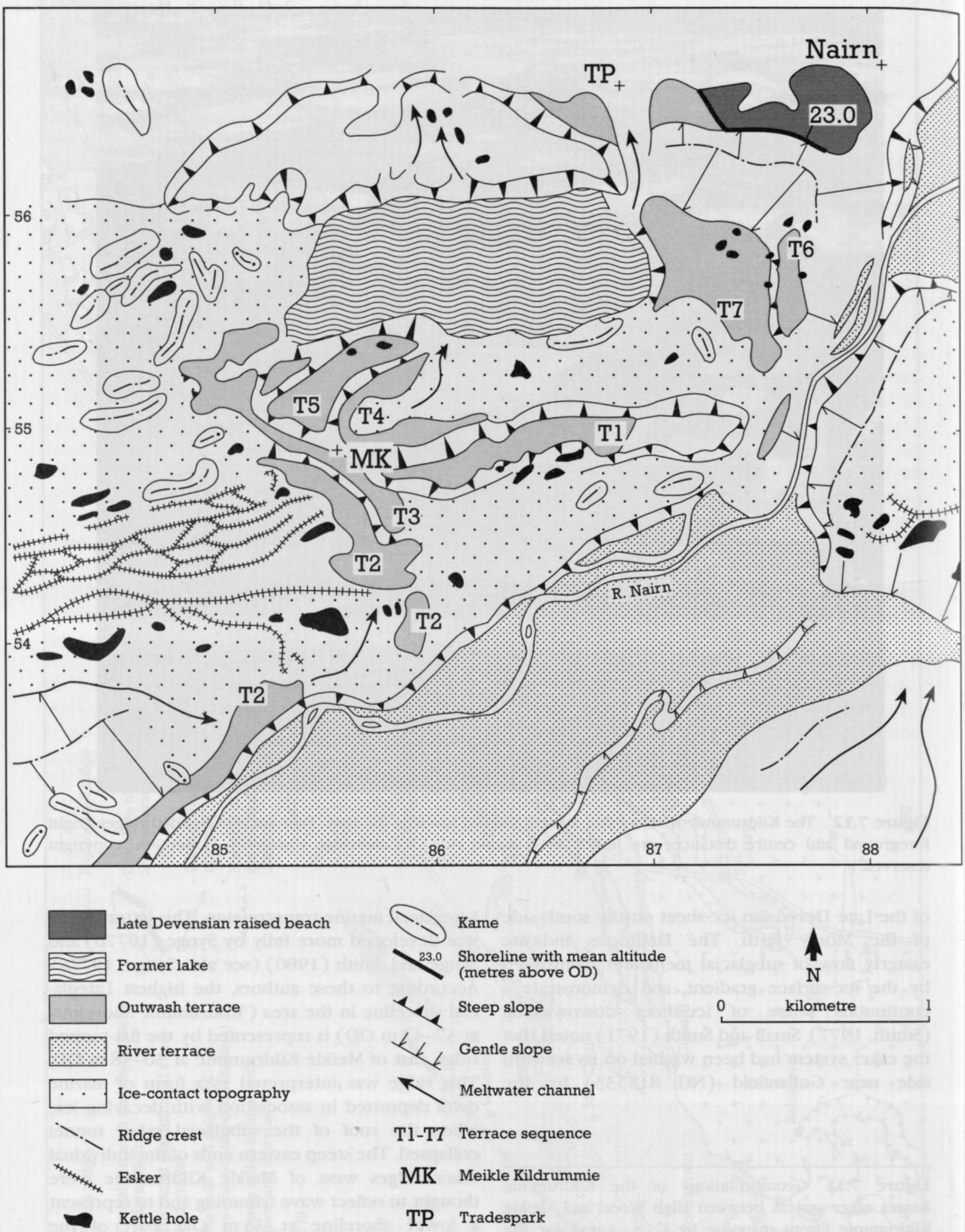

55
Esker ridge
Fluvial terraces and floodplains of River Nairn
Terraced glaciofluvial sand and gravel
Mounds and ridges of ice-contact deposits (kames)
Kettle holes infilled with peat and alluvium
Till
Flat topped ridge
Direction of former ice movement
Glacial drainage channel
Margins of major glacial drainage channel
Meikle Kildrummie
Gollanfield
Bemuchlye
Kinchyle
Loch of the Clans
Tomluncart
A96
Lochside
Wester Lochend
Loch Flemington
B9091
River Nairn
Culblair
Cairnglass
Mid Coul
Clephanton
Nairnside
Tirfogrein
50
Tornagrain
Culaird
Croy
Kilravock Castle
Balnabual
Blackford
High Wood
Settlement
Village
Road
Railway
0
kilometres
2
N
80
85

Figure 7.12 The Kildrummie Kames esker system viewed towards the east. Two areas of braided ridges (right foreground and centre distance) are linked by a single ridge. (Cambridge University Collection: copyright reserved.)

of the Late Devensian ice-sheet on the south side of the Moray Firth. The landforms indicate easterly flow of subglacial meltwater, controlled by the ice-surface gradient, and demonstrate a continuous phase of ice-sheet downwasting (Smith, 1977). Small and Smith (1971) noted that the esker system had been washed on its seaward side near Gollanfield (NH 815533) by the Lateglacial marine transgression. This latter theme was developed more fully by Synge (1977b) and Synge and Smith (1980) (see also Synge, 1977a). According to these authors, the highest Lateglacial shoreline in the area ('Kildrummie Shoreline' at 37–42 m OD) is represented by the flat-topped ridge east of Meikle Kildrummie at 36–38 m OD. This ridge was interpreted as a form of marine delta deposited in association with decaying ice, when the roof of the subglacial esker tunnel collapsed. The steep eastern ends of the individual esker ridges west of Meikle Kildrummie were thought to reflect wave trimming and to represent a lower shoreline at 33 m OD, part of the 'Culcabock Shoreline' at 28–34 m OD. Beach ridges associated with this shoreline were also

Figure 7.11 Geomorphology of the Kildrummie Kames esker system between High Wood and Meikle Kildrummie (from mapping by C. A. Auton for the British Geological Survey 1:50,000 Geological Sheet 84W (Fortrose), in press).


Nairn
TP
23.0
T6
T7
T5
T4
T1
MK
T3
T2
T2
T2
R. Nairn
56
55
54
85
86
87
88
Late Devensian raised beach
Former lake
Outwash terrace
River terrace
Ice-contact topography
Ridge crest
Esker
Kettle hole
Kame
23.0
Shoreline with mean altitude (metres above OD)
Steep slope
Gentle slope
Meltwater channel
T1-T7 Terrace sequence
MK Meikle Kildrummie
TP Tradespark
N
0 kilometre 1

identified between the ridge ends (Synge and Smith, 1980). Below the altitude of these shorelines, the steep slopes of the eskers and kettle holes were degraded by the marine transgression.

Firth (1984) mapped in detail the eastern part of the Kildrummie Kames (Figure 7.13), the adjacent glaciofluvial deposits and the terraces of lower Strathnairn. During the downwasting of the ice-sheet, marginal and submarginal glacial meltwaters formed a series of kame terraces and meltwater channels on the southern slopes of Strathnairn; at the same time subglacial meltwaters drained eastwards forming the Kildrummie esker system. As deglaciation progressed, meltwater from the kame terraces drained into the eskers, and as the ice thinned at the eastern end, the main tunnel roof collapsed forming an open crevasse in which the large flat-topped ridge east of Meikle Kildrummie formed. Firth's (1984) interpretation of the terrace sequence indicates that, while the lower valley remained blocked by stagnant ice, meltwater in Strathnairn drained both across the esker system, forming a gap and terraces between the main esker and the flat-topped ridge, and around the eastern end of the latter and into a proglacial lake occupying the depression to the north of Meikle Kildrummie. Drainage from the proglacial lake was northwards past Tradespark (Figure 7.13), where the highest shoreline fragment in the area is at 23 m OD. Firth (1984) found no evidence that either the esker system or the glaciofluvial deposits immediately to the north had been washed by the sea. Ice remained in the area until relative sea level fell below 21 m OD.

Kildrummie Kames are important in several respects. They are an outstanding example of a braided esker system, one of the finest and largest in Britain. They have largely escaped sand and gravel extraction and other large-scale modifications and therefore demonstrate landform morphology in a particularly clear fashion. Kildrummie Kames offer significant potential for further research on subglacial hydrology and the controls on meltwater routes and sedimentation (see Shreve, 1985a). Recently Shaw *et al.* (1989) have suggested that anastomosing channel patterns, similar to that indicated by the Kildrummie Kames, reflect major subglacial floods. Alternatively, each braided area may represent a series of channels on an ice-cored fan surface developed in front of a receding ice margin (cf. Jenkins, 1991); the total assemblage of landforms therefore represents three successive stages in the ice recession. The well-preserved landforms of Kildrummie Kames offer good opportunity for testing such ideas and for applying the theories of glacier physics and hydrology to reconstruct Late Devensian ice-sheet characteristics and drainage conditions.

In their braided forms, the Kildrummie Kames share morphological similarities with the Carstairs Kames (see below). Proposed origins for the latter have included subglacial and proglacial processes, and recent work (Jenkins, 1991) has suggested that the ridges formed on the surface of buried ice or in englacial tunnels near the ice margin under conditions of high energy flows (large floods). Detailed comparative investigation of the two sites should help clarify the respective origin of their landforms and their implications for patterns of deglaciation. Morphologically, Kildrummie Kames differ from the system of parallel esker ridges at Littlemill and the assemblage of single eskers and kame terraces at Torvean. The interpretation of such differences and their implications for glacier hydrology during deglaciation await resolution.

Conclusion

The Kildrummie Kames represent a classic site for geomorphology, showing a large system of braided esker ridges formed by meltwater rivers during the wastage of the last (Late Devensian) ice-sheet (approximately 14,000–13,000 years ago). The landforms are largely intact and display particularly clearly the surface forms of the eskers. The Kildrummie Kames have significant potential for developing an understanding of glacial drainage systems and patterns of ice decay.

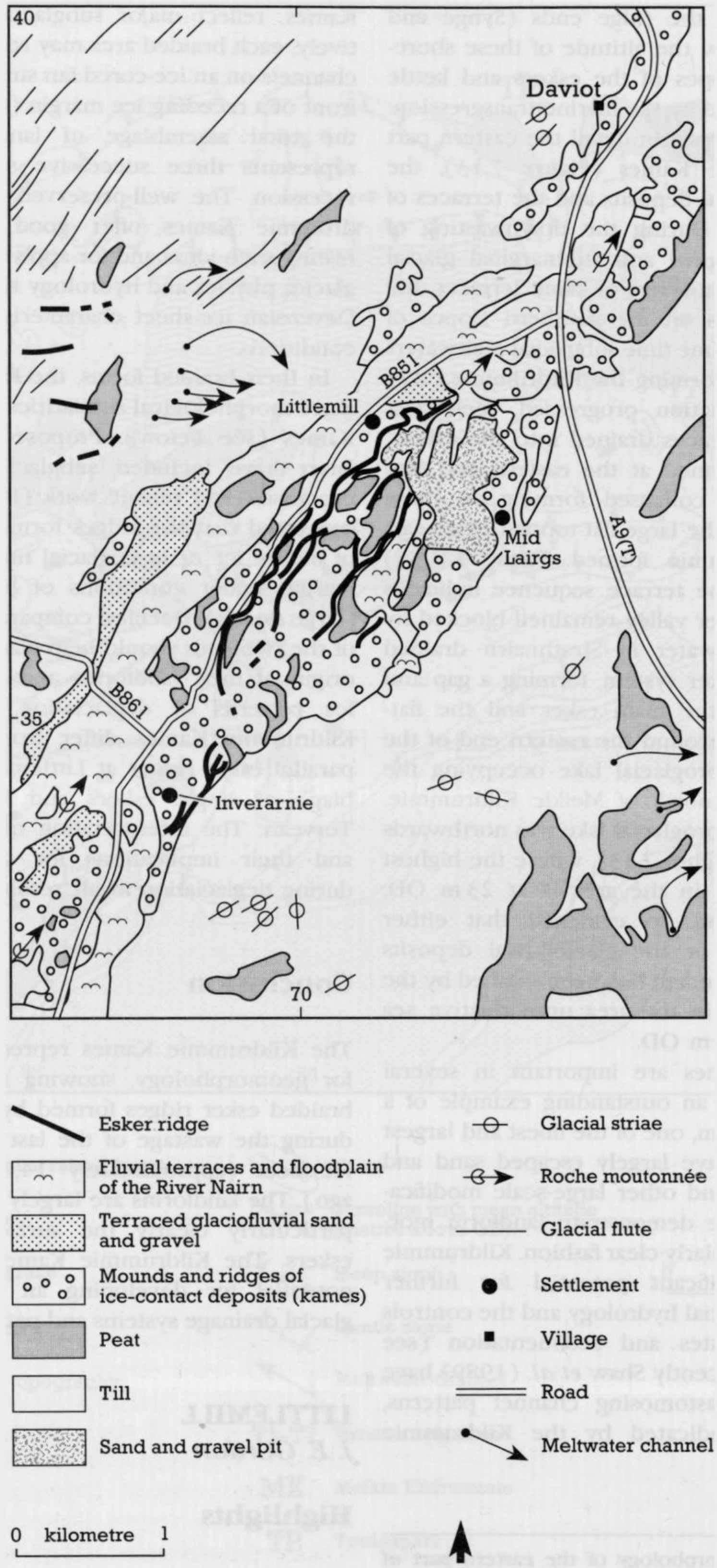
LITTLEMILL

J. E. Gordon

Highlights

The landforms at Littlemill provide an excellent example of a system of large, parallel eskers

Figure 7.13 Geomorphology of the eastern part of the Kildrummie Kames in the vicinity of Meikle Kildrummie (from Firth, 1984).


40
Daviot
B851
Littlemill
Mid
Lairgs
A9(T)
B861
35
Inverarnie
70
Esker ridge
Fluvial terraces and floodplain of the River Nairn
Terraced glaciofluvial sand and gravel
Mounds and ridges of ice-contact deposits (kames)
Peat
Till
Sand and gravel pit
Glacial striae
Roche moutonnée
Glacial flute
Settlement
Village
Road
Meltwater channel
0 kilometre 1
N

formed during the melting of the Late Devensian ice-sheet.

Introduction

The site at Littlemill (NH 695352–NH 717377) extends over a distance of *c.* 3.5 km south-west of Daviot in Strathnairn and includes a system of subparallel esker ridges, kames and kettle holes which together comprise an outstanding assemblage of glaciofluvial landforms. They relate to the wastage of the Late Devensian ice-sheet, forming part of a more extensive suite of related deposits in Strathnairn between Brinmore and Daviot (Harris and Peacock, 1969; Mykura *et al.*, 1978). There have been no detailed studies of the Littlemill landforms. Early descriptions were published by Fraser (1880) and Cameron (1882a, 1882b). In addition, the site has been figured in publications by Sissons (1967a, plate XIIIA) and Gray (1991, figure 315).

Geikie described the main characteristics of the Littlemill eskers, commenting that 'the observer will find one of the most remarkable groups of glacial ridges in the north of Scotland' (1901, p. 497). In the Geological Survey Memoir to the area Horne (1923) referred to a number of boulders scattered over the ridges at their northern end and suggested that they might be partly morainic in origin. Gregory (1926) included a note on them in his survey of Scottish kames, and they have also been recognized and mapped by Harris and Peacock (1969), Small and Smith (1971), Smith (1977), Mykura *et al.* (1978) and Synge and Smith (1980).

Description

The key features occur in a topographic embayment on the east side of the valley and comprise four major and several minor, subparallel esker ridges (Figure 7.14). Typically they are about 15 m high but in places reach as much as 40 m. Their maximum length is almost 2 km. North-east of Littlemill Farm (NH 365372) the eskers converge in a broad, flat-topped mound. A second large mound immediately to the north displays hummocky and linear forms and kettle holes on its surfaces. Fine kettle holes also occur between the main esker ridges, whose striking topographic expression is spectacularly displayed in Sissons (1967a, plate XIIIA). In the north-east part of the site, excellent exposures have been revealed in eskers and associated mounds in the large sand and gravel quarry at Mid-Lairgs, with both transverse and longitudinal sections present. There is considerable variability between sections in the type of material present, ranging from entirely coarse gravel to bedded sands and gravels (see also Harris and Peacock, 1969; Mykura *et al.*, 1978). Large-scale arch bedding was formerly displayed in one transverse section through an esker ridge (1980). At the south-west end of the system, sections in a forestry pit (NH 698354) reveal gravel and sand with boulders up to 0.5 m in size.

Additional interest in the site includes an excellent example of roches moutonnées at Scatraig (NH 713376).

Interpretation

There are few specific references in the literature to the Littlemill landforms. Fraser (1880) interpreted the ridges as lateral moraines, although he noted that they differed from other moraines in their composition of sand and gravel. He suggested that the material accumulated along a glacier margin where it was reworked and stratified by glacial meltwater. Cameron (1882a) noted sand and gravel mounds and terraces north of Littlemill, which he explained in terms of marine submergence. In a subsequent paper (Cameron, 1882b), he extended his observations to include the Littlemill landforms, which he described as kames. He noted sections showing large rounded gravel and, in places, sand layers. Cameron disagreed with 'some geologists' who had proposed a subglacial origin for the ridges, arguing instead that extensive deposits, formed during marine submergence, were later dissected by overspill and drainage from lakes which they dammed. This latter explanation, however, is now discounted in favour of the former: the deposits were probably formed either by an englacial or subglacial meltwater drainage system.

The Littlemill eskers are particularly notable for their size and extent. Although part of the system

Figure 7.14 Geomorphology of the Littlemill esker system between Inverarnie and Daviot (from mapping by J. W. Merritt for the British Geological Survey 1:50,000 Geological Sheet 84W (Fortrose), in press).

has been extensively quarried and part is afforested, the intact ridges show clearly defined esker morphology. The individual ridges are generally similar in form to single eskers elsewhere in the area; for example at Torvean, Edderton, Dornoch, Alness and Brora. The key additional interest that distinguishes the Littlemill features centres on the system of forms there and their spatial arrangement: they are one of the finest examples of a system of subparallel esker ridges in the country. In so far as the key interest lies in the complete network of forms, the Littlemill eskers provide an interesting contrast with the system of braided eskers at Kildrummie Kames (see above). These two sites complement each other, illustrating different types of former glacial drainage pattern. Tentatively, the morphological differences between these two sites may also reflect different origins. The Littlemill landforms appear to be more typical of eskers formed in a subglacial or near subglacial position, whereas those at Kildrummie may have formed in braided channels incised into the surface of buried ice (cf. Carstairs Kames). The quarry at Mid-Lairgs, together with the small forestry gravel pit at the southern end of the site, provides an excellent opportunity to relate esker morphology and sedimentology. Apart from the study of Middle Mause esker by Terwindt and Augustinus (1985), there are no published modern studies of the detailed sedimentology and palaeohydrology of Scottish eskers.

Conclusion

Littlemill is an important landform site, providing a particularly good example of large esker ridges aligned in a parallel arrangement. They were formed by meltwaters during the wastage of the last (Late Devensian) ice-sheet (approximately 14,000–13,000 years ago) and allow an interesting comparison with the braided eskers of Kildrummie Kames, the two sites illustrating different types of glacial drainage system and possibly differences in the details of origin of the landforms.

TORVEAN

J. E. Gordon

Highlights

The landform assemblage at Torvean includes an excellent range of glaciofluvial features formed during the melting of the Late Devensian ice-sheet. It illustrates particularly well the evolution of a glacial drainage system and associated sedimentary environments during deglaciation.

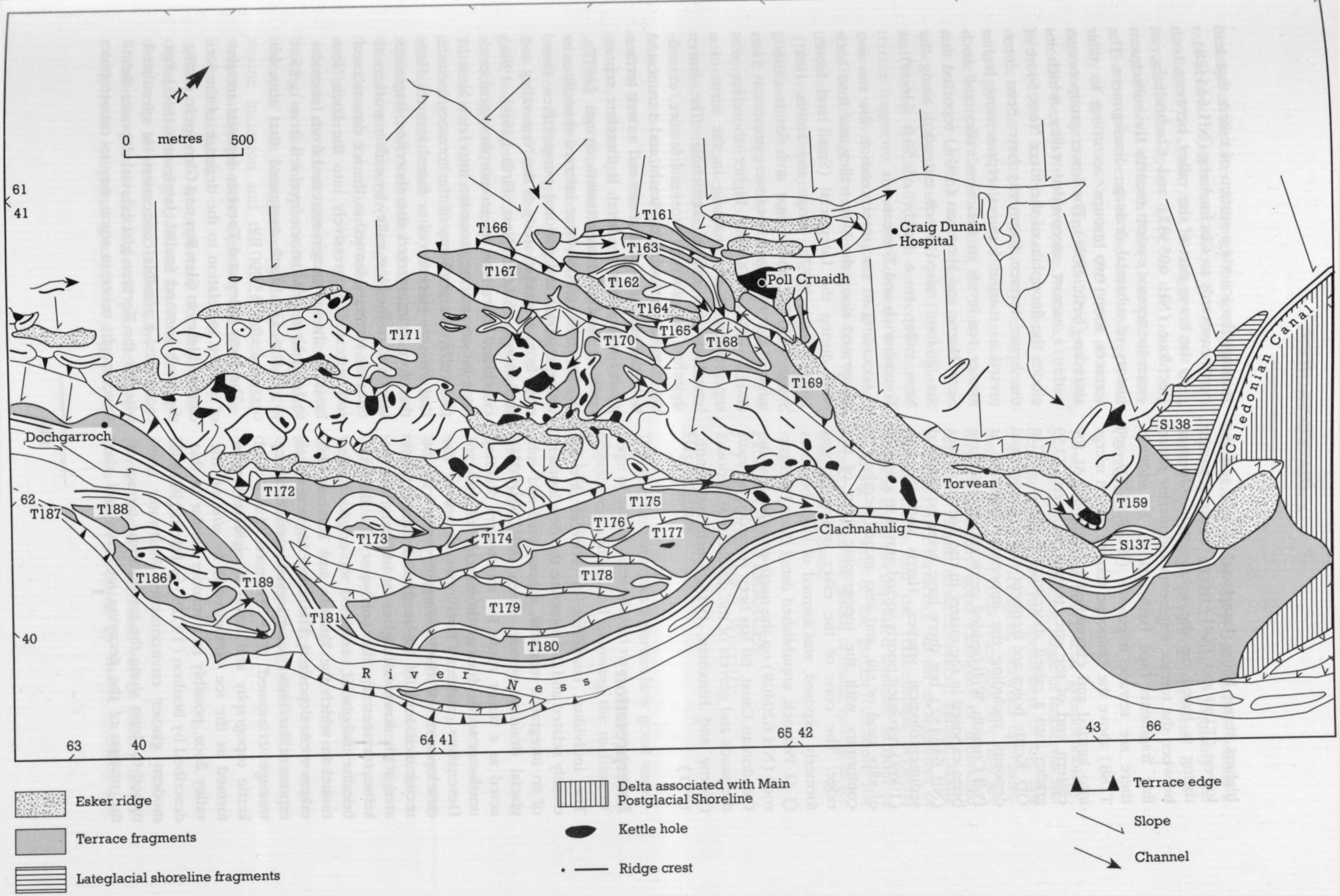
Introduction

The Torvean site (centred on NH 630420) covers an area of *c.* 4.1 km^2 and forms part of an extensive zone of glaciofluvial deposits that extends more than 5 km south-west from the outskirts of Inverness on the west side of the River Ness. It contains an excellent assemblage of glaciofluvial landforms, including one of the best examples in Britain of a suite of kame terraces and one of the highest eskers. It is also important in demonstrating the development of an integrated marginal, submarginal and subglacial drainage system during the wastage of the Late Devensian ice-sheet. Several brief accounts of the Torvean landforms have appeared in the literature (Jamieson, 1865; Aitken, 1880; Horne and Hinxman, 1914; Ogilvie, 1923; Small and Smith, 1971), and they have been mapped in detail by Synge and Smith (1980) and Firth (1984).

Description

Torvean includes a suite of six major and five minor kame terraces, eskers, kames, river terraces and kettle holes (Figure 7.15) (Synge and Smith, 1980; Firth, 1984). The kame terraces form a striking 'staircase' below 120 m OD on the valley side (Figure 7.15, T161–T171). The higher-level terraces merge eastwards with the massive Torvean and Tomnahurich eskers (over 68 m high); the lower terraces descend below the level of the Torvean esker. Below the lowest terrace (T171), at 60–70 m OD a series of eskers, kames and outwash terraces (T172–T174) are truncated abruptly to the south-east by an extensive bluff. Below is a suite of river terraces (T175–T181) with four separate levels (Firth, 1984), the

Figure 7.15 Geomorphology of the Torvean area (from Firth, 1984). The terrace fragments include kame terraces (T161–T171), Lateglacial outwash and river terraces (T172–179, T159), and Holocene river terraces (T180–181).



Caledonian Canal
Craig Dunain Hospital
Poll Cruaidh
Torvean
Clachnahulig
Dochgarroch
River Ness
0 metres 500
N
T159
T161
T162
T163
T164
T165
T166
T167
T168
T169
T170
T171
T172
T173
T174
T175
T176
T177
T178
T179
T180
T181
T186
T187
T188
T189
S137
S138
61
41
62
40
63
40
64 41
65 42
43
66
Esker ridge
Terrace fragments
Lateglacial shoreline fragments
Delta associated with Main Postglacial Shoreline
Kettle hole
Ridge crest
Terrace edge
Slope
Channel

highest three being Lateglacial in age and the lowest (T180 and T181) being Holocene in age; dating is based on the relationships observed between the terrace fragments and marine shoreline fragments (see Firth, 1984). In addition, there are terrace fragments (T178, T179 and T188) above the Holocene terrace which merge into kettled and channelled topography. At the eastern end of the site, terrace fragment T159 grades into a raised shoreline (S138) at 13.7 m OD. Kettle holes are frequent in the glaciofluvial deposits, including the impressive example at Poll Cruaidh. Well-bedded sands and gravels have been exposed in the quarry in the Torvean esker (NH 646432), but there have been no detailed sedimentological studies. Harris and Peacock (1969) recorded poorly-sorted gravel in a matrix of silty sand or silt, and also arched bedding in conformity with the topographic form of the ridge. The core of the esker, where it was formerly exposed, was formed of large boulders (J. D. Peacock, unpublished data). Near Dochgarroch (NH 620408) on the north-west bank of the Caledonian Canal, till has been recorded beneath the sands and gravels of the glaciofluvial deposits (Horne and Hinxman, 1914; Small and Smith, 1971).

Interpretation

The individual landforms at Torvean are all closely related and demonstrate the development of an integrated marginal, submarginal and subglacial drainage system when the Great Glen acted as a major route for meltwaters draining north-eastwards during the wastage of the Late Devensian ice-sheet. Two main stages in the development of the drainage system can be recognized. Initially, ice-marginal drainage associated with downwasting ice is indicated by the kame terraces. To the north-east, the drainage became subglacial, confined in an ice-walled tunnel in which the Torvean and Tomnahurich eskers were deposited. The lower kame terraces represent successive ice-marginal positions as ice wastage continued. The extensive kame and kettle topography and lower lying eskers then formed as the ice downwasted *in situ* on the valley floor, possibly in a manner similar to that described by Boulton (1972b) or Price (1973) in modern glacier environments. Meltwater continued to drain along the lowest kame terrace at the margin of the decaying ice mass and also through the ice via a system of eskers that lead north-eastwards to Clachnahulig (NH 644428).

In the lower part of the valley, between Loch Dochfour (NH 605387) and Clachnahulig, an extensive terrace system records the subsequent history of subaerial drainage development. The terraces form two groups according to their altitudes (Firth, 1984). The lower group occurs within a narrow, steep-sided valley, which includes the floodplain of the River Ness. Some of the lower terrace fragments have been interpreted as marine features, representing higher former sea levels in the Ness valley and Loch Ness. Horne and Hinxman (1914) reported that the '25-foot' raised beach extended along the Ness valley to a height of 50 ft (16 m) at Tomnahurich and Torvean.

According to one interpretation the sea also penetrated along the Ness valley and into Loch Ness during the Lateglacial (Small and Smith, 1971; Synge, 1977b; Synge and Smith, 1980). Synge (1977b) and Synge and Smith (1980) inferred that two shorelines were present at 33 m and 25–28 m OD. The higher shoreline was represented at Clachnahulig in the form of a breached and infilled kettlehole. The lower shoreline was a major erosional feature, extending from Clachnahulig to Dunain, and it truncated both the glaciofluvial deposits and a river terrace graded to a lower sea level. It therefore represented a marine transgression. Synge (1977a, 1977b, 1980) placed these inferred shorelines in wider regional and national perspectives. However, from a detailed study of the Ness valley and the shores of Loch Ness, Firth (1984, 1986) concluded there was no geomorphological evidence for any marine incursion into Loch Ness. In particular, the gradients of the terraces indicate that they are glaciofluvial or fluvial features. Firth therefore reinterpreted the shoreline fragments identified in the Ness valley by earlier workers as outwash terraces, formed as the ice downwasted and retreated progressively into the Loch Ness Basin. As the ice margin retreated from Inverness to Loch Ness, relative sea level fell from *c.* 35 m to 13.8 m OD. Firth suggested that this fall occurred after 13,000 BP.

The Ness valley and Torvean deposits are also of interest in relation to the drainage of the ice-dammed lakes in Glen Roy and Glen Spean during the Loch Lomond Stadial. Jamieson (1865) first recognized a possible connection. He speculated whether the Torvean glaciofluvial deposits themselves might relate in some way to catastrophic drainage of the lakes. Although this specific link is now seen to be incorrect, Sissons (1979c, 1981c) developed the basic idea. Drainage of the Glen Roy and Glen Spean lakes via the Great Glen raised the level of Loch Ness. Overspill of water at the north-east end of the loch enlarged the valley of the River Ness and the floods of water deposited an extensive fan of bouldery gravel out into the Beauly Firth (see also Peacock, 1977a). Firth (1984) has elaborated on some of the details of this event, reconstructing the sequence of Lateglacial and Holocene changes in the level of the loch and demonstrating the links between the evidence around Loch Ness, in the Ness valley and in the Beauly Firth (see Fort Augustus and Dores). Specifically, Firth concluded that the terrace fragments above the Holocene terrace at Torvean were formed during the flood associated with the drainage of the Glen Roy and Glen Spean ice-dammed lake.

Torvean is important in several respects. First, it contains what is believed to be the highest esker in Britain, with a height of over 68 m (Clapperton, 1977). Second, it contains what is one of the finest examples of a suite of kame terraces in Britain. Although individual examples of such landforms are not uncommon (see Moss of Achnacree and the Cairngorms), an assemblage such as that at Torvean is exceptional in terms of the size, extent and number of terraces present.

Third, the total landform assemblage at Torvean illustrates particularly well the relationships between different types of glaciofluvial deposits and landforms and the development of a marginal, submarginal and subglacial drainage system associated with the decay of the last ice-sheet. Torvean is exceptional among sites of this type in illustrating the relationships of kame terraces and eskers; at most other sites, drainage systems are represented by meltwater channels (see Struie Channels and Rammer Cleugh), kames or eskers (see Carstairs Kames), or by some combination of such landforms.

Fourth, the lower terraces at Torvean have a bearing on the interpretation of the Lateglacial history of Loch Ness, including the question of a marine incursion and the effects of the catastrophic drainage of the Glen Roy and Glen Spean ice-dammed lakes.

Fifth, Torvean is important in the wider regional context of glaciofluvial landform development in the Inverness area. Individually, Torvean, Kildrummie Kames and Littlemill provide classic examples of individual glaciofluvial depositional landforms; together they demonstrate within a relatively short distance what is arguably the finest group of such landforms in Britain.

Conclusion

Torvean is notable for glacial geomorphology, containing an outstanding range of landforms and deposits formed by the meltwaters of the last (Late Devensian) ice-sheet, between approximately 14,000 and 13,000 years ago. Not only are there particularly good examples of individual landforms (kame terraces, eskers, kames, kettle holes and river terraces), but the arrangement of the landforms and the relationships between different features (deposited beneath, in front of or along the side of the glacier) illustrate the development of the glacial drainage system as ice wastage progressed.

FINDHORN TERRACES

L. J. McEwen and A. Werritty

Highlights

This site demonstrates a particularly good assemblage of glacial outwash and river terraces formed respectively during and following the melting of the Late Devensian ice-sheet.

Introduction

The site (NH 845366) is located on the southern side of the middle River Findhorn, within the Streens Gorge, 20 km south of Nairn near the settlement of Ballachrochin. It is notable for a series of glaciofluvial and fluvial terraces (Figure 7.16), which occupy the lower part of the north-west facing slope of Carn Torr Mheadhoin (543 m OD) and are cut into the extensive glacial and glaciofluvial deposits found throughout the Streens Gorge (Young, 1980). The area is described by Horne (1923), Young (1980) and Auton (1990b).

Description

Horne originally identified eleven terrace levels. More recent mapping by Auton (1990b) has

Figure 7.16 The Findhorn terraces at Ballachrochin. (British Geological Survey photograph C1415.)

shown that there are thirteen terraces, of which the lowest five occur at 245–275 m OD and exhibit downvalley gradients of 35–50 m km^{-1}. These terraces locally abut terrace 6 at 285 m OD. In section this flat-topped feature comprises 1.0 m of clast-supported, well-rounded gravel underlain by 1.5 m of a horizontally laminated, low-angle cross-bedded, silty, fine-grained sand. This sand in turn passes down into 2.0 m of finely interlaminated sandy silt and clay with dropstone cobbles and sparse interbeds of diamicton. Above terrace 6, terraces 7 to 11 extend from 287–310 m OD, with the terrace at 305 m OD containing a small steep-sided circular kettle hole 5 m deep. By contrast, terrace 12 (at 340 m OD) is cut into bedrock. The sequence ends at 365 m OD with a small outwash fan on the western side of the Allt a'Choire Bhuidhe.

Interpretation

Horne (1923) interpreted the terraces as fluvial features, although accepting that some of the higher levels were probably glaciofluvial in origin. Young (1980) regarded them as eskers. Auton (1990b), in the most recent investigation, interpreted the landforms as kame terraces and thus of glaciofluvial origin, being closely related to the downwasting of an isolated mass of stagnant ice.

A key part of the sequence in Auton's interpretation of the site is terrace 6 (at 285 m OD). This he considers to be the remains of a glaciolacustrine delta, since the sedimentary sequence closely resembles that of the lower part of the Malaspina delta in Alaska, as described by Gustavson *et al.* (1975). Such an interpretation is not new, having already been anticipated in part by Horne (1923). However, this reconstruction clearly requires the presence of a temporary glacial lake. Young (1980) claimed that the higher terraces are eskers and as such do not require the existence of a glacial lake within the valley, as suggested earlier by Bremner (1939c) and Charlesworth (1956). Auton rejected Young's interpretation and developed a model in which most of the landforms in this middle part of the Findhorn Valley are of paraglacial origin, that is they were formed by 'non-glacial processes that are conditioned by glaciation' (Church and Ryder, 1972). In particular, he considered that the terrace sequence at Ballachrochin developed in reponse to a stagnating ice mass in the Streens Gorge, which steadily downwasted during the Late Devensian and in so doing created local, temporary glacial lakes. Successive ice margins have been reconstructed by Auton at 460 m, 400 m, 380–350 m, 340–300 m (310 and 305 m benches cut at this stage), 300–260 m (benches between 255 and 287 m cut at this stage) and 250 m OD (final benches cut after this stage).

All the major river valleys in upland Scotland possess sets of terraces which are of fluvial and glaciofluvial origin. It is unusual, however, to find staircases of terraces which extend 80 m above the valley floor and possess 13 identifiable benches. This site on the River Findhorn is notable on both accounts.

The flight of terraces is one of the highest and most remarkable in Scotland, the sequence of 13 levels being related to a complex pattern of deglaciation in this part of the middle Findhorn valley. Although the site has recently been investigated in considerable detail in term of its glacial history, the Holocene development of the lower, fluvial, terraces has yet to be attempted. Only when this has been completed will the full significance of the site be disclosed.

Conclusion

The principal landforms at this site comprise a sequence of glacial outwash and river terraces. They are remarkable for the number of levels present and their altitudinal extent. Their development reflects the complex pattern of melting and wastage (deglaciation) of the last (Late Devensian) ice-sheet in the area (approximately 14,000–13,000 years ago). The site represents a striking example of terraces formed by glacial meltwater and river processes during and following deglaciation.

COIRE DHO

J. E. Gordon

Highlights

The assemblage of landforms and deposits at Coire Dho provides an excellent illustration of the development and sudden drainage of an ice-dammed lake during the Loch Lomond Stadial. The cross-valley moraines and bedrock surfaces washed by meltwater floods are the most outstanding examples of these features in Britain.

Introduction

Coire Dho (NH 193142) is a *c.* 10 km² area located in upper Glen Moriston, 55 km south-west of Inverness. It provides an excellent assemblage of glacial, glaciofluvial and glaciolacustrine landforms and sediments and is particularly noted for the best example in Britain of cross-valley moraines. The landform assemblage is associated with a Loch Lomond Readvance glacier that impounded a lake in the upper part of the valley. The former presence of the lake is also recorded by shorelines, lacustrine sediments, overspill channels and areas of washed bedrock where the water drained in a succession of floods. The geomorphology of the site was noted briefly by Milne Home (1878) and has been investigated in detail by Sissons (1977b) and also summarized by him (Sissons 1977d).

Description

Although in an early account Milne Home (1878) reported the presence of 'remarkable terraces' and sand and gravel deposits in Coire Dho, the site subsequently attracted little attention until the work of Sissons (1977b). Sissons produced a comprehensive description and interpretation of the geomorphology of Coire Dho and the wider assemblage of landforms extending a further 15 km to the east in Glen Moriston. During the Loch Lomond Readvance, a glacier flowed eastwards along the Cluanie valley and down Glen Moriston to a limit several kilometres east of Dundreggan (Peacock, 1975a; Sissons, 1977b). The glacier transported distinctive erratics from the Cluanie granodiorite intrusion into Coire Dho, a tributary of Glen Moriston. As a lobe of ice extended up Coire Dho, it dammed a lake in the upper part of the valley. The formation of this lake and its subsequent periodic drainage, together with a fluctuating ice margin, produced a remarkable and varied assemblage of landforms and sediments in a relatively small area.

The limit of the ice in Coire Dho is marked by a low end moraine which merges upslope with a large lateral moraine (Figure 7.17). Inside the end moraine and extending downvalley for a distance of 3 km is a sequence of at least 30 cross-valley moraines with individual ridges up to 7–8 m high and 20–40 m wide. They run more or less straight down the valley sides and in some cases across the valley floor. The composition of the ridges varies from boulders and unstratified sand to till comprised of grit, sand and stones. In places the ridges consist of lake-floor sediments with coarser material deposited on top.

Although not included in the GCR site, two of the tributary valleys at the head of Coire Dho were also occupied by Loch Lomond Readvance glaciers, which produced end moraines and hummocky moraines.

Glaciolacustrine and glaciofluvial interests include lake shorelines, lake sediments, washed bedrock, meltwater channels and river terraces. Up to seven former lake shorelines have been identified on the north-east side of Coire Dho (Sissons, 1977b). Like similar shorelines in Glen Roy they are partly erosional and partly depositional features. The highest shoreline at 406 m OD is the clearest and most extensively developed, reaching a maximum width of 15–20 m and extending over a distance of 2.6 km (Figure 7.17). It is associated with a col at 407 m OD, suggesting topographic control on the lake level. Several of the lower shorelines are also at the same altitudes as adjacent cols, indicating that drainage through these cols controlled the level of the corresponding ice-dammed lake.

Lake-floor deposits occur extensively in Coire Dho. Sissons (1977b) recorded several sections which show bedded sands overlying laminated silts, sands and clays. Drop stones are locally present, while penecontemporaneous slumping is indicated by low-angle normal faults and contorted bedding. In places the lacustrine sediments have been incorporated into cross-valley moraine ridges (Sissons, 1977b). They extend up to an altitude of 450 m OD, implying lake levels well above the highest shoreline. At the head of Coire Dho the lake sediments have been gullied by water erosion and now take the form of ridges.

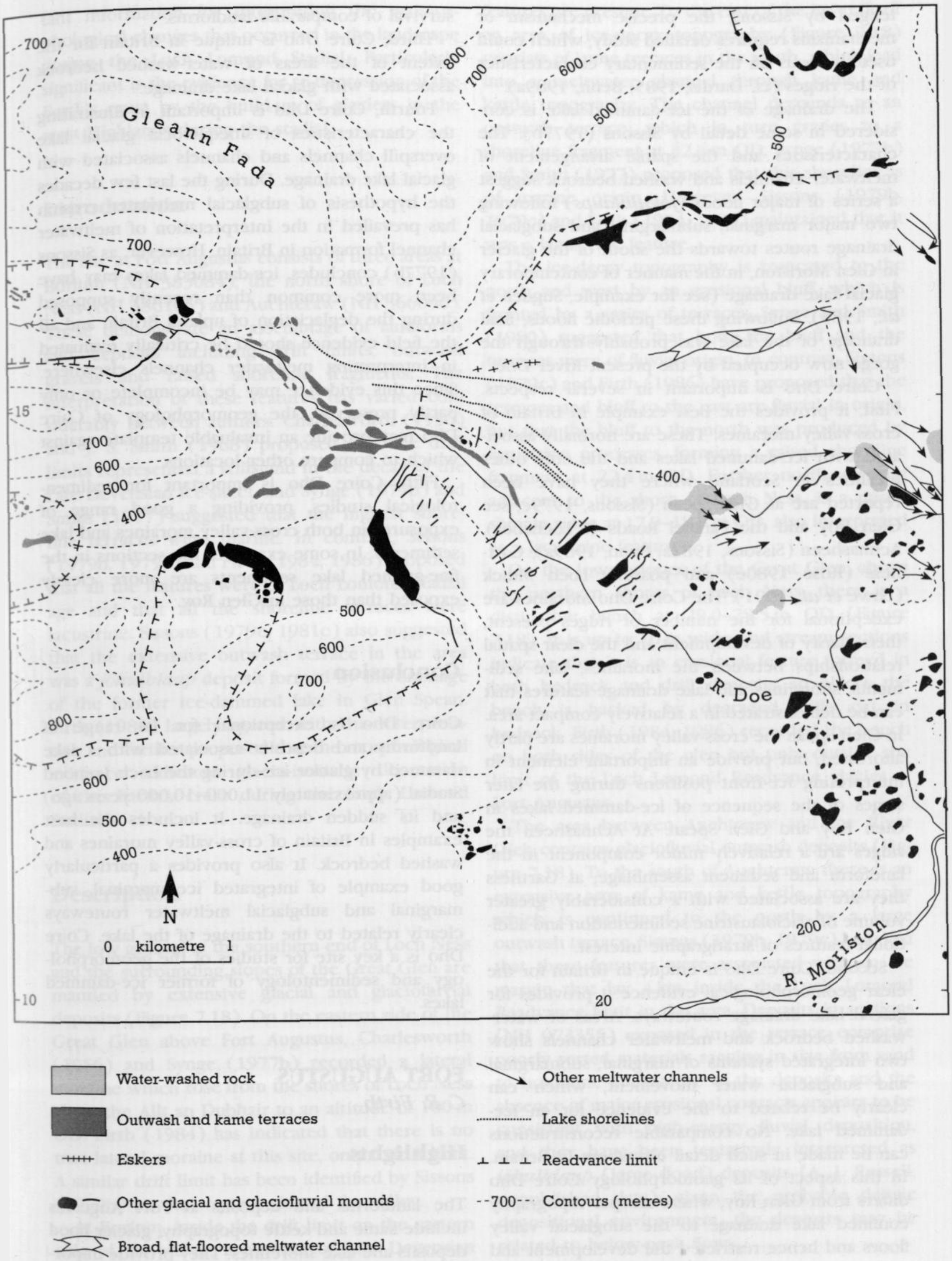
Two suites of terraces are present in Coire Dho. Those at higher levels are formed in lake deposits and are erosional features associated with falling lake levels. The lower terraces comprise coarse-gravel aggradational features unrelated to lake levels. These terraces were probably formed by outwash from the Loch Lomond Readvance glaciers at the head of Coire Dho.

An important and unusual interest in Coire Dho and eastwards into Glen Moriston is the presence of extensive areas of water-washed bedrock. The individual areas of washed bedrock are up to 1.5 km long and up to 0.4 km wide. Together with interconnecting meltwater channels they form two distinct belts over 9 km long. Sissons (1977b, 1977d) considered the water-washed bedrock to be associated with sudden drainage of the ice-dammed lake. Such drainage stripped away the former drift cover, often leaving a well-defined washing limit. Bedrock erosional marks comparable to those ascribed to subglacial floods by Shaw (1988) and Sharpe and Shaw (1989) have not been recorded at Coire Dho. The meltwater channels associated with the washed bedrock occur as two main types. The first occupy pre-existing valleys or depressions and have flat floors up to 0.35 km wide, infilled with glaciofluvial sediments which sometimes demonstrate braided channel surfaces or terraces. These channels are associated with catastrophic lake drainage. The second are smaller, narrower channels typical of subglacial meltwater erosion.

Interpretation

There is a considerable body of literature on the geomorphology of moraines that lie transverse to ice flow (cf. Sugden and John, 1976). Sissons (1977b) considered the Coire Dho features to be sublacustrine cross-valley moraines as described by Andrews (1963a, 1963b) from Baffin Island. Various processes have been proposed to explain the formation of such moraines, including the squeezing of material into basal crevasses (Andrews, 1963b), squeezing or pushing of debris at the ice front (Andrews and Smithson, 1966) and accumulation at the grounding margin of floating ice ramps (Holdsworth, 1973; Barnett and Holdsworth, 1974). Sissons (1977b) favoured an ice-marginal origin for the Coire Dho ridges, arguing that their bouldery composition and close spacing were incompatible with squeezing of material into subglacial crevasses. However, as acknow-

Figure 7.17 Geomorphology of Coire Dho showing landforms associated with the former ice-dammed lake (from Sissons, 1977b).


Gleann Fada
R. Doe
R. Moriston
N
0 kilometre 1
15
10
20
Water-washed rock
Outwash and kame terraces
Eskers
Other glacial and glaciofluvial mounds
Broad, flat-floored meltwater channel
Other meltwater channels
Lake shorelines
Readvance limit
700 Contours (metres)

ledged by Sissons, the precise mechanism or mechanisms requires detailed study, which could usefully focus on the sedimentary characteristics of the ridges (cf. Dardis, 1985; Benn, 1989a).

The drainage of the ice-dammed lake is considered in some detail by Sissons (1977b). The characteristics and the spatial arrangement of meltwater channels and washed bedrock suggest a series of major floods (*jökulhlaups*) following two major marginal, submarginal and subglacial drainage routes towards the snout of the glacier in Glen Moriston, in the manner of contemporary glacial lake drainage (see for example, Sugden *et al.*, 1985). Following these periodic floods, final drainage of the lake was probably through the gorge now occupied by the present River Doe.

Coire Dho is important in several respects. First, it provides the best example in Britain of cross-valley moraines. These are normally associated with ice-dammed lakes and the only other localities in Scotland where they have been reported are at Glen Spean (Sissons, 1979c; see Glen Roy and the Parallel Roads of Lochaber), Achnasheen (Sissons, 1982a; Benn, 1989a), Gartness (Rose 1980e) and possibly Loch Muick (Lowe *et al.*, 1991). The Coire Dho moraines are exceptional for the number of ridges present, their clarity of development and the clear spatial relationships between the moraines, lake sediments, shorelines and lake drainage features that can be demonstrated in a relatively compact area. In Glen Spean the cross-valley moraines are partly afforested, but provide an important element in interpreting ice-front positions during the later stages of the sequence of ice-dammed lakes in Glen Roy and Glen Spean. At Achnasheen the ridges are a relatively minor component in the landform and sediment assemblage; at Gartness they are associated with a considerably greater volume of glaciolaustrine sedimentation and additional features of stratigraphic interest.

Second, Coire Dho is unique in Britain for the clear geomorphological evidence it provides for glacial lake drainage routeways. Areas of water-washed bedrock and meltwater channels show two integrated systems of marginal, submarginal and subglacial water movement, which can clearly be related to the evidence for an ice-dammed lake. No comparable reconstructions can be made in such detail elsewhere in Britain. In this aspect of its geomorphology Coire Dho differs from Glen Roy, where steeper topography confined lake drainage to the subglacial valley floors and hence restricted the development and survival of comparable landforms.

Third, Coire Dho is unique in Britain for the extent of the areas of water-washed bedrock associated with glacial lake drainage.

Fourth, Coire Dho is important in illustrating the characteristics of unequivocal glacial lake overspill channels and channels associated with glacial lake drainage. During the last few decades the hypothesis of subglacial meltwater erosion has prevailed in the interpretation of meltwater channel formation in Britain. However, as Sissons (1977b) concludes, ice-dammed lakes may have been more common than recently supposed during the deglaciation of upland Britain and all the field evidence should be critically evaluated in interpreting meltwater channels elsewhere. Since this evidence may be incomplete or only partly preserved, the geomorphology of Coire Dho may provide an invaluable template against which to compare other locations.

Fifth, Coire Dho is important for sedimentological studies, providing a good range of exposures in both cross-valley moraines and lake sediments. In some examples the sections in the fine-grained lake sediments are more clearly exposed than those in Glen Roy.

Conclusion

Coire Dho is exceptional for its range of landforms and deposits associated with a lake dammed by glacier ice during the Loch Lomond Stadial (approximately 11,000–10,000 years ago) and its sudden drainage. It includes the best examples in Britain of cross-valley moraines and washed bedrock. It also provides a particularly good example of integrated ice marginal, submarginal and subglacial meltwater routeways clearly related to the drainage of the lake. Coire Dho is a key site for studies of the geomorphology and sedimentology of former ice-dammed lakes.

FORT AUGUSTUS

C. R. Firth

Highlights

The landforms and deposits at Fort Augustus include kame and kettle topography, glacier flood deposits and lake shorelines. They provide important information for interpreting the geomorphological changes that occurred in the landscape during the Loch Lomond Stadial. Particularly significant is the evidence for re-depression of the Earth's crust by the build-up of glaciers in the west Highlands during the stadial.

Introduction

The site at Fort Augustus consists of three areas at Borlum (NH 383084), the north shore of Loch Ness (NH 386105) and Auchteraw (NH 366090). These demonstrate an assemblage of landforms and deposits including drift limits, outwash gravels and raised shoreline fragments. The interpretation of these features has varied considerably between authors. Charlesworth (1956) and J. S. Smith (1968) proposed that the drift limits represented a stillstand in the decay of the Late Devensian ice-sheet, and Synge (1977b) and Smith (1977) suggested that the highest shoreline terraces were marine. In contrast, Sissons (1979b, 1979c) and Firth (1984, 1986) proposed that all the features were of Loch Lomond Stadial age and that all the shoreline terraces were lacustrine. Sissons (1979c, 1981c) also suggested that the extensive outwash terrace in the area was a *jökulhlaup* deposit formed by the drainage of the former ice-dammed lake in Glen Spean. Firth (1986) largely agreed with this interpretation and further proposed that the morphological evidence indicated glacio-isostatic depression of the Earth's crust during the Loch Lomond Stadial.

Description

The low ground at the southern end of Loch Ness and the surrounding slopes of the Great Glen are mantled by extensive glacial and glaciofluvial deposits (Figure 7.18). On the eastern side of the Great Glen above Fort Augustus, Charlesworth (1956) and Synge (1977b) recorded a lateral moraine which rose from the shores of Loch Ness along the Allt an Dubhair to an altitude of 100 m OD. Firth (1984) has indicated that there is no true lateral moraine at this site, only a drift limit. A similar drift limit has been identified by Sissons (1979b) on the western side of the valley.

At Borlum, inside the drift limit on the eastern side of the valley, a number of Late Devensian features are present. To the east of the River Tarff an area of ice-decay topography (Figure 7.18) consists of kame terraces in the south, which lead into a meltwater channel through kame and kettle topography. The channel descends to an outwash terrace, which in turn grades to a shoreline fragment at 32.4 m OD. Synge (1977b) and Smith (1977) proposed that this shoreline is of marine origin. However, Sissons (1979b, 1979c) and Firth (1984, 1986) maintained that it was a lacustrine feature.

The ice-decay topography is truncated to the north and west by an erosional bluff, which is fronted by a series of terraces. Synge and Smith (1980) suggested that both the bluff and the terraces were of fluvial origin. In contrast, Sissons (1979c) and Firth (1986) have proposed that the terraces and bluff to the east are fluvial in origin, but that the bluff to the north was produced by lacustrine processes, forming a raised shoreline fragment at 22.4 m OD. Further north, directly adjacent to the shore of Loch Ness, is a raised shingle ridge at 17.9–18.8 m OD, also interpreted as a lacustrine feature.

On the lower slopes of the Great Glen, above the northern shores of Loch Ness, there is a distinctive bench at 29.0–29.5 m OD (Figure 7.18). It is up to 10 m wide, and stream sections indicate that it is an erosional feature formed in both bedrock and drift deposits. In places the bench is backed by degraded cliffs cut in bedrock. Firth (1984, 1986) recorded the bench on both sides of the glen but only outside the limit of the Loch Lomond Readvance glacier at Fort Augustus.

The area between Auchteraw and the River Oich contains glaciofluvial outwash deposits (Figure 7.18). To the south of Auchteraw there is an extensive area of kame and kettle topography which is continued to the north by a large outwash terrace. Sissons (1979b, 1979c) believed that these features were associated with an ice margin that lay 4 km inside the Loch Lomond Readvance limit in the area. Deposits in sections (NH 073355) exposed in the terrace comprise poorly sorted materials ranging in size from sand to boulders. The nature of the deposits and the absence of major erosional contacts appears to be consistent with high-energy fluvial deposition, and they have been tentatively interpreted as *jökulhlaup* (large flood) deposits (A. J. Russell, unpublished data): given the probable deltaic depositional environment, the deposits may be related to below-peak flows.

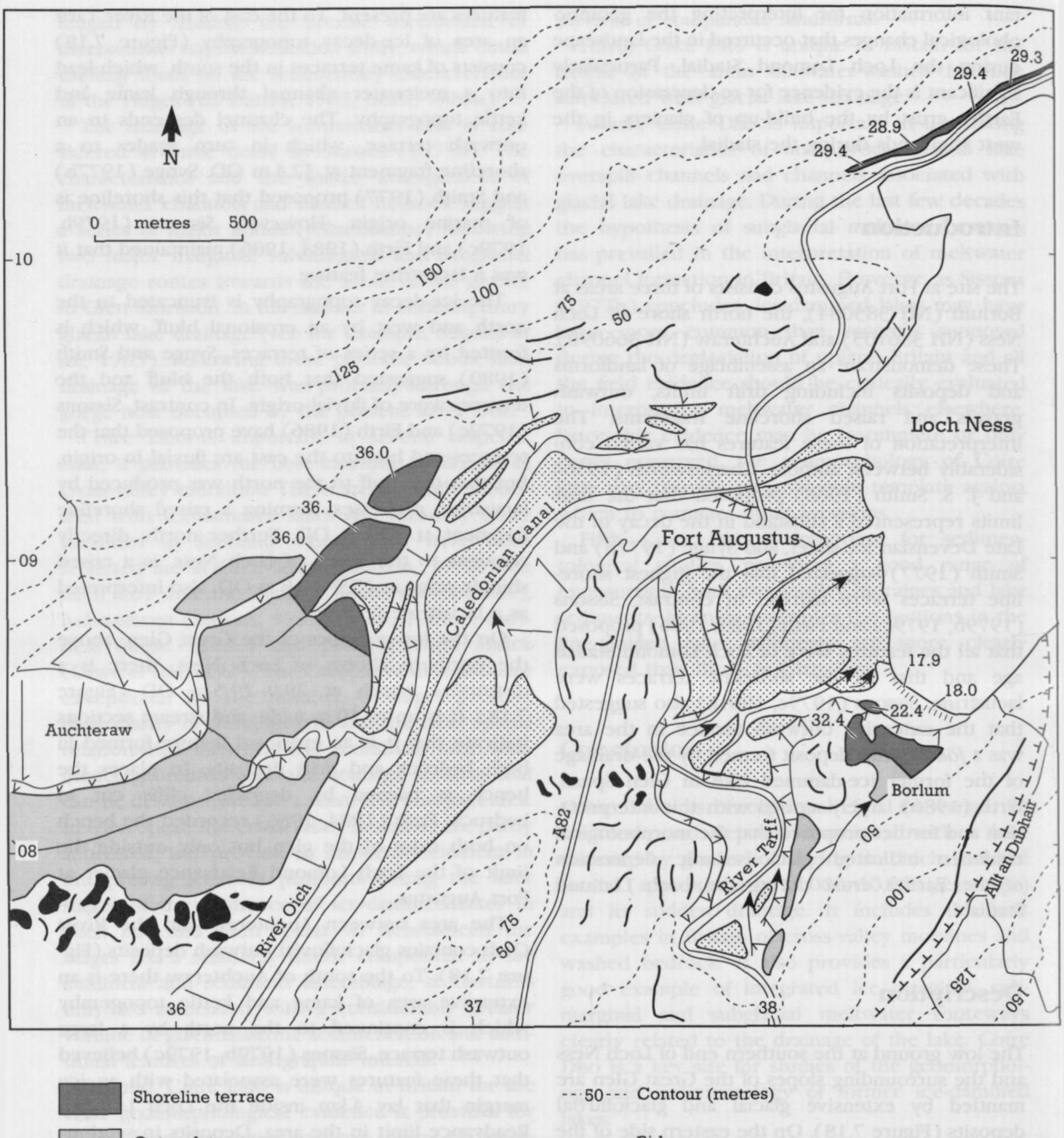


Figure 7.18 Geomorphology of the Fort Augustus area (from Firth, 1984).

Interpretation

The drift limits identified on the slopes of the Great Glen were initially considered to mark a halt in the retreat of the Late Devensian ice-sheet (Charlesworth, 1956; J. S. Smith, 1968). Mapping by Synge (1977b), Sissons (1979b) and Firth (1984) and palaeoenvironmental evidence from Loch Tarff (NH 425100) and Loch Oich (NH 330020) by Pennington *et al.* (1972) implied that the drift limits were deposited during the Loch Lomond Readvance. The limits mark the northernmost extent of readvance ice in the Great Glen and as such are important in the reconstruction of ice coverage during this glacial phase.

Synge (1977b) and Synge and Smith (1980) proposed that the shoreline bench at 29.0–29.5 m OD was a marine feature formed during the decay of the Late Devensian ice-sheet, when the sea penetrated into Loch Ness around 12,800 BP. They considered that marine terraces occurred throughout the River Ness valley, near Inverness, providing a former link between Loch Ness and the sea. However, Firth (1984) reinterpreted the landforms in the Ness valley and concluded that there was no evidence there to support a marine incursion into Loch Ness (see Torvean). Instead he suggested that all the terraces around the shores of the loch were lacustrine in origin. He argued that the erosional feature at Fort Augustus would not have formed in an area of such limited fetch during the period of deglaciation (Firth, 1984, 1986) and proposed that it could only have been produced by periglacial processes during the Loch Lomond Stadial. As such, it is a lacustrine feature and thus comparable to the Parallel Roads of Glen Roy. Dawson *et al.* (1987b) have indicated that such features could easily have formed in an area of limited fetch under periglacial conditions. Firth used the bench to reconstruct the Loch Lomond Stadial lake-level changes of Loch Ness, and it provided important evidence for his idea that the Earth's crust was glacio-isostatically re-depressed at this time (Firth 1986, 1989c). In particular, it demonstrated a rise in loch level from 29 m to 32 m OD between the formation of the erosional terraces at Fort Augustus and the high-level delta at Borlum. Such a rise is present only at the south-west end of the loch and not at the north-east end (see Dores). According to Firth, the simplest explanation of these observations is that the build-up of glaciers in the western Highlands during the stadial was sufficient to re-depress the crust in the area at the south-west end of the loch, resulting in a lake transgression there.

Sissons (1979b, 1979c, 1981c, 1981d) suggested that many of the glaciofluvial features within the Loch Lomond Readvance limits were produced by the catastrophic drainage of the ice-dammed lake in Glen Roy and Glen Spean. He ascribed the outwash terrace at Auchteraw to such an origin and also proposed that it formed part of a more extensive surface including the terrace at 32 m OD at Borlum. Sissons (1981c) suggested that the flood of water into Loch Ness during the *jökulhlaup* was so great that the water level of the loch was temporarily raised by 8.5 m from 22.5 to 31 m OD. He suggested that the loch level then fell to its pre-*jökulhlaup* level. Firth (1984, 1986) agreed that the Auchteraw terrace was the product of a Loch Lomond Stadial *jökulhlaup* but proposed that it descended towards the north-east to grade into a raised shoreline fragment at 36.0–36.1 m OD, and was not associated with the terrace at Borlum. Alternatively, he suggested that the latter was formed during the initial retreat of the Loch Lomond Readvance glacier and thus is distinct from the terraces south-west of Fort Augustus. Firth (1984) interpreted the terrace at Borlum as a delta associated with the 32 m OD loch level and, as a result, he suggested that the *jökulhlaup* flood temporarily raised the loch level by only 4 m from 32 m to 36 m OD.

The field evidence in the Fort Augustus area therefore suggests a sequence of events which spans the period of the Loch Lomond Stadial (Firth, 1984, 1986). During the early part of the stadial, loch level stood at 29 m OD and the erosional benches were formed. The Loch Lomond Readvance then reached its maximum extent; during the initial retreat, loch level stood at 32 m OD. After the ice-front had retreated 4 km, the ice-dammed lake in Glen Spean drained catastrophically to produce a large outwash spread related to a temporarily high loch level at 36 m OD. Subsequently, the level of the loch fell to 22.5 m OD in response to erosion of the outlet of Loch Ness produced by the floodwaters.

The Quaternary landforms and deposits in the Fort Augustus area are important in a number of respects. The features at Borlum are important in determining the Late Devensian and early Holocene evolution of Loch Ness. Synge (1977b) and Synge and Smith (1980) interpreted the 32.4 m OD feature as a marine terrace. In contrast, Sissons (1979c) suggested that it represented a fragment of the *jökulhlaup* deposit. More recently, Firth (1984, 1986), has proposed that the terrace formed during the Loch Lomond Stadial prior to the *jökulhlaup* and thus provides key evidence for the level of Loch Ness before the event. Firth (1984, 1986, 1989c) also used the features in this area to identify re-depression of the Earth's crust during the Loch Lomond Stadial. The evidence from Fort Augustus, together with that from other sites along the Great Glen (see Dores), is therefore important in reconstructing variations in the regional pattern of isostatic uplift in northern Scotland.

The features at Auchteraw represent the first *jökulhlaup* deposit identified in Great Britian (Sissons, 1979c, 1981d). The evidence indicates that the floods had a considerable impact on Loch Ness, being of sufficient volume to temporarily raise the level of the loch by 4 m and of sufficient erosive power eventually to lower the loch exit by 9.5 m (Firth, 1984). The landforms at Auchteraw also demonstrate the nature of early deglaciation of the Loch Lomond Readvance glacier at Fort Augustus, indicating active retreat over a distance of 4 km before the *jökulhlaup* event.

The erosive benches on the north side of Loch Ness are important in the context of the Late Devensian evolution of the area: they provide one of the key lines of evidence relating to changes in water level. They also represent an erosive feature formed by periglacial lacustrine processes at low altitude and thus complement the higher altitude shorelines of Glen Roy and the low altitude marine features of the Main Rock Platform of western Scotland.

Conclusion

The assemblage of landforms and deposits at Fort Augustus provides evidence for a range of geomorphological processes in the Loch Ness area during the Loch Lomond Stadial (about 11,000–10,000 years ago). They include deposits that indicate the drainage pathway of the meltwaters from the Glen Roy ice-dammed lakes and a series of benches and terraces that show the changes in level of Loch Ness and how the build-up of the Loch Lomond Readvance glaciers in the western Highlands was sufficient to affect the isostatic recovery of the Earth's crust (the weight of the ice on the land had depressed the level of the ground surface) following the melting of the Late Devensian ice-sheet (approximately 14,000–13,000 years ago). Together, the features at Fort Augustus contribute significantly to the understanding of key events and changes in the landscape that occurred during the stadial.

DORES

C. R. Firth

Highlights

The landforms at Dores comprise an exceptional suite of raised shingle ridges of lacustrine origin. These shorelines provide important evidence for interpreting geomorphological changes that occurred in the Loch Ness area during the Loch Lomond Stadial.

Introduction

The site at Dores (NH 598354), located on the eastern side of Loch Ness 12.5 km south-west of Inverness, is notable for a series of raised shorelines. In early accounts, Horne and Hinxman (1914) and Ogilvie (1923) commented on the clarity of the '100 ft raised beach' (a marine terrace) around the northern shores of Loch Ness, and the former suggested that fragments of three raised shorelines were present near Dores. J. S. Smith (1968, 1977), Synge (1977b) and Synge and Smith (1980) identified three shingle ridges and proposed that the highest feature was marine in origin. In contrast, Firth (1984) identified four additional shoreline terraces at this locality and suggested that all the features were lacustrine in origin.

Description

The low ground beween Dores and Inverness was noted by Horne and Hinxman (1914) for its extensive glaciofluvial deposits that merge eastward into till. They suggested that the deposits adjacent to Loch Ness up to an altitude of 33 m (100 ft) OD, had been modified by wave action, with three distinct levels of wave activity being recognized near Dores.

J. S. Smith (1968, 1977), Synge (1977b) and Synge and Smith (1980) also identified three

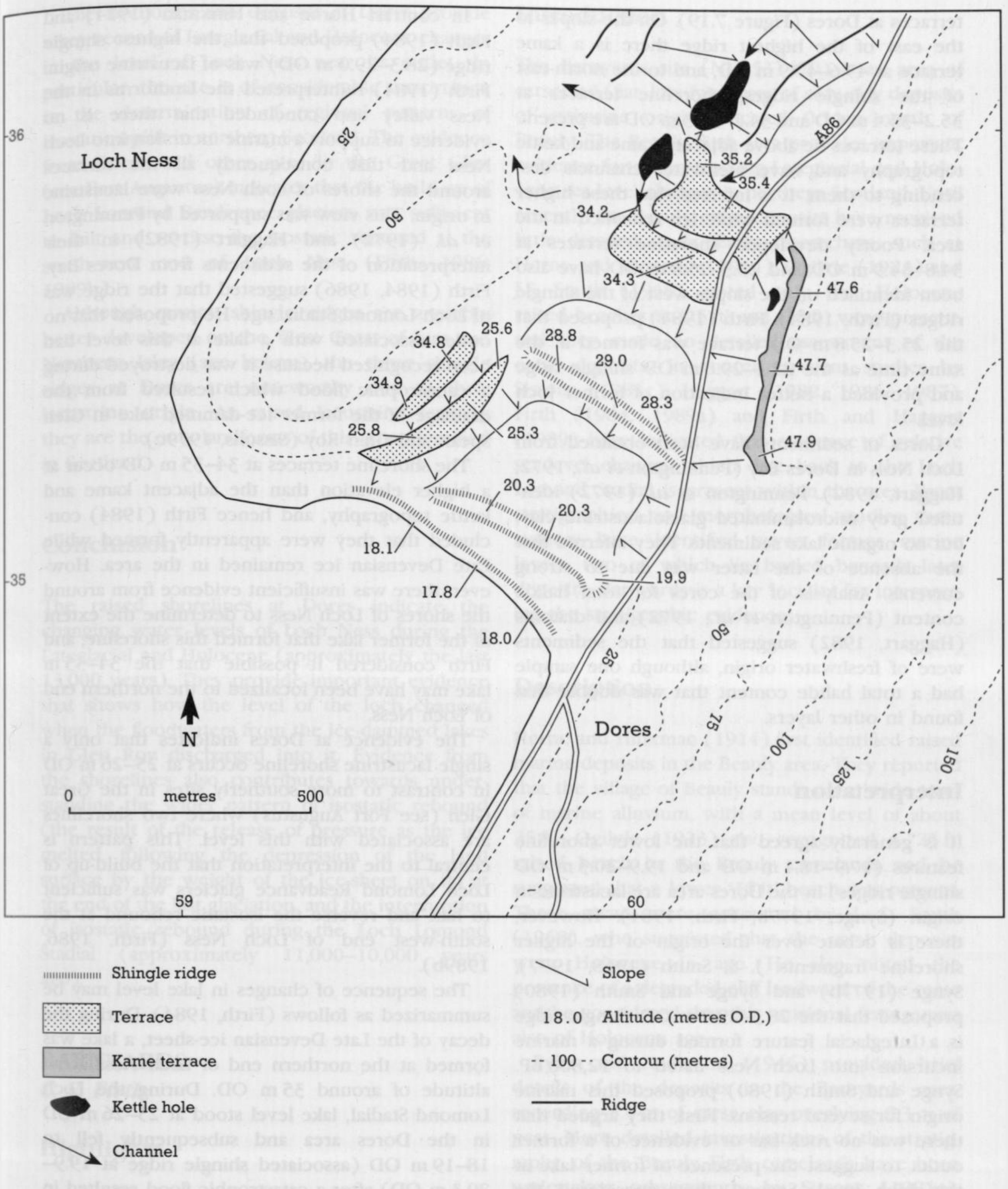


Figure 7.19 Geomorphology of the Dores area (from Firth, 1984).

distinct levels in the deposits at Dores, each level represented by a shingle ridge. The lowest ridge at 17.9–18.1 m OD is related to present loch level (16 m OD), whereas the features at 19.9–20.3 m OD and 28.3–29.0 m OD are indicative of higher water levels (Figure 7.19).

In addition to the three shingle ridges, Firth (1984) identified a series of outwash and shoreline terraces at Dores (Figure 7.19). On the slopes to the east of the highest ridge there is a kame terrace at 47.6–47.9 m OD, and to the north-east of the shingle ridges, shoreline terraces at 35.2–35.4 m OD and 34.2–34.3 m OD are present. These terraces lie above adjacent kame and kettle topography and have meltwater channels descending to them. It is inferred that these higher terraces were formed while ice remained in the area. Poorly developed shoreline terraces at 34.8–34.9 m OD and 25.3–25.8 m OD have also been identified on the slopes west of the shingle ridges (Firth, 1984). Firth (1984) proposed that the 25.3–25.8 m OD terrace was formed at the same time as the 28.3–29.0 m OD shingle ridge and provided a better indication of former loch level.

Cores of sediments have been obtained from Loch Ness in Dores Bay (Pennington *et al.*, 1972; Haggart, 1982). Pennington *et al.* (1972) identified grey microlaminated glaciolacustrine clay, but no organic lake sediments. They inferred that the absence of the latter was due to strong currents. Analysis of the cores for total halide content (Pennington *et al.*, 1972) and diatoms (Haggart, 1982) suggested that the sediments were of freshwater origin, although one sample had a total halide content that was double that found in other layers.

Interpretation

It is generally agreed that the lower shoreline features (17.9–18.1 m OD and 19.9–20.3 m OD shingle ridges) in the Dores area are lacustrine in origin (Synge, 1977b; Firth, 1984). However, there is debate over the origin of the higher shoreline fragments. J. S. Smith (1968, 1977), Synge (1977b) and Synge and Smith (1980) proposed that the 28.3–29.0 m OD shingle ridge is a Lateglacial feature formed during a marine incursion into Loch Ness dated to 12,800 BP. Synge and Smith (1980) proposed this marine origin for several reasons. First, they argued that there was no rock bar or evidence of a former outlet to suggest the presence of former lake at this high level. Second, they considered the sediments from Dores Bay and, in particular, the layer with a high halide content as being evidence in support of a marine incursion. Third, they identified marine terraces at a corresponding altitude throughout the Ness valley, thus providing a former link between Loch Ness and the sea.

In contrast Horne and Hinxman (1914) and Firth (1984) proposed that the highest shingle ridge (28.3–29.0 m OD) was of lacustrine origin. Firth (1984) reinterpreted the landforms in the Ness valley and concluded that there is no evidence to support a marine incursion into Loch Ness and that consequently all the terraces around the shores of Loch Ness were lacustrine in origin. This view was supported by Pennington *et al.* (1972) and Haggart (1982) in their interpretation of the sediments from Dores Bay. Firth (1984, 1986) suggested that the ridge was of Loch Lomond Stadial age. He proposed that no outlet associated with a lake at this level had been recognized because it was destroyed during a catastrophic flood which resulted from the drainage of the former ice-dammed lake in Glen Spean and Glen Roy (Sissons, 1979c).

The shoreline terraces at 34–35 m OD occur at a higher elevation than the adjacent kame and kettle topography, and hence Firth (1984) concluded that they were apparently formed while Late Devensian ice remained in the area. However, there was insufficient evidence from around the shores of Loch Ness to determine the extent of the former lake that formed this shoreline, and Firth considered it possible that the 34–35 m lake may have been localized to the northern end of Loch Ness.

The evidence at Dores indicates that only a single lacustrine shoreline occurs at 25–26 m OD in contrast to more southerly sites in the Great Glen (see Fort Augustus) where two shorelines are associated with this level. This pattern is central to the interpretation that the build-up of Loch Lomond Readvance glaciers was sufficient to halt and reverse the isostatic rebound at the south-west end of Loch Ness (Firth, 1986, 1989b).

The sequence of changes in lake level may be summarized as follows (Firth, 1984). During the decay of the Late Devensian ice-sheet, a lake was formed at the northern end of Loch Ness at an altitude of around 35 m OD. During the Loch Lomond Stadial, lake level stood at 25–26 m OD in the Dores area and subsequently fell to 18–19 m OD (associated shingle ridge at 19.9–20.3 m OD) after a catastrophic flood resulted in the erosion of the outlet along the Ness Valley. During the Holocene, lake level fell to 15 m OD as a result of further downcutting at the outlet, only to be raised to the present day 16 m OD level as a result of the construction of the Caledonian Canal.

The landforms and deposits at Dores provide a key record of Lateglacial and Holocene changes in the level of Loch Ness near its outlet. In particular, the site is of considerable importance in the determination of regional patterns of isostatic uplift in northern Scotland. The evidence from Dores and other sites in the Great Glen (see Fort Augustus) indicates that the build-up of Loch Lomond Readvance glaciers was sufficient to halt and reverse the isostatic rebound at the south-west end of Loch Ness (Firth, 1986, 1989b).

Although marine shingle ridges are arguably better developed on the West Coast of Jura and Northern Islay (see below), the three shingle ridges at Dores are noteworthy due to their lacustrine origin. As raised lacustrine features they are the only landforms of this type identified in Scotland.

Conclusion

The raised shorelines at Dores indicate the changing water levels of Loch Ness during the Lateglacial and Holocene (approximately the last 13,000 years). They provide important evidence that shows how the level of the loch changed when the floodwaters from the ice-dammed lakes in Glen Roy discharged into it. Evidence from the shorelines also contributes towards understanding the wider pattern of isostatic rebound (the result of the release of pressure as the ice melted, following the depression of the land surface by the weight of the ice-sheet on it) at the end of the last glaciation, and the interruption of isostatic rebound during the Loch Lomond Stadial (approximately 11,000–10,000 years ago).

BARNYARDS

C. R. Firth

Highlights

The sub-surface deposits at Barnyards include a sequence of estuarine sediments and peat. These provide a detailed record, supported by radiocarbon dating, of the changes in relative sea level that occurred in the Beauly Firth area during the Lateglacial and Holocene.

Introduction

The Barnyards site (NH 531470) is an area of carseland (flat, low-lying area of silty clay deposits of estuarine origin) located 0.5 km north of Beauly. The Beauly Firth area provides important evidence for reconstructing Lateglacial and Holocene sea-level changes in northern Scotland. Until recently the Beauly carse deposits have received little detailed study. Early researchers, such as Horne and Hinxman (1914), Ogilvie (1923) and J.S. Smith (1968), noted only that Holocene raised beaches at '25 ft' and '15 ft' were present, and they made no detailed assessment of the carse deposits. In contrast, recent studies by Sissons (1981c), Haggart (1982, 1986, 1987), Firth (1984, 1989a) and Firth and Haggart (1989) have indicated that evidence of relative sea-level changes which date back to the Loch Lomond Stadial is present within the area. From stratigraphical and morphological studies these authors have identified seven former marine levels, two of which lie buried beneath later deposits. Barnyards is a key locality for interpreting the stratigraphic evidence.

Description

Horne and Hinxman (1914) first identified raised marine deposits in the Beauly area. They reported that the village of Beauly stands on a 'wide tract of marine alluvium, with a mean level of about 25 ft'. Ogilvie (1923) also recognized a '25 ft' raised beach in the Beauly carselands and he suggested that a lower '15 ft' beach was present. These views were reiterated by J. S. Smith (1968), who suggested that the carse deposits were Holocene in age. He also noted the presence of a degraded cliff landward of the carse and he considered that this erosional feature was also of Holocene age.

Eyles and Anderson (1946) provided brief details of the deposits in the Barnyards area, recording 3.4 m of carse clay overlying 0.3 m of peat. More detailed investigations of the stratigraphy of the Beauly Firth carselands have been undertaken subsequently by Sissons (1981c), Haggart (1982, 1986, 1987), Firth (1984) and Firth and Haggart (1989). Sissons (1981c) confined his investigations to the carselands south of the Beauly River and in the basin of Moniack Burn. He noted that the clay–silt carse deposits are underlain by an extensive gravel layer. Sissons

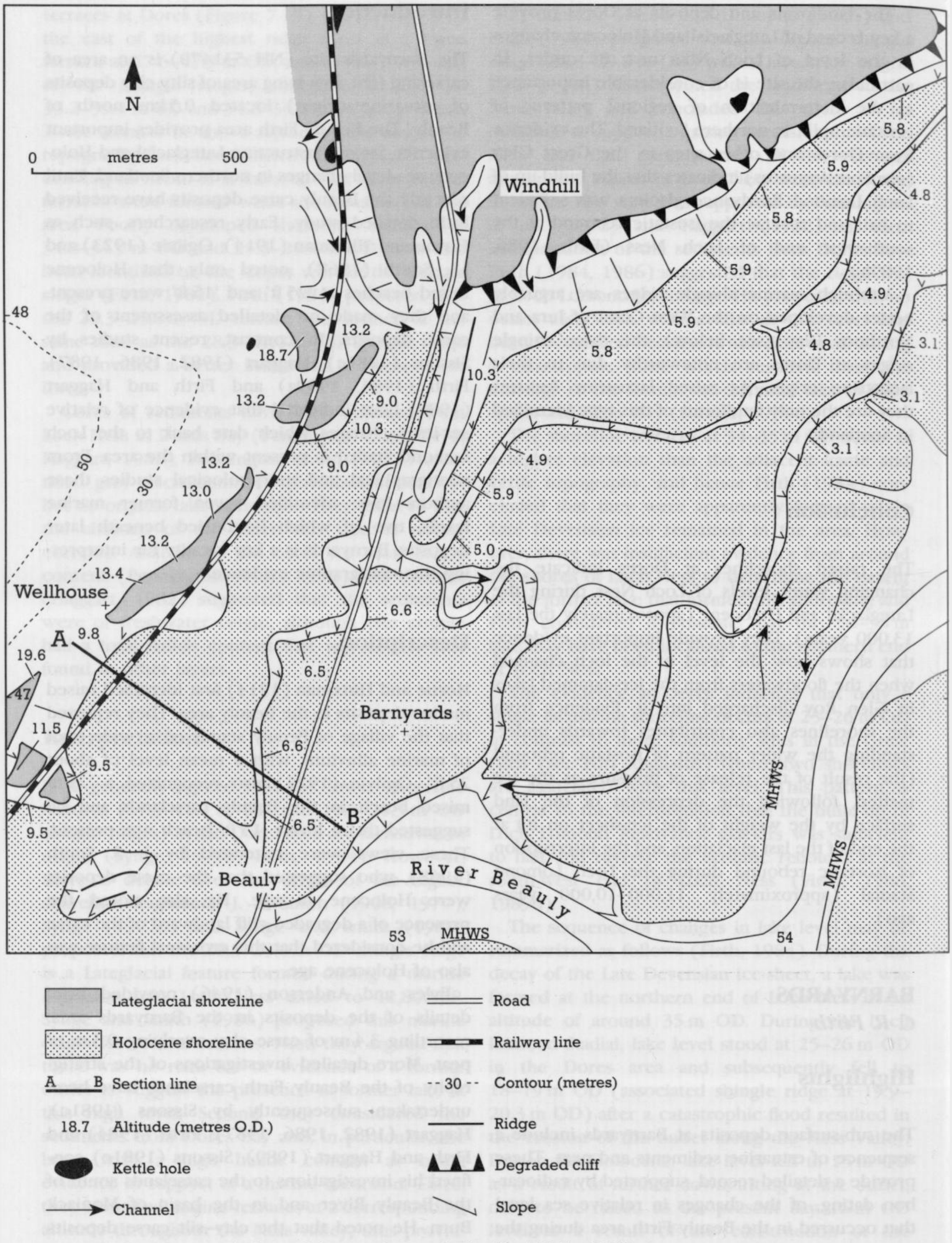


Figure 7.20 Geomorphology of the Beauly carselands (from Firth, 1984).

(1981c) indicated that the gravel layer rises landward from below −1 m OD to a maximum altitude of 2 m OD. He noted that it rests on Lateglacial marine sediments and that it terminates landward near the base of the degraded cliff that backs the carselands. Between the cliff and the buried gravel layer he identified a steeply sloping surface of erosion, which rises to 6–6.5 m OD at the base of the cliff. Sissons (1981c) concluded that these buried features were marine in origin.

Similar stratigraphical investigations were conducted by Firth (1984) on the carselands north of the Beauly River (Figure 7.20). Firth (1984) also identified a buried gravel layer rising to near 2 m OD (for example, south-east of Windhill, Figure 7.20) and a steeply sloping erosion surface which terminated at the base of a degraded cliff, at an altitude of about 8 m OD. Firth (1984) also suggested that these features were marine.

Haggart (1982, 1986, 1987) undertook stratigraphical investigations of the carselands between Wellhouse and Barnyards (Figure 7.20, A-B). In this area he identified a sequence of marine and terrestrial deposits (Figure 7.21). At the base of the sequence till is overlain by light-grey, silty clay. The latter is truncated by a layer of silt, sand and gravel, which is succeeded by grey, clayey silt rising to an altitude of 7.6 m OD. This layer is overlain by peat, the base of which has been dated to 9610 ± 130 BP (Birm–1123). Haggart (1986) has interpreted this clayey silt/peat contact as a regressive overlap caused by a fall in relative sea level. An additional radiocarbon date from a buried peat layer farther seaward indicates that relative sea level was still falling after 9200 BP. Lying above the peat in the sequence is a grey, marine silty clay (carse deposits), which rises to a maximum altitude of 9.5 m OD. This in turn is overlain by another peat whose base has been dated to 5510 ± 80 BP (Birm–1122) (Haggart, 1982, 1986). Haggart (1982) also identified a light-grey, micaceous silty sand within the carse deposits. He noted that this sand layer rises to a maximum altitude of 9.3 m OD and is marine in origin. A similar deposit at Moniack, 4 km to the south-east, was dated to 7270 ± 90 BP (Birm–1126) (Haggart, 1982). A similar sequence of marine and terrestrial deposits was identified by Firth (1984) in the carseland north of Barnyards.

The surface morphology of the Beauly carselands has been mapped in detail by Firth (1984). He noted that the degraded cliff truncates Lateglacial marine deposits and extends as far west as Windhill (Figure 7.20). Directly south of Windhill, a broad sand ridge with a maximum altitude of 10.3 m OD has been identified (Haggart, 1982; Firth, 1984). Both Haggart (1982) and Firth (1984) have interpreted this ridge as a Holocene sand spit. Firth (1984) has also indicated that five separate terrace levels are present in the carselands. The highest level at 9.0–9.8 m OD occurs west of the sand ridge (Figure 7.20). Lower levels are present at 7.5–6.6 m, 5.8–5.9 m, 4.8–5.0 m and 3.1 m OD, each lower level extending farther east. On the slopes west of the carselands Firth (1984) identified a series of Lateglacial marine terraces at 19.6 m, 18.7 m, 13.4–13.0 m, and 11.5 m OD (Figure 7.20); to the north of the carselands a kettled outwash surface grades into a Lateglacial shoreline fragment at 27 m OD.

Interpretation

The stratigraphical and morphological investigations of the carse deposits in the Beauly area provide a detailed sequence of Late Quaternary relative sea-level movements for northern Scotland. It is agreed by all authors that the carse deposits are of Holocene age, a fact reinforced by the palaeoenvironmental evidence presented by Haggart (1982, 1986). In contrast, some debate exists over the age of the degraded cliffline. The early researchers (Horne and Hinxman, 1914; Ogilvie, 1923; J. S. Smith, 1968) proposed that the cliff was Holocene in age, being formed at the culmination of the Main Postglacial Transgression. In contrast, Sissons (1981c) and Firth (1984) suggested that the cliff was formed in association with the buried gravel layer and was a Lateglacial feature. This view was advanced for three reasons. First, the cliff, the steeply sloping surface of marine erosion and the buried gravel layer are continuous. Second, the cliff is partly buried by a variety of Holocene deposits. Third, the deposition of the Holocene silty clays (carse deposits) could not have occurred at the same time as the erosion that produced the cliff.

Sissons (1981c) and Firth (1984) concluded that the buried gravel layer was formed by marine erosion during a slow transgression that occurred during the Loch Lomond Stadial. Both authors correlated the inner margin of the buried gravel layer at about 2 m OD with the Main Lateglacial Shoreline identified in the Forth

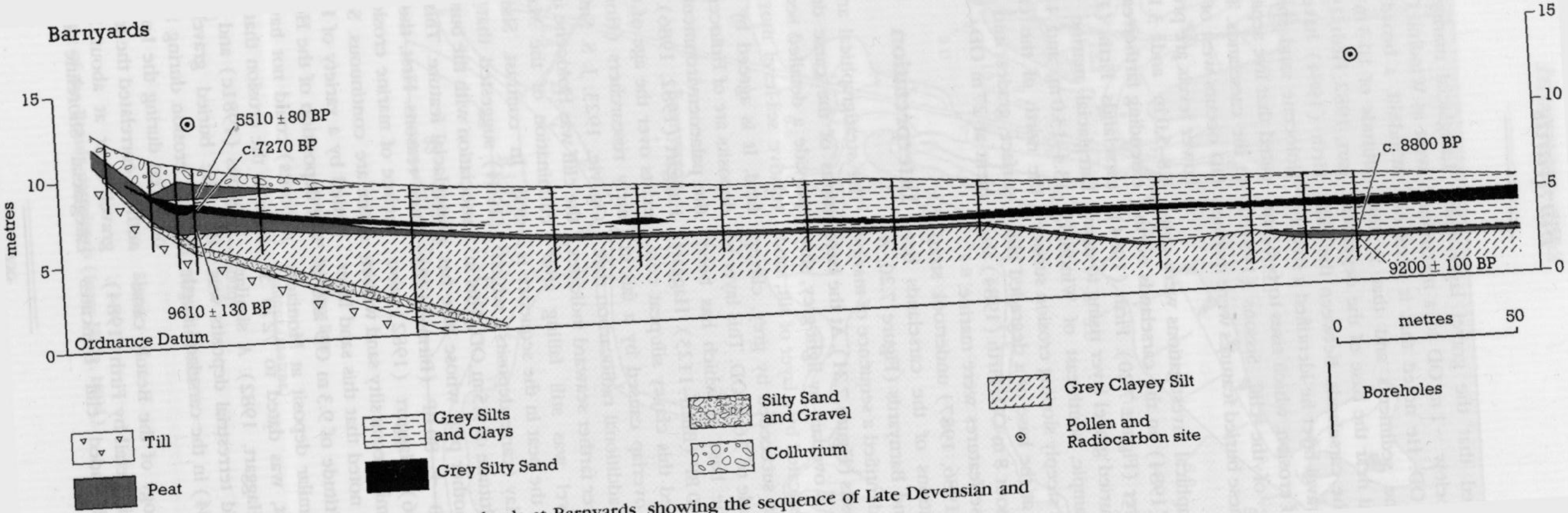


Figure 7.21 Section through the Beauly carselands at Barnyards, showing the sequence of Late Devensian and Holocene deposits (from Haggart, 1986).

estuary (Sissons, 1969, 1976a). Sissons (1981c) suggested that the marine transgression must have continued at a faster rate in order to produce the marine erosion surface which separates the buried gravel layer from the degraded cliff. This transgressive event culminated at 7–8 m OD. Similar steeply sloping surfaces of marine erosion have been identified in the Forth estuary (Sissons, 1976a).

Haggart (1982, 1986) suggested that relative sea level then fell at the beginning of the Holocene, with marine-estuarine, grey, clayey silt being deposited in the Barnyards area up to an altitude of 7.6 m OD until about 9600 BP. Haggart (1986) proposed that these buried marine deposits were equivalent to the Main Buried Beach identified in the Forth and Tay estuaries (see Western Forth Valley and Carey) (Sissons, 1966; Cullingford *et al.*, 1980).

Haggart (1982, 1986) presented evidence that relative sea level continued to fall during the early Holocene, until around 8800 BP, when a major transgression started, during which the marine, grey silty clay was deposited. Interruption of the deposition of the silty clays occurred around 7200 BP (Haggart, 1982, 1986, 1987, 1988b) with the formation of a grey, micaceous, silty fine sand layer. This deposit was thought to represent either a period of increased marine transgression or a storm surge event (Haggart, 1982, 1986, 1987, 1988b). It has been correlated with similar deposits identified throughout eastern Scotland (see Silver Moss and Maryton) (Smith *et al.*, 1985a; Dawson *et al.*, 1990), and is now ascribed to a tsunami associated with the second Storegga Slide on the Norwegian continental slope (Dawson *et al.*, 1988; Long *et al.*, 1989a).

The transgressive event which deposited the carse silty clays culminated at about 6500 BP with the formation of the highest Holocene shoreline fragment in the area, at 9.5 m OD (Haggart, 1982; Firth, 1984; Firth and Haggart, 1989). Firth (1984) correlated this shoreline fragment with the Main Postglacial Shoreline, which has been identified throughout eastern Scotland (Sissons and Smith, 1965b; D.E. Smith, 1968; Morrison *et al.*, 1981). Relative sea level then fell to its present level via intermediate shorelines at 7.5 m, 5.9 m, 4.9 m and 3.1 m OD. These shoreline fragments formed the basis of the Holocene shorelines diagram produced by Firth (1984) and Firth and Haggart (1989), which incorporated six tilted shorelines declining in altitude towards N20°E.

The sequence of deposits at Beauly represents a key stratigraphic record of Late Quaternary environmental and geomorphological changes in northern Scotland. In this respect it complements the interest at Munlochy Valley, where the evidence is principally morphological. It demonstrates that a slow transgression during the Loch Lomond Stadial culminated in the formation of the Main Lateglacial Shoreline, and illustrates the subsequent rapid transgression that formed the marine erosion surface. The area also reveals the early Holocene regression, during which the Main Buried Beach was formed. Similarly the area records the Holocene transgression that culminated in the formation of the Main Postglacial Shoreline, as well as a possible storm surge deposit dated to 7200 BP. The four, lower, Holocene shorelines demonstrate interruptions in the subsequent fall of relative sea level to its present level.

Similar changes in relative sea level have been identified in other areas of Scotland, namely the Forth and Tay estuaries (Morrison *et al.*, 1981) and more recently at Creich in the Dornoch Firth (Smith *et al.*, 1991b). However, the Beauly carse deposits are important because they contain a wealth of stratigraphical and morphological evidence within such a limited area. Haggart (unpublished data) has suggested that further stratigraphical investigations may identify an equivalent to the Lower Buried Beach of the Forth Valley (Sissons, 1966).

The area is an integral member of a national network of Quaternary sites which illustrate the changes in relative sea level in Scotland (see Silver Moss, Western Forth Valley, Carey, Dryleys, Maryton and Philorth Valley). The area also provides details which are important in the determination of regional and national patterns of isostatic movements in the British Isles (Haggart, 1989; Shennan, 1989). For example, Firth and Haggart (1989) noted apparent shifts in the isobases of different shorelines, implying, if confirmed, shifts in the centre of isostatic uplift between the formation of different shorelines (see also Gray, 1983, 1985). Furthermore, the gradients of shorelines in the Moray Firth area are steeper than expected from existing isobase maps (Sissons, 1967a, 1983a; Jardine, 1982) suggesting that the pattern of isostatic uplift in Scotland may not be represented by a simple ellipsoid (Firth and Haggart, 1989). In addition, the complexity of isostatic uplift is attested from comparison of sea-level curves from the Western Forth Valley, Lower Strathearn, the eastern Solway Firth and the inner Moray Firth, which suggests apparent differences in relative rates of uplift between the different areas (Haggart, 1989).

Conclusion

The sediments at Barnyards contain a detailed record of relative sea-level changes in the Beauly Firth area during the Lateglacial and Holocene (approximately the last 13,000 years). The record shows several significant fluctuations in relative sea-level position, providing valuable comparisons with the changes that are documented at reference sites elsewhere in Scotland. Together, the records from these sites allow the wider patterns of isostatic movements (movements of the Earth's crust triggered by ice-sheet growth and loading, and melting and unloading) and sea-level changes to be established.

MUNLOCHY VALLEY

C. R. Firth

Highlights

Munlochy Valley is notable for a series of raised shorelines. In conjunction with a succession of estuarine and peat deposits buried beneath the valley floor, these provide a detailed record of coastline changes during the Lateglacial and Holocene.

Introduction

The site (NH 645528) lies 0.5 km south-west of Munlochy and comprises an area on the north-west side of Munlochy Valley and part of the valley floor. It is the most representative area for a series of raised shoreline fragments at the head of Munlochy Bay. Munlochy Valley has long been recognized for the detailed morphological evidence it provides of changes in relative sea level. Horne and Hinxman (1914), Ogilvie (1923) and J. S. Smith (1966, 1968) all noted the highest raised marine shoreline in the valley at 90–100 ft (27–30 m) OD. However, only Ogilvie (1923) proposed that this feature was formed in close association with a downwasting ice-sheet. These same authors also indicated that other raised marine features are present lower in the valley, although the only description provided was by Horne and Hinxman (1914), who identified raised shoreline fragments at 50 ft (15 m) and 25 ft (8 m) OD. In contrast, Firth (1984) has identified eleven raised marine levels, six of these being Lateglacial in age and five Holocene. Firth (1984, 1989a) also suggested that the highest shorelines in the valley were formed in close association with a downwasting ice mass.

Description

Within Munlochy Valley and on the slopes above Munlochy Bay there are a series of raised marine shoreline fragments and glaciofluvial features (Firth, 1984, 1989a) (Figure 7.22). The highest and most distinctive of the marine terraces occurs at an altitude of 28.9–29.4 m OD and extends for 2 km along the northern slope of the valley. The lower marine terraces are only poorly developed, occurring in a 'staircase', one feature above another. They indicate four marine levels at 27.0 m, 24.6 m, 17.2–17.5 m and 14–15 m OD.

The floor of Munlochy Valley is composed of grey, silty clays up to 2 m thick, which contain shell fragments and overlie sands and gravels. Towards the head of the valley the silty clay deposits become peaty. These sediments underlie a series of horizontal surfaces, former salt marshes, linked by gently sloping ramps, former mudflats. The horizontal surfaces are interpreted as raised marine shoreline fragments and they occur at five distinct levels (8.0 m, 7.7–6.8 m, 5.3–5.5 m, 4.2–4.3 m, 3.0–3.2 m OD).

Around the shores at Munlochy Bay there is a degraded cliffline, against which, for the most part, raised shingle beaches are deposited. West of Munlochy, however, fine-grained estuarine deposits lie adjacent to the cliffline. Stratigraphical investigations by Firth (1984) indicate that the cliff is fronted by a steeply sloping surface, which descends from *c.* 5 m to 0 m OD. Beyond this there is an extensive planar surface which can be traced throughout the bay and is interpreted as a platform of marine erosion.

Above the highest marine terrace the slopes comprise kame and kettle topography and are dissected by meltwater channels indicative of a downwasting ice mass. The meltwater channels can be traced westwards, either to kame and

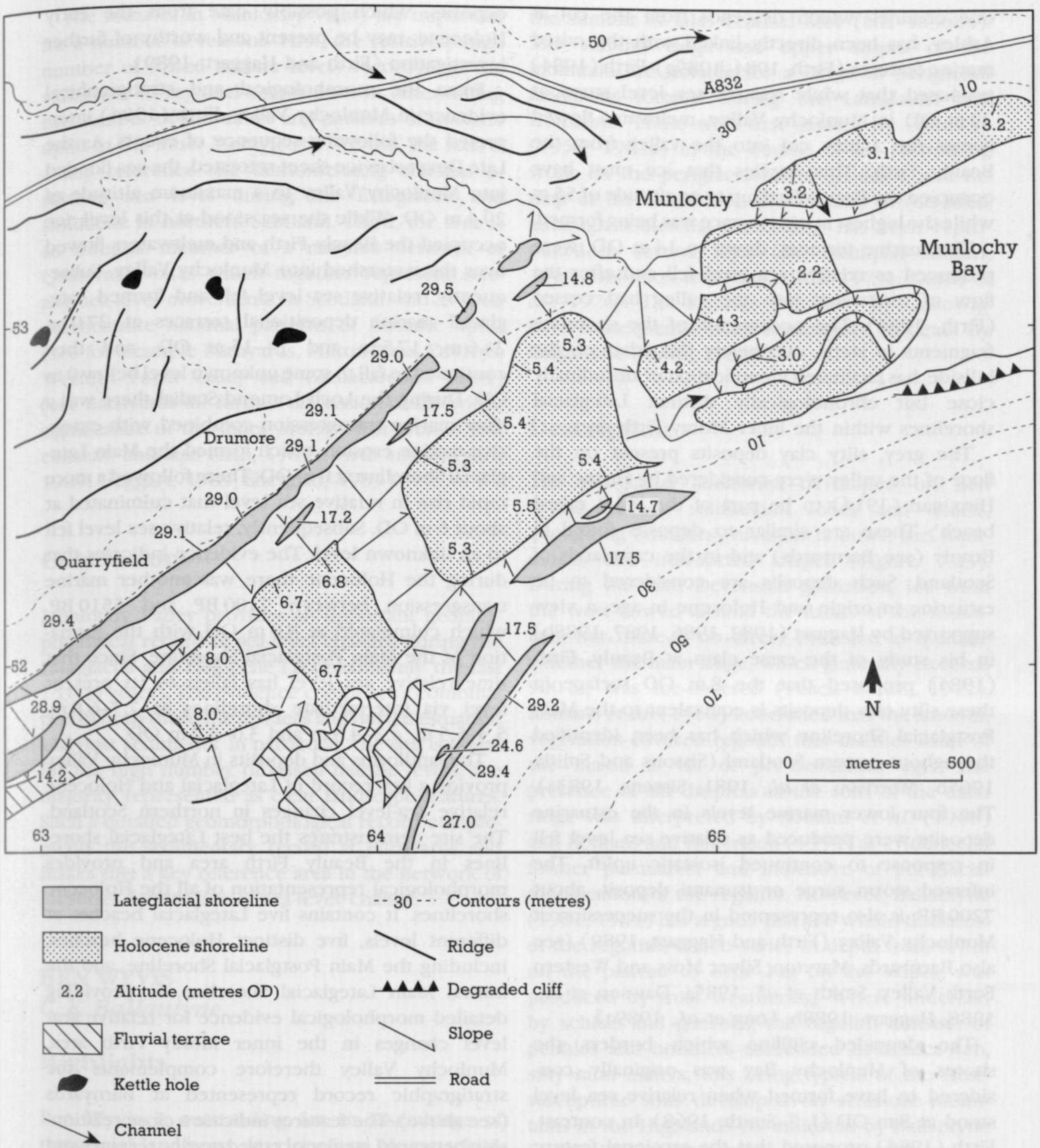


Figure 7.22 Geomorphology of Munlochy Valley (from Firth, 1984).

kettle topography or to cols that separate the Munlochy Valley drainage basin from the Beauly Firth. The clearest of these meltwater channels descends from the col near Ashley (NH 633502) past Bogalian Church (NH 635505) to an altitude of 30 m on the southern slopes of Munlochy Valley.

Interpretation

The glaciofluvial features which mantle the upper slopes of Munlochy Valley testify to the decay of the Late Devensian ice-sheet. Many of the melt-water channels associated with these deposits ultimately lead into Munlochy Valley, but only one channel, which descends from the col at Ashley, has been directly linked with the raised marine features (Firth, 1984, 1989a). Firth (1984) proposed that while relative sea level stood at 29 m OD in Munlochy Valley, meltwater flowed across the Ashley col into the valley from the Beauly Firth. This implies that ice must have occupied the Beauly Firth up to an altitude of 55 m while the highest marine terrace was being formed.

The marine terraces, down to 14 m OD, were produced as relative sea level fell and after the flow of meltwater into the valley had ceased (Firth, 1984). The occurrence of the shoreline fragments as steps, one below the other on the hillside, has facilitated identification of altitudinally close but chronologically distinct Lateglacial shorelines within the inner Moray Firth area.

The grey, silty clay deposits present on the floor of the valley were considered by Horne and Hinxman (1914) to be part of the '25 ft raised beach'. These are similar to deposits found at Beauly (see Barnyards) and in the carselands of Scotland. Such deposits are considered to be estuarine in origin and Holocene in age, a view supported by Haggart (1982, 1986, 1987, 1988b) in his study of the carse clays at Beauly. Firth (1984) proposed that the 8 m OD surface in these silty clay deposits is equivalent to the Main Postglacial Shoreline which has been identified throughout eastern Scotland (Sissons and Smith, 1965b; Morrison *et al.*, 1981; Sissons, 1983a). The four lower marine levels in the estuarine deposits were produced as relative sea level fell in response to continued isostatic uplift. The inferred storm surge or tsunami deposit, about 7200 BP, is also represented in the succession at Munlochy Valley (Firth and Haggart, 1989) (see also Barnyards, Maryton, Silver Moss and Western Forth Valley; Smith *et al.*, 1985a; Dawson *et al.*, 1988; Haggart, 1988b; Long *et al.*, 1989a).

The degraded cliffline which borders the shores of Munlochy Bay was originally considered to have formed when relative sea level stood at 8 m OD (J. S. Smith, 1968). In contrast, Firth (1984) proposed that the erosional feature was produced at the same time as the extensive surface of marine planation that occurs throughout Munlochy Bay, and which rises to 0 m OD. This erosional feature has been equated to the Main Lateglacial Shoreline and is thought to have formed during the Loch Lomond Stadial (Sissons, 1981c; Firth, 1984; Firth and Haggart, 1989).

Limited investigations of the estuarine deposits in Munlochy Valley indicate that buried marine deposits, which possibly date from the early Holocene, may be present and worthy of further investigation (Firth and Haggart, 1989).

From the morphological and stratigraphical evidence in Munlochy Valley, Firth (1984) interpreted the following sequence of events. As the Late Devensian ice-sheet retreated, the sea flooded into Munlochy Valley to a maximum altitude of 29.4 m OD. While the sea stood at this level, ice occupied the Beauly Firth and meltwaters flowed over the watershed into Munlochy Valley. Subsequently, relative sea level fell and formed Lateglacial marine depositional terraces at 27.0 m, 24.6 m, 17.5 m and 14–15 m OD, and then continued to fall to some unknown level below 0 m OD. During the Loch Lomond Stadial there was a slow marine transgression combined with extensive marine erosion which formed the Main Lateglacial Shoreline at 0 m OD. There followed a more rapid rise in relative sea level that culminated at about 6 m OD. Subsequently, relative sea level fell to an unknown level. The evidence indicates that during the Holocene there was another marine transgression between 7100 BP and 5510 BP, which culminated at 8.0 m OD with the formation of the Main Postglacial Shoreline. Since that time relative sea level has fallen to its present level via intermediate shorelines at 7.7–6.8 m, 5.3–5.5 m, 4.2–4.3 m and 3.0–3.2 m OD.

The landforms and deposits in Munlochy Valley provide a key record of Lateglacial and Holocene relative sea-level changes in northern Scotland. The site demonstrates the best Lateglacial shorelines in the Beauly Firth area and provides morphological representation of all the Holocene shorelines. It contains five Lateglacial beaches at different levels, five distinct Holocene beaches, including the Main Postglacial Shoreline, and the buried Main Lateglacial Shoreline. In providing detailed morphological evidence for relative sea-level changes in the inner Moray Firth area, Munlochy Valley therefore complements the stratigraphic record represented at Barnyards (see above). The features indicate a close relationship between Lateglacial raised marine terraces and ice-sheet decay and illustrate the fall in relative sea level associated with deglaciation in Scotland. The area also provides evidence of a period of marine erosion during the Loch Lomond Stadial and of a major marine transgression during the Holocene, which culminated in the formation of the Main Postglacial Shoreline. The four lower Holocene shorelines demonstrate temporary stillstands in the fall of relative sea level to its present position.

The features in Munlochy Valley are important for a number of reasons. First, the relatively high number of raised marine levels recorded in the valley are of regional significance in determining the number of shorelines and patterns of isostatic uplift in the inner Moray Firth. Second, the area is a key reference site demonstrating changes in relative sea level during the Lateglacial and Holocene in northern Scotland. Third, the area is an integral member of a national network of Quaternary sites which together represent relative sea-level movements in Scotland, and as such demonstrate national patterns of isostatic uplift (see for example Barnyards, Milton Ness, Dryleys, Western Forth Valley and Glenacardoch Point) (see Barnyards for further discussion of the wider significance of the inner Moray Firth area in this context, and also Firth, 1989a; Firth and Haggart, 1989; Haggart, 1989; Shennan, 1989).

Conclusion

Munlochy Valley provides an important geomorphological record of sea-level changes during the Lateglacial and Holocene (approximately the last 13,000 years). The evidence comprises a combination of both shoreline terraces and buried estuarine and peat sediments. In particular, the site is noted for the high number of raised marine levels, the majority represented as clear landscape features. Such a detailed geomorphological record complements the sedimentary record at Barnyards and makes this a key reference area in the network of localities for studies of sea-level change.

BEN WYVIS

C. K. Ballantyne

Highlights

Ben Wyvis is outstanding for an assemblage of periglacial landforms developed on Moine schist, most notably non-sorted, patterned ground features and solifluction sheets and lobes.

Introduction

The Ben Wyvis massif in Easter Ross, 30 km north-west of Inverness, is composed of Moine schists and gneisses and rises to 1046 m OD at the summit of Glas Leathad Mór (NH 463684). The summit ridge and upper slopes of the mountain are notable for a range of periglacial landforms formed during the Lateglacial and Holocene. These were first studied by Galloway (1958, 1961a) in the course of his pioneering work on the periglaciation of Scotland, and his map of the solifluction phenomena in this area, although somewhat misleading, has been reproduced in several texts (for example, Sissons, 1965; Embleton and King, 1968, 1975b; Curtis *et al*., 1976). The features described by Galloway have subsequently been investigated in detail by Ballantyne (1981, 1986b).

Description

The periglacial landforms developed on Ben Wyvis include solifluction lobes and sheets, 'ploughing boulders', nivation hollows, turf hummocks and non-sorted stripes (Figure 7.23). During the Late Devensian glaciation, ice from the west flowed around the flanks of the mountain, but there is no direct evidence to indicate whether the main ridge, which generally exceeds 900 m, was ice-covered (Peach *et al*., 1912). Romans *et al*. (1966) concluded that the smooth, vegetation-covered regolith that mantles most of the massif is till of pre-Devensian age. The presence of silt droplets in the soils of the main ridge was interpreted by Romans *et al*. (1966) and Romans and Robertson (1974) as evidence of former permafrost and indicative of periglacial modification of the regolith. However, Ballantyne (1981, 1984) has argued that the whole thickness of the regolith, which varies in depth from 0.7 m on the plateau to over 2 m on the slopes, was produced by frost weathering. Where underlain by schists and gneisses, the regolith consists of pebbles and boulders embedded in a mica-rich, silty sand matrix, this being typical of the frost-susceptible soils developed on schistose mountains in the Highlands. As indicated by Ballantyne (1981, 1987a), the nature of the regolith represents a primary control on the range of periglacial landforms that develop on a particular mountain summit.

Lobes and sheets of debris are outstandingly well-developed on the steep (25°–30°) north-west flank of Ben Wyvis (Figure 7.23), where Galloway described 'stone-banked' (actually turf-banked) and smaller 'turf-banked' (actually vegetation-covered) lobes. He explained the distribu-

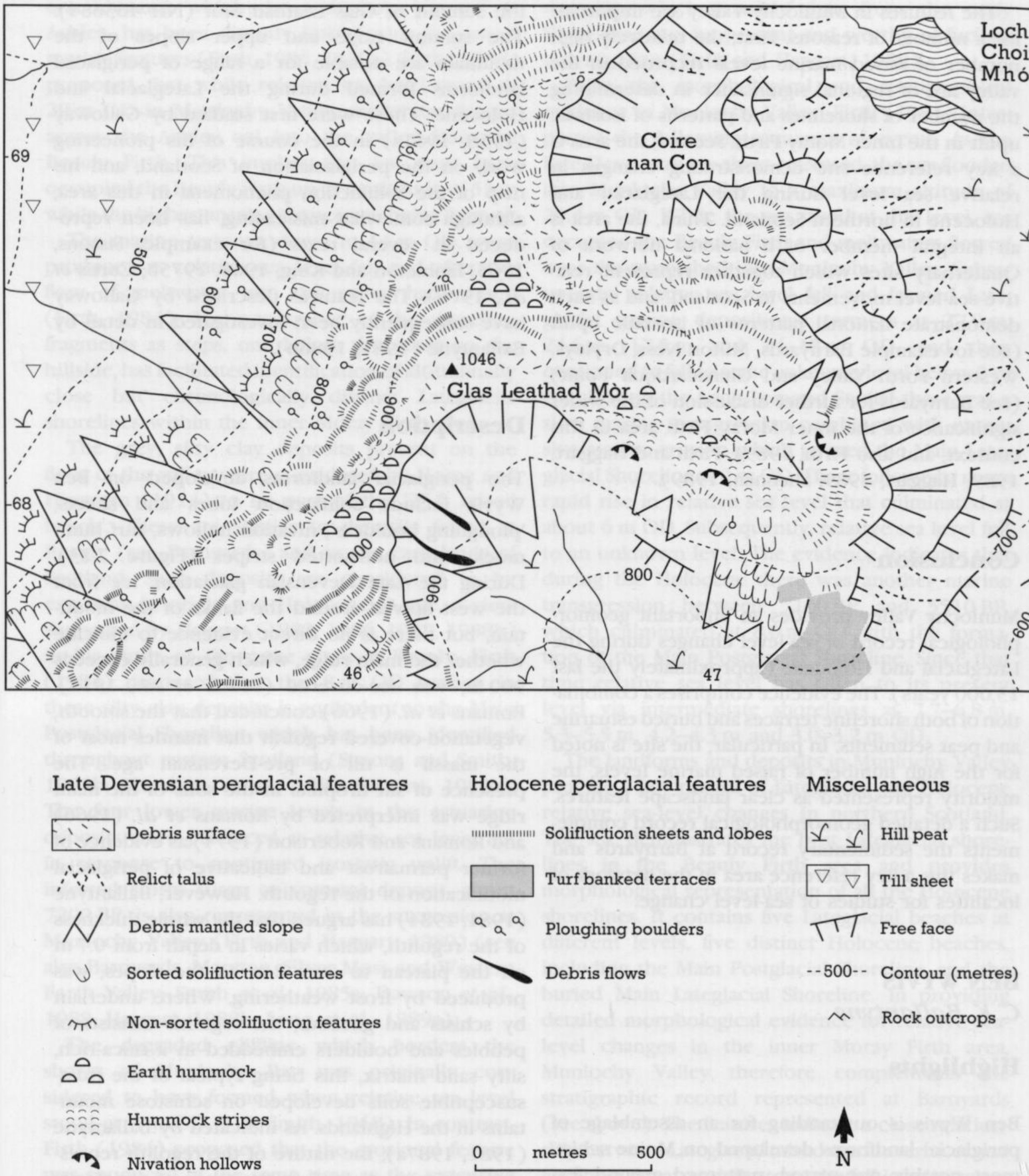


Figure 7.23 Periglacial landforms and deposits on the summit ridge of Ben Wyvis (from Ballantyne, 1984).

tion of the two types in terms of lithological differences. Ballantyne (1981) found that the vegetation-covered features had encroached on the turf-banked lobes, burying the relict block-slopes on which the latter were developed. He concluded that the fossil turf-banked lobes, which show pronounced evidence of vertical frost sorting, had moved downslope by a combination of frost creep and gelifluction, probably under permafrost conditions. The vegetation-covered features show a transition from sheets with straight-fronted scarps on gentle slopes near the crest of the slope, through lobe-fronted sheets, to individual lobes that descend to an altitude of about 750 m OD. These forms are non-sorted and have developed by gelifluction *sensu stricto*, and are currently moving downslope at a rate of a few millimetres per year. The vertically sorted, turf-banked lobes are apparently inactive, apart from the washing out of interstitial fine material, evident in places in the form of spreads of sand in front of lobe 'risers'. However, in one excavation a buried podsol was found containing Holocene pollen assemblages (Ballantyne, 1984), implying movement under climatic conditions not dissimilar from those of today. Both types of feature are also developed on the east side of the massif, as are relict, vegetation-covered boulder lobes, active ploughing boulders and, on sheltered slopes, active turf-banked terraces produced by frost creep (Figure 7.23). Nivation benches on the higher eastern slopes of the mountain are relict features (Ballantyne, 1985).

On the plateau area and the surrounding gentle slopes, Galloway (1961a) identified 'ring' and 'stripe' patterns in the vegetation. The former take the form of turf hummocks 0.06–0.44 m high and 0.28–1.27 m in diameter; on very gentle slopes these tend to form lines downslope which, in turn, grade into a well-developed, non-sorted ridge-and-furrow stripe pattern of similar dimensions (Ballantyne, 1986b). Transitions between these types occur at 1–6° and 6–11°, respectively and relief stripes are poorly developed on slopes greater than 20° and absent from slopes above 25°. The hummocks are clearest to the north of the main summit and the stripes are superbly developed south-east of Tom a'Choinnich (NH 464700). Excavation of these patterned ground features revealed mature podsols underlying both the up-raised portions and the depressions, but no evidence of lateral frost sorting (Ballantyne, 1986b). The origin of these features is uncertain. Galloway (1958, 1961a) interpreted them as being inherited from fossil sorted polygons and stripes formed under climatic conditions more severe than at present (see also Chattopadhyay, 1982). Ballantyne (1986b) offered the alternative explanation that the features are the product of modification by mass displacement of non-sorted, vegetation-defined patterns similar to those found in the high arctic at present (see Washburn, 1979, pp. 151–153).

Interpretation

Ben Wyvis is an important locality for its range of types and degree of development of relict and active periglacial features. In particular, the massif supports the most extensive known area of non-sorted relict stripes in Scotland, together with some of the finest examples of active non-sorted solifluction sheets and lobes. The presence of the undisturbed podsols within the inactive features suggests that they are of Lateglacial age (Ballantyne, 1986b). The frost-susceptible nature of the regolith derived from the Moine schist and gneiss bedrock is a fundamental control on the development of these features, and hence the periglacial landforms found on Ben Wyvis contrast with those found on mountain summits underlain by different lithologies and therefore regoliths (see Lochnagar, An Teallach, Ward Hill, Ronas Hill and the Cairngorms). Particularly striking is the contrast between the assemblage of periglacial features on Ben Wyvis and that on An Teallach, a nearby mountain of Torridonian sandstone of similar altitude and relief. Active solifluction features, 'ploughing boulders', earth hummocks and non-sorted stripes are absent from the coarser regolith of the latter, which supports instead a wide range of wind-related forms, such as deflation surfaces and niveo-aeolian sand deposits (Ballantyne, 1984, 1987a).

Conclusion

Ben Wyvis is important in the network of localities for periglacial landforms, providing an exceptionally good range of active and fossil features developed on Moine schist. It is particularly noted for the fine development of an assemblage of patterned ground forms that comprise vegetated hummocks and vegetated ridges and furrows; these originally formed under more severe climatic conditions than at present. Ben Wyvis also displays excellent examples of sheets and lobes of debris, moved downslope by slow mass movement of the soil; some of these features are still active.