Quaternary of Scotland

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Chapter 16

Western Central Lowlands

INTRODUCTION

D. G. Sutherland and J. E. Gordon

The commonly termed Central Lowlands of Scotland (Figure 16.1) do in fact contain a number of hill groups reaching over 600 m OD. The term, therefore, is somewhat inexact but it is useful in highlighting the contrast between the Midland Valley and the mountainous areas to both the north and south. As both these mountain areas were major sources of ice during the Pleistocene, and as there is no evidence for a significant build up of ice within the central belt itself, the history of glaciation of that area is indeed that of a lowland that has been repeatedly invaded by external ice. At times the ice originating in the south-west Highlands has been dominant, whilst at other times Southern Uplands ice has expanded to the north over ground once glaciated from the opposite direction. This led J. Geikie (1877) to coin the phrase, by analogy with social history, of the 'debatable ground' for the southern central belt where the two ice masses held alternate dominance. The Quaternary history of the western Central Lowlands has been reviewed in part recently by Price (1980) and Jardine (1986).

The western Central Lowlands have long been known for mammalian fossil occurrences, including mammoth, reindeer and woolly rhinoceros, that pre-date the last ice-sheet glaciation. These derive from two distinct areas, the Ayrshire Lowlands, as at Kilmaurs (Bryce, 1865b; Young and Craig, 1869), Dreghorn (Craig, 1888) and, most recently, Sourlie (Jardine and Dickson, 1987; Jardine *et al.*, 1988), and from the lower Clyde Valley, as at Bishopbriggs (Bryce, 1859; Rolfe, 1966), Baillieston (Kirsop, 1882), Mount Florida (Macgregor and Ritchie, 1940), Chapelhall (Bryce, 1859) and Carluke (Smith, 1871). In all the locations the fossils are described as occurring within or below deposits of the last ice-sheet, and radiocarbon dates are available from three localities. Samples from Bishopbriggs (Rolfe, 1966) and Sourlie (Jardine and Dickson, 1987; Jardine *et al.*, 1988) suggest ages of about 27,000–30,000 BP for the fauna, but the two museum samples dated from Kilmaurs gave contradictory ages of 13,700 + 1700 − 1300 BP (GX–0634) (Sissons, 1967b) and >40,000 BP (Birm–93) (Shotton *et al.*, 1970).

Two other types of deposit pre-dating the last glaciation have been reported from the same general areas: terrestrial organic sediments, and sands, silts and clays containing marine shells. These have not, in general, been studied in detail, although the organic sediments at Sourlie contain plant macro- and micro-fossils indicative of a treeless vegetation (Jardine and Dickson, 1987; Jardine *et al.*, 1988). The marine deposits are best exposed at Afton Lodge. As with other high-level shell beds in Scotland, it has been disputed whether they are *in situ* (for example, Holden, 1977a) or have been transported as large glacial erratics (Eyles *et al.*, 1949). Sutherland (1981a) has suggested that they are indeed *in situ* and result from a marine incursion during the period of build-up of the last ice-sheet, which he further suggested occurred during the Early Devensian. He also considered that the shelly deposit, which apparently overlay the stratum containing the terrestrial fossils at Kilmaurs (Bryce, 1865b), confirmed that such a marine transgression had occurred. Similar deposits may occur in the south of Arran (Bryce, 1865a; Tyrrell, 1928; Sutherland, 1981a). The dating and sedimentology of all these deposits, however, is uncertain and awaits new evidence.

The last expansion of ice into the western Central Lowlands occurred during the Late Devensian. The initial advance was from the south-west Highlands, and as this ice advanced into the lower Clyde Valley, it dammed the river, producing a sequence of glacial sediments overlying terrestrial and lacustrine deposits (Sissons, 1964; Price, 1975). Throughout the lower Clyde Valley area there are also numerous buried channels, possibly the result of subglacial meltwater erosion (Clough *et al.*, 1916, 1920; Sissons, 1967a; Jardine, 1977; Menzies, 1981). The advancing ice overrode these channels and buried them under glacial deposits. The most spectacular results of this process are seen at the Falls of Clyde, for here, on deglaciation, the river did not regain its old buried valley (Ross, 1927) but cut a new one, with the consequent formation of a sequence of waterfalls.

In the Glasgow area there has long been recognized two till units, red and grey in colour. In places the red till (containing Old Red Sandstone lithologies) has been observed to overlie the grey till (containing Carboniferous lithologies) and they are sometimes seen to be separated by, or overlie, sands and gravels (Bennie, 1868; Clough *et al.*, 1925; Jardine, 1973; Browne and McMillan, 1989). Although it has been proposed that the till units might represent

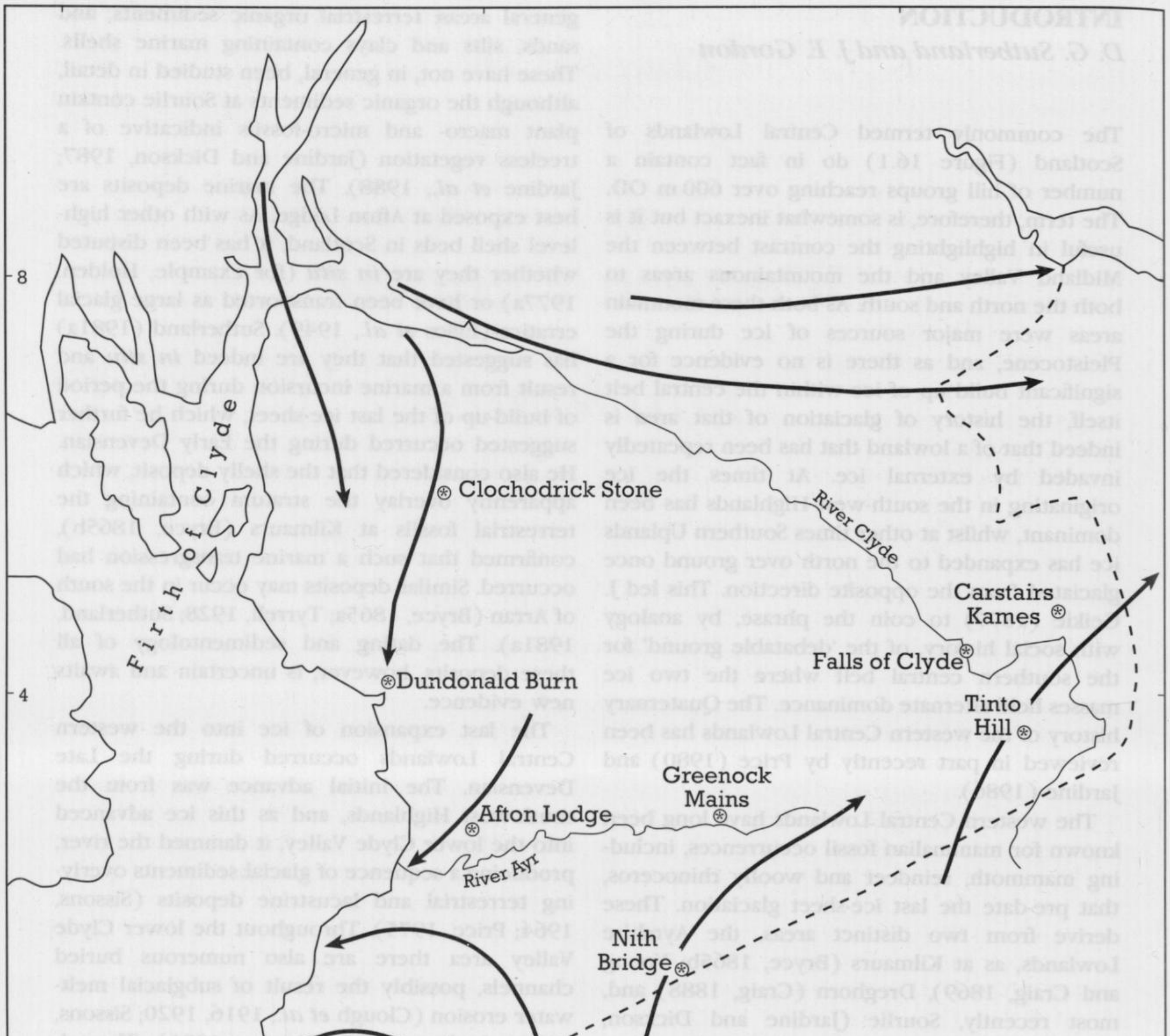

Figure 16.1 Location map of the western Central Lowlands.

separate glacial periods (Sissons, 1967a; Jardine, 1968), more recent work (Menzies, 1976, 1981; Abd-Alla, 1988) suggests that the contrasts in till colour and composition simply reflect the distribution of different bedrock lithologies eroded by the ice. Locally, the till contains marine fossils

(Wright, 1896; Browne and McMillan, 1989). However, an earlier till has been recognized by Browne and McMillan (1989). This till is stratigraphically below the till units described above, has not proved to be fossiliferous and may have been subject to a period of subaerial weathering (Browne and McMillan, 1989). The glacial deposits in the Glasgow area are extensively drumlinized (Elder *et al.*, 1935; Rose and Letzer, 1975, 1977; Menzies, 1981; Rose, 1987). The orientations of the drumlins clearly indicate how the ice flowlines diverged as the ice moved out from the Highlands and across the Midland Valley (Sissons, 1967a).

The Highland ice transported a characteristic sequence of erratics, a fine example of which is Clochodrick Stone. These erratics can be traced into the northern margins of the Southern Uplands (Sutherland, 1984a), indicating that the expansion of Highland ice occurred at a relatively early stage of the last glaciation, for subsequently the Southern Uplands ice became more dominant, advancing northwards into the southern Central Lowlands and deflecting the Highland ice to both east and west. The stratigraphic consequences of this differential development of the two ice centres is a bipartite till sequence throughout much of the southern Central Lowlands, in which a basal till derived from Highland ice is overlain by a till carrying Southern Uplands erratics. Such a sequence is well illustrated at Nith Bridge (Holden, 1977a, 1977c).

On deglaciation very extensive sequences of meltwater channels, eskers and kames were formed (MacLellan, 1969; Cameron *et al.*, 1977). From slightly to the west of the Ayrshire–Clyde watershed, these glaciofluvial features are oriented to the east or north-east and drainage was to the North Sea (Sutherland, 1984a, 1991a). The most outstanding examples of the glaciofluvial deposits formed at this time are the Carstairs Kames (Goodlet, 1964; Sissons, 1967a; MacLellan, 1969), but they are only part of a wider integrated glacial drainage system that operated during the greater part of the deglaciation of central Scotland. Only after the lower Clyde Valley had become free of ice could meltwaters abandon their easterly routes and flow towards the north-west (Browne and McMillan, 1989).

In Ayrshire, west of the Clyde watershed, there is a relative paucity of meltwater phenomena (Holden, 1977a). However, in the upper basin of the River Ayr, there is a particularly interesting sequence of deposits in which an upper till unit, as seen at Greenock Mains, has been interpreted as resulting from a late readvance of the ice-sheet (Holden, 1977a, 1977d). If this is indeed correct, then it implies that active ice occupied the Firth of Clyde after much of the Central Lowlands had been deglaciated. A westwards flow of ice across Kintyre from Arran and carrying Ailsa Craig microgranite to the north coast of Ireland may have occurred at this time and been the counterpart of the readvance in Ayrshire. For reasons of climatic amelioration and the assistance that the deeper waters of the inner Firth of Clyde would have given to ice wastage by calving, this late-stage ice mass may have collapsed rapidly (Sutherland, 1984a). Radiocarbon dating of marine shells around the head of the Firth of Clyde has indicated that these events took place prior to 13,000 BP (Browne *et al.*, 1977; Sutherland, 1986).

During the Loch Lomond Stadial small glaciers formed on Arran (Gemmell, 1973; D. G. Sutherland, unpublished data), and periglacial activity was intense. Ice wedges formed near sea level (Rose, 1975), and radiocarbon dating of buried organic sediments on the flanks of Late Devensian drumlins indicates significant slope instability and solifluction at this time (Dickson *et al.*, 1976). The summits and slopes of the hills in the south of the area are extensively covered in frost-weathered debris and solifluction deposits (Galloway, 1961a; Tivy, 1962; Ragg and Bibby, 1966). On Tinto Hill, where the vegetation has been stripped back, stone stripes are actively forming today.

On deglaciation of the Ayrshire coast the marine limit was at about 25 m OD (Jardine, 1971), or as much as 28 m OD (Boyd, 1986a), with the sea penetrating inland along the lower part of the river valleys, such as that of the Irvine (Boyd, 1986a). Around Arran, the marine limit was also formed on deglaciation, the sea reaching to around 27 m OD in the south of the island and over 30 m OD in the north (Gemmell, 1973; D. G. Sutherland, unpublished data). There has been debate as to whether the sea entered the Clyde estuary area at this time via the Lochwinnoch Gap, while the lower estuary was still occupied by ice (Peacock, 1971c; Price, 1975; Price *et al.*, 1980). The situation remains unclear, not least because of the difficulties in defining the marine limit in the Glasgow area (Sutherland, 1984a), and although rockhead altitude in the Lochwinnoch Gap is sufficiently low for the sea to have passed along its length (Ward, 1977; Institute of

Geological Sciences, 1982), such an event still awaits demonstration by the identification of suitably placed marine sediments.

The western Central Lowlands have been the focus of much research on Quaternary deposits during the last 150 years but, curiously, relatively little has been published in recent times on the Lateglacial and Holocene vegetational history of the area. An exception is the work of Boyd (1982, 1986c, 1988; Boyd and Dickson, 1986) who has studied Holocene environmental change in the Irvine area. On Arran, vegetational change during the Holocene has been studied at a number of sites (Robinson, 1981, 1983; Boyd and Dickson, 1987; Afleck *et al.*, 1988; Edwards and McIntosh, 1988; Robinson and Dickson, 1988) and, in Ayrshire, the history of forest clearance has been investigated at Bloak Moss (Turner, 1965, 1970).

In the Irvine area, as well as more widely along the Ayrshire coast, there is well-preserved evidence for the sea-level changes that occurred during the Holocene (see Dundonald Burn). Following a period of relatively low sea level in the early Holocene, the Main Postglacial Transgression resulted in marine invasion of the coastal zone and the burial of terrestrial peats by marine sediments (Jardine, 1964, 1971; Boyd, 1988). At and following the maximum of the transgression, estuarine sediments were laid down in sheltered embayments; on the more open coasts extensive sequences of shingle ridges were deposited and large sand-dune systems developed on their surfaces, as near Irvine.

AFTON LODGE

J. E. Gordon

Highlights

The sediments exposed in stream sections at Afton Lodge include a high-level shelly clay with a fossil marine fauna. They form part of a suite of such deposits in Scotland which have featured prominently in studies of glacial history and sea-level changes.

Introduction

The site at Afton Lodge (NS 417259) comprises a series of exposures along the Ladykirk Burn, 8 km north-east of Ayr, at an altitude of about 85 m OD. It is important for representing the high-level marine deposits of west-central Scotland. Their origin, like that of similar deposits at Clava and Kintyre, has been the subject of considerable debate. Originally, the deposits were interpreted as *in situ* marine sediments, and later as ice-rafted blocks of frozen sea-floor sediments. Holden (1977a) reopened the debate, arguing that the deposits represent a pre-Late Devensian sea-level stand between 115 m to 150 m OD. Sutherland (1981a) supported Holden's interpretation and further suggested that the high-level marine deposits found around Scotland were the product of isostatic downwarping in front of an expanding ice-sheet, possibly during the Early Devensian. The deposits at Afton Lodge were first described by Eyles (1922) and subsequently by Eyles *et al.* (1949), Holden (1977a, 1977b) and Abd-Alla (1988).

Description

Eyles (1922) and Eyles *et al.* (1949) recorded the following sequence at Afton Lodge:

3.	Red till	up to 4.9 m
2.	Laminated, greyish-green, variegated clay	1.5 m
1.	Stiff, blue to black, stoneless clay with shells	0.6 m

The shelly clay extended for 300 m at an altitude of between 76 m and 91 m OD and yielded shells of nine species of mollusc (Table 16.1).

In his detailed study of the glaciation of central Ayrshire, Holden (1977a, 1977b) re-examined the Afton Lodge section and noted the following sequence of deposits:

3.	Sand and gravel comprising angular clasts up to 0.3 m in a red-brown, coarse, sandy, open-textured matrix	3 m
2.	Coarse gravel, dipping east-south-east at 5°	0.3 m
1.	Stiff, black, shelly, silty clay containing bivalves and Foraminifera	5 m

He considered that bed 3 was not till as suggested by Eyles *et al.* (1949), but rather a slope-wash deposit. The typical till of the area did not overlie the shelly clay, but is its lateral equivalent and could be traced upstream from it. Holden described a sharp, vertical contact between these two units, but in fact they are

Table 16.1 List of mollusc shells recorded at Afton Lodge by Eyles (1922) and Eyles *et al.* (1949). (Modern names are from J. D. Peacock, unpublished data.)

Specimen	Modern name
Astarte compressa Mont.	*Tridonta montagui* (Dillwyn)
A. sulcata da Costa	*Astarte sulcata* (da Costa)
Cyprina islandica L.	*Arctica islandica* (L.)
Pecten islandicus Chemnitz	*Chlamys islandica* (Müller)
Leda pernula Müller	*Nuculana pernula* (Müller)
Hydrobia ulvae Pennant	
Natica affinis Gmelin	*Tectonatica clausa* (Broderip and Sowerby)
Drillia turricula Sowerby	*Oenopota turricula* (Montagu)
Trophon clathratus L.	*Boreotrophon clathratus* (L.)

interdigitated. Abd-Alla (1988) considered that the shelly clay was a marine deposit that could be distinguished on the basis of grain size distribution and geochemistry from the shelly till at locations elsewhere in Ayrshire.

Holden (1977a, 1977b) described stratification in the upper part of bed 1, consisting of alternate layers of coarse sand and silty clay; below, the deposit was a homogeneous silty clay. Shells of molluscs in the clay were nearly perfectly preserved. Small ones occurred whole, larger ones as fragments. Foraminifera and ostracods identified by M. Kean were listed by Holden (Table 16.2). As quoted by Holden, Kean reported that the assemblage was one which could be found in the Firth of Clyde today between 15 m and 50 m depth.

Table 16.2 Fauna recovered from the Afton Lodge marine clay listed in Holden (1977a)

Mollusca
Arctica islandica (L.)
Astarte elliptica (Brown)
Foraminifera
Ammonia beccarri (L.)
Quinqueloculina seminulum (L.)
Elphidium excavatum (Terquem)
Elphidium articulatum (d'Orbigny)
Elphidium clavatum (Cushman)
Elphidium sp.
Fissurina cf. *lucida* (Williamson)
Ostracoda
Cyprideis torosa Jones
Cytheropteron latissimum (Norman)

Interpretation

High-level marine deposits with shells in west-central Scotland were first described by Smith (1850b) in clays beneath till at 510 ft (155 m OD) at Chapelhall, near Airdrie. Crosskey (1865), however, believed that the shelly clay was in fact on top of the till and therefore conformed with the position of similar deposits throughout western Scotland (Clyde beds). Geikie essentially followed Smith's interpretation of the deposits and, indeed, until the discovery of a similar shell bed at Clava, the Chapelhall site became a keystone in the marine submergence hypothesis of the 19th century, representing the minimum level of the transgression (J. Geikie, 1874, 1877). However, reinvestigation of the site by a British Association Committee failed to reveal any evidence of a shelly clay (Horne *et al.*, 1895).

Despite the setback at Chapelhall and doubts over Clava (Horne *et al.*, 1894 minority report; Bell, 1895a, 1895b, 1897a), the submergence hypothesis still persisted (Reade, 1896; Smith, 1896a, 1898; Gregory, 1927), in part on the strength of the presence of marine shells in the till of west-central Scotland. Numerous instances of these were reported by Smith (1862, 1896c, 1898, 1901), Geikie *et al.* (1869), Eyles (1922), Richey *et al.* (1930) and Eyles *et al.* (1949). Generally the shells are scattered throughout the till, and they are clearly glacially derived (Eyles, 1922; Richey *et al.*, 1930; Eyles *et al.*, 1949) despite the contrary views of Smith (1898) and Gregory (1926). Locally, however, the shells occur in denser concentrations associated with intact masses of blue-grey, stoneless clay; for example at Afton Lodge where the best exposures now exist, Tarshaw and Catrine (Eyles *et al.*, 1949).

Eyles *et al.* (1949) argued that the shelly clays were sea-floor sediments transported onshore in a frozen state by ice and deposited as erratics. They considered that the clays were too isolated in occurrence to be *in situ*, pre-glacial or interglacial marine deposits.

The hypothesis of ice moving onshore in Ayrshire from the Firth of Clyde had earlier been suggested by Bell (1871), Craig (1873) and Smith (1891). From the distribution of erratics, drumlin orientations and the very existence of the shelly till, Eyles *et al.* (1949) also concurred that the ice movement during the glacial maximum in central Ayrshire was from the west. During a later phase, however, this trend was reversed. In north Ayrshire the same patterns had been established by Richey *et al.* (1930) and the shelly till there explained in a similar manner. Further support for the movement of ice eastwards was later provided by McLellan (1969) working in Lanarkshire.

Holden argued that bed 1 was a marine clay and was *in situ*. His key evidence was that the ice movement in the area was offshore. In his study of the glacial evidence in central Ayrshire he found no support for any ice movement from the west. The northern part of central Ayrshire was glaciated by Highland ice moving south, then bifurcating to the east and west as it encountered ice from the Southern Uplands (see also Goodlet, 1970). The topographic location of Afton Lodge, in the lee of a ridge to ice moving from the north-east, was admirably suited to the preservation of a marine deposit. Holden's other arguments for the deposit being *in situ* are not altogether convincing. His doubts regarding the feasibility of ice transporting large masses of unconsolidated sediment with the bedding preserved are not supported by reports of large-scale block inclusions or till rafts elsewhere (Moran, 1971; Dreimanis, 1976; Aber, 1985; see also Clava). Holden also argued that the marine clays at Clava and Kintyre were remarkably similar to those at Afton Lodge and proposed that they too were *in situ*. Since there was no evidence of a Lateglacial or Holocene submergence of the required magnitude, and the fauna at Afton Lodge were warm temperate, he concluded that the Afton Lodge and Kintyre deposits represented a pre-Late Devensian sea-level stand of between 115 m and 150 m OD.

The general conclusions reached by Holden (1977a) were supported by Sutherland (1981a) in a wider study of the high-level shell beds in Scotland. Sutherland argued that these deposits were *in situ* and demonstrated that, with the possible exception of Clava, isostatic depression in front of an expanding Scottish ice-sheet could have been sufficiently great to explain the altitudes at which the marine clays occurred. The faunas associated with the shell beds were indicative of the North Atlantic Drift reaching the Scottish coasts at the time of the formation of the deposits, and Sutherland suggested that this was compatible with the evidence of Ruddiman *et al.* (1980) that a relatively mild oceanic climate in the North Atlantic accompanied the build up of ice-sheets in the Northern Hemisphere. The explanation offered by Sutherland apparently entailed an Early Devensian expansion of the Scottish ice. However, to date, no unambiguous evidence has been discovered for an Early Devensian glaciation of Scotland (Bowen *et al.*, 1986; see also chapter 5). Furthermore, amino acid analyses of shells from the high-level marine deposits suggest that they may not all have formed contemporaneously (see Tangy Glen and Clava; D. G. Sutherland, unpublished data). However, the general mechanism for the formation of the high-level shell beds proposed by Sutherland (1981a) may be correct even if the chronology is in error.

Afton Lodge is therefore an important site representing the high-level marine clays of west-central Scotland. There is a continuing debate as to whether these sediments are indeed *in situ* and represent a marine transgression pre-dating the Late Devensian ice-sheet glaciation or whether they are very large ice-transported erratics (see Clava, Tangy Glen and Burn of Benholm). On either interpretation the sediments preserve a marine fauna indicative of the climate at the time of deposition. Amino acid analysis of the contained shells is likely to help resolve the outstanding question as to the age of the marine event represented by the clays.

Conclusion

Afton Lodge is notable for a high-level deposit of marine clay containing shells of marine molluscs. It is one of several such deposits in Scotland, which are of critical importance for studies of Quaternary history. It has been questioned whether these sediments, with their marine fossils, are evidence of a former high sea level or of the transport of marine sediments by a former ice-sheet on to the land. Although the precise age, origin and correlations of the deposit at Afton Lodge have yet to be firmly established, its importance for research, as part of the network of high-level shell beds, is unquestioned.

NITH BRIDGE

D. G. Sutherland

Highlights

The river-bank section at Nith Bridge demonstrates a multiple till sequence. This shows that during the main Late Devensian glaciation, the area was successively crossed by ice from sources in the Highlands and Southern Uplands.

Introduction

This site (NS 594141) comprises a section on the south-west bank of the River Nith at Nith Bridge, 6 km south of Cumnock. It shows a sequence of tills and glaciofluvial deposits that is important in illustrating ice-movement patterns in south-central Scotland and, in particular, the interaction of two ice masses with their respective sources in the western Highlands and the Southern Uplands. The intercalation of tills deposited by these two ice masses has long been noted (Geikie, 1863a). It is now generally thought that the tills were deposited by the Late Devensian ice-sheet and that the relative strengths of the two ice masses reflects variations in the climate during the progress of the last glaciation (Bowen *et al.*, 1986). The Nith Bridge section has been investigated by Holden (1977a, 1977c; see also Holden and Jardine, 1980).

Description

The sediments exposed on the south-west bank of the River Nith at Nith Bridge have been described by Holden (1977a, 1977c; Holden and Jardine, 1980). He described the following sequence (Figure 16.2):

5.	Till, grey, coarse-grained and gravelly	up to 3.5 m
4.	Gravel	<0.5 m
3.	Till, brown, less compact and more clayey than bed 1 and containing shell fragments	2 m

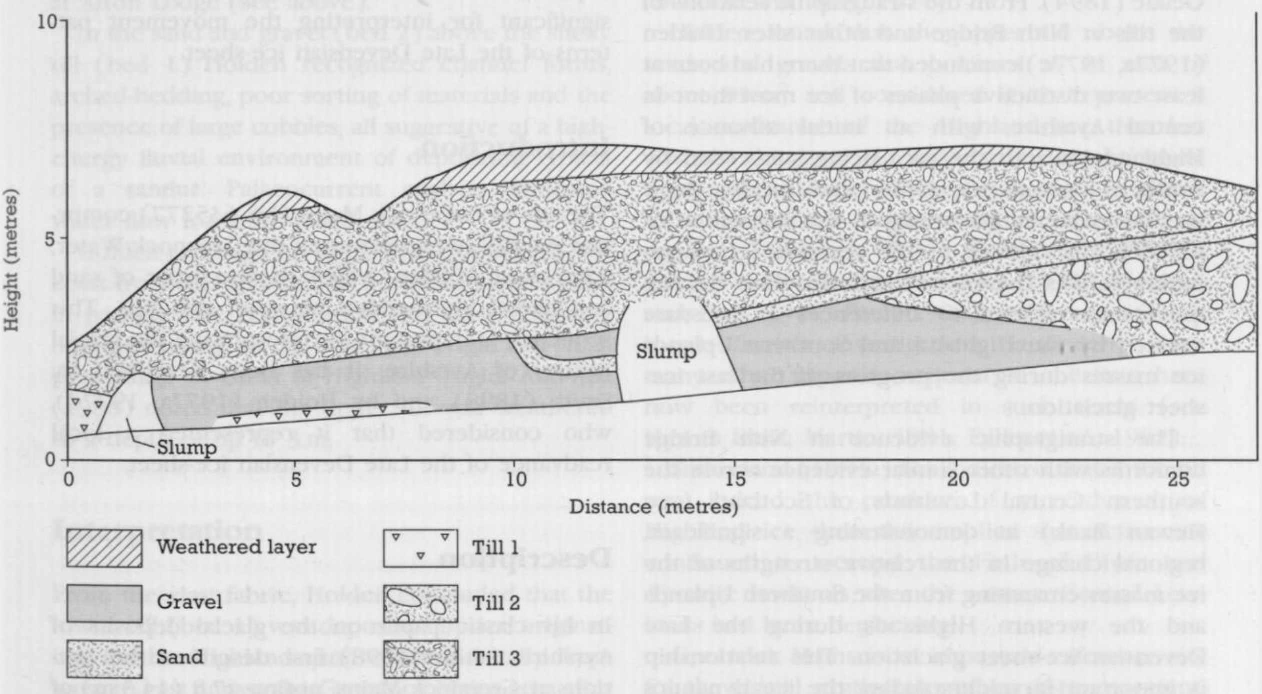

Figure 16.2 Nith Bridge: sequence of sediments (from Holden and Jardine, 1980).

2. Gravels and minor sand horizons *c.* 2 m
1. Till, purple, stiff and sandy at least 1.5 m

Bed 1 occurs immediately above river level. Beds 2 and 3 are truncated and unconformably overlain by bed 4. However, when examined in the field, bed 4 appears to be a line of stones in the till.

Interpretation

Holden investigated the particle size, lithology and clast fabric of the tills. He concluded that the two lower tills had a similar provenance, both being deposited by ice originating in the Highlands and probably flowing across central Ayrshire from the Firth of Clyde area (Holden, 1977c). This view of ice movement is in accord with that of Bell (1871), Craig (1873), Smith (1891), Richey *et al.* (1930), Eyles *et al.* (1949) and McLellan (1967a, 1969) based on those authors' investigations of other sites in Ayrshire and Lanarkshire.

The uppermost till, in contrast, has a southern provenance, as indicated by its erratic content and clast fabrics (Holden, 1977a). This difference demonstrated the former existence of two separate ice masses in central Ayrshire, long established by Geikie (1863a, 1901), Geikie *et al.* (1871) and Geikie (1894). From the stratigraphic relations of the tills at Nith Bridge and other sites, Holden (1977a, 1977c) concluded that there had been at least two distinctive phases of ice movement in central Ayrshire, with an initial advance of Highland ice into the area being succeeded by Southern Uplands ice. Other than locally, there was no evidence for breaks in the deposition of the deposits relating to the separate ice movements. It was therefore concluded that the ice movements related to differences in pressure exerted by the Highland and Southern Uplands ice masses during the progress of the last ice-sheet glaciation.

The stratigraphic evidence at Nith Bridge conforms with other similar evidence across the southern Central Lowlands of Scotland (see Hewan Bank) in demonstrating a significant, regional change in the relative strengths of the ice masses emanating from the Southern Uplands and the western Highlands during the Late Devensian ice-sheet glaciation. This relationship is important in understanding the ice dynamics and the palaeoclimate of Scotland during that glaciation, since it clearly demonstrates a significant shift in the relative importance of the different ice accumulation areas. Such a shift was presumably climatically driven (Bowen *et al.*, 1986) and merits further investigation through modelling of palaeoclimate and the dynamic behaviour of the last ice-sheet.

Conclusion

The deposits at Nith Bridge are important for interpreting the glacial history of the western Central Lowlands. They demonstrate that during the Late Devensian glaciation (about 18,000 years ago), ice from the Highlands first crossed the area and was then replaced by ice coming from the Southern Uplands. Nith Bridge is a valuable reference site for the glacial sequence in this area and for studying the interactions between ice masses from different sources.

GREENOCK MAINS

J. E. Gordon

Highlights

The sequence of glacial and glaciofluvial deposits exposed in stream sections at Greenock Mains is significant for interpreting the movement patterns of the Late Devensian ice-sheet.

Introduction

The site at Greenock Mains (NS 635277) comprises a series of exposures on the Greenock Water, 8 km west of Sorn, which show a layer of sand and gravel interbedded between two tills. This sequence is important for interpreting the glacial history of Ayrshire. It has been described by Smith (1898), and by Holden (1977a, 1977d), who considered that it represented a local readvance of the Late Devensian ice-sheet.

Description

In his classic paper on the glacial deposits of Ayrshire, Smith (1898) first described the sections at Greenock Mains, noting 47 ft (14.3 m) of upper boulder clay, stratified in part, overlying

32 ft (11.1 m) of sand, gravel and lower boulder clay. He recorded that the upper boulder clay was shelly in its upper part.

More recent descriptions of the site have been given by Holden (1977a, 1977d) and Abd-Alla (1988). The basic sequence comprises:

3.	Red-brown, sandy till with clasts of sandstone, shale, siltstone and occasional igneous rocks	up to 6 m
2.	Sand and gravel	up to 20 m
1.	Chocolate-brown, sandy till with shells and clasts of sandstone, shale, igneous and metamorphic rocks; locally with dark grey, silty-clay matrix	up to at least 7 m

Abd-Alla (1988) found that the deposits in bed 1 differed significantly between the two sections that he studied in terms of their grain-size distributions and geochemistry, and to a lesser extent in the relative proportions of the clay minerals present. The deposits in one section closely resembled the shelly till present at other localities in Ayrshire. They also showed an increase in clay and silt content with depth and were weathered in their upper part to a depth of up to 5 m. At the other section, the deposits were comparable in their properties to the shelly clay at Afton Lodge (see above).

In the sand and gravel (bed 2) above the shelly till (bed 1) Holden recognized channel forms, arched-bedding, poor sorting of materials and the presence of large cobbles, all suggestive of a high-energy fluvial environment of deposition typical of a sandur. Palaeocurrent analysis indicated water flow from the north-east.

Holden recorded no shells in the upper till, but apart from this and colour, both tills were similar in particle size composition and their relatively high percentage of clasts of local origin and small percentage of clasts of Highland origin. Abd-Alla (1988) noted that the upper till was weathered to a depth of up to 3 m.

Interpretation

From the clast fabric, Holden concluded that the lower till (bed 1) was deposited by ice originating in the Highlands and moving locally from west to east across the Greenock Mains area after it had bifurcated in central Ayrshire in the presence of Southern Uplands ice. It is part of the distinctive shelly till unit of central and southern Ayrshire (Geikie *et al.*, 1869; Smith, 1898; Richey *et al.*, 1930; Eyles *et al.*, 1949) (see also Afton Lodge) and is one of a number of exposures in the Ayr Valley and near Muirkirk referred to by Geikie (1863a), Smith (1901) and Holden (1977a). Abd-Alla (1988) argued that at one section at Greenock Mains, bed 1 was an *in situ* marine deposit on the grounds of the similarity of its properties to those of the shelly clay at Afton Lodge, for which he accepted an *in situ* marine origin. However, as at Afton Lodge, such a contention requires further investigation, together with full evaluation of the alternative hypothesis of ice transport of a large block of sediment (see also Clava).

From a study of field relations Holden inferred that the overlying sands and gravels were part of the same series of deposits as the extensive surface sands and gravels in the Ayr valley. The latter were interpreted by Geikie (1894) and Charlesworth (1926b) as proglacial lake sediments, but Holden considered them to be ice-contact deposits. From the weathering indicated by the clay minerals and the downwashing of fines in the shelly till of bed 1, Abd-Alla suggested that at least a short interval occurred before the deposition of the overlying sand and gravel; such a suggestion is compatible with observations in modern glacier forefields (Boulton and Dent, 1974).

Holden found that the upper till above the sands and gravels was confined to an area of about 8 km^2 and considered it to represent a local readvance of the Highland ice that last covered the area. He apparently did not investigate the possibility of whether it might be a flow till or part of a single, complex sequence of deposits similar to those recorded in modern glacier environments (Boulton, 1972b; Boulton and Paul, 1976; Paul, 1983). Such a possibility merits further investigation, particularly since many other tripartite sequences in Britain have now been reinterpreted in such terms (see Hewan Bank; Martin, 1981; Eyles *et al.*, 1982).

Sutherland (1984a) has indicated that if the till was indeed the product of a readvance of Highland ice then this implies that active ice continued to occupy the Firth of Clyde and Ayrshire lowlands after the eastern Central Lowlands had been deglaciated.

Greenock Mains is an important reference site for the glacial stratigraphy of Ayrshire, representing the classic shelly till and glaciofluvial sediments of the area. It is also notable for the presence of an upper till which may represent a local readvance of the Late Devensian ice-sheet or may be part of a single, complex sequence of deposits. The upper till is distinct from other tills in a similar stratigraphic position farther south in Ayrshire (such as at Nith Bridge) in that it was deposited by ice flowing outwards from the Firth of Clyde and not from the Southern Uplands.

Conclusion

The ice-deposited sediments at Greenock Mains are important for interpreting the glacial history of Ayrshire. They include two tills derived from the last (Late Devensian) ice-sheet: a lower shelly till characteristic of this area and an upper till which may represent a local readvance of the ice. Greenock Mains forms part of a network of reference sites for reconstructing the pattern of movement and retreat of the last ice-sheet (approximately 18,000–13,000 years ago).

CARSTAIRS KAMES

J. E. Gordon

Highlights

Carstairs Kames is one of the best examples of an esker system in Britain. The landforms and deposits provide important morphological and sedimentological evidence for interpreting the processes of glacial drainage development.

Introduction

Carstairs Kames is one of the most famous geomorphological sites in Britain for an assemblage of glaciofluvial landforms. Although the features, which extend over a distance of *c.* 5.5 km (between NS 937467 and NS 981497), 8 km east of Lanark, have been described in the scientific literature for almost 150 years, their mode of origin is still a source of debate. The main explanations are that they are either subglacial eskers or a form of ice-marginal deposit. The site has been described by Chambers (1848), A. Geikie (1863a, 1874, 1901), Milne Home (1871, 1881c), Dougall (1868), Jamieson (1874), Ramsay (1878), Smith (1901), Gregory (1912, 1913, 1915a, 1915b, 1915c, 1926), Charlesworth (1926b), Macgregor (1927), Sissons (1961c, 1967a), Goodlet (1964), McLellan (1967a, 1967b, 1969), Boulton (1972b), Jardine and Dickson (1980), Laxton and Nickless (1980) and Jenkins (1991).

Description

The Carstairs Kames consist largely of sand and gravel and comprise a series of anastomosing, subparallel ridges and mounds interspersed with kettle holes (Figures 16.3 and 16.4) (A. Geikie, 1874; Gregory, 1913, 1915a; Goodlet, 1964). They formerly extended over a distance of about 7 km, running west-south-west to east-north-east from Newmill (NS 920455) to Woodend Moss (NS 980495) but have been extensively quarried, and the GCR site is restricted to the morphologically most impressive remnants north-east of Carstairs village where the ridges attain heights of 25 m above the adjacent peat bogs. On its northern side, the ridge complex presents a relatively steep face to the flat peat bogs, but on the opposite side glaciofluvial deposits continue southwards in a zone of lower, more subdued mounds. Over a wider area, the Carstairs Kames form part of an extensive belt of glaciofluvial deposits extending south-west to north-east along the valley of the Douglas Water to the Carstairs area (Sissons, 1967a; Goodlet, 1970; Cameron *et al.*, 1977) and north-east from there towards the Edinburgh area (Sutherland, 1984a, 1991a; Jenkins, 1991). Many workers have mentioned in passing the composition of the kames. More detailed accounts have been given by Gregory (1913, 1915a) and particularly Goodlet (1964), McLellan (1969) and Laxton and Nickless (1980). Gregory described bedded gravels with layers of coarse pebbly sand resting upon boulder clay. Gravel was most prevalent and coarsest on the north side of the kames. Goodlet, who monitored the changing faces in working pits over a period of several years, established a threefold stratigraphic succession for the Carstairs area:

3.	Later Beds:	peat
		sand
		gravel
2.	Middle Beds:	Carstairs Station Sands
1.	Earlier Beds:	Upper Gravels
		Main Sands
		Lower Gravels
		Boulder Drift

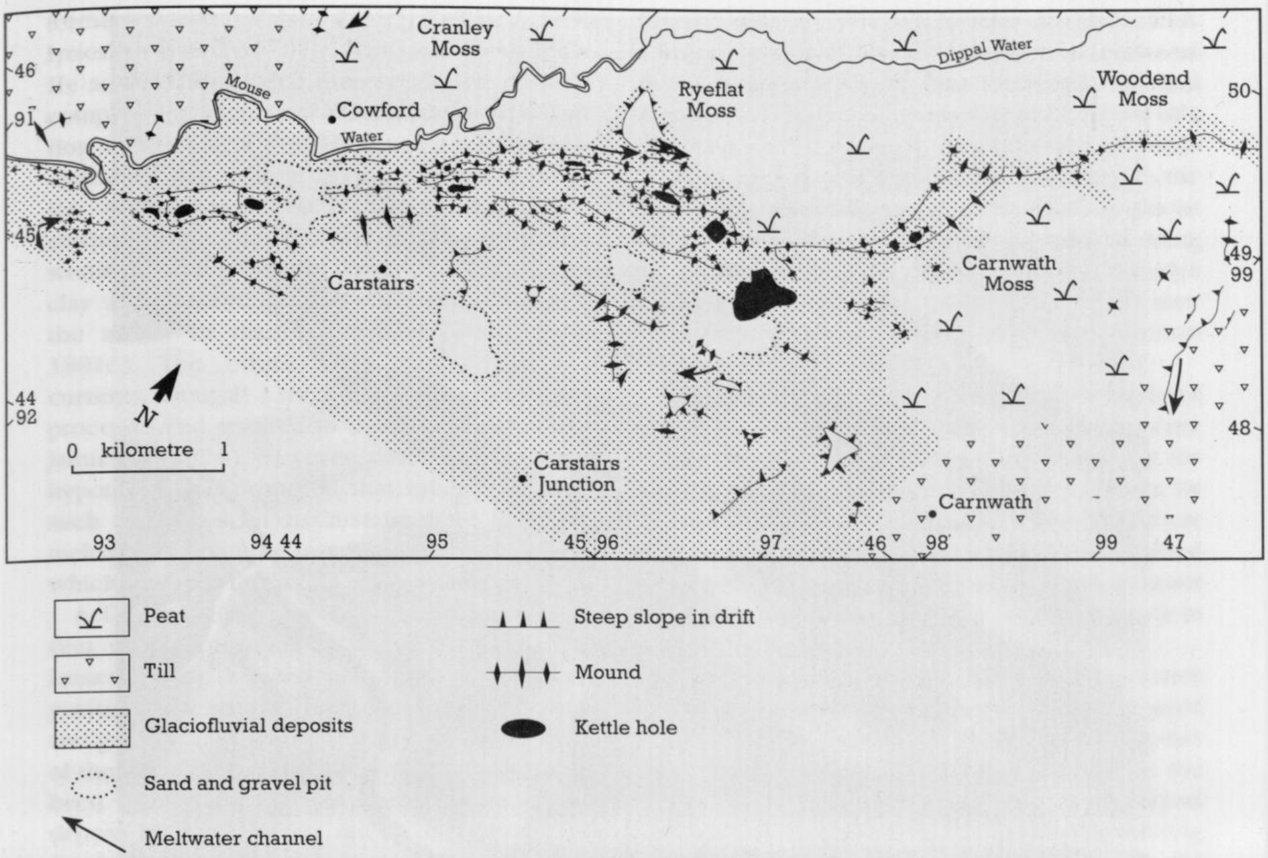

Figure 16.3 Geomorphology of the Carstairs area (from McLellan, 1969).

The kames consisted of the lowest member (1), which he sub-divided into the four units listed. The Boulder Drift had an extremely variable matrix ranging from fine to coarse, clayey sand, with embedded boulders up to 1–2 m in size. The Lower Gravels consisted of clasts 0.07–0.1 m in size and larger stones in a sandy matrix. Sometimes poorly defined bedding was present. The Main Sands, a unit of relatively pure sand with a few bands of gravel, were up to 12–15 m thick and showed clear current bedding with palaeocurrents directed to the east and north-east. They were interdigitated with the poorly bedded Upper Gravels, or separated from them by a thin clay layer. Goodlet also described extensive folding and faulting in the deposits. McLellan (1967a, 1967b, 1969) later recorded decreasing grain size of materials and an increasing proportion of sand in an easterly direction along the kames.

Laxton and Nickless (1980) investigated the sediments of the kames both in sections and from boreholes. They concluded that although Goodlet's stratigraphic framework was valid for the pits which he examined, it was not substantiated over a wider area where their own results suggested a complex variation of facies through time. The ridges largely comprise what they term 'glacial sands and gravels', a poorly sorted cobble and boulder gravel with a clayey, sandy matrix. The ridges are underlain by well-bedded glaciofluvial sand and gravel rapidly grading laterally into glaciolacustrine deposits, noted earlier by Gregory (1915a). In some of the boreholes, till occurs below the glaciofluvial deposits. In the north-east part of the site the mounds consist of glaciolacustrine deposits – laminated clays, silts and fine sand.

Jenkins (1991) distinguished two types of landforms on the basis of morphology and sedimentary characteristics. The first type are the esker-like ridges composed of coarse boulder gravel in a matrix of poorly sorted finer gravel, sand and silt. These deposits are sometimes covered in finer gravel and draped by laminated, fine-to-medium sand, in places with trough cross-bedding. The second type are elongate mounds, up to 20 m high and several hundreds of metres

Figure 16.4 Carstairs Kames showing the interlinked form of the ridges and mounds, with intervening kettle holes. (© British Crown copyright 1992/MOD reproduced with the permission of the Controller of Her Britannic Majesty's Stationery Office.)

long. They mainly comprise medium–coarse sand with trough cross-bedding and channel scours. The mounds are often capped by massive or trough cross-bedded gravel up to 3 m thick and are interspersed with kettle holes.

The lithological composition of the kames is predominantly of materials from sources to the south and south-west, with only a very few rocks of Highland origin present (Gregory, 1912, 1915c; Goodlet, 1964; McLellan, 1969). This agrees with the general pattern established for the drift over a wider area on the northern side of the Southern Uplands (Stark, 1902; Gregory, 1915c; McCall and Goodlet, 1952).

Interpretation

In view of their striking landscape form the Carstairs Kames have long attracted the attention of geomorphologists and geologists. They have been referred to in many textbooks and papers, including the several geological guides to the Glasgow region (McCallien, 1938; Bassett, 1958; Jardine, 1980a). Considerable debate has centred on the origin of the features (Sissons, 1976b) and their implications for the pattern of glacial events in the area. In an early reference, Chambers (1848, p. 213) noted a range of sandhills at Carstairs which he believed were the remains of former marine plains. Later, Geikie (1863a) lyrically described their form and composition. He acknowledged that their origin was probably complex and suggested water currents in association with ice as a possible mechanism, probably operating also with marine processes and drift ice. Milne Home (1871, 1881c) advocated a marine origin for the kames. He interpreted stratified sand and gravel layers overlying boulder clay as submarine banks or deposits formed by the action of marine currents (Milne Home, 1881c). The ridges were formed by water currents. Dougall (1868), too, favoured marine processes and referred to the 'beach' at Carstairs. Jamieson (1874), however, dismissed the marine hypothesis and proposed that eskers and kames such as those seen at Carstairs were formed by meltwaters along the margins of the later glaciers which covered the area.

A. Geikie (1874) provided a systematic description of the morphology and sediments of the kames, noting in particular their variable composition, the stratification and dip of the sands and gravels and the occasionally contorted nature of the beds. He concluded that the kames had not been formed through erosion of a pre-existing deposit by rain or rivers, but he did not speculate on their origin.

Ramsay (1878, p. 386) referred to the 'beautiful' examples of kames at Carstairs and other localities in Scotland, including them in the assemblage of landforms and deposits of the glacial epoch. Somewhat surprisingly, he later described kames or eskers as marine gravelly mounds (p. 430).

Geikie (1901) described the characteristics of the Carstairs Kames, noting that kames and eskers in general were 'a fruitful source of wonder and legend to the people'. After paying due respect to several mythological theories, he stated that no satisfactory explanation so far accounted for them. They were superficial deposits overlying the till and formed during the closing stages of the glacial period. Lacking the characteristics of moraines in the normal sense, they seemed to be associated with meltwater. Smith (1901), however, was rather more specific, suggesting that the Carstairs Kames and related features were the product of fluvial and subaerial denudation of a large delta of drift.

In a series of papers on kames, Gregory (1912, 1913, 1915a, 1915c, 1926) described and discussed many of the characteristics of the Carstairs features. He considered them to be the most famous and typical representative of the Scottish kames (Gregory, 1913). They were glaciofluvial deposits derived mainly from the south and laid down as a marginal formation along the front of a receding glacier. Although they shared similarities in form with eskers, they were not eskers in the true sense, that is deposited on the beds of glacial rivers, since they lacked the seasonal bedding characteristic of these features seen in Sweden and Ireland. Moreover, unlike typical eskers they were aligned across the inferred former direction of glacial drainage in the area.

Macgregor (1927) proposed another mode of origin for the kames. He believed that they were either deposited against a remnant of stagnant ice in the low ground to the north of Carstairs by meltwaters issuing from the glaciers of the Clyde and Douglas valleys, or else they were deposited in a narrow, ice-walled channel between stagnant ice to the north and still-active ice to the south in the Southern Uplands.

Despite the predominantly southern provenance of the constituents, Charlesworth (1926b) argued in the face of previous opinion that the kames were formed by northern ice originating in the Highlands. In his view they were ice-marginal features associated with drainage off a wasting ice-sheet receding from the maximum of the Lammermuir–Stranraer glacial 'stage', supposedly a readvance of the last ice-sheet. In support he pointed to their apparent continuity with deposits both to the north-east and south-west, which he argued were associated with the northern ice of the readvance. He also argued that the steep north face of the kames represented an ice-contact slope (see Charlesworth, 1957, plate 15B). Several factors could explain the high content of southern erratics: they could have been deposits of southern ice reworked and incorporated during the readvance from the north or during fluctuations in the zone of convergence of northern and southern ice at the time of the ice maximum, or even brought to the area by river transport from the south.

Subsequently, Linton (1933) supported Charlesworth's views. However, from a reassessment of the field evidence, Sissons (1961c) showed that in its central and eastern areas the supposed moraine almost everywhere consisted of glaciofluvial 'dead'-ice deposits. Furthermore, over much of the area the last ice came from the Southern Uplands, not the Highlands as Charlesworth had suggested. The Carstairs Kames and their predominantly southern lithologies were associated with this southern ice, which probably advanced over some older Highland till, as happened farther east (Eckford, 1952; McCall and Goodlet, 1952). On morphological grounds Sissons argued that the kames were typical of subglacially formed eskers, and the whole system related to a complex meltwater drainage network under the Southern Uplands ice. The trend of this drainage system accorded with the direction of movement of the last ice-sheet (Sissons, 1967a) and was associated with the supposed Perth Readvance (Sissons, 1963a, 1964).

From his detailed studies of the sediments and structures in the ridges, Goodlet (1964) concluded that the Carstairs Kames were part of a complex terminal moraine formed during a halt-stage in the retreat of Southern Uplands ice, which had readvanced northwards over a wide area (see McCall and Goodlet, 1952) after Highland ice had withdrawn. The Boulder Drift ridges were deposited partly as ice-cored moraines, and as the ice receded, the Lower Gravels and Main Sands were superimposed as outwash deposits. During the later melting of the buried ice, these sediments were modified by erosion and subsidence. Goodlet argued that the deposits were laid down transverse to the last ice movement which, together with their internal composition, made it improbable that they were eskers as Sissons had suggested.

McLellan (1967a, 1967b, 1969) interpreted the available exposures at Carstairs to indicate that the deposits were entirely water-laid, and in his conclusions he fully supported Sissons' view that the kames were part of a subglacial esker system. In McLellan's opinion the Boulder Drift material simply represented coarse proximal sediments which became finer in a downstream direction. However, Boulton (1972b) has shown that there is support from modern glacial environments for the type of interpretation proposed by Goodlet. Boulton argued that the morphology, sediments and internal structure of the kames were unlike those of any known subglacial features, but were identical to those of many supraglacial fluvial deposits accumulated in association with ice-cored moraines. If the analogy is valid, the Carstairs Kames are neither moraines nor eskers, but glaciofluvial deposits originally laid down between ice-cored moraine ridges which blocked and controlled the supraglacial and proglacial drainage. Upon melting of the buried ice in the moraine ridges, inversion of relief gave topographic prominence to the glaciofluvial sediments. Boulton also suggested that many other Pleistocene stratified ice-contact deposits, such as the Bar Hill–Wrexham moraine (Boulton and Worsley, 1965; Yates and Moseley, 1967) and the Escrick moraine (Gaunt, 1970), may have formed in a similar fashion.

Laxton and Nickless (1980) emphasized the complex variation of facies within the whole suite of deposits in the Carstairs area in which they distinguished glacial sand and gravel, glaciofluvial sand and gravel and glaciolacustrine deposits. They envisaged an integrated assemblage of subglacial and proglacial depositional environments in which subglacial streams formed the ridges, then discharged from below the ice. The ridges showed strong similarities with the Guelph Esker in Ontario (Saunderson, 1977), which comprises poorly sorted and bedded material, becoming more graded distally. As suggested by Saunderson (1977) such deposits could have been laid down under sliding bed conditions during high-velocity flow in subglacial tunnels. The underlying glaciofluvial deposits could reflect earlier subglacial deposition under lower velocity in less physically constrained conditions. Laxton and Nickless (1980) therefore supported the esker hypothesis for the origin of the Carstairs Kames. However, they did not consider the origin of the folding and faulting recorded by Goodlet (1964).

More recently, Jenkins (1991) has developed these ideas, drawing analogies with the formation of meltwater drainage systems in modern glacier environments. From the geomorphology and sediments he inferred that the overall environment of deposition at Carstairs was one of englacial or supraglacial streams 'feeding' a subaerial fan overlying buried ice. The ridges of boulder gravel were formed by high-energy flows in englacial tunnels or supraglacial channels near to the ice margin. The sandy mounds were formed by lower-energy, braided streams that fanned out across a surface of buried ice. The laminated finer sand was probably deposited by shallow sheet-floods, whereas the capping gravels represented high-energy floods. Subsequent melting of the buried ice, indicated by the presence of kettle holes and faulting in the sediments, resulted in topographic inversion, with the areas of greatest sediment thickness in the channels now forming upstanding ridges and mounds (cf. Boulton, 1972b).

Jenkins (1991) also considered the deposits at Carstairs in their wider regional context, particularly in relation to the style of deglaciation. He showed that the Carstairs features form part of a sequence of ice-marginal landform and sediment associations that together indicate continuous recession of the last ice-sheet on the south side of the Pentland Hills from the southern outskirts of Edinburgh towards the south-west, accompanied in places by the development of zones of partly buried, stagnant ice. Such a pattern accords with the interpretation of Sutherland (1984a).

In terms of their size, extent and morphology, the Carstairs Kames are one of the most striking assemblages of glaciofluvial landforms in Britain. In terms of their braided morphology, the Carstairs Kames resemble most closely the Kildrummie Kames near Nairn (see above), but differ from a number of large single-ridge features that are typical subglacial eskers, for example at Bedshiel (Stevenson, 1868; McGregor, 1974), Torvean (see above) and Littlemill (see above). Although they are frequently acknowledged to be classic examples of kames or eskers, the precise origin of the Carstairs Kames has been disputed among geomorphologists and geologists for almost 150 years. The most recent studies suggest that they are either subglacial eskers or eskers formed in an englacial or supraglacial position in association with proglacial outwash fans that later became topographically inverted. A key feature to emerge from these studies is that the ridges do not exist in isolation, but are part of a complex and integrated suite of glacial, glaciofluvial and glaciolacustrine deposits in the Carstairs area. To approach a fuller understanding of their formation, they need to be viewed in this wider context. The site clearly has further important research potential in the field of glacial sedimentology and its application to the interpretation and reconstruction of Pleistocene glacial environments and hydrological processes (cf. Kildrummie Kames). Carstairs is a particularly appropriate site for such work because of the existing body of information on the sediments.

Conclusion

Carstairs Kames is a classic site, long renowned for its glacial landforms. These comprise a series of esker ridges, kames and kettle holes, one of the best of such assemblages in Britain formed by the meltwater rivers of the last ice-sheet as it decayed approximately 14,000–13,000 years ago. The site has a long history of research and has featured in many publications. Although the precise origin of the landforms has been much debated, the site is unquestionably of the highest value for studies of meltwater drainage development, processes of meltwater sedimentation and patterns of glaciofluvial landscape development.

CLOCHODRICK STONE

J. E. Gordon

Highlights

Clochodrick Stone is a notable example of a glacial erratic boulder. Historically, such features were among the first considered to require systematic documentation and conservation.

Introduction

The Clochodrick Stone (NS 374613) is a particularly good example of a lowland glacial erratic boulder. It is located 3 km north-east of Lochwinnoch and has been described by Milne Home (1872b).

Description

The large glacial erratic known as the Clochodrick Stone (Clach a'Druidh) (Figure 16.5) is located at an altitude of about 100 m above sea level. It measures 6.7 m in length, 6.1 m in width, 20.6 m in circumference and stands up to 4.0 m above ground level. The rock of which it is composed is a trachytic porphyritic olivine basalt and it is crossed by a series of hematite veins. The boulder rests on lavas of slightly different composition, and it was recorded in the First Report of the Boulder Committee (Milne Home, 1872b) that bedrock of the same type as the boulder occurs in the hills two or three miles to the west and north.

Interpretation

The Clochodrick Stone is a particularly good example of a large erratic boulder. Although erratics and erratic trains are relatively widespread

Figure 16.5 Clochodrick Stone. (Photo: J. E. Gordon.)

in Scotland (see for example, Bell, 1874; Milne Home, 1884; Cumming and Bate, 1933; Sissons, 1967a; Shakesby, 1978; Sutherland, 1984a), the Clochodrick Stone is particularly striking in terms of its size and lowland setting. It was probably transported to its present position by ice from the south-west Highlands moving across the Clyde estuary. This ice moved across and around the Renfrewshire hills towards the south-east (Price, 1975; Paterson *et al.*, 1990).

The Clochodrick Stone is also of more general historical interest in the field of earth-science conservation. It is representative of a suite of features that were among the first to be considered worthy of protection. In 1871 the Royal Society of Edinburgh established the Boulder Committee under the direction of D. Milne Home to identify all the glacial erratics in Scotland that appeared remarkable in terms of size and superficial markings and to recommend measures for their conservation (Milne Home, 1872a, 1872b). This exercise, to some extent a forerunner of the Geological Conservation Review, represents a far-sighted attempt to recognize geomorphological features under threat and to address the need for site survey, assessment and protection. Unfortunately, and unlike the GCR, there was no contemporary legislative framework to underpin the work of the Committee and positive action was to be confined to persuading landowners not to destroy those boulders that merited preservation for further study (Milne Home, 1872a, 1872b). In all, the Committee produced ten reports, the tenth and final one providing a county by county compendium of the boulders listed in the earlier reports (Milne Home, 1884).

Conclusion

Clochodrick Stone is a representative example of a large ice-transported (erratic) boulder. Such boulders were among the first geological features recognized to require systematic survey for conservation during the 19th century; they provide graphic evidence of former ice-sheet movements, in this case from the north-west.

FALLS OF CLYDE

L. J. McEwen and A. Werritty

Highlights

This site is selected for an excellent example of the glacial diversion of drainage. The present route of the River Clyde occupies a bedrock gorge which was cut following the infilling of its former course by glacial deposits.

Introduction

The Falls of Clyde (NS 885406 to NS 882421), 3 km south of Lanark, provide a notable example of glacial disruption of drainage. The Falls of Clyde serve as the local base level for the upper River Clyde, effectively isolating the upper part of the river from its lower reaches. This is the result of glacial deposits blocking the original channel of the Clyde, forcing the river to cut a new bedrock channel. The origin of the falls has been considered by Ross (1927), George (1958), Linton (1963), Sissons (1976b) and Whittow (1977).

Description

The Falls of Clyde are located to the south of Lanark at a point where the River Clyde abruptly changes in both character and direction. Whereas 3 km upstream it is an alluvial, meandering channel flowing south-west through a wide valley, 5 km south-east of Lanark it becomes a relatively straight, narrow, rock-controlled channel flowing to the north-west. Within the designated site the river drops 55 m within 1.8 km. In contrast, the long profile of the Clyde upstream of the site is graded to a base-level at about 183 m OD and requires 32 km to register a comparable descent (George, 1958). The gorge itself, which contains the site, is 7 km long overall and locally up to 50 m deep. The gorge is incised into a pre-glacial surface cut across gently-dipping greywackes of the Lower Old Red Sandstone (Whittow, 1977).

The site consists of two major waterfalls, Bonnington Linn and Cora Linn, separated from each other by a slot gorge. Cora Linn, the larger of the two falls (27 m high), comprises a series of cascades over benches formed from the near horizontally bedded and more resistant sandstone units within the greywackes. The angle made by the top of the falls is oblique to the flow of the main channel indicating that the falls have retreated asymmetrically upstream leaving an enlarged section immediately downstream which now forms the plunge pool. Thus Cora Linn provides a very good example of a waterfall whose configuration is controlled by the detailed stratigraphy and relative resistance of the underlying bedrock. The upper of the two falls, Bonnington Linn, is wider than Cora Linn but not so high. It consists of a single cascade segmented into three parts with large rocky 'islands' separating the individual units. As with the lower falls, the angle is oblique to the main flow of the river.

The shales within the Lower Old Red Sandstone (which dip downstream very gently) provide the risers of the 'staircase' into which the falls are incised. At low flows, it is clear at Cora Linn that there is minimal development of an inner channel within each riser, and very little bedload is at present being transported through the whole rock-controlled section. As a result, the edges of the more massive sandstone units exposed in the bed of the falls have undergone minimal abrasion and rounding.

Between the lower falls at Cora Linn and the upper falls at Bonnington Linn the river descends steeply in a series of rapids over bedrock steps masked by occasional bouldery deposits which, because of their lithology and minimal rounding, are clearly recent and local in origin. The resulting 'step–pool system' is controlled in terms of its detailed morphology (height of 'steps' and dimensions of 'pools') by the spacing of the local joint systems and variation in the relative resistance of the constituent strata. This 1 km long gorge separating Bonnington Linn and Cora Linn is relatively straight, has near vertical sidewalls, 25 m high, and displays a well-developed set of rapids over a very bouldery bed. The local sandstone here is virtually flat-bedded, permitting only limited development of potholes. However, some have developed at the margins of the gorge in response to abrasion and selective exploitation of joint planes.

The current flow over the falls is regulated to some extent by extraction of water at Bonnington Linn for hydro-electric power. Under normal flow conditions this represents only a small proportion of the total.

Interpretation

The explanation for this dramatic change in river level and river character has been attributed to a number of causes. George (1958) described the gorge as an outstanding example of rejuvenation related to a Tertiary lowering of sea levels. Linton (1963), on the other hand, explained the gorge as a product of lowered base-level, where the river descended into an 'ice-cut trough' that Sissons (1976b) subsequently claimed was scoured by a Highlands ice stream which flowed up this part of the Clyde Valley. A third, but less plausible, explanation is that offered by Whittow (1977) who argued that the gorge was the result of rejuvenation caused by tectonic uplift. However, construction of the hydro-electric power station at Bonnington revealed a buried former channel of the Clyde to the east of the present river course (Ross, 1927), and McLellan (1969) mapped the full extent of an area of glacial deposits blocking this channel. Upstream of these deposits a former lake existed in which abundant silts, sands and clays were deposited (Laxton and Nickless, 1980). This former lake basin explains the low river gradient upstream of the falls. The latter were cut upon deglaciation, the Clyde eroding a new channel in bedrock before regaining its original course at the mouth of the gorge.

Disruption of pre-existing river courses has occurred in the Highlands due to glacial erosion of cols and valley heads and the production of glacial breaches (Linton, 1949a, 1951a, 1963) (see also the Cairngorms). The Falls of Clyde, however, provide the most dramatic example in Scotland of disruption of a major river course resulting from glacial deposition in the original river channel and therefore differs from other sites such as Corrieshalloch Gorge (see above). The individual landforms demonstrate specific geological controls on the form and configuration of the waterfalls, rapids and slot gorge which collectively comprise the site.

Conclusion

The Falls of Clyde provide a particularly striking example of the effects of glacial disruption of drainage. The original channel of the Clyde was infilled with glacial deposits, forcing the river to adopt a new course. The latter takes the form of a bedrock gorge and is distinguished by the presence of two waterfalls. The site is important in illustrating some of the indirect, but nevertheless significant, effects of glaciation on the landscape.

DUNDONALD BURN

D. G. Sutherland

Highlights

The sediments exposed in the stream section at Dundonald Burn include a sequence of estuarine, littoral, aeolian and buried peat deposits. These provide important sedimentary, pollen and marine fossil evidence for changes in sea level and coastal environmental conditions during the Holocene.

Introduction

The site at Dundonald Burn (NS 337372) comprises a stream section, located 2 km south-east of Irvine. Along the Ayrshire coast, from south of Ayr to north of Ardrossan, major coastal embayments have existed at two distinct periods. During the Lateglacial, sea level was initially at 26–28 m OD (Jardine, 1971; Boyd, 1986a) and in areas such as the valley of the River Irvine the sea penetrated inland for over 10 km. Sea level fell from this altitude during the Lateglacial and early Holocene only to flood the lowlands again during the middle Holocene, attaining a maximum altitude of approximately 12 m OD (Jardine, 1971; Boyd, 1982, 1986b). Sedimentary sequences related to the period of low sea level during the early Holocene and the subsequent Main Postglacial Transgression have been studied along the Dundonald Burn close to its confluence with the River Irvine and at the nearby 'Great Bend' (NS 324372) on the River Irvine (Crosskey, 1864; Smith, 1896b; Jardine, 1971; Jardine and Morrison, 1980; Akpan and Farrow, 1984; Boyd, 1986b, 1988).

Description

The stratigraphic sequence exposed by the Dundonald Burn has been most recently recorded by Boyd (1988) as follows:

5.	Orange sand with occasional organic detritus	?
4.	Peat with occasional silt and fine gravel	0.04 m

3. Bedded organic detritus containing some sand 0.15 m
2. Dark, bedded organic detritus 0.14 m
1. Finely, horizontally bedded clay grading upwards into organic detritus 0.03 m

The basal clays (bed 1) may be equivalent to the grey sands exposed at the base of the Great Bend section (Smith, 1896b; Boyd, 1986b), since Smith (1896b) reported that the sands became peaty towards the eastern end of the section. *Pholas* borings and shells occur *in situ* in these grey sands. At the Great Bend, these sands are unconformably overlain by sands and gravels (Boyd, 1986b), the lateral equivalents of bed 5 at Dundonald Burn. At the Great Bend, a 'basal gravel' layer has been recognized as being distinct from the remainder of these sands and gravels. This 'basal gravel' rests on the grey sands.

The sands and gravels are fossiliferous, containing abundant shells of marine molluscs as well as various types of algae (Smith, 1896b; Jardine and Morrison, 1980; Akpan and Farrow, 1984; Boyd, 1986b). From this area also a number of whale (*Balaena glacialis* (Müller)) bones have been recovered (Crosskey, 1864; Smith, 1896b; Jardine and Morrison, 1980). The marine sands and gravels are up to 4.5 m thick and comprise a series of ridges with an amplitude between 0.5 m and 2.0 m (Jardine, 1971; Jardine and Morrison, 1980). Wind-deposited sands with interstratified peat lenses rest upon these marine deposits and extend as much as 2 km inland. Abundant Mesolithic and younger artifacts have been found among the sand dunes (Jardine and Morrison, 1980).

Analysis of the contained fauna has allowed inferences to be made about the conditions of deposition. The occurrence of *Pholas* shells in the grey sands at the Great Bend implies that these were exposed in the intertidal zone following deposition. The overlying 'basal gravel', however, contains faunal elements indicative of deposition in water depths of around 10 m (Akpan and Farrow, 1984; Boyd, 1986b), whereas the upper marine sands and gravels were laid down in sublittoral water (Akpan and Farrow, 1984; Boyd, 1986b).

Further information as to the chronology of events and the local environment during the early Holocene derives from pollen analysis and radiocarbon dating of the Dundonald Burn organic deposits (beds 2, 3 and 4). Boyd (1988) recognized five local pollen assemblage zones in these organic deposits. The basal *Salix–Filipendula*–Filicales zone indicates a period of open vegetation, and was considered to be of Loch Lomond Stadial or very early Holocene age. The next pollen zone is characterized by pollen of taxa which indicate the expansion of sedges and birch and thereafter a pronounced expansion of coryloid pollen, these vegetational changes being typical of the early Holocene in central Scotland. Following the *Corylus* rise there was a period of locally dense *Salix*-dominated woodland. The final pollen zone was defined on the basis of two samples from an isolated peat fragment in the overlying sands (bed 5), and is characterized by *Quercus*, *Ulmus* and *Alnus* pollen indicating immigration of mixed boreal forest into the area prior to marine inudation and erosion of the top of the organic horizon. By comparison with other dated pollen diagrams, the *Corylus* rise may be placed at around 9300 BP and the arrival of alder at approximately 7000 BP (Boyd, 1988).

Four separate samples have been radiocarbon dated from the organic beds. The basal 0.02 m gave an age of 9780 ± 90 BP (SRR–382) and the top 0.02 m 8070 ± 70 BP (SRR–381) (Harkness and Wilson, 1979), both of these dates being in agreement with the relative dating based on pollen analysis. Two further samples from within the organic beds, although not so critically placed, are in accord with the other radiocarbon dates: 8950 ± 90 BP (GU–373) (Ergin *et al.*, 1972) from the top 0.05 m of the organic horizon and 9530 ± 150 BP and 9620 ± 150 BP (Q–642) (Godwin and Willis, 1962) from two assays on wood from within the organic horizon.

Two other dates are of relevance. A thin peat layer resting on littoral sands and gravels at 10.4 m OD and overlain by blown sand a few hundred metres to the south-west of the Dundonald Burn exposure has been dated to 3944 ± 190 BP (Birm–221) (Shotton and Williams, 1971). A biserially barbed point, manufactured from a red deer antler and probably contemporaneous with Mesolithic occupation of the area, was recovered from the bed of the River Irvine approximately 1 km from Dundonald Burn (Lacaille, 1954; Jardine and Morrison, 1980) and this has been dated to 5840 ± 80 BP (OxA–1947) (Bonsall and Smith, 1990).

Interpretation

Based on the available information, the following inferences may be made as to relative sea-level change during the early to middle Holocene along this part of the Ayrshire Coast. During the early Holocene, sea level was low, the intertidal zone occurring at around 2 m OD (the *Pholas* bed). Peat accumulated on low ground inland of the coast, as at Dundonald Burn. Thereafter sea level started to rise, this rise continuing until after 8000 BP and probably after 7000 BP. During this transgression, the sands overlying the peat at Dundonald Burn were deposited. At the time of the maximum of the transgression, the basal gravel at the Great Bend was deposited in a water depth of about 10 m, and sand and gravel ridges were built up to an altitude of 12 m OD. During the subsequent regression towards present sea level, the series of sand and gravel ridges were formed in the littoral zone, and aeolian sands accumulated on their surface.

An organic bed in a stratigraphically similar position to that at Dundonald Burn has been reported near Troon, and radiocarbon dates on the top and base of that deposit support the concept of a low early Holocene sea level. The dates are 8015 ± 120 BP (IGS-C14/149) for the top and 9090 ± 320 BP (IGS-C14/150) for the base (Welin *et al.*, 1975).

The Dundonald Burn area is the only location on the North Ayrshire coast at which the Holocene coastal sediments have been studied in detail. The information obtained has revealed complex changes in both the terrestrial and marine environment, particularly during the early to middle Holocene. These changes have been in response to the climatic amelioration at the onset of the Holocene, but most especially to the variations in sea level and the corresponding migration of the shoreline.

A number of other localities in west-central Scotland, such as Linwood Moss (Jardine, 1971) and Girvan (Jardine, 1962, 1963, 1971) have broadly similar records of environmental change but none of these has provided the range of detail comparable to that in the evidence from the Dundonald Burn area.

Conclusion

The sediments at Dundonald Burn provide valuable evidence for interpreting the sea-level history of the western Central Lowlands. Changes in the coastal environment during early and middle Holocene times (approximately 10,000–6,000 years ago), culminating in the advance of the sea known as the Main Postglacial Transgression (see Silver Moss above), have been revealed by detailed analyses of the sediments and the fauna and pollen that they contain. Dundonald Burn is an integral component in the network of sites for demonstrating Holocene sea-level change.

TINTO HILL

C. K. Ballantyne

Highlights

Tinto Hill is important for studies of periglacial processes, illustrating the best examples of active stone stripes in Scotland.

Introduction

Tinto Hill (NS 953343) is a broad, rounded hill, elongated in an east–west direction. It is composed of felsite intruded into Old Red Sandstone and, rising to 707 m OD, dominates the middle Clyde Valley. Its lower slopes are covered by drift, and along the northern flank, generally at an altitude of less 300 m OD, there is an impressive sequence of meltwater channels (Sissons, 1961b). However, Tinto Hill is most important for periglacial geomorphology, demonstrating an assemblage of active stone stripes (Miller *et al.*, 1954; Galloway, 1958; Ballantyne, 1981, 1987a).

Description

The upper parts of Tinto Hill are apparently bare of glacial deposits and, where the vegetation cover is broken, are covered by frost-shattered debris consisting of angular felsite clasts set in a peaty, sandy matrix. On vegetation-free areas this debris is being arranged at the surface into outstanding examples of active stone stripes (Figure 16.6), the first and possibly finest examples of their kind reported in Scotland (Miller *et al.*, 1954; Galloway, 1958).

Miller *et al.* (1954) reported patterned ground occurring in three main areas: to the south of the summit of Tinto, south-east of there in the gully known as the Dimple, and on the northern side of the hill in Maurice's Cleugh. On the south side of the hill the features were found down to an

Figure 16.6 Stone stripes are particularly well developed on Tinto Hill. (Photo: J. E. Gordon.)

altitude of 580 m OD and on the north they were reported as low as 400 m OD. At present, the best-developed area of stripes lies south of the summit where they descend to 570 m OD.

On vegetation-free debris slopes, with a gradient of approximately 20°, and where the coarse fraction consists of material generally less than 0.15 m in length, the regolith is being frost-sorted into well-developed 'gutters' between lines of slightly updomed fine-grained material. The stripes are aligned directly downslope and the long axes of pebbles tend to be oriented downslope. Both coarse and fine stripes range in width from about 0.1 m to 0.3 m, and sorting extends to a depth of between 0.08 m and 0.15 m. Below the sorted surface layer, coarse and fine material is intermingled amongst black peaty humus.

In the Dimple, Miller *et al.* (1954) also found a form of sorted circle that they termed 'inverted garlands'. These consisted of convex-upslope, arcuate arrangements of flat or flat-lying clasts, 0.15–0.3 m across. The long axes of the clasts were arranged along the arc with the clasts lying on edge. Excavations to a depth of 0.5–0.6 m revealed a preponderance of similar clasts to those at the surface but with little development of the matrix found under the areas of stripe development.

Miller *et al.* (1954) reported that stripes had started to reform on artificially disturbed ground after two winters. Ballantyne (1981, 1987a) found that a single winter was sufficient for perfect regeneration of stripes on ground dug over to a depth of 0.3 m, and recorded downslope movement of surface clasts averaging 0.25 m (maximum 0.63 m) over a six month period covering the winter of 1977–78. Such experiments prove conclusively the present-day activity of these features. By comparing different editions of Ordnance Survey 1:10,560 maps, Miller *et al.* (1954) observed that the extent of bare ground on the surface of Tinto Hill had increased greatly since 1862. The present extent of development of the patterned ground seems likely therefore to be due to increased grazing pressure on the hill over the last 100 years (see Ballantyne, 1991a).

Interpretation

The processes responsible for the formation of the stripes are not fully understood. Frost heave resulting from the development of needle ice is important, but Miller *et al.* (1954) considered that the stripes also played a role in the drainage of the hill, noting that there was no gullying of the areas where stripes were developed. Ballantyne (1987a) also suggested a possible role for running water, speculating that the development of rill networks on a bare ground surface may have been an initial condition for the development of lateral sorting. He also suggested that surface wash may have been in part responsible for the high rates of movement he observed for surface clasts. To explain the origin of similar features in the Lake District, Warburton (1987) invoked density-driven convection of soil water, upfreezing of clasts, and downslope movement of debris resulting from creep and rillwash.

Scottish mountains carry a wide range of relict and active periglacial features (Ballantyne, 1984, 1987a). In southern Scotland, the summits and slopes of the main hill groups are mantled by frost-weathered detritus that has been extensively soliflucted (Galloway, 1961a; Tivy 1962; Ragg and Bibby, 1966). On Tinto Hill, where the vegetation has been stripped clear, the surface of this material displays the most outstanding development hitherto reported of active stone stripes in Scotland. Although active stone stripes are known from a number of mountains in the Highlands and Islands (see the Cairngorms and Western Hills of Rum; Godard, 1959; Ballantyne, 1987a; Carter *et al.*, 1987), the examples on Tinto Hill are exceptional for their size, clarity and degree of development. Tinto Hill is also the first locality in Scotland at which such features were described in detail.

Conclusion

Tinto Hill is an important component of the network of sites for periglacial geomorphology, that is for features formed under extremely cold, but non-glacial conditions. The results are evident in intense weathering of bedrock by frost action and other related processes and in frost disturbance of the soil, producing surface arrangements of stones and finer material in the form of stripes and circles, known as patterned ground. Tinto Hill is particularly notable for active-process studies of the formation of stone stripes.