Quaternary of Scotland

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Chapter 13

Western Highland Boundary

INTRODUCTION

D. G. Sutherland

The Western Highland Boundary area is taken to extend from the Teith valley, by Callander, west to the Firth of Clyde (Figure 13.1). This area has been of fundamental importance in defining the sequence of events during the closing stages of the Devensian cold phase. Lying adjacent to one of the principal centres of ice dispersal in the south-west Highlands it has been readily invaded by ice, but being outside the Highland zone, the extent of ice erosion has not been as great as in the mountains. Thus for the period since the end of the last ice-sheet glaciation there is an almost complete record of glacial events, sea-level change and environmental change, and these subjects have formed the main themes of research.

In this area there is little evidence of Quaternary events prior to the main Late Devensian ice-sheet. It can reasonably be presumed that the major ice-moulded landforms and overdeepened valleys leading out from the Highlands relate to repeated phases of ice-sheet glaciation, but no dated material has been found that pre-dates the Late Devensian. The last ice-sheet flowed to the south and south-east across this area, depositing a till, termed the Wilderness Till by Rose *et al.* (1988). Subsequently, during ice retreat, relative sea level was high, with marine invasion of the Western Forth Valley, the Firth of Clyde (see Geilston) and the Loch Lomond basin (see South Loch Lomond). Briefly, prior to marine invasion of this last area, an ice-dammed lake formed in the Blane Valley (Rose, 1980e; Rose *et al.*, 1988) as the ice retreated, but still blocked the connection between Loch Lomond and the Firth of Clyde.

At the period of maximum marine invasion, the neck of land between the Loch Lomond basin and the Western Forth Valley was the only land connection between the Highlands and southern Scotland. It is notable that whereas the early phases of retreat of the last ice-sheet were accompanied around the Scottish coast by deposition of sediments (Errol beds) containing high-arctic marine faunas, the final phase of deglaciation as the ice was retreating into the Highlands accorded with a milder marine climate and the deposition of sediments containing boreo-arctic marine faunas (Clyde beds, see Geilston). This is in accord with the radiocarbon dates on marine shells, which suggest that the head of the Firth of Clyde was deglaciated at around 13,000 BP (Sutherland, 1986).

The Lateglacial Interstadial climatic amelioration is also marked in the terrestrial record at such sites as Tynaspirit and Muir Park Reservoir (Donner, 1957; Vasari and Vasari, 1968; Vasari, 1977), where an initially open vegetation typical of disturbed ground was succeeded later in the interstadial by closed vegetation dominated by grasslands, scrub or heath with, possibly, in favoured localities, copses of tree birch. For much of the early to middle interstadial, relative sea level fell rapidly, probably to near or below 5 m above present.

The onset of the severe conditions of the Loch Lomond Stadial is pronounced in both the marine and the terrestrial records. The interstadial vegetation cover was disrupted and open-habitat vegetation again became dominant; in the nearshore waters a restricted fauna with high-arctic affinities replaced the interstadial fauna (Peacock *et al.*, 1978; Peacock, 1981b). The return to severe conditions appears to have been accompanied by increased erosion in the shore zone, and a marked rock-cut shoreline, the Main Rock Platform, was formed (Sissons, 1974d; Gray, 1978a) or at least extensively modified from a pre-existing feature (Browne and McMillan, 1984; Gray and Ivanovich, 1988). The cliff associated with this shoreline can still be clearly observed around the southern shores of Loch Lomond as well as the shores of the Firth of Clyde.

Glaciers once again readvanced into the area down the principal outlet valleys from the Highlands, into Gareloch (see Rhu Point), Loch Lomond (see Croftamie, Aucheneck and Gartness), the Western Forth Valley and the Teith valley (see Mollands). It was in the southern Loch Lomond basin that the readvance nature of this local glaciation was first recognized (Simpson, 1933): hence this has become the most critical area for the definition of the Loch Lomond Readvance. The readvancing ice overrode or reworked the shelly Clyde beds, and radiocarbon dating of the included shells has established conclusively that the glacial event occurred after 11,500 to 11,000 BP. In addition, near Callander in the Teith valley (at NN 63790509), Lateglacial Interstadial lacustrine sediments have been recorded below till deposited by the Loch Lomond Readvance glacier in that valley (Merritt *et al.*, 1990). The interstadial sediments have been radiocarbon dated to 12,750 ± 70 BP (SRR–2317) and are succeeded by 2 m of Loch Lomond

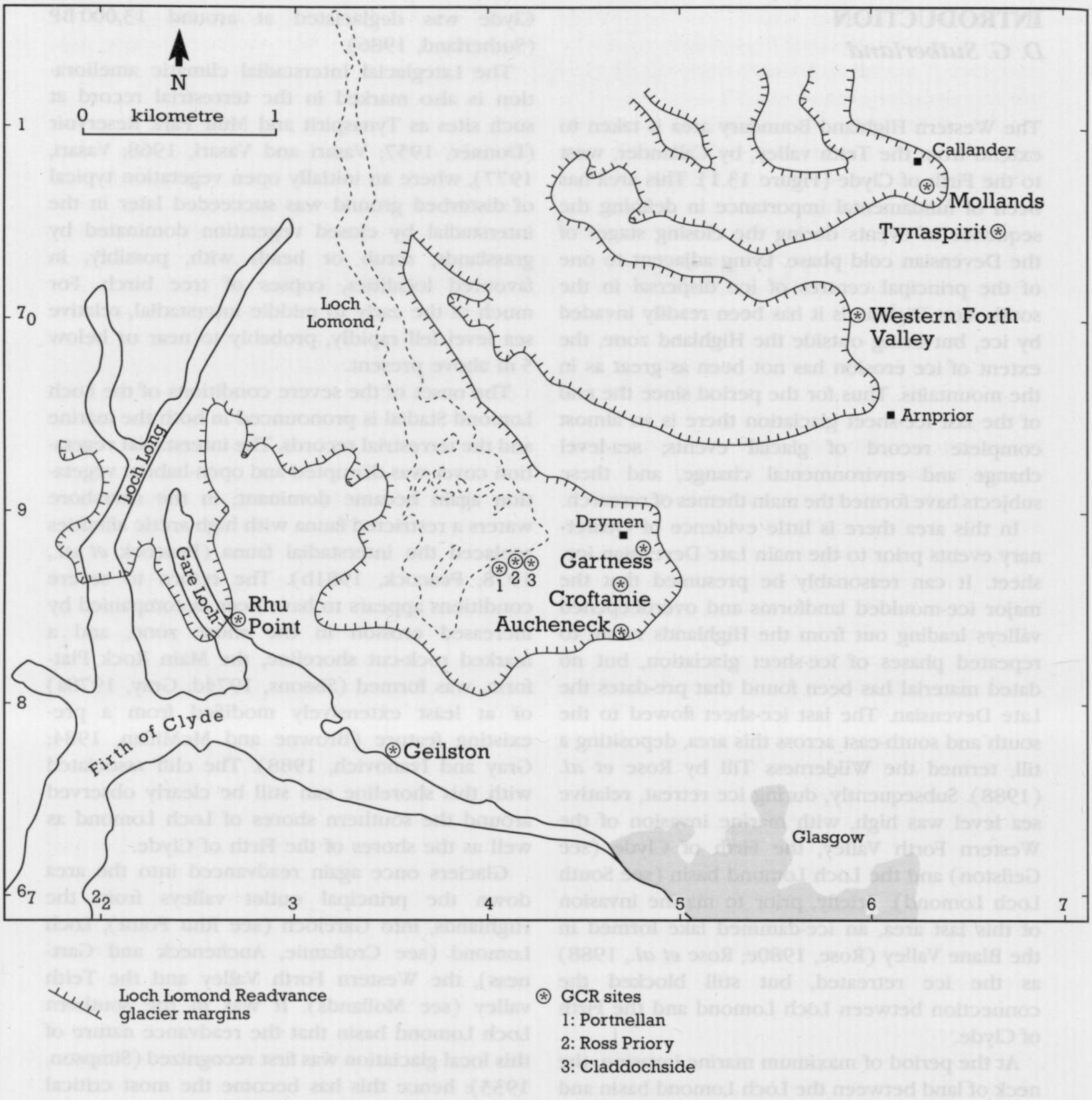


Figure 13.1 Location map of the Western Highland Boundary area.

Stadial lacustrine sediments that were emplaced prior to deposition of the overlying till. An implication of this sequence is that the readvance reached its maximum late in the stadial. More critically, at Croftamie, a layer of plant detritus, with a radiocarbon age of about 10,500 BP, is overlain first, by silts deposited in a lake dammed as the Loch Lomond glacier advanced into the Endrick and Blane valleys, and second, by till deposited directly by the glacier (Rose *et al.*, 1988). This indicates that the Loch Lomond glacier reached its maximum extent after 10,500 BP. This chronology is also supported in the Western Forth Valley, where a marine shoreline, termed the High Buried Shoreline, was formed following a rapid marine transgression at approximately the time of deposition of the Menteith Moraine at the maximum of the readvance. This shoreline has an inferred age of between 10,100 and 10,500 BP (Sissons, 1966, 1976b).

In this area there are major and instructive contrasts in the form of the moraines deposited at or close to the maximum of the readvance. In places they take the form of small, clear end moraines (Aucheneck), whereas elsewhere they are massive push moraines (Western Forth Valley). A further contrast is at Gartness where the Loch Lomond glacier terminated in an ice-dammed lake and constructed a series of large arcuate ridges.

The age and extent of the readvance are also limited by the mutual distribution of basinal sites in which Lateglacial Interstadial sediments are present or where the earliest deposited sediments are of early Holocene age (see Mollands and Tynaspirit). Early deglaciation of the Mollands site relative to the Highland interior is indicated by the relative changes in the pollen assemblages at the base of the sedimentary sequences (Lowe and Walker, 1981).

After retreat of the ice, sea level in the Western Forth Valley fell, with halts to form particular shorelines at approximately 9600 BP and 8600 BP (Sissons, 1966, 1983a; Sissons and Brooks, 1971). The overall regression continued, however, until about 8300 BP when a marked marine transgression began, culminating at approximately 6800 BP with the formation of the Main Postglacial Shoreline (Sissons, 1983a). Subsequently, the sea fell progressively to its present level. Similar, but less well-documented changes of sea level occurred around the Firth of Clyde, with Loch Lomond being freshwater during the early to middle Holocene; later a marine episode started around 6900 BP, continuing to 5500 BP (Dickson *et al.*, 1978). This marine event may in fact have been twofold, with a brief return to freshwater conditions (Stewart, 1987).

The Holocene vegetational history of the area has been investigated at a number of sites (Donner, 1957; Turner, 1965; Vasari and Vasari, 1968; Vasari, 1977; Dickson *et al.*, 1978; Stewart, 1979; Lowe, 1982a; Stewart *et al.*, 1984). Of particular interest is the position of the area between the pine forest zone to the north and the oak forest zone to the south (Stewart *et al.*, 1984).

AUCHENECK

J. E. Gordon

Highlights

The landforms at Aucheneck demonstrate important aspects of the geomorphology of the Loch Lomond Readvance; they include one of the best examples of an end-moraine ridge in the type area for the readvance.

Introduction

The site (NS 478830) is located west of Aucheneck athwart the Finnich Glen and covers an area of *c.* 1 km^2. It is important for an assemblage of landforms associated with the Loch Lomond Readvance glacier in the Loch Lomond basin, the area in which the readvance was first recognized (Simpson, 1933). In particular, it contains one of the finest segments of a till moraine ridge associated with the former Loch Lomond glacier. It is also notable for good sections in the moraine and clear contrasts in landform patterns and soil development 'inside' and 'outside' the ice limit. The only detailed account of the site is by Rose (1981), although the moraine as a whole is discussed in a number of publications (Renwick and Gregory, 1907; Gregory, 1928; Simpson, 1933; Dickson *et al.*, 1978; Rose, 1980d).

Description

The geomorphology of the Aucheneck area is shown in Figure 13.2. The terminal moraine is best developed on the west side of the glen, where it forms a prominent landform, 5–7 m high and about 40 m wide, on the otherwise subdued relief of Cameron Muir. Immediately inside the terminal ridge three further ridge fragments occur, then an area of hummocky drift and meltwater channels. On the east side of Finnich Glen (NS 482828) there are good stream sections in the moraine. These show dark, reddish-brown, sandy till, locally with flow banding (Rose, 1981). Clast fabrics are orientated parallel to the ridge (Rose, 1981). Several subglacial meltwater channels occur on the north side of the ridge, trending towards the north and east. The channels appear to form two groups (Rose, 1981): those aligned west–east were formed by meltwater draining directly from the ice, whereas those aligned north–south may have received part of their discharge from the Carnock catchment.

At NS 483834 one of the channels leads into an esker. Of further interest is the contrast in landform type and development 'outside' and 'inside' the moraine limit (Figure 13.2). On the

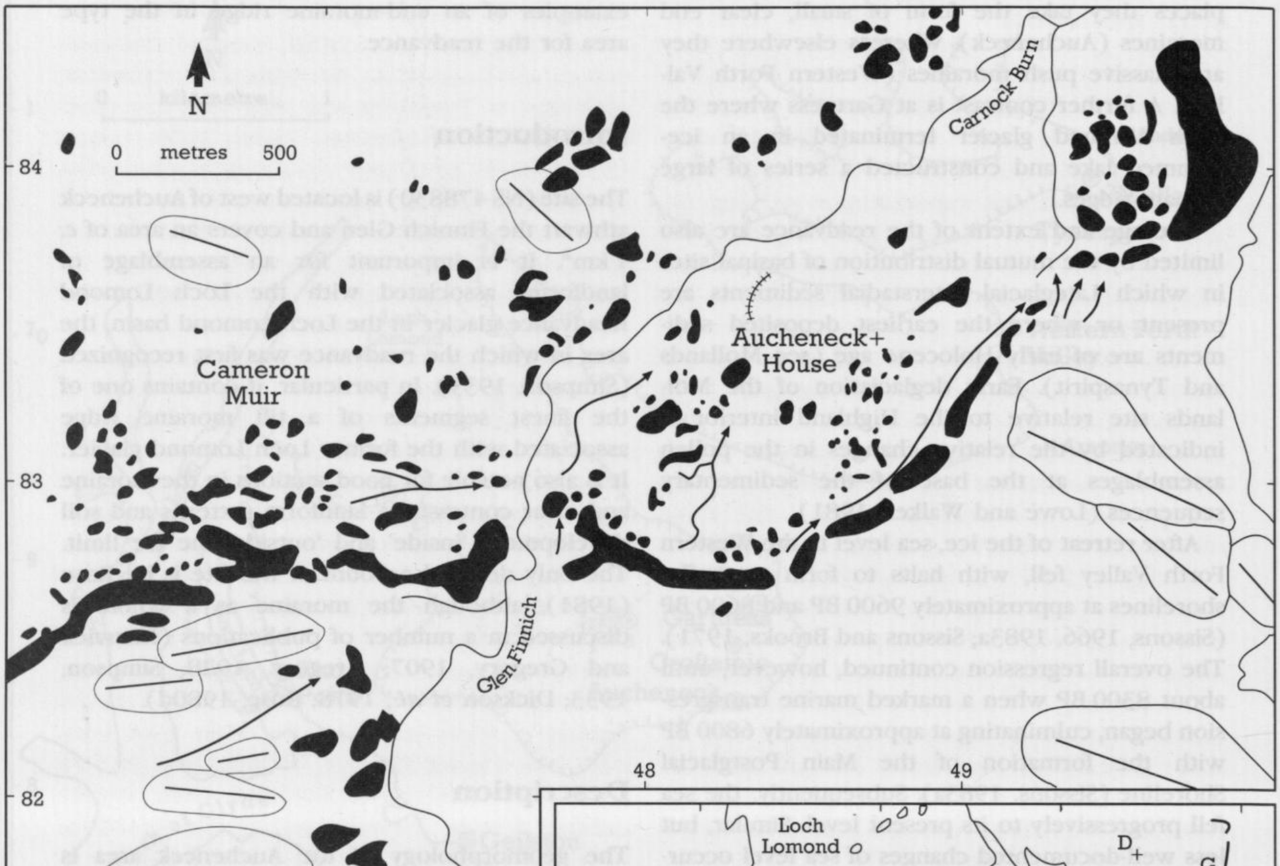


Figure 13.2 Landforms and deposits associated with the Loch Lomond Readvance ice limit at Aucheneck (from Rose, 1981). Inset shows the wider extent of the moraine that marks the ice limit at the southern end of Loch Lomond (from Dickson *et al.*, 1978).

south side, there are low drumlins with ridge crests orientated west–east; on the north side, the drift has a sharper, more irregular, hummocky form, and drumlins (outside the site) have long axes aligned NW–SE. There is also a contrast in the form of the Carnock valley on either side of the ice limit; on the south side, the valley is relatively wide, and bedrock is exposed along the sides; to the north, an earlier valley has been infilled with till, and the present burn occupies a narrow course cut in this material and locally a bedrock gorge. Shells of marine molluscs and Foraminifera have been recorded in the till 'inside' the moraine, for example along the Carnock Burn west of Aucheneck House (NS 487835) (Simpson, 1928, 1933; J. Rose, unpublished data), but have not been found 'outside' the moraine. There is also a contrast in soil development 'inside' and 'outside' the ice limit with higher levels of podsolization and indurated layer development on the 'outer' side (J. Rose, unpublished data).

Interpretation

The Aucheneck moraine is part of a near continuous end-moraine system extending around the south end of Loch Lomond from Conic Hill to Glen Fruin (Renwick and Gregory, 1907; Gregory, 1928; Simpson, 1928, 1929, 1933; Dickson *et al.*, 1978; Rose 1980d). Gregory (1928) considered that the best remnant on the east side was at Aucheneck. Renwick (1895) first recognized that the fragment in Glen Fruin was associated with Loch Lomond basin ice rather than ice coming from the west, as postulated by Bell (1891b, 1893c, 1894, 1896b). Subsequently, from the evidence of the moraine itself and the distinctive shelly till (see Croftamie (below), and Jack, 1875) that occurred inside the line of the moraine, but not outside it, Simpson (1933) inferred a readvance of ice during the wastage of the last ice-sheet, which he called the Loch Lomond Readvance. Charlesworth (1956) identified the moraine as part of his Lateglacial 'Stage M' or 'Moraine glaciation'. From pollen studies Donner (1957) placed the readvance during the climatic deterioration represented in Lateglacial Pollen Zone III of the Jessen–Godwin scheme. Subsequently radiocarbon dating has confirmed that the readvance occurred between *c.* 11,000–10,000 BP (see Gartness and Croftamie), and the period of climatic deterioration has been called the Loch Lomond Stadial (Gray and Lowe, 1977a) after the area where the readvance was first named by Simpson (1933). A summary of the stratigraphic evidence justifying the designation as a type area is given in Rose (1989).

Rose (1981) considered that the moraine at Aucheneck formed by a combination of debris pushed up at the ice margin and also material that slumped off the glacier surface. The ice limit is clearly defined, not only by the moraine, but also by the contrast in landforms 'inside' and 'outside' it. 'Outside', the drumlins have a west–east orientation associated with the last movement of the Late Devensian ice-sheet across the area (Rose, 1981, 1987) and their relatively subdued appearance reflects the effects of gelifluction during the Loch Lomond Stadial. The landforms inside the limit are associated with a north-west to south-east ice movement of the piedmont lobe of the Loch Lomond glacier and have not been modified to the same extent by periglacial mass movement.

Single and multiple end moraines were widely formed during the Loch Lomond Readvance in the Highlands and Southern Uplands of Scotland, the Lake District and North Wales (see Cnoc a'Mhoraire, Tauchers, Gribun, Lochnagar, the Cairngorms, and An Teallach) (Sissons, 1974c, 1979e, 1980a; Gray, 1982a). The particular significance of Aucheneck centres on it being one of the best examples of a till ridge in the type area for the readvance (Simpson, 1933; Jardine, 1981; Rose, 1989) and the clear assemblage of evidence it provides for ice readvance: the end moraine itself and the contrasts in till lithology (shell and Foraminifera content), landforms and soils inside and outside the ice limit. The exposures, additional landform assemblage, including meltwater channels, hummocky drift and an esker, and proximity to dated biostratigraphy make Aucheneck a better representative site than, for example, the equally fine moraine in Glen Fruin. Moreover, the multiple end-moraine sequence at Aucheneck may be significant in illustrating local fluctuations of the ice margin during the stadial. Aucheneck complements the sites at Gartness where Loch Lomond Readvance end moraines were formed subaqueously and Croftamie where the local shelly till of the readvance is well represented.

Conclusion

Aucheneck provides an excellent representative assemblage of landforms formed by a Loch Lomond Readvance glacier (approximately 11,000–10,000 years ago) in the type area where this readvance was first recognized. In particular, it includes one of the best examples of an end-moraine ridge in the area and is important in demonstrating other characteristic landforms produced by the ice readvance.

CROFTAMIE

J. E. Gordon

Highlights

The sequence of deposits at Croftamie includes plant detritus interbedded between two tills. The organic material has yielded important palaeoenvironmental and dating information, allowing the glacial history of the area during the Late Devensian to be established. The site provides important evidence for the timing of the Loch Lomond Readvance in the type area.

Introduction

The section at Croftamie (NS 473861), which occurs in a cutting along the now disused Forth and Clyde Junction Railway, is important for Late Devensian stratigraphy in the type area for the Loch Lomond Readvance. It shows the stratigraphic relationship between the Wilderness Till (deposited by the main Late Devensian ice-sheet) and the Gartocharn Till (deposited by a piedmont glacier during the Loch Lomond Stadial). Beds of organic detritus (plant remains representative of a dwarf-shrub/grassland association) and laminated lake sediments occur between the two tills. Radiocarbon assay of the organic sediments has allowed a limiting date to be placed on the maximum of the Loch Lomond Readvance in its type area (Rose *et al.*, 1988). This important site also has a long history of research (McFarlane, 1858; Smith, 1858; Jack, 1875; Simpson, 1933; Rose *et al.*, 1988).

Description

At the time of their discovery, the deposits at Croftamie generated considerable interest because of their fossil content. McFarlane (1858) and Smith (1858) described 12 ft (3.7 m) of till overlying 7 ft (2.1 m) of blue clay. Near the bottom of the latter, just above sandstone bedrock, the antler of a reindeer, *Rangifer tarandus* (L.) and a number of marine shells were found. Jack (1875) correlated the till above the clays at Croftamie with the distinctive shelly till unit that he identified in the lower Endrick Valley. He listed the macrofauna found in numerous till exposures in the area, including *Arctica islandica* (L.), *Nicania montagui* (Dillwyn), *Neptunea antiqua* (L.), *Littorina littorea* (L.) and *Balanus* sp. from Croftamie.

The most recent investigations of the Croftamie deposits are by Rose (1981) and Rose *et al.* (1988). The sequence comprises:

5. Till with marine fauna derived from Clyde beds (Gartocharn Till) — up to 5 m
4. Rhythmically laminated clays and silts (Blane Valley Silts) — up to 0.4 m
3. Felted plant detritus — up to 0.08 m
2. Till, mainly of locally derived bedrock (Wilderness Till) — up to 1.5 m
1. Old Red Sandstone bedrock

The Wilderness Till is associated with an ice-sheet moving west–east and represents glaciation during the Late Devensian glacial maximum. The Blane Valley Silts are interpreted as diatactic varves formed in a proglacial lake dammed back in the Blane Valley by the Loch Lomond Readvance. The number of varves indicates that the lake existed for at least 50 years. The overlying Gartocharn Till includes material incorporated from Clyde beds deposited in the Loch Lomond area during the Lateglacial Interstadial. The organic detritus (bed 3) contains a sparse, poorly preserved pollen assemblage (dominantly Caryophyllaceae, *Salix*, Gramineae, Cyperaceae and Cruciferae, but also with *Artemisia*, *Valeriana* and *Selaginella*) typical of an open-habitat, dwarf-shrub/grassland environment, and gave a radiocarbon date of 10,560 ± 160 BP (Q–2673) (Rose *et al.*, 1988). It therefore accumulated during the Loch Lomond Stadial, before the onset of the glacial lake sedimentation.

Interpretation

The significance of the Croftamie deposits in interpreting the Pleistocene sequence in Scotland was recognized in the last century. Together with other fossil remains in the drift of Scotland, the reindeer horn was considered to provide evidence for ameliorating climatic conditions and restricted ice extent at some time during the Pleistocene before a subsequent ice advance (Geikie, 1863a). Jack (1875) concluded that the marine fauna had been alive during one of the milder phases of the glacial period when Loch Lomond was an arm of the sea, although in conditions slightly colder than at present. The shelly till was therefore the product of subsequent glaciation. This explanation of the evidence was also adopted by later workers in the area (Geikie, 1894; Bell, 1895d; Cunningham Craig, 1901), following some discussion as to whether the marine event was a local extension of the sea into Loch Lomond or a great interglacial submergence (J. Geikie, 1874, 1877).

Following detailed fieldwork in the area Simpson (1928, 1929, 1933) developed the ideas of Jack, Geikie and Cunningham Craig, assembling the evidence and formulating carefully the case for a Lateglacial readvance of ice in the Loch Lomond valley following a period of marine occupation. He observed that shelly till only occurred inside a prominent end moraine, which he traced around the southern end of Loch Lomond (see Aucheneck and Gartness). He called the glacial event the Loch Lomond Readvance and noted that it was also represented in the Western Forth Valley (see below).

Charlesworth (1956) subsequently extended the limits of the readvance, incorporating the Loch Lomond and Forth valley landforms and deposits as part of his Lateglacial 'Stage M' or 'Moraine Glaciation'. The name Loch Lomond Readvance, however, was retained by Sissons (1965, 1967a), who revised the ice limits suggested by Charlesworth. More recently these limits have been further established over large areas of the Highlands and Islands and the Southern Uplands (Sissons *et al.*, 1973; Sissons, 1979e, 1983b).

The detailed work of Rose (1981) and Rose *et al.* (1988) has allowed a clearer interpretation of the full sequence of events at Croftamie: (1) deposition of till by the Late Devensian ice-sheet (Wilderness Till); (2) deposition of marine clayey silts (Clyde beds) (elsewhere in the area); (3) formation of a proglacial lake by the advancing Loch Lomond Readvance (Blane Valley Silts); (4) deposition of the shelly till (Gartocharn Till), in part derived from Clyde beds sediments; and (5) maintenance of the proglacial lake which drained into the Forth valley (Blane Valley Silts). The radiocarbon date from the organic sediments implies that the Loch Lomond glacier reached its maximum extent after 10,560 ± 160 BP, in agreement with the evidence from the Vale of Leven that glaciomarine sedimentation continued until after 10,350 ± 125 BP (SRR–1529) (Browne and Graham, 1981). This also accords with the inference that the Loch Lomond Stadial glacier in the Western Forth valley reached its maximum extent between 10,500 BP and 10,100 BP (Sissons, 1983a; Sutherland, 1984a), and that the Creran glacier reached its maximum after 10,500 BP and perhaps as late as 10,000 BP (see South Shian and Balure of Shian) (Peacock *et al.*, 1989). However, these dates are significantly at variance with dates previously obtained from elsewhere that have been used to infer the time of the maximum glacier extent (see Sutherland, 1986; Rose *et al.*, 1988): they are at least 400 years younger than the other dates from sediments overridden by Loch Lomond Stadial glaciers, and they also overlap in age ranges with dates from lacustrine sediments that were deposited immediately on retreat of the stadial glaciers (Rose *et al.*, 1988) (see also Kingshouse, Loch an t-Suidhe, Mollands, Tynaspirit, Rhu Point and Loch Cleat). Rose *et al.* (1988) argued that this variance could relate to three factors. First, many of the dates are from marine shells, but environmental and sedimentation factors tend to favour a higher probability of sampling shells from the middle part of the interstadial, rather than the later part (see also Sutherland, 1986). Second, there may be errors in the dates on basal organic lake sediments caused by mineral carbon and hard-water contamination (see Sutherland, 1980). Third, because of variations in individual glacier dynamics and glacier response to climate, the fluctuations of the glaciers are likely to have been diachronous. Since the material dated at Croftamie is plant detritus, the date obtained should be less susceptible to mineral carbon and hard water errors than dates obtained from organic lake sediments (gyttja); Rose *et al.* (1988) suggested that dates on the latter material may be slightly too old. The evidence from Croftamie and Inverleven therefore indicates relatively later deglaciation of Loch Lomond Stadial glaciers than suggested elsewhere (Lowe, 1978; Lowe and Walker, 1980, 1984; Walker and Lowe, 1980, 1982; Dawson *et al.*, 1987a) (but see Kingshouse). A further complication in interpreting the different radiocarbon dates arises from the variations in atmospheric radiocarbon production known to have occurred during the Lateglacial (Ammann and

Lotter, 1989; Zbinden *et al.*, 1989; Bard *et al.*, 1990), but this may have affected all the dates.

Croftamie is a site of highest importance in several respects. It provides a key sequence of Lateglacial deposits in the type area for the Loch Lomond Readvance. In stratigraphic terms, it unequivocably demonstrates the superposition of till deposited during the Loch Lomond Stadial on till deposited by the main Late Devensian ice-sheet. It is the only site at which plant material has been used to date the maximum of the Loch Lomond Readvance. Moreover, the results of this dating, corroborated by additional dates from Inverleven and South Shian and Balure of Shian, provide significant evidence that the maximum extent of the Loch Lomond Readvance glaciers may have occurred after 10,500 BP. The interest at Croftamie complements that at Aucheneck, Gartness and South Loch Lomond (Portnellan, Ross Priory and Claddochside), and together these sites provide a comprehensive demonstration of the Lateglacial stratigraphy and landforms, both glacial and marine, in the area where the Loch Lomond Readvance was first recognized.

Conclusion

Croftamie is important for interpreting the glacial history in the type area for the Loch Lomond Readvance. The site has a long history of research and is particularly significant in showing organic deposits interbedded between tills deposited by the Late Devensian ice-sheet (approximately 18,000 years ago) and a Loch Lomond Stadial glacier (approximately 10,500 years ago). The organic deposits represent a warmer phase between the two glacial episodes, and the pollen they contain provides details of environmental conditions during that period. The organic deposits also provide an important means of dating the readvance. Croftamie is therefore a key reference site for establishing particular details of the nature and timing of the Loch Lomond Readvance in its type area.

GARTNESS

J. E. Gordon

Highlights

The interest of Gartness includes an assemblage of glacial, glaciolacustrine and marine landforms and deposits. These provide evidence for the glacial history of the Western Highland Boundary area and the associated landscape changes during the Late Devensian. Of particular note is a series of end-moraine ridges formed in a glacial lake.

Introduction

The interests at Gartness extend over an area of *c.* 10 km^2 (centred on NS 495875) in the Endrick Valley to the east of Drymen. They include an assemblage of Late Devensian sediments and landforms located in the type area for the Loch Lomond Readvance. The sequence of sediments includes evidence for glaciation by the Late Devensian ice-sheet, proglacial lake formation, marine transgression, glaciation during the Loch Lomond Stadial and further proglacial lake development (Rose, 1980e, 1981). The key landforms are a series of Loch Lomond Readvance end-moraine ridges formed partly subaqueously, in a proglacial lake, and partly subaerially. The area has a long history of investigation (Jamieson, 1865, 1905; Jack, 1875; J. Geikie, 1877, 1894; Clough *et al.*, 1925; Gregory, 1928; Simpson, 1933; Sissons, 1967a; Browne and McMillan, 1989), but the most detailed modern accounts are by Rose (1980e, 1981); it has also been described by Price (1983).

Description

Early descriptions of the area (Jamieson, 1865; Jack, 1875; J. Geikie, 1877) drew attention to the occurrence of extensive deposits (about 13 km^2) of sand and gravel, sometimes interbedded with clay. These deposits, which formed a series of rounded hills resembling 'drumlins' (Jack, 1875), contained marine shells (e.g. *Arctica islandica* (L.), *Mya truncata* (L.), *Chlamys islandica* (Müller) and *Boreotrophon clathratus* (Ström)) (Jamieson, 1865; Jack, 1875) similar in character of assemblage to that in the Clyde beds (Jamieson, 1865). According to Jack (1875), the sands and gravels were stratigraphically above the distinctive shelly till of the area (see Croftamie) and were locally overlain by till.

Additional details were given by Simpson (1933), and he included the Gartness deposits as part of the end moraine system of the Loch Lomond Readvance glacier that occupied the

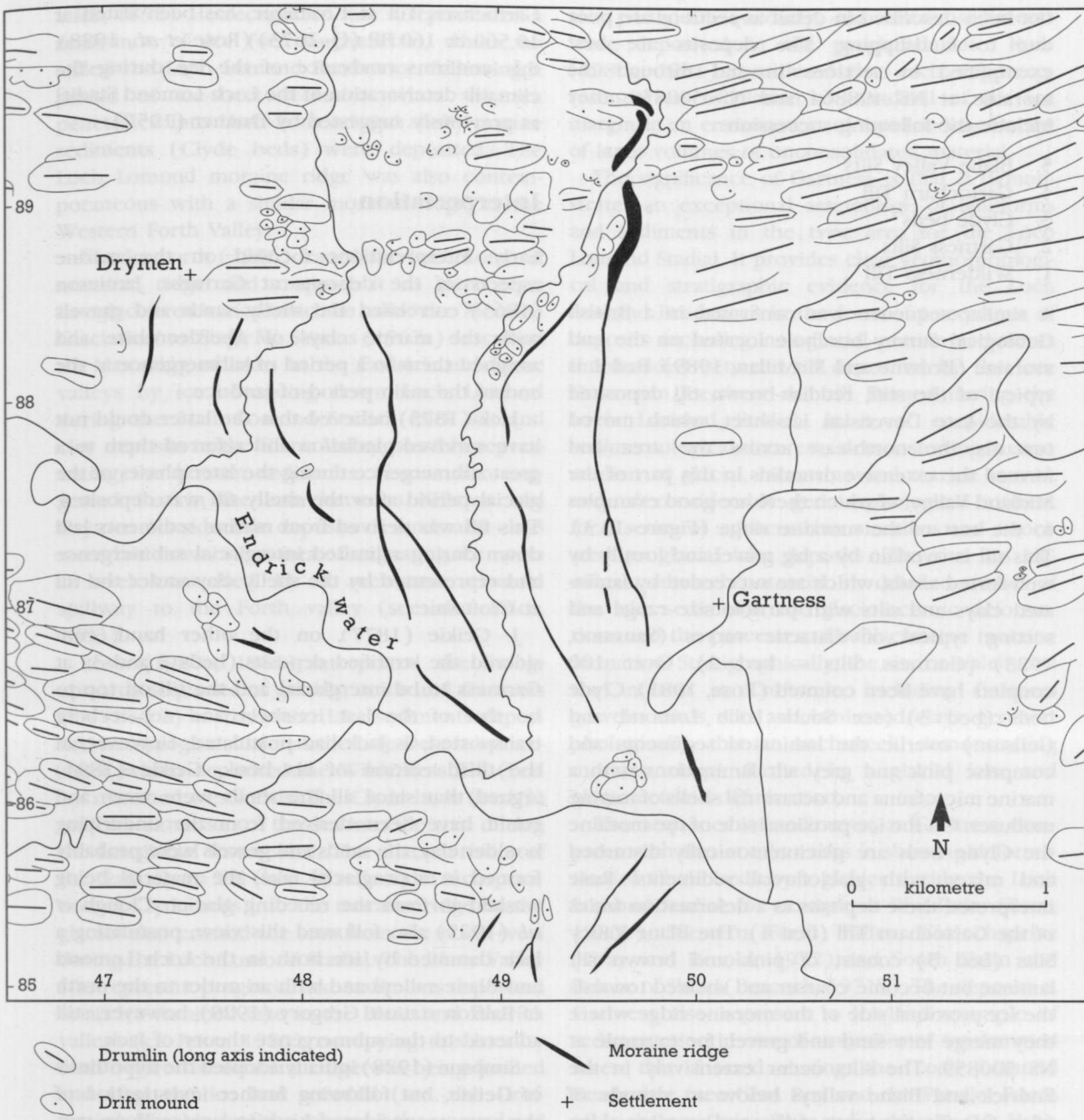


Figure 13.3 Landforms and deposits associated with the Loch Lomond Readvance ice limit at Gartness (from Rose, 1980e, 1981).

Loch Lomond basin.

In a comprehensive investigation, Rose (1980e, 1981) has described and mapped in detail the landforms and sediments of the Gartness area. The principal landform is an end-moraine ridge running approximately north–south from about NS 495895 to NS 501860 (Figure 13.3). The northern part of the moraine ridge comprises sand and gravel near Drumhead (NS 495882), and till where it curves round to the west upslope (NS 495895). The southern part (between NS 495882 and NS 501860) comprises deformed silts resting on a succession of earlier deposits. On the ice-distal (east) side these deposits are largely undisturbed; on the ice-proximal (west) side they are glaciotectonically deformed. These deformations have also been noted by Browne and McMillan (1989) but have not been described in detail as sections are poor due to landslipping. The deposits are best exemplified in sections in and through the moraine at NS 498864 and NS 500859; they include the following succession:

5. Blane Valley Silts
4. Gartocharn Till
3. Clyde beds
2. Gartness Silts
1. Wilderness Till

A similar sequence was confirmed in a British Geological Survey borehole located on the end moraine (Browne and McMillan, 1989). Bed 1 is typical of the stiff, reddish-brown till deposited by the Late Devensian ice-sheet, which moved towards the north-east across the area and formed the extensive drumlins in this part of the Midland Valley, of which there are good examples to the east of the moraine ridge (Figure 13.3). This till is overlain by a lag gravel and locally by well-sorted sands, which are succeeded by laminated clays and silts with particle size range and sorting typical of diatactic varves (Sauramo, 1923) (Gartness Silts – bed 2). Over 100 couplets have been counted (Rose, 1981). Clyde beds (bed 3) (see South Loch Lomond and Geilston) overlie the laminated sediments and comprise pink and grey silt laminations with a marine microfauna and occasional shells of marine molluscs. On the ice-proximal side of the moraine the Clyde beds are glaciotectonically disturbed and mixed with glaciofluvial sediments. Rose interpreted these deposits as a deformation facies of the Gartocharn Till (bed 4). The Blane Valley Silts (bed 5) consist of pink and brown silt laminae but become coarser and sheared towards the ice-proximal side of the moraine ridge where they merge into sand and gravel, for example at NS 500859. The silts occur extensively in the Endrick and Blane valleys below an altitude of 65 m OD. To the west of the end-moraine ridge there is a series of five further moraine ridges (Figure 13.3), partly buried by Blane Valley Silts. The ridge at Drumbeg (NS 483880), near Drymen, is associated with a large accumulation of deltaic sands and gravels seen exposed in quarry sections (NS 484882) (Browne and McMillan, 1989).

Shells derived from the Clyde beds and reworked into glaciofluvial gravels exposed in the quarry at Drumbeg gave a radiocarbon date of 11,700 ± 170 BP (I–2235) (Sissons, 1967b) and plant detritus, below Blane Valley Silts and Gartocharn Till at Croftamie, has been dated at 10,560 ± 160 BP (Q–2673) (Rose *et al.*, 1988); this confirms readvance of the ice during the climatic deterioration of the Loch Lomond Stadial as previously suggested by Donner (1957).

Interpretation

Early interpretations focused on the marine aspects of the deposits at Gartness. Jamieson (1865) correlated the shelly sands and gravels with the marine clays of Aberdeenshire and assigned them to a period of submergence at the end of the main period of land ice.

Jack (1875) believed that the latter could not have survived glaciation and referred them to a great submergence during the later phases of the glacial period after the shelly till was deposited. This till was derived from marine sediments laid down during a limited interglacial submergence and represented by the shelly clay under the till at Croftamie.

J. Geikie (1877), on the other hand, considered the stratified deposits (beds 2 and 3) at Gartness to be interglacial and the till on top to be that of the last ice-sheet and not iceberg transported, as Jack had postulated. However, in the third edition of his book, Geikie (1894) argued that since all the shells were worn and could have been derived from the underlying boulder clay, the sands and gravels were probably formed in a proglacial lake, the material being washed in from the receding glacier. Clough *et al.* (1925) also followed this view, postulating a lake dammed by ice both in the Loch Lomond and Blane valleys and with an outlet to the north of Balfron station. Gregory (1928), however, still adhered to the submergence theory of Jack.

Simpson (1928) initially adopted the hypothesis of Geikie, but following further investigation of the area, reconsidered his views since there was no evidence elsewhere to substantiate the required submergence up to 65 m OD and, moreover, the whole aspect of the deposits was typically morainic (Simpson, 1933). They comprised englacial debris laid down as a moraine ridge in front of a receding glacier, partly in water and partly on land. As Renwick and Gregory (1907) had earlier done, Simpson (1928, 1929, 1933) traced the moraine almost continuously around the south end of Loch Lomond and linked it with the well-known ridge in Glen Fruin (Bell, 1891b, 1893c, 1894, 1896b; Renwick, 1895). He recognized that it represented a readvance of ice (see Auchenecк), which he called the Loch Lomond Readvance, following a period of ice-sheet recession when the sea penetrated into Loch Lomond and shelly marine sediments (Clyde beds) were deposited. The Loch Lomond moraine ridge was also contemporaneous with a similar moraine ridge in the Western Forth Valley.

Charlesworth (1956) traced the Loch Lomond moraine ridge and mapped it as part of a Lateglacial readvance which he called the 'Moraine Glaciation' or 'Stage M'. Sissons (1967a) described the damming of lakes in the Endrick and Blane valleys by ice advancing down Loch Lomond during the Loch Lomond Stadial, thick silt and clay deposits in the Blane Valley possibly representing the bottom sediments. Sissons also suggested that in the area between Killearn and Drymen considerable deposits of sands and clays were laid down in an area of stagnating ice up to a level controlled by a meltwater channel spillway to the Forth valley (see also Price, 1983).

Rose (1980e, 1981) interpreted the fining-upwards sequence of gravels, sands and Gartness Silts (bed 2) as freshwater lake sediments deposited in a proglacial lake as the Late Devensian ice-sheet, which deposited the Wilderness Till (bed 1), retreated westwards. The Clyde beds (bed 3) indicate extension of the sea into the area during the Lateglacial Interstadial. The characteristics of the Gartocharn Till (bed 4) reflect the incorporation of Clyde beds into the moraine ridge by the glacier that crossed the area from the north-west during the Loch Lomond Stadial. The Blane Valley Silts represent proglacial lake sediments deposited in an ice-dammed lake in the Blane and Endrick valleys (cf. Price, 1983), occupying this locality both before the moraine ridge was being formed and after the ice had receded (see also Croftamie). The level of the lake and the upper level of sedimentation were controlled by a meltwater channel at 65 m OD across the lowest col on the Endrick–Blane watershed at Ballat (NS 528907). The water drained northwards and into a contemporaneous glacier in the Forth valley. The southern part of the moraine ridge was formed subaqueously by the deposition and subsequent deformation of lake sediments at the ice margin. Where the ice grounded above the lake level, the moraine ridge was formed of sand and gravel or till. As the glacier retreated from its maximum extent, five further moraine ridges were formed, also partly subaqueously, and deltaic sediments were deposited in the proglacial lake. Rose (1980e, 1981) considered that each ridge represented an oscillation or standstill of the ice margin in an environment of rapid sedimentation of large volumes of unconsolidated material.

The significance of Gartness is that it demonstrates an exceptional assemblage of landforms and sediments in the type area for the Loch Lomond Stadial. It provides clear geomorphological and stratigraphic evidence for the Loch Lomond Readvance in the form of a sequence of deposits including non-glacial marine sediments interbedded between till deposited by the Late Devensian ice-sheet and till formed during the Loch Lomond Stadial. It is of considerable sedimentological interest, demonstrating a succession of glacial, lacustrine and marine events, and of considerable geomorphological interest for a series of sublacustrine moraines and associated proglacial lake deposits. The site has significant research potential for detailed studies of the lake sediments, the glaciotectonic deformations and the processes of sublacustrine moraine formation. Stratigraphically, the site complements the interest at Croftamie, including Gartness gravels, sands, silts and laminated clays; geomorphologically, that at Auchenecк, demonstrating moraine ridges formed in a glacial lake and glaciotectonic deformation.

The sequence of sediments at Gartness compares with that at other sites in showing deformation of Clyde beds by a glacier during the Loch Lomond Stadial; for example at Rhu Point (Rose, 1980c), Western Forth Valley, Kinlochspelve (Gray and Brooks, 1972) and South Shian and Balure of Shian (Peacock, 1971b). The deposits at Gartness also represent a lowland example of sedimentation in one of a number of ice-dammed lakes that formed during the Loch Lomond Readvance (see Glen Roy and the Parallel Roads of Lochaber, Coire Dho and Achnasheen). However, apart from Achnasheen (Benn, 1989a) and parts of Glen Roy (Peacock, 1986), there have been no detailed sedimentological studies. In addition to Gartness, sublacustrine moraine ridges of Loch Lomond Stadial age are also reported from Coire Dho (Sissons, 1977b), Glen Spean (Sissons, 1979c) (see Glen Roy and the Parallel Roads of Lochaber) and Achnasheen (Sissons, 1982a). Together these sites provide a range of sedimentary environments that merit further detailed, comparative study of sedimentation in glacial lakes.

Conclusion

The landforms and deposits at Gartness demonstrate the sequence of landscape changes that occurred in the Loch Lomond area during the Late Devensian. The sediments provide evidence for ice-sheet glaciation (approximately 18,000 years ago), the formation of a proglacial lake, invasion by the sea, then renewed glaciation during the Loch Lomond Stadial (approximately 11,000–10,000 years ago) with contemporary glacial lake formation. The principal landforms are a series of end-moraine ridges that formed in the later ice-dammed lake. Gartness is important for interpreting key facets of the geomorphological changes that occurred during the Late Devensian in the type area for the Loch Lomond Stadial and the Loch Lomond Readvance.

SOUTH LOCH LOMOND: PORTNELLAN, ROSS PRIORY AND CLADDOCHSIDE

J.E. Gordon

Highlights

The assemblage of landforms and deposits on the south shore of Loch Lomond provides important evidence for the geomorphological changes that occurred at the end of the Late Devensian in the type area for the Loch Lomond Stadial and its associated glacier readvance. These include the formation of marine shorelines, fossiliferous marine deposits and glaciation of the Loch Lomond Readvance.

Introduction

Three localities, at Portnellan (NS 404873), Ross Priory (NS 413876) and Claddochside (NS 427878) on the south shore of Loch Lomond *c.* 6 km north-east of Balloch, illustrate important aspects of the Lateglacial and Holocene history of the Loch Lomond area, the type area for the Loch Lomond Readvance. They provide important stratigraphic and geomorphological evidence, described by Rose (1980f), particularly for the sequence of marine and glacial events, and show that the Main Rock Platform of western Scotland was significantly developed before the time of the maximum extent of the readvance. The sediments from the floor of the southern basin of the loch also provide a record of Holocene marine incursions, vegetational history and palaeomagnetism (Dickson *et al.*, 1978; Thompson and Morton, 1979; Turner and Thompson, 1979; Stewart, 1987).

Description

The three localities on the shore of the loch have been described by Rose (1980f). Together they show a succession of marine and glacial features. One of the most distinctive is a shore platform developed extensively along the southern shore. At Ross Priory it extends for about 0.5 km offshore to about 1 m below the loch level; it is also well displayed at Portnellan and Claddochside. In places it is associated with an impressive backing cliff up to about 15 m high, for example at Portnellan. At Claddochside, the cliff is cut in Old Red Sandstone bedrock. The junction of the cliff and platform is at about 12 m OD. At Portnellan, the platform and cliff are covered by till deposited during the Loch Lomond Readvance. This is the Gartocharn shelly till of the area, partly derived from reworked Clyde beds (see Croftamie) (Jack, 1875). Gartocharn Till also buries Clyde beds in foreshore sections at Claddochside, and a similar succession has been recorded on Inchlonaig (NS 380935) to the north (Cunningham Craig, 1901).

The sediments laid down in the Loch Lomond basin, immediately following retreat of the Loch Lomond Readvance, have been described from a borehole in the lower Endrick Valley (NS 44838829), *c.* 3 km north-east of Claddochside (Elliot, 1984; Browne and McMillan, 1989). In that borehole *c.* 7 m of finely-bedded silty clay with occasional laminae of silt or sand overlay the Gartocharn Till (see Croftamie). The sediments were characterized by a marine microflora and microfauna (dinoflagellate cysts and Foraminifera) and occasional shell fragments of marine molluscs and crustacea. Browne and McMillan (1989) noted the possibility that the fossils may have been derived from the underlying shelly sediments but considered that it was more likely that the fauna was contemporaneous with the enclosing sediment. These sediments were overlain in the borehole by over 13.5 m of lacustrine and fluvial deposits of presumed Holocene age.

A middle Holocene marine invasion of the Loch Lomond basin is indicated by raised shorelines around the southern part of the loch at about 13 m and 12 m OD. The latter is the most conspicuous, its width in part reflecting exhumation of the Lateglacial shore platform (Dickson *et al.*, 1978; Rose, 1980f). It is best seen at Portnellan and Ross Priory. Rose (1980f) traced these shorelines through the Vale of Leven to the Clyde estuary, thereby confirming their marine origin (see Dickson *et al.*, 1978, figure 1). Shells in deposits related to the transgression have been recorded near Luss (Robertson, 1868; Brady *et al.*, 1874). A further shoreline at 9 m OD was considered by Rose (1980f) to be lacustrine in origin, related to present lake level.

The middle Holocene marine transgression is also represented in sediment cores from the southern basin of Loch Lomond (Dickson *et al.*, 1978). The marine deposits, interbedded with freshwater sediments, are distinguished by low remnant magnetic susceptibility and intensity and by the presence of marine plankton and absence of freshwater plants. Radiocarbon dates on organic material from one core place the transgression between 6900 BP and 5450 BP. More detailed results were presented by Stewart (1987). He showed that there had been two phases to the marine transgression, the earlier one lasting from approximately 7200 BP until about 6400 BP and the later one, following a brief non-marine period, terminated at approximately 5500 BP.

Interpretation

The three localities show a sequence of events (Rose, 1980f) beginning with a Lateglacial marine transgression and deposition of Clyde beds (see Geilston), seen at Claddochside. The existence of such marine deposits in the Loch Lomond basin has long been recognized principally on account of their fossiliferous nature (Adamson, 1823; Brady *et al.*, 1874; Jack, 1875; Cunningham Craig, 1901). Deposition of the Clyde beds was followed by the formation of the shore platform. Rose (1980f) has correlated this platform with the Main Rock Platform of western Scotland (see Isle of Lismore) (Gray, 1974a, 1978a; Sissons, 1974d). Subsequently, during the Loch Lomond Stadial, a glacier advanced across the area depositing till over both the shore platform and the Clyde beds. Together with Gare Loch (Rose, 1980b) and Loch Spelve (Gray, 1974a), Portnellan is one of only a few localities providing important evidence that the Main Rock Platform was predominantly formed before the Loch Lomond Readvance reached its maximum extent. Also, the burial by till of the Clyde beds, which postdate *c.* 13,000 BP (see Geilston), provides clear stratigraphic evidence for the Loch Lomond Readvance (Cunningham Craig, 1901; Simpson, 1933).

The evidence from the borehole in the lower Endrick Valley for a marine deposit immediately overlying the Gartocharn Till deposited during the Loch Lomond Readvance, implies that the sea entered the Loch Lomond basin towards the end of the Loch Lomond Stadial (Browne and McMillan, 1989). This conclusion is dependent upon the marine fossils contained in the sediment being *in situ* and not derived from the underlying shelly deposits. Comparison may be made, however, with the Western Forth Valley, where Sissons (1966, 1976b) has demonstrated that a marine transgression, culminating between 10,500 BP and 10,100 BP, was approximately contemporaneous with the maximum of the readvance.

During the Holocene, the radiocarbon dates indicate that entry of the sea into Loch Lomond was some 1100 years later than the start of the Main Postglacial Transgression in the Western Forth Valley (Sissons and Brooks, 1971), a delay which reflects the time required for the sea to surmount the outwash fan barrier formed by the Loch Lomond Readvance across the Vale of Leven at Alexandria, between Loch Lomond and the Clyde estuary (Dickson *et al.*, 1978). This early marine phase also coincides with the maximum of the transgression (6800–6650 BP) in the Forth valley (Sissons, 1983a).

The Holocene palaeomagnetic record from Loch Lomond shows similarities to those from Lake Windermere and Lough Neagh, but is particularly significant in providing much finer detail because of a higher rate of sedimentation (Dickson *et al.*, 1978). It provides the most precise and detailed geomagnetic record so far obtained for the last 7000 years (Turner and Thompson, 1979).

Portnellan, Ross Priory and Claddochside complement the interest at Croftamie, Gartness and Aucheneck by illustrating the sequence of Lateglacial and early and middle Holocene marine episodes and their relationships to the glacial deposits of the Loch Lomond Readvance in the type area for the readvance and the Loch Lomond Stadial. The lake-bed sediments are also of considerable importance for the detailed palaeomagnetic record they preserve and for the succession showing Holocene marine transgression deposits interbedded with freshwater lake deposits.

Conclusion

The landforms and sediments at this site are important for the evidence they provide for the sequence of glacial and marine events at the end of the Devensian. In particular, they show a shore platform and fossiliferous Lateglacial marine deposits that formed before the Loch Lomond Stadial (approximately 11,000–10,000 years ago). During the latter phase, a shelly till was deposited by a glacier readvance (Loch Lomond Readvance). Raised shorelines and sediments from the floor of the loch also indicate two episodes during the Holocene (the last 10,000 years) when the sea encroached into Loch Lomond. This sequence is important because of its location in the type area for the Loch Lomond Stadial.

GEILSTON

D. G. Sutherland

Highlights

The deposits exposed in stream sections at Geilston include a sequence of fossiliferous marine sediments, the Clyde beds, which provide important evidence for marine palaeoenvironmental conditions during the latter part of the Late Devensian. Geilston is one of the few sites with good exposures which have been studied in detail.

Introduction

The site (NS 341777) comprises a series of stream sections along a 0.4 km reach of the Geilston Burn at Cardross. It is one of the few localities where *in situ*, fossiliferous Clyde beds sediments can be observed in sections. Radiocarbon dates from the site also provide a limiting date on the time of deglaciation of the area, and the sediments record the changing environment from glacial to glaciomarine to marine as the last ice-sheet decayed and the area became ice-free (Rose, 1980a).

It has long been known that certain of the silts, sands and clays exposed at low altitudes (generally below 35 m OD) and in many foreshore areas around the head of the Firth of Clyde contain marine fossil faunal assemblages that are indicative of a climate colder than that of the present (Smith, 1838; Jamieson, 1865; Crosskey and Robertson, 1867–1875; Brady *et al.*, 1874). Furthermore, it was also realized by these researchers that the changes in the fossil faunas reflected changes in the level of the sea (Robertson, 1883) as well as changing climates. In recent years, radiocarbon dating and quantitative analysis of the faunal assemblages have clarified the age of the sediments and the changes in climate and sea level that accompanied their deposition (Peacock *et al.*, 1977, 1978; Peacock, 1981b, 1983a, 1989b). The informal term 'Clyde beds' was proposed by Peacock (1975c) for those marine sediments deposited around the Scottish coast (but known principally in the area of the Firth of Clyde) subsequent to the deposition of the arctic 'Errol beds' (see Inchcoonans and Gallowflat), but prior to the establishment of a marine climate similar to that of today in the early Holocene. The Clyde beds thus cover the period from approximately 13,000 BP to around 10,000 BP.

Description

Rose (1980a) identified the following stratigraphic succession in the Geilston deposits (Figure 13.4):

5. Beach sands and gravels unconformably overlying bed 4
4. Clayey silt } Clyde beds
3. Laminated silts } Clyde beds
2. Glaciomarine till
1. Lodgement till

At the base the stiff, reddish-brown lodgement till (bed 1) has a relatively high silt–clay content and a dominant NW–SE fabric. The overlying glaciomarine till (bed 2) is similar in colour and lithology to the lodgement till but has a much lower silt–clay content. It contains a marine microfauna. Resting on the glaciomarine till is a sequence of colour laminated (pale olive-brown to brown) silts (bed 3) of which 26 couplets were reported by Rose (1980a). The individual laminae fine upwards and the colour change relates not to differences in particle size, but to the relative proportions of materials derived from Dalradian (pale laminae) or Old Red Sandstone bedrock. Foraminiferal remains increase in abundance through the lower half of the bed, remaining constant in frequency in the sediments

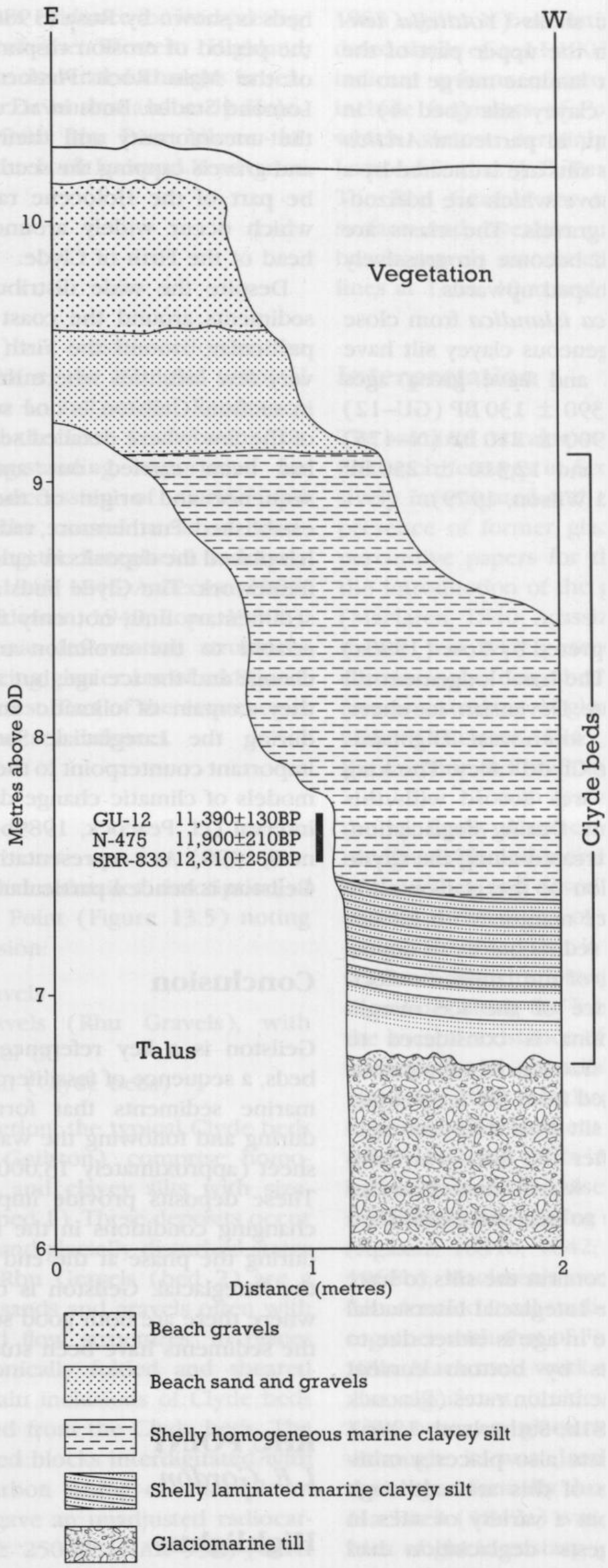


Figure 13.4 Geilston: sequence of sediments (from Rose, 1980a).

above this level. Mollusc shells (*Yoldiella lenticula* (Müller)) occur in the upper part of the laminated silts. The upper laminae merge into an overlying homogeneous clayey silt (bed 4) in which shells are abundant, in particular *Arctica islandica* (L.). The clayey silts are truncated by a marked unconformity, above which are horizontally bedded sands and gravels. The clasts are generally subrounded and become progressively more disc-like or blade-shaped upwards.

Three samples of *Arctica islandica* from close to the base of the homogeneous clayey silt have been radiocarbon dated and have given ages (Sutherland, 1986) of 11,390 ± 130 BP (GU–12) (Baxter *et al*., 1969); 11,900 ± 210 BP (N–475) (Yamasaki *et al*., 1969); and 12,310 ± 250 BP (SRR–833) (Harkness and Wilson, 1979).

Interpretation

The sediments were interpreted by Rose (1980a) in the following manner. The basal lodgement till was deposited by the Late Devensian ice-sheet, which flowed from the south-west Highlands towards the east along the Clyde valley. The long axes of drumlins in the area accord with this direction of ice movement. During deglaciation, the tidewater ice front retreated along the Clyde estuary, allowing deposition of the glaciomarine till beneath the floating ice margin. With further ice retreat the laminated sediments were deposited, the upward thinning of the laminae reflecting the increasing distance of the ice margin from the site. Each lamina is considered to represent the suspension fraction of subaqueous sediment plumes discharged from the ice margin. The homogeneous clayey silt with abundant macrofauna was deposited after the area was completely deglaciated, and when clearer water allowed *Arctica islandica* to become established (Peacock, 1981b).

The radiocarbon dates confirm the silts to have been deposited during the Lateglacial Interstadial but the considerable range in age is either due to mixing of the sediments by bottom current activity or very low sedimentation rates (Peacock *et al*., 1978; Peacock, 1981b; Sutherland, 1986). The oldest radiocarbon date also places a minimum age on deglaciation of this area although consideration of dates from a variety of sites in the Clyde estuary suggests deglaciation had occurred by 12,600 BP (Sutherland, 1986).

The unconformity which truncates the Clyde beds is shown by Rose (1980a) to correlate with the period of erosion responsible for the cutting of the Main Rock Platform during the Loch Lomond Stadial. Both in accord with that age for the unconformity and their altitude, the sands and gravels capping the section are considered to be part of the Holocene raised beach deposits which occur widely around the coasts of the head of the Firth of Clyde.

Despite the wide distribution of Clyde beds sediments around the coast of Scotland and, in particular, around the Firth of Clyde, there are very few localities where they can be examined in section. Geilston is one such locality and one of the few where detailed sedimentological work has been carried out and the stratigraphic sequence and origin of the sediments is well established. Furthermore, radiocarbon dating here has placed the deposits in a clear geochronometric framework. The Clyde beds are a very important sedimentary unit, not only for historical reasons related to the evolution of ideas on climatic change and the ice age, but also for the evidence they contain of climatic and sea-level changes during the Lateglacial. Such evidence is an important counterpoint to the terrestrially-derived models of climatic change during the same time interval (cf. Peacock, 1989b; Peacock and Harkness, 1990). As a representative of the Clyde beds, Geilston is hence a particularly important site.

Conclusion

Geilston is a key reference site for the Clyde beds, a sequence of fossiliferous glaciomarine and marine sediments that formed in the period during and following the wastage of the last ice-sheet (approximately 13,000–11,000 years ago). These deposits provide important evidence for changing conditions in the marine environment during the phase at the end of Devensian times, the Lateglacial. Geilston is one of the few sites where there are both good sections available and the sediments have been studied and dated.

RHU POINT

J. E. Gordon

Highlights

Deposits exposed in the coastal section at Rhu

Point provide important evidence for interpreting the glacial history of the Western Highland Boundary area and the associated changes in sea-level during the Late Devensian and early Holocene. The evidence from Rhu Point allows the nature and timing of the Loch Lomond Readvance to be established.

Introduction

The site (NS 264841) is a coastal section on the north side of Rhu Point, cut into the terminal moraine ridge of the Loch Lomond Readvance glacier that occupied the Gare Loch basin. The deposits are of long-standing importance for demonstrating the succession of marine and glacial episodes in the coastal areas of west-central Scotland during the Lateglacial and early Holocene (Maclaren, 1845, 1846; Anderson, 1896; McCallien, 1937b; Anderson, 1949; Rose, 1980c). Excellent glaciotectonic deformation structures formed by the advancing glacier are of additional sedimentological interest. Part of the sequence is now concealed behind sea defences.

Description

Rose (1980c) provided a detailed description of the deposits at Rhu Point (Figure 13.5) noting the following succession:

3. Raised beach gravels
2. Glaciofluvial gravels (Rhu Gravels), with included blocks of till
1. Marine, clayey silt (Clyde beds)

At the base of the section, the typical Clyde beds of the region (see Geilston), comprise homogeneous clayey silts and clayey silts with size-graded laminations (bed 1). These deposits occur in both undisturbed and glacially disturbed states (Figure 13.5). The Rhu Gravels (bed 2) are a suite of glaciofluvial sands and gravels often with current bedding and flow structures. In places they are glaciotectonically folded and sheared and sometimes contain inclusions of Clyde beds and shelly till derived from the Clyde beds. The till occurs as detached blocks interdigitated with the gravels. Radiocarbon dating of a sample of shells from the till gave an unadjusted radiocarbon age of 11,520 ± 250 BP (HAR–931) (Otlet and Walker, 1979). Adjusting the radiocarbon date for the apparent age of seawater (Harkness, 1983), gives a best estimate for the age of the dated shells of *c.* 11,100 BP. The molluscan shells indicate a fauna of interstadial aspect, but also include fragments of *Portlandia arctica* (Gray) which almost certainly date from the Loch Lomond Stadial (J. D. Peacock, unpublished data). The Rhu Gravels are truncated by an erosion surface and overlain unconformably by raised beach gravels associated with successive shorelines at 14 m, 10 m and 8 m OD.

Interpretation

The terminal moraine at Rhu Point was one of the first such features in Scotland to be comprehensively investigated and explained in terms of the presence of former glaciers. In two remarkably perceptive papers for their time, not long after the introduction of the glacial theory to Scotland (Maclaren, 1840; Agassiz, 1841b) and before this theory was widely accepted, Charles Maclaren convincingly described the evidence for the former existence of glacier ice in the Gare Loch valley (Maclaren, 1845, 1846). He inferred that the moraine at Rhu Point was probably the last of a number of such features to be formed before the ice finally disappeared. Maclaren (1846) also recognized lateral moraine ridges on the east side of the valley and described the terminal moraine at Rhu as consisting of clay overlain by sand and gravel. He noted that it had been trimmed by the sea and also reported a sequence of raised shorelines along the loch side. 'In short, marks of the ancient existence of a glacier in the valley are numerous and remarkably complete' (Maclaren, 1849, p. 165). Maclaren's papers represent an important development at a time when the glacial theory was still in its infancy. Although moraines had been identified elsewhere, notably by Agassiz and Buckland during their tour of Scotland (Agassiz, 1841b, 1842; Buckland, 1841a; Davies, 1968b), Maclaren's contribution was one of the first detailed local studies of this type of evidence, together with that of Forbes (1846) in the Cuillin Hills. Maclaren's work in the Gare Loch area was also significant in identifying geomorphological links between glaciation and raised shorelines, although it was Jamieson (1865) who later developed formally the concept of glacio-isostasy. Maclaren (1842a) was also first to introduce the idea of glacio-eustasy.

In a subsequent account of the Gare Loch area, Anderson (1896) largely followed Maclaren's

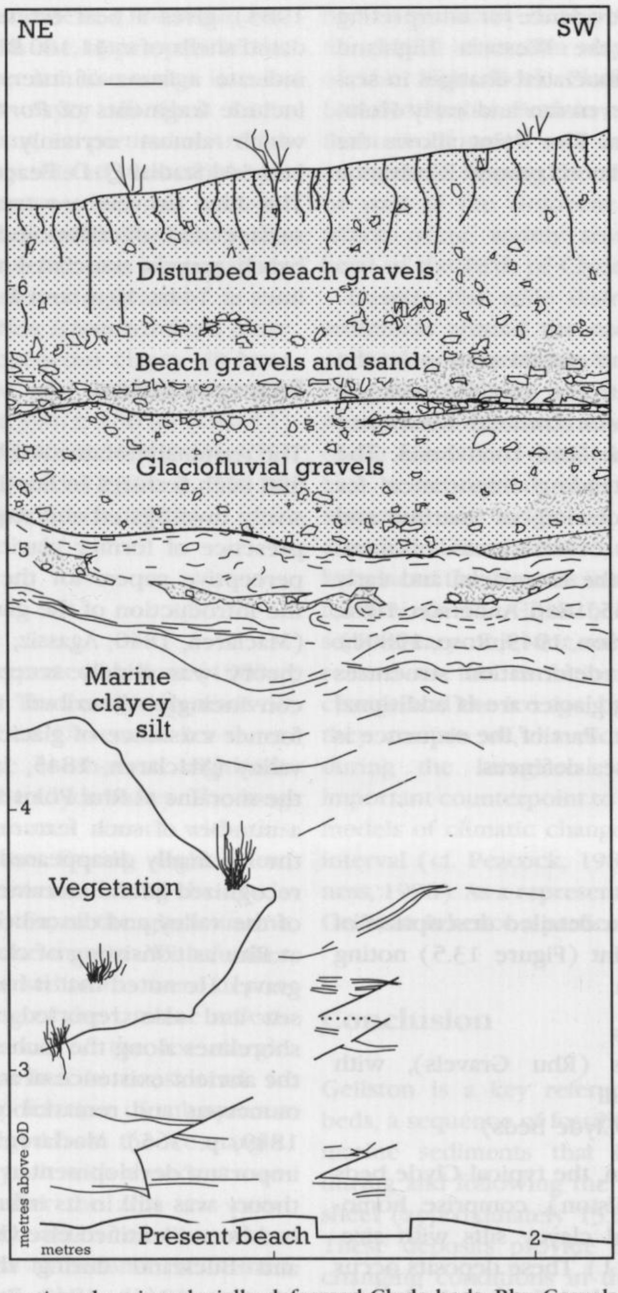


Figure 13.5 Rhu Point: section showing glacially deformed Clyde beds, Rhu Gravels and Holocene raised beach deposits (from Rose, 1980c).

interpretation of the Rhu Point deposits. Later, McCallien (1937) described in detail sections on the north side of the promontory at Rhu, noting, in particular, raised beach sediments unconformably overlying deformed 'morainic' material comprising sand and gravel which in turn rested on finely laminated clays. He interpreted the sediments as representing a readvance of ice which pushed up marine clays from the sea floor and dumped them along with morainic sands and gravels. Subsequently the deposits were trimmed by the sea. McCallien suggested that the Rhu moraine was a product of the Loch Lomond Readvance postulated by Simpson (1933) from evidence in the Loch Lomond and Western Forth valleys.

Anderson (1949) described the same sequence of deposits as McCallien, but also reported the presence of molluscan shell fragments, ostracods, Foraminifera, plant seeds and beetle fragments in the marine clay, which he stated were identical with those occurring widely elsewhere in the Clyde estuary (Clyde beds). He also traced the lateral continuation of the moraine ridge on both sides of Gare Loch and observed that the '100 foot' raised beach terminated at the moraine ridge, whereas the '25 foot' beach continued along the side of the loch inside the moraine. Anderson therefore concluded that the moraine ridge marked the limit of a late valley glacier readvance which, from its relationship with the raised shorelines, was contemporaneous with the Loch Lomond Readvance.

Charlesworth (1956) correlated the Rhu moraine ridge with his 'Stage M' readvance in the Highlands, which included Simpson's Loch Lomond Readvance moraines. Later, Sissons (1967a) mapped it as part of the Loch Lomond Readvance.

From the evidence at Rhu Point and in the adjacent area, Rose (1980c) interpreted the following sequence of events. As the Late Devensian ice-sheet wasted, the sea flooded into Gare Loch to a marine limit at 24 m OD. Deposition of the Clyde beds began and continued until at least 11,100 BP. A glacier then advanced along the Gare Loch valley forming a moraine ridge at Rhu Point, which consists primarily of glaciotectonized Clyde beds and sand and gravel deposited by meltwater streams flowing parallel to the ice front and towards the valley centre. The radiocarbon date on shells in the shelly till confirms that the moraine was formed during the Loch Lomond Stadial. The deformation structures in the earlier deposits indicate an oscillating ice front. Subaerial meltwater flow is suggested by the sedimentary characteristics of the sands and gravels, and this implies that sea level must have stood at or below 2.3 m OD, the lowest elevation at which these deposits occur. Subsequently, relative sea level rose during the Holocene transgression to 14 m OD, then fell to its present level via intermediate shorelines at 10 and 8 m OD.

The sequence of deposits at Rhu Point provides a key stratigraphic record of Lateglacial and early Holocene environmental and geomorphological changes in western Scotland. It is particularly important in integrating both terrestrial and marine evidence in a single radiocarbon-dated succession. It demonstrates the period of incursion of 'sub-arctic' seas, represented by the Clyde beds, following the recession of outlet glaciers from the main Late Devensian ice-sheet. Clear evidence for a subsequent readvance of ice is provided by the deformation and incorporation of Clyde beds into an end moraine ridge and the superimposition of glaciofluvial deposits with till inclusions. Radiocarbon assay constrains the date of this ice readvance to a period after the later part of the Lateglacial Interstadial and provides a maximum date for the local maximum extent of the Loch Lomond Readvance in Gare Loch. The two lower shorelines demonstrate temporary stillstands in the fall of relative sea level to its present position.

Broadly similar sequences, but without the Holocene beach sediments, occur at South Shian and Balure of Shian (see above), where glacially disturbed marine sediments (Clyde beds) are overlain by outwash from a Loch Lomond Stadial glacier in the valley of Loch Creran; at Gartness (see above), where deformed marine sediments are overlain by Loch Lomond Readvance till, and in the Western Forth Valley (see below) and at Loch Spelve (Gray and Brooks, 1972), where marine sediments are incorporated into Loch Lomond Readvance moraines. The significance of Rhu Point is, first, as a key reference site demonstrating the sequence of marine and glacial events during the Lateglacial and early Holocene in west-central Scotland. Second, Rhu Point is a site of considerable historical interest as one of the first localities in Scotland where glacier theory was applied in a detailed study to explain surface landforms and deposits. Finally, Rhu Point is notable for the glaciotectonic deformation structures in both the marine and glaciofluvial deposits; these have not been investigated in detail but have significant potential for research.

Conclusion

The deposits at Rhu Point have a long history of research and have provided important information for interpreting the sequence of Late Devensian glacial events in western Scotland. They show clear evidence for glaciation during the Loch Lomond Stadial (approximately 11,000–10,000 years ago) after a phase of marine sedimentation following the wastage of the main Late Devensian ice-sheet (approximately 13,000 years ago). Rhu Point forms part of the network of sites that demonstrate geomorphological processes associated with the Loch Lomond glacier readvance and provide evidence for its timing.

WESTERN FORTH VALLEY
D. E. Smith

Highlights

The interest of this area includes an outstanding assemblage of moraine ridges, outwash sediments and a sequence of buried estuarine deposits and peats. These landforms and deposits provide an exceptionally detailed record of the glacial history and sequence of sea-level changes in central Scotland at the end of the Late Devensian and during the early and middle Holocene.

Introduction

At the head of the Forth valley, around the Lake of Menteith (Figure 13.6), a belt of moraine ridges, glaciofluvial deposits and sequences of marine deposits record the advance and decay of a Loch Lomond Readvance glacier, together with related and subsequent changes in relative sea level. This assemblage of landforms and deposits has been studied for over 100 years (Jamieson, 1865; Simpson, 1933; D. E. Smith, 1965, 1968; Newey, 1966; Sissons, 1966, 1972b, 1976e; Sissons and Smith, 1965b; Sissons *et al.*, 1965; Sissons and Brooks, 1971; Brooks, 1972; Gray and Brooks, 1972; Kemp, 1971, 1976). It represents probably the most detailed evidence for readvance, deglaciation and relative sea-level change during the Late Devensian and early Holocene in Scotland. The extensive early literature on the area has been reviewed by Smith (1965).

The main features of this area are particularly well-illustrated at four key sites: these are identified on the accompanying generalized geomorphological map (Figure 13.6) as site I (Inchie), site II (Easter Garden), site III (West Moss-side) and site IV (Easter Poldar). In the account that follows, the landforms and deposits attributable to glacial advance, retreat and relative sea-level change are summarized before more detailed descriptions and interpretations are given for the key sites.

Description

The Forth valley is a broad lowland running some 40 km eastwards from the edge of the Highlands to the head of the Firth of Forth. The surrounding landscape reflects the varied geology of the area, but the lowland is distinguished by extensive areas of raised estuarine deposits, which occur on both sides of the River Forth throughout its length. These deposits consist of a grey silty clay with occasional lenses of sand, and are known locally as carse clay. They form a remarkably uniform surface, in which local changes of level of more than 1 m are rare. These carselands extend up to 3 km either side of the Forth, and occupy an area in excess of 50 km. A sharp break of slope occurs where they meet the sides of the lowland, which are for the most part mantled in glacial and glaciofluvial deposits.

West of the village of Kippen (NS 650948), the head of the lowland is occupied by large numbers of glacial and glaciofluvial features, and the carselands are restricted to narrow areas along the Forth and Goodie Water. It is these landforms and deposits which represent the key interest.

Glacial events

The glacial and glaciofluvial landforms and deposits of the Western Forth Valley have long attracted attention, with Jamieson (1865) apparently the first to have recognized an ice limit. In 1933, Simpson maintained that subsequent to general ice-sheet glaciation, ice had readvanced eastwards into the area, citing as evidence for this a section near Inchie where grey clay with marine shells was overlain by sands and gravels (see below). He called this event the Loch Lomond Readvance. In 1956, Charlesworth supported the view that an important ice limit could be identified here, correlating it with his 'Moraine Glaciation'.

Since 1962, more systematic studies of the glacial and glaciofluvial landforms and deposits of the area have been undertaken (for example, Sissons *et al.*, 1965; Smith, 1965). These studies confirm the evidence of a readvance moraine, and describe the landforms and deposits of the area in some detail. The frontal margin of a major ice limit can be traced in a broad belt of moraine ridges which forms an arc across the valley between Port of Menteith (NN 584012) and Buchlyvie (NS 575937). The northern and southern limbs of this belt (A and B, Figure 13.6) are elongate areas each composed of a large number of small ridges, most of which trend across the valley. These areas are dissected by deep channels leading eastward, and in some of these channels there are terraces composed of coarse

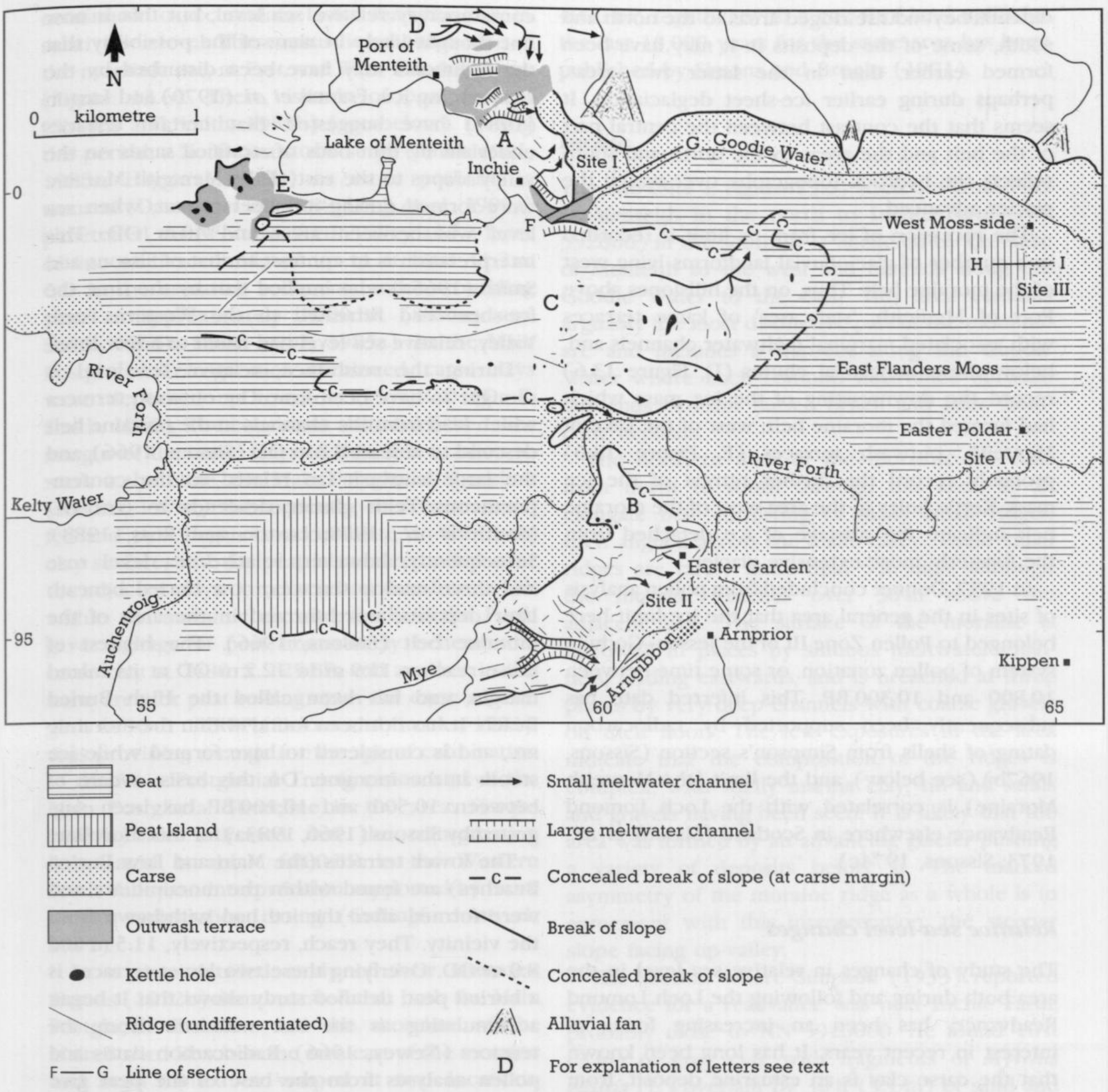


Figure 13.6 Geomorphology of the Western Forth Valley.

sands and gravels. The two areas of ridges are thought to be push moraines; the channels, routeways for proglacial meltwaters (Smith, 1965).

The central part of the belt (C, Figure 13.6) does not contain such clear evidence. It consists of a broad ridge running parallel to the axis of the valley, with a number of smaller ridges on its surface. The area extends about 1 km east of the ridged areas to the north and south. Exposures show the main ridge to be composed of bedrock (Smith, 1965; Laxton, 1984), whereas the smaller ridges are apparently formed of sands and gravels. Many of the smaller ridges are orientated parallel to the valley axis and to the axis of the main ridge, rather than across it; only a few of them continue the trends of the northern and southern limbs of the belt. Through this area thread a number of sinuous meltwater channels. It is possible that some of the ridges may have been crevasse fillings, and some channel systems may have operated proglacially. Smith (1965) argued that, in view of the fact that this central area extends beyond the ridged areas to the north and south, some of the deposits in it may have been formed earlier than in the latter two areas, perhaps during earlier ice-sheet deglaciation. It seems that the contrast between the central part of the belt and the areas to the north and south reflects the bedrock topography over which the glacier advanced.

The recession of ice from its limit is recorded in a number of glaciofluvial landforms lying west of the moraine belt. Thus, on the hillslopes above Port of Menteith, 'staircases' of kame terraces with associated marginal meltwater channels and, below these, subglacial chutes (D, Figure 13.6) record the downwasting of the ice mass which had formed the moraine belt; west of the Lake of Menteith, outwash terraces (E, Figure 13.6) probably record the further retreat of the ice mass. Kettle holes in the area west of the moraine belt indicate the wastage of ice detached from the formerly more extensive glacier.

In 1957, Donner concluded from pollen analysis of sites in the general area that the ice limit here belonged to Pollen Zone III of the Jessen–Godwin system of pollen zonation, or some time between 10,800 and 10,300 BP. This inferred date has subsequently been supported by radiocarbon dating of shells from Simpson's section (Sissons, 1967b) (see below), and the limit (the Menteith Moraine) is correlated with the Loch Lomond Readvance elsewhere in Scotland (Sissons *et al.*, 1973; Sissons, 1974c).

Relative sea-level changes

The study of changes in relative sea level in the area both during and following the Loch Lomond Readvance, has been an increasing focus of interest in recent years. It has long been known that the carse clay is an estuarine deposit, from the many faunal remains found and recorded during a period of over 300 years (Smith, 1965). However, detailed stratigraphical investigations since the mid–1960s (for example, Sissons and Smith, 1965b; Sissons, 1966, 1972b; Smith, 1968; Sissons and Brooks, 1971; Kemp, 1976; D. E. Smith *et al.*, 1978; M. Robinson, unpublished data) have identified a detailed sequence of relative sea-level changes in the area, in which the carse clays are only one element.

Relative sea levels prior to the Loch Lomond Readvance are not well known. Simpson (1933) believed that the altitude of the top of the shelly clay at Inchie, 65 ft (19.8 m) OD, reflected contemporary relative sea level, but this is now not thought likely in view of the possibility that the sediments may have been disturbed by the readvancing ice. Francis *et al.* (1970) and Laxton (1984) have suggested that certain terraces underlain by thin beds of stratified sands on the valley slopes to the east of the Menteith Moraine were formed during ice-sheet retreat, when sea level was between 18 m and 40 m OD. This interpretation is in contrast to that of Sissons and Smith (1965a) who implied that by the time the ice-sheet had retreated to the Western Forth Valley, relative sea level had fallen to a low level.

During the readvance, relative sea level is thought to have been low. The outwash terraces which lead from the channels in the moraine belt descend to at least 8.8 m OD (Sissons, 1966), and the large outwash fan related to the contemporaneous Teith glacier descends to 6 m OD (Smith *et al.*, 1978; Laxton and Ross, 1983). Subsequently, however, relative sea level rose and three marine terraces, now buried beneath later deposits, were formed in the area of the moraine belt (Sissons, 1966). The highest of these reaches 11.9 m to 12.2 m OD at its inland margin, and has been called the High Buried Beach. It has not been found within the morainic arc, and is considered to have formed while ice stood at the moraine. On this basis, a date of between 10,500 and 10,100 BP has been suggested by Sissons (1966, 1983a) for this shoreline.

The lower terraces (the Main and Low Buried Beaches) are found within the morainic arc and were formed after the ice had withdrawn from the vicinity. They reach, respectively, 11.5 m and 8.0 m OD. Overlying these two lower terraces is a buried peat; detailed study shows that it began accumulating as the sea withdrew from the terraces (Newey, 1966). Radiocarbon dates and pollen analyses from the base of the peat give ages of around 9600 BP for the Main Buried Beach and around 8700 BP for the Low Buried Beach (Sissons, 1966, 1983a; Sissons and Brooks, 1971). From the form of the three buried beaches, Sissons concluded that each had resulted from a brief transgression.

After falling to an unknown level, reached at possibly 8500 BP, relative sea level again rose, and the carse clays began to accumulate in the now expanded Forth estuary. This transgression is known as the Main Postglacial Transgression (Sissons, 1974c). As the sea rose, silts and clays were deposited on the peat on the surface of the buried beaches. In two areas, however, peat continued to accumulate faster than the rise in relative sea level. These areas lie on either side of the morainic arc, at East and West Flanders Moss (Figure 13.6). There, islands of peat formed (Sissons and Smith, 1965b) (see below). During this period, a North Sea storm surge (Smith *et al.*, 1985a; Haggart, 1988b) or more probably a tsunami (Dawson *et al.*, 1988; Long *et al.*, 1989a) penetrated the Western Forth Valley and a layer of fine sand accumulated up to at least 11.2 m OD in the estuarine sediments and surrounding peat at approximately 7000 BP (Sissons and Smith, 1965b; Smith *et al.*, 1985a). As the Main Postglacial Transgression continued, carse clays were deposited up to about 15 m OD (D. E. Smith, 1968). The consistent altitude of the inner margin of the carse clays in this area is taken to mark a shoreline, the Main Postglacial Shoreline (Sissons, 1974c). Subsequently, relative sea level fell and peat began to accumulate on the carse clay surface, and the peat islands expanded over the adjacent clays. A radiocarbon date from a site within the morainic arc and south of the Forth gave the age of peat immediately beneath the carse clay at 7480 ± 125 BP, and another in the same area for peat resting upon the carse surface gave 6490 ± 125 BP (Sissons and Brooks, 1971), thus providing a range for the age of culmination of the Main Postglacial Transgression and of the Main Postglacial Shoreline in the area. Sissons (1983a) has indicated that the transgression culminated at about 6800 BP in the Western Forth Valley, an interpretation supported by more recent radiocarbon dating (Cullingford *et al.*, 1991).

In a very detailed study of their altitudes, Sissons (1972b) demonstrated that both the Main Postglacial Shoreline and the shoreline of the Main Buried Beach in the area east of the moraine had been faulted or warped at two locations. Since between these points the gradients of the shorelines resulting from isostatic uplift were the same, it was concluded that during the period between the formation of the two shorelines (around 3000 years), there had been no differential uplift in the area except at the dislocations. This demonstration of dislocation and non-uniform uplift has since been corroborated by studies elsewhere in Scotland, and may indicate that raised shoreline altitudes in isostatically affected areas may be more complex than had been previously thought.

A curve of relative sea-level change for the area of the morainic arc, for the period from 10,500 to 4000 BP, together with a curve of land uplift for the last 10,000 years for the same area has been published by Sissons and Brooks (1971).

Inchie

The site (Site I, Figure 13.6) stretches from Port of Menteith in the north to Inchie Farm (NN 592000) in the south. It is bordered by the Lake of Menteith to the west and extends along the Goodie Water to the east. This area contains arguably the most distinctive part of the morainic arc and includes a transect along the Goodie Water where Loch Lomond Readvance outwash descends beneath buried beach and later Holocene deposits.

The northern limb of the morainic arc runs from north to south through this area, as an elongate belt consisting of many small ridges, each aligned across the main valley. These small ridges are rarely more than 5 m high, although the moraine reaches over 30 m above the adjacent lake. The surface of the moraine is furrowed in places by sinuous meltwater channels, leading eastwards, and is breached at three places by very deep channels with coarse gravels on their floors. The few exposures in the area indicate that the composition of the ridges is complex, with shelly marine clay, till and sands and gravels having been seen. It is likely that the area was formed by an advancing glacier pushing a variety of deposits before it. The marked asymmetry of the moraine ridge as a whole is in agreement with this interpretation, the steeper slope facing up-valley.

The section where Simpson (1933) reported evidence for a readvance was near Inchie Farm, probably close to NN 5920000. He found 10 ft (3 m) of grey clay with fragments of *Mytilus edulis* (L.) overlain by 30 ft (9.1 m) of sand and gravel. In 1967, Sissons identified a similar sequence near that location and on the lake shore, and obtained a radiocarbon date of 11,800 ± 170 BP (I–2234) for a specimen of *Mytilus edulis* (L.) (Sissons, 1967b), concluding that the readvance had occurred during the climatic deterioration at the end of the Lateglacial, the Loch Lomond Stadial. The fauna from the grey clay in Sisson's section (S. M. Smith, *in* Gray and Brooks, 1972) is as follows:

Littorina littorea (L.)
Littorina obtusata (L.)
Buccinum undatum L.

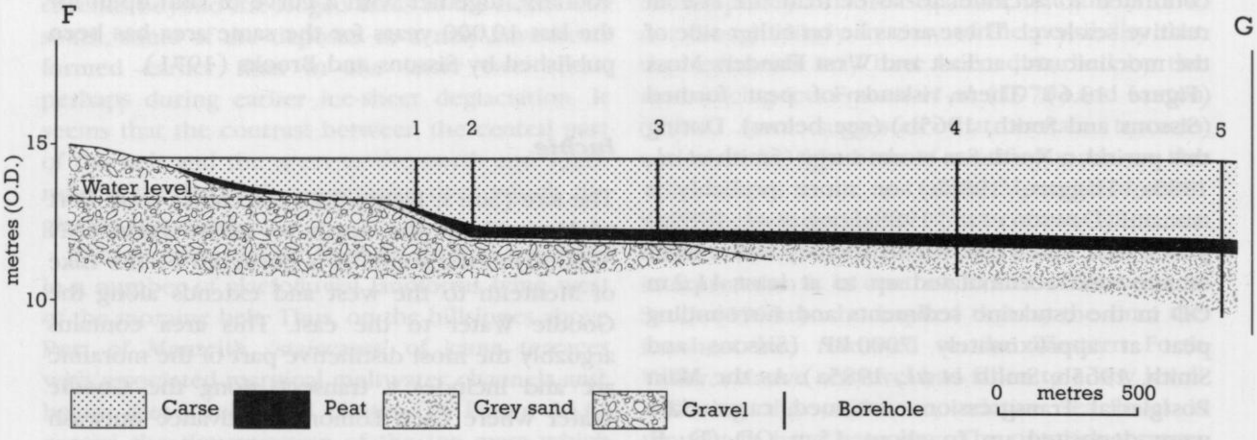


Figure 13.7 Western Forth Valley: section along the Goodie Water (from Sissons *et al.*, 1965). See Figure 13.6 for location of section.

Mytilus edulis (L.)
Nuculana pernula (Müller)
Chlamys sp.
Macoma sp.

Gray and Brooks (1972) also concluded that pollen from the grey clay indicated a Lateglacial Interstadial age for the deposit, and a largely open habitat locally was suggested by the low percentages of arboreal pollen. Taken with the stratigraphical evidence, these observations further support the correlation with the Loch Lomond Readvance.

The deep channels through the site carried outwash deposits eastward, as is indicated from the coarse sands and gravels on their floors. The largest channel, in the south of the site, contains a wide outwash terrace, part of which occurs on the proximal side of the moraine, indicating that it was deposited as ice began to waste back. This terrace, near Inchie Farm, slopes eastwards from 23.5 m OD. Beyond the moraine it descends beneath the carse clays, but its descent can be followed in the banks of the Goodie Water, where it passes beneath peat and fine-grained grey sand. The sequence was traced by Sissons *et al.* (1965) in exposures and boreholes and is shown in Figure 13.7. The outwash descends to at least 9 m OD and it was concluded that relative sea level at the time of deposition lay below that altitude. The fine grey sand above has a level surface at 11 m OD and was interpreted as forming part of the Main Buried Beach, which thus appears to have accumulated following a marine transgression across the outwash. The peat above the sand demonstrates a marine regression, and the estuarine (carse) clay which overlies this peat, and reaches 14.7 m OD here, was laid down during the Main Postglacial Transgression.

Although the floors of the channels at the northern end of the moraine in this area descend to below 20 m OD there is no indication that the carse clays were deposited in them, and therefore no indication that the sea at the culmination of the Main Postglacial Transgression entered the Lake of Menteith.

Thus the landforms and deposits at Inchie demonstrate glacial advance, retreat and subsequent relative sea-level changes. Though the sequence is known in detail, it is interesting that so far no evidence of the High Buried Beach has been found in this area. It may be that the beach is confined to the sides of the depression through which the Goodie Water flows, in a similar manner to the situation at Easter Garden, discussed below.

Easter Garden

The site (Site II, Figure 13.6) lies on the left bank of the Garden Burn near Arnprior (NS 612948), south of the River Forth. It includes the ice-distal (outer) portion of the morainic arc, together with carselands south of the Forth and along the Arngibbon and Garden Burns. The area was studied in detail by Sissons (1966). It contains some fine morainic topography, but is particularly notable for the sub-carse deposits, which include outwash gravels, together with High, Main, and Low Buried Beaches.

The southern limb of the morainic arc consists of a large number of small ridges intersected by shallow meltwater channels. It is kettled in places and appears to be largely composed of sands and gravels. To the south of the site, the moraine is dissected by a large meltwater channel system, in which the main channel exceeds 20 m in depth. This was probably excavated largely by proglacial meltwaters.

The carseland stratigraphy in this area (Sissons, 1966) reveals a number of interesting features. South of Easter Garden (NS 607957), the carselands at the foot of the moraine are underlain by outwash gravels, which come from the mouth of the meltwater channel to the south. The surface of these gravels is slightly irregular, but falls north-eastward down to 11 m OD. Between Easter Garden and the moraine, and in a small area south of Easter Garden, the outwash is overlain by a deposit of silty sand which is pinkish or pale brown in colour except at its surface, where it is grey. In places, this deposit is laminated and its surface is level at about 12 m OD. It is part of the High Buried Beach (Sissons, 1966) and this location is the farthest up-valley it has been found.

South of Easter Garden and north of the Arngibbon Burn, the outwash surface and High Buried Beach have been dissected by a channel up to 200 m broad and 3 m deep, which appears to originate at the mouth of the meltwater channel system referred to above. This channel is largely floored with deposits of a grey silty fine-grained sand with occasional bands of silt or clay, lying at around 11 m OD. Where the channel ends north-east of Easter Garden, these sediments form a wide surface lying at 10.7 m OD. Sissons identified this as the Main Buried Beach. North of the abandoned railway line, a sharp break of slope occurs in the Main Buried Beach deposits and a lower area of grey silty clay, becoming more sandy with depth, ensues, lying at 6.4 m OD. This has been interpreted as the Low Buried Beach.

The buried surfaces of the outwash, and the High, Main and Low Buried Beaches are covered in peat, which becomes thicker over the lower surfaces. This peat is, in turn, overlain by carse clays, which reach 15 m OD in this area and belong to the Main Postglacial Shoreline. In some areas nearby the carse clays are covered in peat.

At the mouth of the large meltwater channel system mentioned above, the Arngibbon Burn has deposited an alluvial fan, which extends into the southern part of the site (Sissons *et al.*, 1965). Boreholes through the fan show that it overlies carse clay, whereas boreholes nearby in the floor of the main meltwater channel show peat, overlying lacustrine clay, which overlies estuarine (carse) clay. The alluvial fan was deposited across the mouth of the meltwater channel, and it seems that here the alluvial fan, built out across the carse clay, temporarily dammed a lake in the mouth of the meltwater channel system.

The sequence of events recorded in this area is therefore as follows. First, a readvance of ice formed a large moraine belt, and meltwaters discharged proglacially across it. At the southern end of the moraine a large proglacial meltwater system deposited an outwash fan in a north-easterly direction. The lowest elevation of the outwash, 8 m OD, indicates that relative sea level could not have been higher than this at the time. Then, relative sea level rose, and the High Buried Beach was deposited on part of the outwash surface. The ice must have been at the moraine during this period, because a large channel, emanating from the mouth of the meltwater channel system, was subsequently cut in both the outwash and the High Buried Beach. The size and position of this channel suggests that it was probably cut by proglacial meltwaters. Subsequently, relative sea level fell and deposits of the Main Buried Beach were laid down across lower parts of the outwash and in the channel. A further fall in relative sea level was followed by deposition of the Low Buried Beach. Eventually, relative sea level fell further and peat accumulated on the surfaces revealed. Later, the Main Postglacial Transgression led to the deposition of the carse clays. Subsequently, relative sea level fell again, and as peat began to accumulate on the carse clay surface, a small fan was built up by the Arngibbon Burn at the mouth of the large meltwater channel system, trapping a small lake in the lower part of the main channel. The lake eventually filled with clay, and peat also accumulated on these sediments.

West Moss-side

South of the Farm of West Moss-side (NS 648996), an area of East Flanders Moss (Site III, Figure 13.6) has provided a focus of interest for studies of Holocene relative sea-level changes. It is in this area that peat continued to accumulate during the Main Postglacial Transgression, form-

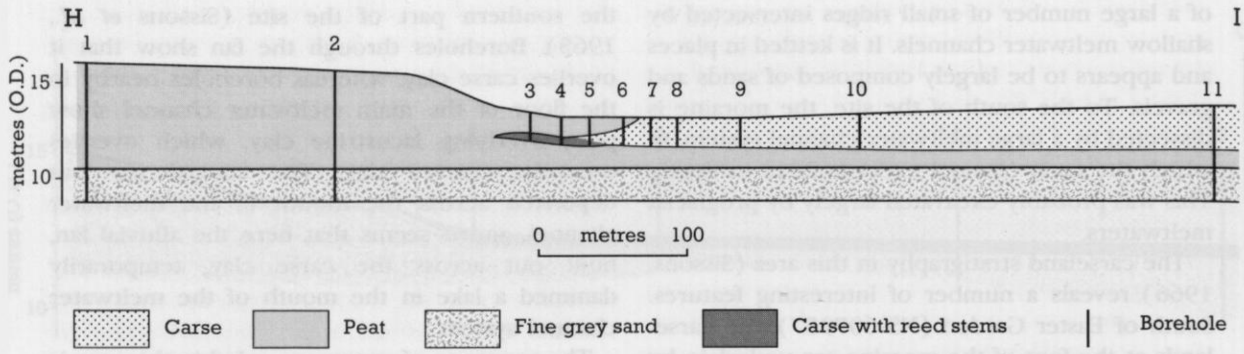


Figure 13.8 Western Forth Valley: section at West Moss-side, East Flanders Moss (from Sissons and Smith, 1965b). See Figure 13.6 for location of section.

ing an island in the then expanded estuary of the Forth. The peat stratigraphy of this area has been examined in detail by Smith (1965) and by Sissons and Smith (1965b).

East Flanders Moss is a remnant of a much more extensive peat bog that once covered the carselands of the Forth Valley. Clearance of the peat in the Forth Valley began in the eighteenth century (Tait, 1794) and ended in 1865 (Cadell, 1913). The termination of most peat clearances appears to have been for economic or social reasons, but near West Flanders Moss there is evidence that as the clearance progressed, the farmers encountered an increasingly boggy carse surface, which declined in altitude sharply.

In 1950, a survey of East Flanders Moss was undertaken by the Department of Agriculture for Scotland (Peat Section). From a number of boreholes they found that the peat was widely underlain by the level surface of the carseland, but that near West Moss-side a depression of over 4 m lay beneath the peat. Durno (1956) undertook pollen analysis of a core from this depression, finding that the basal peat began to accumulate in Zone V of the Jessen–Godwin system of pollen zonation, significantly earlier than peat elsewhere on the carseland surface. He concluded that the marine transgression in which the estuarine (carse) clay had accumulated had ended east of East Flanders Moss.

Smith (1965) and Sissons and Smith (1965b) later examined the stratigraphy in detail (Figure 13.8). They found that beneath the peat the carse clay formed a wedge at the edge of the depression. They identified a similar sequence at West Flanders Moss, west of the morainic arc. They also found that the peat at the base of the depression in East Flanders Moss continued beneath the carse clay, and that it rested upon a remarkably level surface lying at *c.* 10.0 m OD. They concluded that the surface upon which the peat had commenced accumulating was that of a buried beach (later identified as the Main Buried Beach by Kemp (1976)), and that this peat had managed to continue accumulating in a small area throughout the Main Postglacial Transgression. After the sea subsequently withdrew, the peat island expanded across the adjacent carse surface, at an altitude of approximately 12 m OD.

In West Flanders Moss, a thin (about 0.03 m) layer of grey, micaceous, silty fine sand has been identified within the carse and continuing into the peat, beneath the carse clay 'wedge'. This is thought to have been deposited during a North Sea storm surge (Smith *et al.*, 1985a; Haggart, 1988b) or more probably a tsunami event (Dawson *et al.*, 1988; Long *et al.*, 1989a). Recent work suggests that this layer may also be present beneath East Flanders Moss.

Easter Poldar

The detailed and often complex sub-carse stratigraphy in the Western Forth Valley can normally only be examined through detailed coring. However, at a number of sites along the Forth and Goodie Water, some elements of the stratigraphy can be examined in exposures. The best individual sites are along the river bank from Faraway (NS 615964) to Easter Poldar (NS 647972).

Near the Farm of Easter Poldar, on the left bank of the River Forth, an exposure in the carse clay and the underlying deposits was first recorded in 1964 (Smith, 1965). The sequence of deposits is as follows:

	Thickness (m)	Altitude (m) OD (surface = 12.56)
5. Brown silty clay, with reed stems	4.31	8.25
4. Blue-grey silty clay, with reed stems	0.15	8.10
3. Woody peat	0.24	7.86
2. *Sphagnum* peat	0.09	7.77
1. Fine-grained blue-grey silty sand with reed stems, especially in the upper part (base not seen), to	0.06	7.71

In 1966, Sissons identified the surface of the fine-grained, blue-grey, silty sand (bed 1) as part of the Low Buried Beach. The presence of increasing numbers of reeds in its upper part suggests that the overlying peat may have started to accumulate shortly after the sea withdrew from the surface. The peat (beds 2 and 3) is much compressed, but the transition from *Sphagnum* peat (bed 2) to a more woody peat (bed 3) indicates that conditions became less moist. The sediments above the peat are estuarine carse clay (beds 4 and 5), the brown coloration in the upper part (bed 5) probably being due to oxidation from the face of the exposure.

Interpretation

The assemblage of landforms and the sequences of deposits in the Western Forth Valley are among the most detailed for the Late Devensian and early Holocene in Scotland. The glacial and glaciofluvial landforms represent arguably the finest evidence for a readvance ice limit and subsequent ice decay anywhere in the British Isles, and the detail of the record of relative sea-level change is unsurpassed in Scotland.

At a number of other sites (Loch Etive, South Shian and Balure of Shian, and Rhu Point) it can be demonstrated that the Loch Lomond Readvance glaciers discharged into the sea or constructed outwash plains graded to sea level. However, it is only in the Western Forth Valley that a specific sequence of sea-level changes can be established at, or close to the time of the maximum of the readvance.

Early to middle Holocene sea-level changes have been studied in greater detail in the Western Forth Valley than in any other locality in Scotland. Both the sedimentary sequences and the landforms arising from sea-level change have been analysed, unlike in most areas where one or the other approach to sea-level change studies has been adopted. In consequence, fundamental information on the nature of isostatic uplift has been established in this area, notably the role of fault-reactivation and block movement. This last aspect has had important consequences for the study of neotectonic activity in Scotland.

The geomorphology of the morainic system has yet to be fully mapped, but it is evident from the details so far revealed, especially from exposures, that the moraine sediments will greatly repay further study. In this regard, two sites where the moraine is displayed (Inchie and Easter Garden) will be crucial. At all the key sites discussed here, the carse and sub-carse deposits have yielded a remarkably detailed story, but further work is needed to reveal the extent of tsumani or storm surge deposits, the progress of marine transgression and regression, and in particular further evidence for neotectonic activity. It is evident that the Western Forth Valley will play an important part in future scientific enquiry into both glacial events and relative sea-level changes in Scotland.

Conclusion

The Western Forth Valley is a critical reference area for studies of the Loch Lomond Readvance, and particularly for the sequence of sea-level changes that occurred around and following the maximum of the ice readvance (approximately 10,500 years ago). The key interest includes a complex of moraine ridges and outwash sediments (deposited in front of the glacier by meltwater rivers) and a sequence of buried estuarine deposits. The latter provide the most detailed record of sea-level changes in Scotland at the time of the readvance and later during early to middle Holocene times (approximately 10,500–6000 years ago). The area has a long history of research, and its landforms and sediments have been studied in great detail. In addition, the results of the work provide a standard framework of sea-level changes for comparison with other areas. Furthermore, the Western Forth Valley has allowed important insights into the processes that accompany isostatic recovery, that is, upward movement of the Earth's crust following ice melting.

MOLLANDS
J. J. Lowe

Highlights

The sediments that infill the floor of a kettle hole at Mollands provide an important record, supported by radiocarbon dating, of the Holocene vegetational history of this important ecological area located at the boundary between the Highlands and the Central Lowlands. Together with Tynaspirit, Mollands also provides significant evidence for establishing a glacial chronology for the area.

Introduction

The site at Mollands (NN 628068) is an infilled kettle hole located *c.* 1 km south of Bridgend, Callander. It is important for pollen stratigraphy at the Lateglacial–Holocene boundary and during the Holocene. It has also been significant in establishing a glacial chronology for the Callander area. The results obtained from Mollands (Lowe, 1977, 1978, 1982a, 1982b; Lowe and Walker, 1977) complement those from Tynaspirit (see below), and together these two sites provide one of the strongest lines of support for recently proposed schemes of the Late Devensian glacial chronology of Scotland (see Gray and Lowe, 1977b; Price, 1983; Lowe and Walker, 1984; Sutherland, 1984a).

Description

The limit of the last glacier advance in the Teith valley is marked by a well-defined terminal moraine (the Callander Moraine) which can be observed on both sides of the river just downstream from Callander (Figure 13.9). Upstream of the moraine some sharply delimited eskers occur, as for example around Clash and Gart (NN 636068 to NN 644064) and on both banks of the River Teith downstream of the site of Callander Castle (NN 632075 to NN 635073 and NN 632073 to Clash). A series of kame terraces has also been mapped in the area between the Callander Moraine and the town of Callander (Thompson, 1972; Merritt and Laxton, 1982). At Mollands, on the ice-proximal side of the moraine ridge (Figure 13.9), lake sediments and peats have filled a depression which exceeds 8 m in depth from the ground surface and which is bounded on its eastern and south-eastern edges by kame terraces. The site is therefore interpreted as a kettle hole, formed by melting of a block of buried ice that persisted until after the formation of the kame terraces. The sediment succession at Mollands should therefore provide a minimum age for the retreat of the Loch Lomond Readvance ice in the vicinity of Callander (see Sissons *et al.*, 1973; Lowe and Walker, 1977 for details of methodology).

The basal sediments are very variable, with a number of thinly bedded units, including rhythmites (Figure 13.10). Collectively, the basal sediments comprise a fining-upwards sequence from compact sands at the base (8.32 m to 7.50 m) through finely laminated silts, sands and clays (7.50 m to 7.30 m) to laminated organic and inorganic muds (see Lowe, 1978). The sediments proved to be non-polleniferous below 7.32 m, but a detailed pollen stratigraphy was based on samples obtained from the remainder of the succession. Three radiocarbon dates (HV–5645 to HV–5647) were obtained from the profile (Figure 13.10).

Interpretation

The vegetational succession (Figure 13.10) that can be inferred is one of successive plant colonization of the slopes around the site from initially bare, stoney surfaces to a woodland cover. The lowermost pollen zone (Mo a I) is dominated by pollen of grasses, sedges, sorrel, the dandelion group (*Taraxacum*) and meadow rues (*Thalictrum*), with spores of the clubmosses (*Selaginella* and *Lycopodium*) also well represented. These species thrive on bare, gravelly or stoney surfaces free of competition from shrub and woodland associations. The zones Mo a II to Mo c record successive invasions of the district,

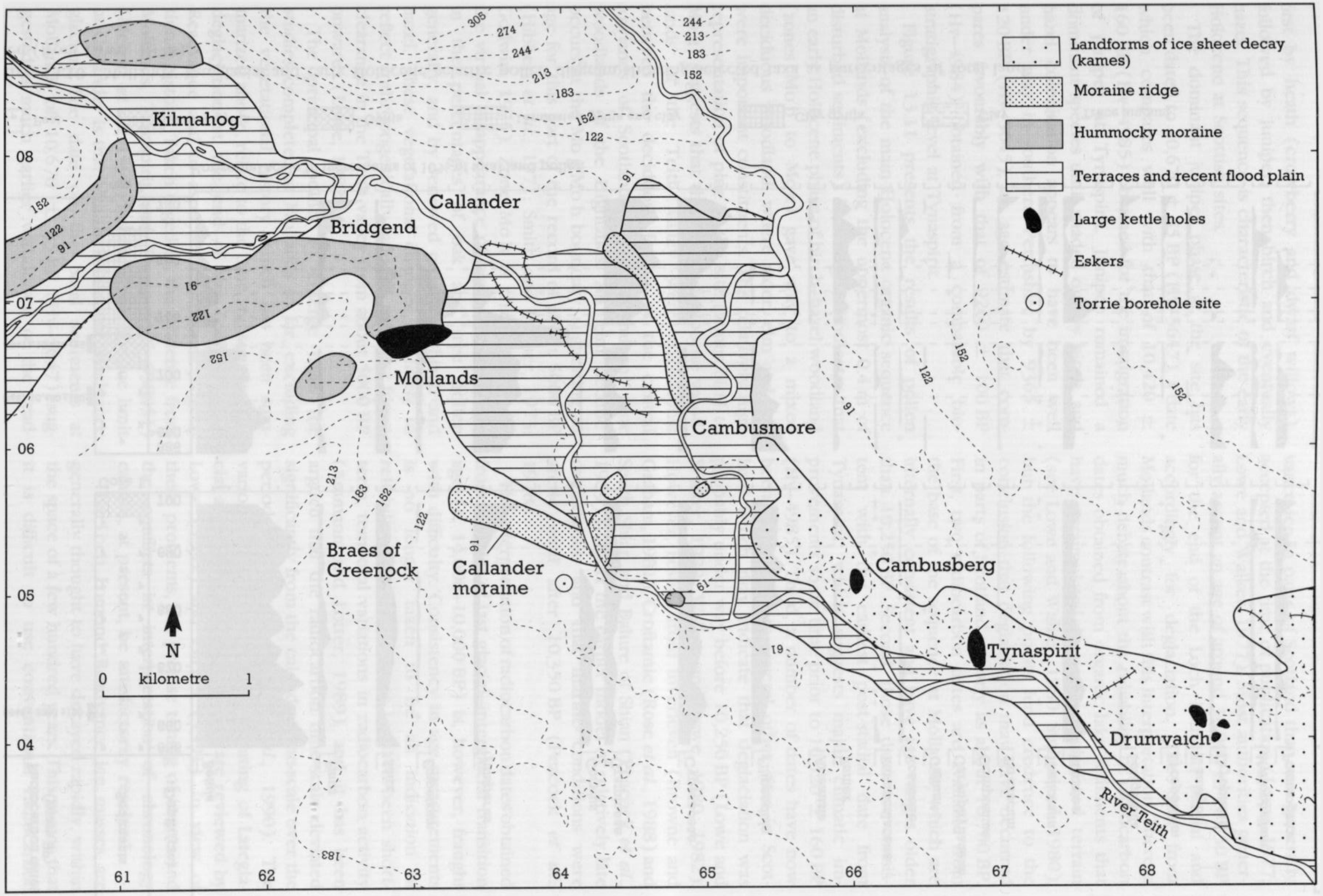


Figure 13.9 Glacial and glaciofluvial landforms of the Callander area (from Lowe, 1978, after Thompson, 1972).

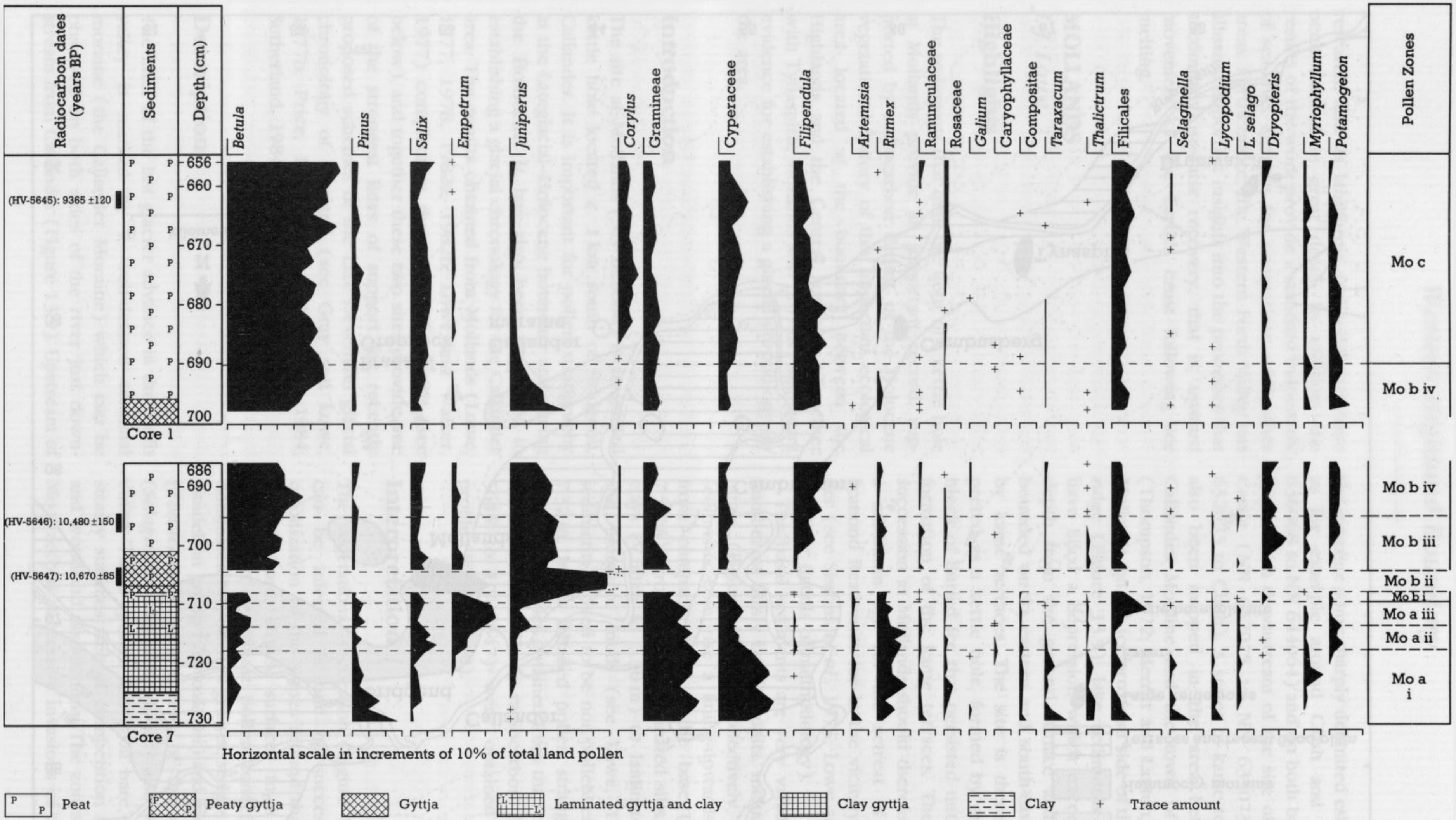


Figure 13.10 Mollands: Lateglacial and early Holocene relative pollen diagram showing selected taxa as percentages of total land pollen (from Lowe, 1978).

first by heath (crowberry and dwarf willows), followed by juniper, then birch and eventually hazel. This sequence is characteristic of the early Holocene at Scottish sites.

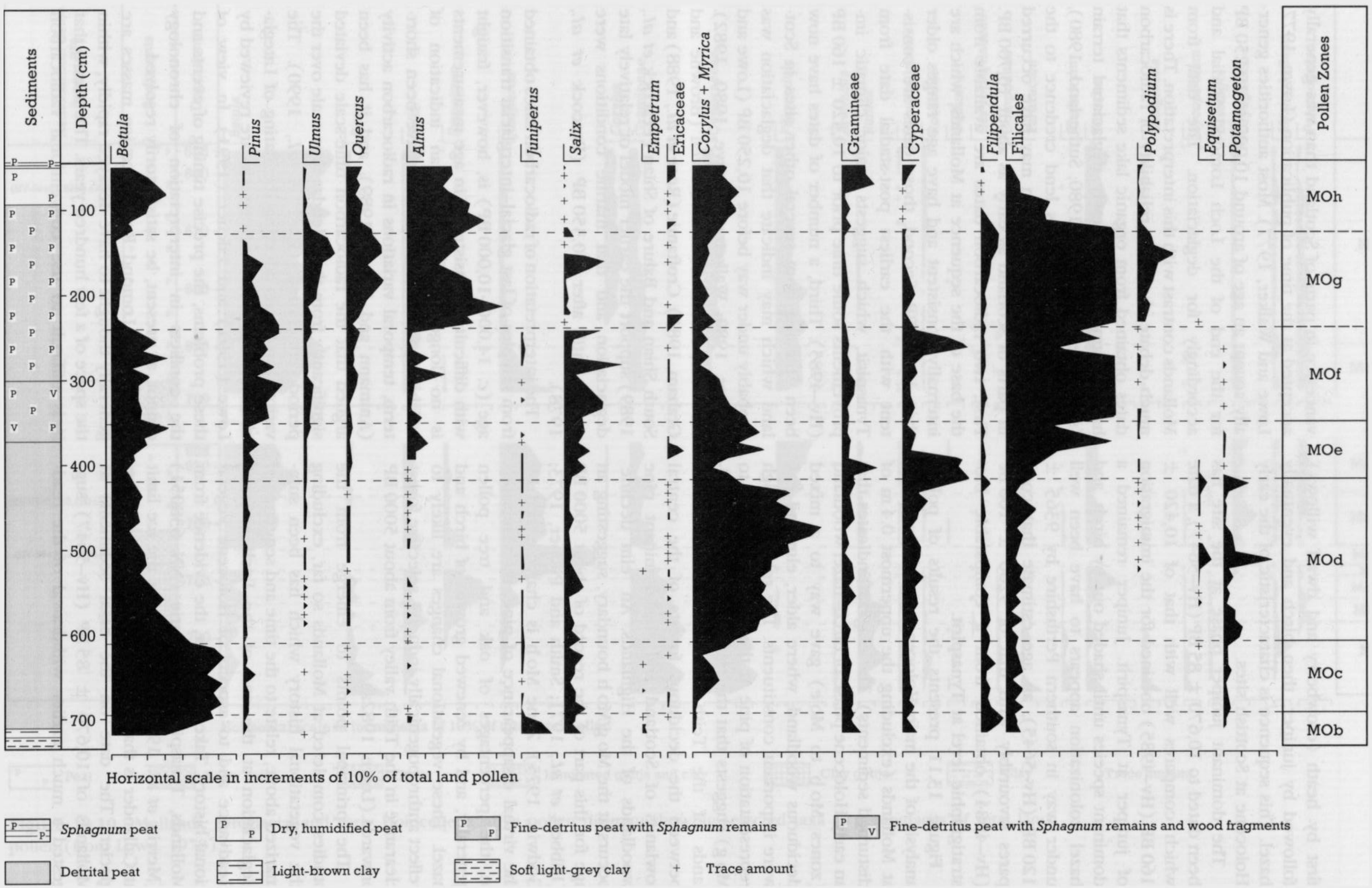
The dominant juniper phase at the site has been dated to 10,670 ± 85 BP (Hv–5647), a date which compares well with that of 10,420 ± 160 BP (Hv–4985) obtained for the immigration of juniper at Tynaspirit. Juniper remained a dominant species until shaded out by birch, and hazel colonization appears to have been well under way in southern Perthshire by 9365 ± 120 BP (Hv–5645), an age estimate that compares favourably with that of 9260 ± 100 BP (Hv–4984) obtained from a comparable biostratigraphic level at Tynaspirit.

Figure 13.11 presents the results of pollen analysis of the main Holocene organic sequence at Mollands (excluding the uppermost 0.4 m of disturbed sediments). The diagram indicates that an early Holocene phase of birch–hazel woodland (zones Mo b to Mo e) gave way to a mixed deciduous woodland, where alder, elm and oak were important constituents. The relatively high representation of pine at the site (zones Mo f to Mo g) suggests that the middle Holocene woodlands of the Teith valley were transitional between the deciduous forests of the central lowlands of Scotland and the dominant pine woodlands of the Highlands. An 'elm decline' occurs at the Mo g/Mo h boundary, suggesting an age for this part of the record of about 5000 BP (Hibbert *et al.*, 1971; Smith and Pilcher, 1973; Godwin, 1975). Zone Mo h is characterized by the virtual disappearance of pine, by reductions in the percentages of oak and tree pollen generally, and by renewed growth of birch and hazel. These vegetational changes are likely to reflect anthropogenically induced, selective forest clearance in the Teith valley from about 5000 BP onwards (Lowe, 1982a).

The principal points to emerge from the studies completed at Mollands so far, excluding the vegetational history which has been summarized above, relate to the time and sequence of deglaciation at the end of the Loch Lomond Readvance and to aspects of Holocene vegetational history. Taken together, the evidence from Mollands, Tynaspirit and Torrie (NN 638051) (Merritt *et al.*, 1990) confirms that the ice limit at Callander is that of a Loch Lomond Readvance glacier. The date on the basal sediments at Mollands of 10,670 ± 85 BP (Hv–5647) suggested a much earlier withdrawal of the readvance ice in parts of Scotland than was generally accepted at the time of publication (Lowe, 1977; Lowe and Walker, 1977). Most authorities generally accept an age of around 10,000 to 10,250 BP for the end of the Loch Lomond Stadial and accordingly for deglaciation. The data from Mollands contrast with this interpretation. There is much debate about the reliability of radiocarbon dates obtained from organic lake sediments that have accumulated in newly deglaciated terrain (see Lowe and Walker, 1980; Sutherland, 1980), but the following points lend credence to the conclusion that deglaciation may have occurred in parts of Scotland as early as about 10,700 BP. First, two radiocarbon dates are available from the base of the sequence at Mollands, which are internally consistent and have age ranges older than 10,250 BP. Second, those dates are consistent with the earliest post-stadial date from Tynaspirit, which suggests major climatic improvements some time prior to 10,420 ± 160 BP (Hv–4985). Third, a number of dates have now been obtained from several other sites in Scotland which may indicate that deglaciation was probably under way before 10,250 BP (Lowe and Walker, 1980; Walker and Lowe, 1980, 1982). However, results from Inverleven (Browne and Graham, 1981), Croftamie (Rose *et al.*, 1988) and South Shian and Balure of Shian (Peacock *et al.*, 1989) support the earlier model of relatively late deglaciation and that marine conditions were arctic until after 10,350 BP (Peacock *et al.*, 1978).

The interpretation of radiocarbon dates obtained from samples of last glacial–interglacial transition age (*c.* 14,000–10,000 BP) is, however, fraught with difficulty. Consistency in age measurements is no longer taken to be an indication of reliability, for there appear to have been short-term, temporal variations in radiocarbon activity (Ammann and Lotter, 1989), and it has been argued that the radiocarbon time-scale deviated significantly from the calendar time-scale over the period concerned (Bard *et al.*, 1990). The various problems affecting the dating of Lateglacial and early Holocene deposits are reviewed by Lowe (1991) and Pilcher (1991). In view of these problems, the precise timing of events and the conflicts in interpretation of chronology cannot, at present, be satisfactorily resolved.

The Loch Lomond Readvance ice masses are generally thought to have decayed rapidly, within the space of a few hundred years. This means that it is difficult to use conventional radiocarbon



Sediments
Depth (cm)
Betula
Pinus
Ulmus
Quercus
Alnus
Juniperus
Salix
Empetrum
Ericaceae
Corylus + Myrica
Gramineae
Cyperaceae
Filipendula
Filicales
Polypodium
Equisetum
Potamogeton
Pollen Zones
MOh
MOg
MOf
MOe
MOd
MOc
MOb
100
200
300
400
500
600
700
Horizontal scale in increments of 10% of total land pollen
Sphagnum peat
Dry, humidified peat
Fine-detritus peat with Sphagnum remains
Fine-detritus peat with Sphagnum remains and wood fragments
Detrital peat
Light-brown clay
Soft light-grey clay
Trace amount

dates to assess the pattern and timing of deglaciation in Scotland owing mainly to a lack of resolution in the method (standard error ranges of Lateglacial/early Holocene dates are commonly of the order of 200 to 300 years) (see also Price, 1983) and to the methodological problems mentioned above. Recently, however, it has been proposed that patterns of ice retreat can be inferred from contrasts between the pollen assemblages recorded in the basal sediments from depressions that lie within the Loch Lomond Readvance limits and which have received sediment from the time of deglaciation (Lowe and Walker, 1981; Tipping, 1988). First proposed by Pennington (1978) for sites in the English Lake District, the conclusions are based upon the recognition of a full stadial–early Holocene pollen-stratigraphic sequence at sites where deglaciation occurred early, whereas curtailed sequences (the earlier pollen assemblages are not represented) characterize sites in areas of delayed deglaciation. The Mollands site has proved crucial in this developing argument.

Using this approach, Lowe and Walker (1981) have concluded that climatic amelioration, which promoted widespread glacier retreat, resulted in an immediate response near the termini of long valley glaciers (such as at Mollands), but ice-melt was delayed in areas where the ice was thicker or closer to source catchments (for example, parts of Rannoch Moor – see Kingshouse). On the basis of a comparison of pollen spectra from basal samples at three sites in Glen More (Isle of Mull), Walker and Lowe (1985) have also proposed that a pattern of valley retreat of Loch Lomond Readvance ice can be deciphered. A more recent study of four sites in the Varragill–Sligachan valleys of Skye, which lay within the Loch Lomond Readvance limits, also indicates progressive ice-front retreat (Walker *et al.*, 1988; Lowe and Walker, 1991; Benn *et al.*, 1992). Tipping (1988), however, has sounded a note of caution about the general applicability of this approach, finding that sites along Loch Awe did not show progressive changes in the pollen sequences in the basal sediments from the sites he examined.

This methodology therefore offers the prospect of determining general patterns of regional ice decay in Scotland, and may enable the distinction of areas characterized by progressive ice-margin retreat from those characterized by widespread downwasting of ice. The Mollands site contains the most detailed and fullest Late Devensian–Holocene pollen record so far reported from Britain. It has the added interest that radiocarbon dates obtained from the basal sediments support the contention that ice retreat may have occurred early at some valley-glacier termini as an immediate response to changes in glacier budgets.

The site offers one of the best resolutions of Holocene vegetational development reported from the south-east Grampians and adjacent lowlands, in particular in relation to the early Holocene part of the sequence. The biostratigraphic boundaries are distinct throughout, including the late Holocene 'elm decline'. The site appears to be located in what was an important ecotonal transition between the dominant mixed deciduous woodlands of the central lowlands of Scotland and the pine woods that dominated the Highlands (McVean and Ratcliffe, 1962). It is therefore an important reference site for the succession of Holocene pollen zones in the Western Highland Boundary area.

Figure 13.11 Mollands: main Holocene relative pollen diagram showing selected taxa as percentages of total land pollen (from Lowe, 1982a).

Conclusion

Mollands is important in two main respects. First, the pollen grains preserved in the sediments provide a valuable and detailed record of vegetational history during the Holocene (last 10,000 years) in the West Highland Boundary area, an important ecological zone of transition between the Highlands and Central Lowlands. Second, Mollands is important for establishing the timing of Loch Lomond Readvance deglaciation and, together with Tynaspirit, for establishing a chronological sequence of ice advance and retreat in the Callander area during the latter part of the last ice age.

TYNASPIRIT

J. J. Lowe

Highlights

The infilled kettle hole at Tynaspirit contains detailed sedimentary and pollen records, supported by radiocarbon dating, of the vegetational history and environmental changes that occurred during the Lateglacial and early Holocene. In conjunction with evidence from nearby Mollands, Tynaspirit is important for establishing the glacial chronology at the end of the Late Devensian.

Introduction

The site at Tynaspirit (NN 666047) is an infilled kettle hole located on the north side of the A84, about 0.5 km south-east of Cambusbeg Farm. The identification of the limits of the Loch Lomond Readvance has been based upon geomorphological evidence, but the chronology of the glacial event has in many areas rested largely upon relative dating by pollen stratigraphy, supported at some sites by radiocarbon dating. The basis of this approach has been outlined by Sissons *et al.* (1973). The site of Tynaspirit not only illustrates the methodology employed, but together with the evidence from the neighbouring site of Mollands (see above) provides a critical test of its application (Lowe, 1977, 1978; Lowe and Walker, 1977). Together these sites offer one of the strongest lines of support for dating the readvance and they are unique in their close geographical proximity to the local geomorphological evidence. Palynological data for later parts of the Holocene have also been reported from this site (Lowe, 1982a, 1982b).

Description

The drift geology of the area around Callander in Perthshire has been evaluated most recently by Thompson (1972) and Merritt and Laxton (1982). In summary, there are two major suites of glacial/fluvial landforms in the Teith Valley that are separated by a clear arcuate terminal moraine (the Callander Moraine, Figure 13.9), which is best observed from the A84 looking north towards Drumdhu Wood (NN 644074). To the south-east of this moraine, from the quarries near Cambusbeg to those at Easter Coillechat (NN 688038), there is an extensive spread of sand and gravel mounds, mapped by Thompson as a series of kames and kame terraces with occasional eskers. To the north-west of the moraine, as far as Kilmahog (NN 611083), smaller-scale terraces, eskers and moraines have been mapped. Those deposits lying 'outside' (to the south-east of) the terminal moraine have been dated to the time of decay of the Late Devensian ice-sheet, whereas the Callander Moraine marks the maximum position of the Loch Lomond Readvance glacier (Merritt *et al.*, 1990), which originated in the higher ground to the north and west, the ice moving down the valleys currently occupied by Lochs Lubnaig, Katrine and Venacher. The landforms lying 'within' the moraine were thus attributed to melting of this younger ice mass (see also Smith *et al.*, 1978).

The boggy, peat-filled depression at Tynaspirit occupies a kettle hole within the suite of sand and gravel mounds considered to date from the melting of the Late Devensian ice-sheet. A small lochan formerly occupied the depression, and a suite of lake sediments and peats has built up to the present ground level. The site was chosen for detailed study since it provided an opportunity to test the suggested chronology of events in the Teith valley. However, the results of stratigraphic investigations undertaken at this site also have much wider significance.

Coring at the site revealed several minor basins within the boggy area, but detailed investigations concentrated on two of these: the deepest basin (T1 – 6.65 m depth), and a shallower one (T2 – 4.45 m depth) which contained richer organic sediments more suitable for radiocarbon dating. Both basins contain a 'tripartite' sediment sequence at their base (Figure 13.12). For example, at T2 (Figure 13.13) the lowermost 0.33 m comprises (1) a basal set of inorganic sediments (beds 1 to 3), (2) an organic-rich layer (beds 4 to 6) and (3) an upper bed of inorganic sediments (bed 7). Experience has shown that this 'tripartite' sequence is typical of successions spanning the Lateglacial period (13,000 to 10,000 BP), an assertion which can be readily confirmed by pollen stratigraphy (see Lowe and Walker, 1977, 1984).

At Tynaspirit the relative age of the sediment succession was established through pollen analysis and confirmed by radiocarbon dating (Lowe, 1977, 1978; Lowe and Walker, 1977); five radiocarbon dates (Hv–4984, Hv–4985 and Hv–4987 to Hv–4989) were obtained (Figure 13.13). Seven local pollen assemblage zones have been defined (T2a to T2g) (Figure 13.13), but the sequence can be simplified as follows.

Interpretation

The earliest pollen zone (T2a) is dominated by pollen of herbaceous taxa, such as *Rumex*,

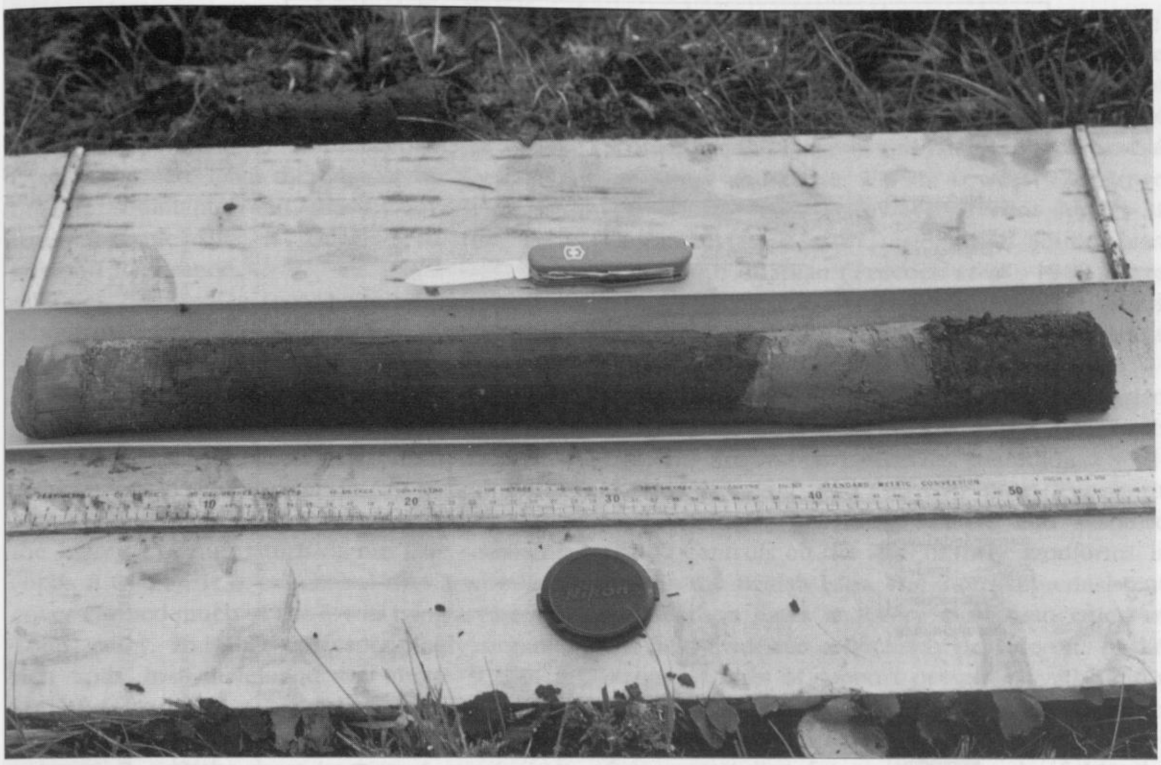


Figure 13.12 Core from the basal sediments at Tynaspirit. From the left, the sequence comprises Late Devensian minerogenic sediments, organic Lateglacial Interstadial sediments, Loch Lomond Stadial silts and clays, and early Holocene organic lake muds. (Photo: M. J. C. Walker.)

grasses, sedges and *Thalictrum*, and of dwarf shrubs. The assemblage reflects an open, treeless landscape varying from stoney, bare soils on steep or exposed sites to a luxuriant heath associated with rich herb vegetation in more favoured localities. The end of this phase is dated to 12,750 ± 120 BP (Hv–4989) confirming that the sediments began to accumulate at Tynaspirit immediately or shortly after wastage of the Late Devensian ice-sheet in the Teith valley.

The next two pollen zones (T2b and T2c) record the increasing importance of birch and juniper in the vicinity of the site. The data are interpreted as indicating the gradual spread of birch and juniper copses across the Teith valley, with perhaps more extensive birch woodland in sheltered valley-bottom sites. At the same time it is likely that the ground cover of dwarf shrubs and herb vegetation continued to fill across unwooded sections of the valley, and that organic detritus built up within the developing soils. It appears that a major expansion of birch and juniper occurred in the area at 12,395 ± 195 BP (Hv–4988), but that these communities were severely disturbed and all but disappeared from the area by 11,385 ± 290 BP (Hv–4987). Overall, the pollen data imply a relatively mild climatic episode from perhaps as early as 12,750 to about 11,400 years ago.

Zone T2d is characterized by a return to minerogenic sedimentation, a dramatic reduction in birch percentages, an initial reduction in juniper and a return to high percentages of dwarf-shrub and herbaceous taxa. Those taxa common in the basal assemblage (zone T2a) (for example, *Rumex*, Compositae, grasses and sedges) are also well represented in zone T2d. The term 'revertance' is used to denote a return to the open, treeless conditions inferred for zone T2a. However, the later phase (zone T2d) records much higher representations of taxa indicative of bare, disturbed stoney surfaces, such as the clubmosses (*Selaginella* and *Lycopodium*) and the wormwoods or mugwort (*Artemisia*). The evidence suggests a harsh climatic environment, dated to between 11,385 ± 290 and 10,420 ± 160 BP (Hv–4985).

These conclusions are supported by the results of more recent investigations in the area by Merritt *et al.* (1990). Organic silts discovered

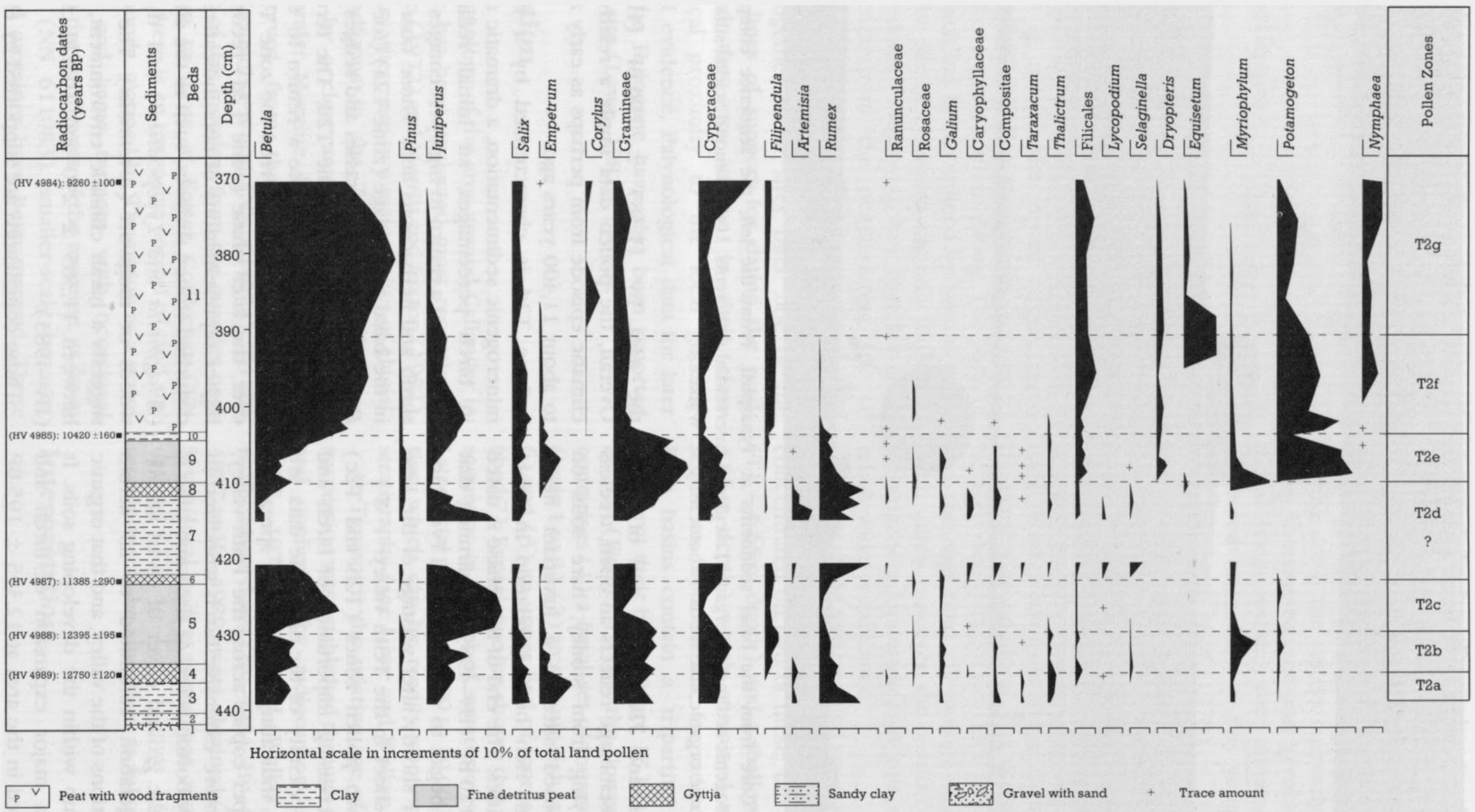


Figure 13.13 Tynaspirit: relative pollen diagram showing selected taxa as percentages of total land pollen (from Lowe, 1978).

beneath till at Callander have been assigned to the Lateglacial Interstadial on the basis of radiocarbon dating, pollen stratigraphy and their arthropod fauna. A radiocarbon date of 12,750 ± 70 BP (SRR–2317) from basal sediments matches almost exactly the date from the base of the Tynaspirit organic sediments, and the till overlying the dated organic silts is ascribed to the Loch Lomond Readvance.

Zones T2e to T2g record the development of woodland within the Teith valley. A progressive succession of (from base) *Empetrum*, juniper and birch, followed by the immigration of *Corylus* is a sequence recognized at numerous sites in Britain, one which characterizes the start of the Holocene Stage. From the dominance in the pollen assemblages of birch and juniper in particular, and from the highly organic nature of the lake sediments (beds 8 to 11), it is concluded that a woodland cover clothed much of the lower lying area of the Teith valley, and that correspondingly organic-rich soils had developed by about 9,260 ± 100 BP (Hv–4984).

The simplest explanation of the Tynaspirit succession, and the most important conclusions based upon the reported data, are as follows.

The Late Devensian ice-sheet must have disappeared from the lower parts of the Teith valley some time prior to about 12,800 BP. Several dates from other sites in Scotland (Sissons, 1976b; Gray and Lowe, 1977b; Sutherland, 1984a) indicate that around 13,000 BP or shortly after, most of the British Isles was ice-free.

Relatively stable and probably mild climatic conditions persisted for almost 2000 years. Whether or not ice disappeared entirely from Scotland during this period remains a contentious point (Sutherland, 1984a), one that is difficult to resolve on the basis of available evidence. Certainly the evidence from Tynaspirit would seem to imply substantial retreat of ice from the Callander area.

The data from Tynaspirit support Thompson's view (1972) that any glacier readvance into this area during the Loch Lomond Stadial did not extend beyond the vicinity of Callander and that an earlier suggestion by Francis *et al.* (1970) that the readvance extended to Drumvaich (*c.* 1 km east-south-east of Tynaspirit) is incorrect.

The 10,420 ± 160 BP date from Tynaspirit suggests that the harsh climatic conditions that promoted the Loch Lomond Readvance had substantially improved by some time earlier than 10,400 years ago, since the dated sample is not from the earliest post-stadial sediments at the site. This date, together with the evidence from the neighbouring site of Mollands, led to a revision of the estimated age of deglaciation in parts of Scotland at the close of the Loch Lomond Stadial (see Gray and Lowe, 1977b; Lowe, 1978; Lowe and Walker, 1980). However, recent studies at Croftamie (Rose *et al.*, 1988) and South Shian and Balure of Shian (Peacock *et al.*, 1989) have indicated that Loch Lomond Readvance glaciers at those localities attained their maximum extents relatively late in the Stadial, after 10,500 BP.

The close association of (1) Late Devensian ice-sheet landforms of deglaciation, (2) Loch Lomond Readvance landforms, including a well-defined ice limit, and (3) two sites (Tynaspirit and Mollands) providing relative and absolute dating controls on the ages of those landforms, is rare in the British Isles. The internally consistent radiocarbon dates and very close association of the field evidence collectively provide one of the strongest lines of support presently available for the Late Devensian chronology outlined earlier in this report. The area around Callander is therefore outstanding for exemplifying the field relations of the geomorphological evidence together with the pollen stratigraphy and radiocarbon dating evidence for the Lateglacial in Scotland. Tynaspirit is therefore a site of major importance in the Quaternary geology of the British Isles.

Tynaspirit, together with Mollands, is also significant in illustrating one of the two methodological approaches used in dating the Loch Lomond Readvance. In many areas the chronology of the event has been established through pollen stratigraphy and sometimes radiocarbon dating of organic lake sediments at sites inside and outside the inferred ice limits (Donner, 1957; Sissons *et al.*, 1973; Walker, 1975a; Walker *et al.*, 1988; Tipping, 1988). The other approach has involved radiocarbon dating of marine shells and organic deposits incorporated or overridden by Loch Lomond Readvance glaciers (see South Shian and Balure of Shian, Rhu Point, Croftamie, and the Western Forth Valley). These two approaches have tended to produce contrasting conclusions, the time of the maximum of the readvance inferred from the first approach often being apparently earlier than that inferred from the second approach. It remains to be established whether this contrast is due to methodological problems (see Mollands) or whether it does indeed reflect diachroneity in the response of the various glaciers to rapid climatic change at the

Late Devensian–Holocene boundary.

Conclusion

Evidence from Tynaspirit in conjunction with that from Mollands, is important for establishing the pattern and timing of glaciation and environmental change during the Lateglacial, the period between about 13,000 and 10,000 years ago. The sediment and pollen data from the site, supported by radiocarbon dating, provide a full record of Lateglacial environmental conditions from the time of wastage of the main Late Devensian ice-sheet (approximately 13,000 years ago), indicating that Loch Lomond Readvance glaciers did not extend as far as the site. In contrast, Mollands contains only a Holocene pollen record, indicating that the ice limit which lies between it and Tynaspirit was formed during the Loch Lomond Readvance (approximately 11,000–10,000 years ago). Together these two sites provide a particularly good illustration of this type of approach used to date Loch Lomond Readvance deposits.