Quaternary of Scotland

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Chapter 8

North-east Scotland

INTRODUCTION

D. G. Sutherland and J. E. Gordon

North-east Scotland covers the mainly lowland area between lower Strathspey and Aberdeen (Figure 8.1). Geologically, it is underlain by the same Dalradian metamorphic rocks and younger granitic intrusions as the central and south-west Highlands, and hence its lowland character indicates a distinctive geomorphological evolution. Since the early Tertiary, north-east Scotland has been a 'hinge zone' between the mountain zone to the west, which has been uplifted and subsequently dissected to produce spectacular mountain scenery, and the North Sea Basin, which has undergone continuing downwarping (Hall, 1987). This relative stability has resulted in the preservation of Tertiary gravel deposits and extensive areas of deeply weathered bedrock.

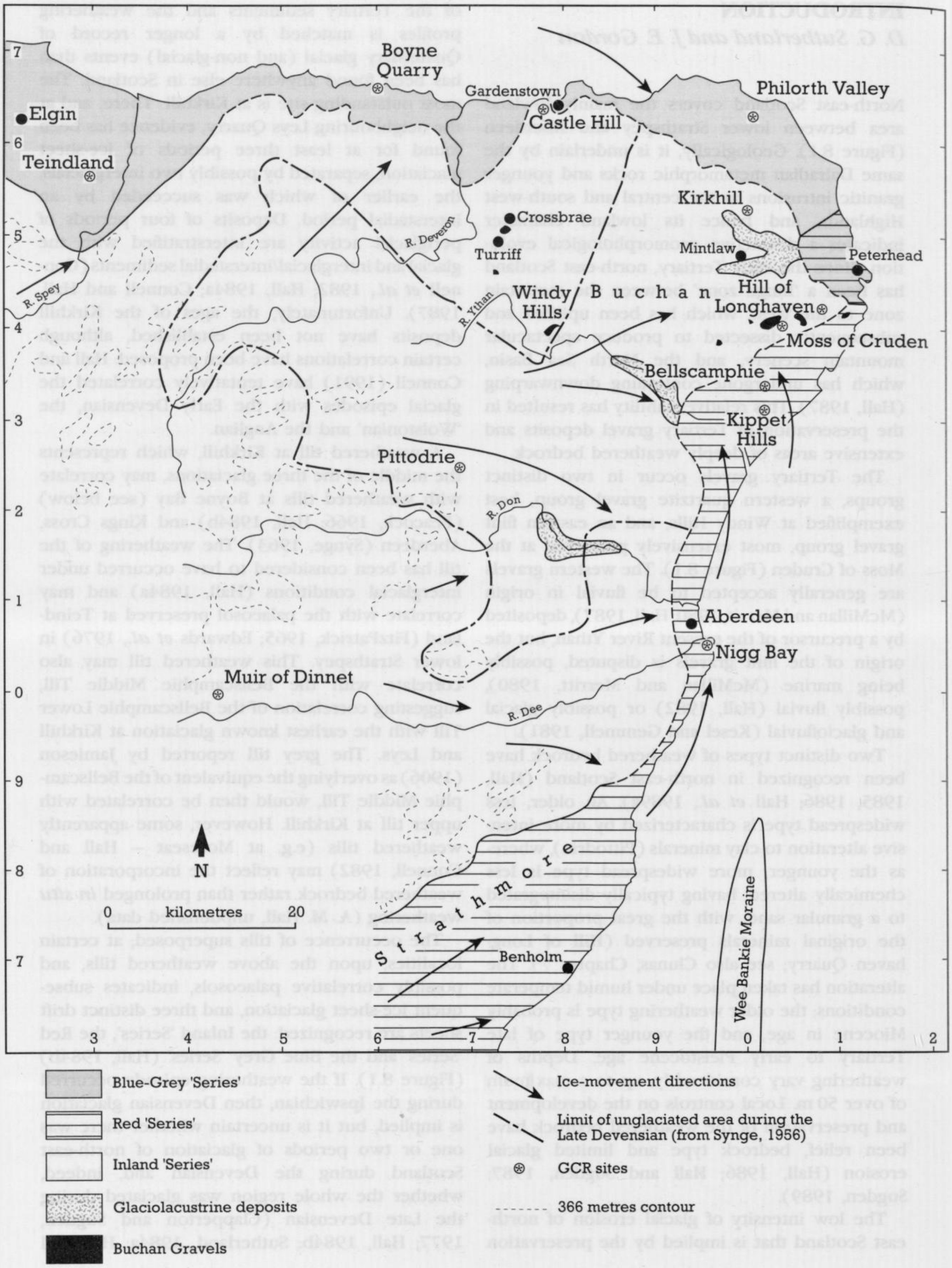
The Tertiary gravels occur in two distinct groups, a western quartzite gravel group, best exemplified at Windy Hills, and an eastern flint gravel group, most extensively preserved at the Moss of Cruden (Figure 8.1). The western gravels are generally accepted to be fluvial in origin (McMillan and Merrit, 1980; Hall, 1987), deposited by a precursor of the present River Ythan, but the origin of the flint gravels is disputed, possibly being marine (McMillan and Merritt, 1980), possibly fluvial (Hall, 1982) or possibly glacial and glaciofluvial (Kesel and Gemmell, 1981).

Two distinct types of weathered bedrock have been recognized in north-east Scotland (Hall, 1985, 1986; Hall *et al.*, 1989a). An older, less widespread type is characterized by more intensive alteration to clay minerals (Pittodrie), whereas the younger, more widespread type is less chemically altered, having typically disintegrated to a granular sand, with the great proportion of the original minerals preserved (Hill of Longhaven Quarry; see also Clunas, Chapter 7). The alteration has taken place under humid temperate conditions; the older weathering type is probably Miocene in age, and the younger type of late Tertiary to early Pleistocene age. Depths of weathering vary considerably, up to a maximum of over 50 m. Local controls on the development and preservation of the weathered bedrock have been relief, bedrock type and limited glacial erosion (Hall, 1986; Hall and Sugden, 1987; Sugden, 1989).

The low intensity of glacial erosion of north-east Scotland that is implied by the preservation of the Tertiary sediments and the weathering profiles is matched by a longer record of Quaternary glacial (and non-glacial) events than has been found anywhere else in Scotland. The most outstanding site is at Kirkhill. There, and at the neighbouring Leys Quarry, evidence has been found for at least three periods of ice-sheet glaciation, separated by possibly two interglacials, the earlier of which was succeeded by an interstadial period. Deposits of four periods of periglacial activity are interstratified with the glacial and interglacial/interstadial sediments (Connell *et al.*, 1982; Hall, 1984a; Connell and Hall, 1987). Unfortunately, the ages of the Kirkhill deposits have not been established, although certain correlations have been proposed: Hall and Connell (1991) have tentatively correlated the glacial episodes with the Early Devensian, the 'Wolstonian' and the Anglian.

A weathered till at Kirkhill, which represents the middle of the three glaciations, may correlate with weathered tills at Boyne Bay (see below) (Peacock, 1966; Hall, 1984b) and Kings Cross, Aberdeen (Synge, 1963). The weathering of the till has been considered to have occurred under interglacial conditions (Hall, 1984a) and may correlate with the palaeosol preserved at Teindland (FitzPatrick, 1965; Edwards *et al.*, 1976) in lower Strathspey. This weathered till may also correlate with the Bellscamphie Middle Till, suggesting correlation of the Bellscamphie Lower Till with the earliest known glaciation at Kirkhill and Leys. The grey till reported by Jamieson (1906) as overlying the equivalent of the Bellscamphie Middle Till, would then be correlated with upper till at Kirkhill. However, some apparently weathered tills (e.g. at Moreseat – Hall and Connell, 1982) may reflect the incorporation of weathered bedrock rather than prolonged *in situ* weathering (A. M. Hall, unpublished data).

The occurrence of tills superposed, at certain localities, upon the above weathered tills, and possibly correlative palaeosols, indicates subsequent ice-sheet glaciation, and three distinct drift sheets are recognized: the Inland 'Series', the Red 'Series' and the Blue Grey 'Series' (Hall, 1984b) (Figure 8.1). If the weathering episode occurred during the Ipswichian, then Devensian glaciation is implied, but it is uncertain whether there was one or two periods of glaciation of north-east Scotland during the Devensian and, indeed, whether the whole region was glaciated during the Late Devensian (Clapperton and Sugden, 1977; Hall, 1984b; Sutherland, 1984a; Hall and


Boyne Quarry
Gardenstown
Philorth Valley
Elgin
Castle Hill
Teindland
Kirkhill
Crossbrae
Turriff
Mintlaw
Peterhead
R. Deveron
R. Spey
R. Ythan
Windy Hills
B u c h a n
Hill of Longhaven
Moss of Cruden
Bellscamphie
Kippet Hills
Pittodrie
R. Don
Aberdeen
Nigg Bay
Muir of Dinnet
R. Dee
N
0 kilometres 20
S t r a t h m o r e
Benholm
Wee Bankie Moraine
Blue-Grey 'Series'
Red 'Series'
Inland 'Series'
Glaciolacustrine deposits
Buchan Gravels
Ice-movement directions
Limit of unglaciated area during the Late Devensian (from Synge, 1956)
GCR sites
366 metres contour

Connell, 1991). For example, at King Edward (NJ 722561) till and glaciofluvial gravels overlie an apparently *in situ* shell bed at *c.* 46 m OD (Jamieson, 1866; Horne in Read, 1923; Sutherland, 1984b). If the shell bed is indeed *in situ*, then its radiocarbon and amino acid age (Miller *et al.*, 1987) implies Early Devensian glaciation. Further, the nearby Middle Devensian interstadial deposit at Crossbrae Farm, unaffected by subsequent glaciation (Hall, 1984b), suggests that at least part of the north-east was ice-free at the time of the last glacial maximum.

Also uncertain is the status of deposits found along the coasts, such as at Boyne Bay, Castle Hill and the Red 'Series' drift deposits that occur inland of the east coast southwards from Peterhead (see Bellscamphie). These deposits consist of interstratified tills, glaciolacustrine, glaciomarine and glaciofluvial sediments (Murdoch, 1977; Hall, 1984b; Peacock, 1984b). They are coeval with lacustrine deposition along valleys, such as those of the Ugie Water and River Ythan (McMillan and Aitken, 1981; Merritt, 1981), and this implies that for at least part, if not all, of the period when the glacial sediments were being deposited, the interior of Buchan was ice-free. Glaciomarine sediments at St Fergus have been radiocarbon dated to approximately 15,000 BP (Hall and Jarvis, 1989). These sediments rest on glacial deposits derived from the Moray Firth but their stratigraphic relationship to the Red 'Series' deposits remains to be established. The presence of pre-Quaternary palynomorphs in radiocarbon-dated material from the Red 'Series' at Errolston indicates that the date obtained is of no practical value in establishing the age of these deposits (Peacock, 1984b; Connell *et al.*, 1985). Other possible interglacial or interstadial sites in north-east Scotland, at Tipperty Brickworks and Balmedie Village, have not been confirmed (cf. Bremner, 1938, 1943a; Peacock, 1980b; Edwards and Connell, 1981).

During final ice retreat, glaciofluvial deposition resulted in the formation of major esker and kame systems parallel to the coast (Kippet Hills), in places associated with glacial lakes (Merritt, 1981; Thomas, 1984; Aitken, 1991); lakes also formed along valleys inland (Aitken, 1990).

Figure 8.1 Location map and principal features of the Quaternary geomorphology of north-east Scotland (from Hall and Connell, 1991).

Elsewhere, sequences of large outwash terraces were constructed along some principal valleys, the relationships of these to both ice-decay features and raised sea levels being particularly well exemplified in lower Strathspey. In topographically suitable hollows, stagnant ice masses became isolated from the main retreating ice mass, resulting in the formation of complex sequences of kames, kettle holes and eskers (Muir of Dinnet).

Environmental change during the Lateglacial has been relatively little studied in the north-east, although radiocarbon-dated Lateglacial Interstadial profiles have been described from Loch Kinord (Muir of Dinnet), Loch of Park and Garral Hill (Donner, 1957; Vasari and Vasari, 1968; Vasari, 1977). These sites indicate that an initial phase of open-habitat vegetation was succeeded by closed heath and scrub vegetation. Interestingly, two pine needles were recovered from Lateglacial deposits at Loch Kinord, suggesting local occurrence of pine in this area during the interstadial. Locally, tree birch may also have developed.

The Loch Lomond Stadial resulted in a return to tundra vegetation with marked slope instability and inwashing of sediment into closed basins. Sediment cores show a typical Lateglacial 'tripartite' sequence (Gunson, 1975), and radiocarbon dates have been obtained from peat beneath solifluction deposits at several sites (Clapperton and Sugden, 1977; Hall, 1984b; Connell and Hall, 1987). It is also possible that at this period some of the fossil frost polygon networks found in north-east Scotland were formed, although formation during the retreat of the last ice-sheet is also possible (Gemmell and Ralston, 1984, 1985; Armstrong and Paterson, 1985). Whatever the timing, the impact of periglacial processes on the soils of north-east Scotland has been widespread (FitzPatrick, 1956, 1958, 1969, 1972, 1975a, 1987; Galloway, 1961b, 1961c; Connell and Hall, 1987).

During the Holocene, sea level was below that of the present day for considerable periods. In the middle Holocene, the Main Postglacial Transgression resulted in marine invasion of the lower parts of the river valleys, with deposition of estuarine silts, fine sands and clays on terrestrial peats and fluvial muds. The transgression reached its maximum after 6100 BP in the Ythan valley (Smith *et al.*, 1983) and between 6300 and 5700 BP in the Philorth valley (Smith *et al.*, 1982). The subsequent regression was accompanied by renewed terrestrial sedimentation in the valley mouths.

Holocene vegetation history has been investigated at several localities (Durno, 1956, 1957), but there are few well-dated pollen profiles. The most detailed studies have been at sites in the Dee Valley at Loch Kinord (see Muir of Dinnet), Loch Davan, Loch of Park and Braeroddach Loch (Vasari and Vasari, 1968; Edwards, 1978). During the middle Holocene, pine forest developed in the western part of the area, whereas birch–hazel forest was predominant to the east and on the coastal lowlands (Vasari and Vasari, 1968; Gunson, 1975; Birks, 1977). The impact of Man on the landscape is apparent in the pollen and sediment records before 5000 BP (Edwards, 1978, 1979b; Edwards and Rowntree, 1980).

WINDY HILLS

J. E. Gordon and D. G. Sutherland

Highlights

Windy Hills is a locality of outstanding importance for a suite of quartzite gravels deposited by a pre-Quaternary river. The sedimentary characteristics of the gravels and their subsequent, post-depositional modifications provide unique evidence for interpreting long-term landscape evolution in north-east Scotland.

Introduction

The Windy Hills site lies about 12 km south-east of Turriff. It covers two areas (total 0.43 km^2) between NJ 786392 and NJ 805402 on the top of a low ridge orientated south-west to north-east, overlooking the River Ythan to the south-east. The crest of the ridge, at about 120 m OD, is some 90 m above the valley bottom. Windy Hills is important for the unique, so-called 'Pliocene' gravels of Buchan. Long recognized as lithologically distinct deposits because of their very high proportions of quartzite and flint (Christie, 1831), the gravels were discussed in early papers by Ferguson (1850, 1855, 1857, 1877, 1893), Jamieson (1858, 1865, 1874, 1882b, 1906) and Wilson (1886), and they were described in some detail in an important paper by Flett and Read (1921). More recently there has been renewed interest in these deposits (Clapperton, 1977; Gemmell and Kesel, 1979, 1982; Koppi and FitzPatrick, 1980; McMillan and Merritt, 1980; Kesel and Gemmell, 1981; McMillan and Aitken, 1981; Merritt, 1981; Merritt and McMillan, 1982; Hall, 1982, 1983, 1984c).

The gravels (termed the Buchan Gravels by McMillan and Merritt (1980) and Buchan Gravels Group by Hall (1984c)) occur in a restricted area of Buchan (Figure 8.1) and comprise two lithologically distinct groups of well-rounded, water-worn pebbles discontinuously capping a number of hilltops at altitudes between 75 m and 150 m OD: a western quartzite-dominated group in the Windy Hills and Turriff areas (termed the Windy Hills Gravels by McMillan and Merritt (1980) and Windy Hills Formation by Hall (1984c)), and an eastern flint-dominated group on the summits of a broad ridge running north-east from the Hill of Dudwick (NJ 979378) to Stirling Hill (NK 125413) (termed the Buchan Ridge Gravels by McMillan and Merritt (1980) and Buchan Ridge Formation by Hall (1984c)). It has been assumed in the past that these two distinct groups are of the same age although there is no evidence that this is so.

Description

The most extensive occurrence and best exposures of the quartzite gravels are at Windy Hills. Detailed accounts of their stratigraphic relations and sedimentary character have been given by Flett and Read (1921), Read (1923), FitzPatrick (1975a, 1975b), Clapperton (1977), McMillan and Merritt (1980) and Kesel and Gemmell (1981). At Windy Hills over 10 m of predominantly quartzite gravels interbedded with white quartz sand overlie deeply weathered and kaolinized pelitic schist (Koppi, 1977; Koppi and FitzPatrick, 1980; Kesel and Gemmell, 1981; Hall *et al.*, 1989a). The quartzite pebbles are comparatively fresh and unweathered and some show chatter marks, in contrast to occasional cobbles of granite and schist, which are nearly always decomposed to a kaolinitic sand. A small number of flint pebbles is also present, some weathered with a dull grey or white rind, and the very rare presence of chert of Lower Cretaceous age is also recorded (Flett and Read, 1921; Hall, 1987). Jamieson (1865) reported the presence of (?)Late Cretaceous fossils typical of the Chalk associated with the flints at Windy Hills, but gave no specific identifications; his observations have not been confirmed. However, among the flints at Delgaty, near Turriff, Christie (1831) found fossils, principally of sponges or alcyonaria. Details of fossils from other sites are given by Salter (1857) and Ferguson (1857).

Clast imbrication and rare cross-bedding indicate that the gravels were deposited by water flowing from approximately west-south-west to east-north-east (McMillan and Merritt, 1980; Kesel and Gemmell, 1981). Preservation of such sedimentary structures implies little disturbance of the gravels since deposition, but the upper 1 m has been cryoturbated. This shows several features associated with periglacial modification: ice-wedge casts up to a metre across, vertically aligned clasts, an indurated horizon, clasts with silt cappings and an increase in clast concentration at the surface (FitzPatrick, 1975a, 1975b, 1987). The gravels are only overlain by patches of till (Bremner, 1916b; Kesel and Gemmell, 1981), but unweathered erratics have been incorporated into the upper layer of the gravels, probably by frost churning (Clapperton, 1977).

Interpretation

The quartzite of the gravels was considered by Flett and Read (1921) to be unlike that of any known quartzite outcrop in north-east Scotland but was comparable to the quartzite of Scaraben in Caithness. Koppi (1977) and Kesel and Gemmell (1981), however, examined the quartzite in thin section and concluded that it was most probably derived from Banffshire quartzites. This conclusion was supported by the heavy-mineral assemblage associated with the gravels. Hall (1987) has suggested the further possibility that much of the quartzite debris was recycled from Devonian conglomerates.

Jamieson (1858, 1865) originally interpreted the gravels to be locally derived and of pre-glacial marine origin, but later suggested glacial derivation from the floor of the Moray Firth (Jamieson, 1906). Wilson (1886) thought that they were residual deposits from a denuded chalk cover and had been glacially reworked. Flett and Read (1921) concluded that the gravels were remnants of formerly more extensive marine deposits resting on an old platform and were of Tertiary, possibly Pliocene, age.

Recent interpretations are agreed that the Windy Hills gravels are fluvial in origin (McMillan and Merritt, 1980; Kesel and Gemmell, 1981; Hall 1982, 1983, 1987), although Kesel and Gemmell (1981) also considered a glaciofluvial origin as a possibility in view of certain grain-surface textures, identified on a scanning electron microscope, suggestive of glacial transport.

An important facet of the Windy Hills site is that the gravels, together with the associated deep weathering, glacial and periglacial phenomena, hold important clues about landscape evolution and environmental change in north-east Scotland during the late Tertiary and Pleistocene (see also Moss of Cruden):

1. The weathering characteristics of both the gravels and the underlying bedrock led Hall (1983, 1987) to conclude that the gravels were probably Neogene in age, being deposited along a proto-Ythan valley. Subsequent surface lowering has resulted in topographic inversion with the gravels now occupying hill-top positions.
2. The presence of flint has been used as evidence of Late Cretaceous marine transgression (Wilson, 1886; Flett and Read, 1921; Hall, 1983, 1987).
3. Hall (1983, 1985, 1987) associated the kaolinitic alteration in the gravels and the underlying bedrock with his clayey grus weathering type. The latter is older (probably Miocene in age) than the gruss weathering type (Pliocene to Pleistocene in age) based on a greater degree of alteration (see Hall *et al.*, 1989a).
4. The occurrence of deep-weathering profiles and the Windy Hills and Buchan Ridge gravels also testify to the limited and selective nature of glacial erosion in the Buchan area (Clayton, 1974; Hall, 1982, 1986; Hall and Sugden, 1987), despite the evidence for repeated ice-sheet invasion during the Quaternary (see Kirkhill).

Windy Hills is the most important locality for the quartzite gravels of probable Tertiary age of north-east Scotland. The site is complementary to that of Moss of Cruden, where flint gravels of broadly similar age are preserved, although the origin of the two gravel bodies may not be the same. The gravels provide a rare insight into the middle to late Tertiary environment of north-east Scotland and their occurrence, together with that of contemporaneous deep-weathering profiles, provides an important reference level for the extent of glacial erosion in this region.

Conclusion

Windy Hills is the type area for the famous quartzite gravels of Buchan. These deposits are now agreed to have been formed by a pre-Quaternary river; subsequent erosion has lowered the adjacent landscape, leaving the gravels in their present hill-top location. The gravels show evidence of weathering and frost-disturbance and are locally overlain by glacial deposits. They are important for the unique evidence they provide about the long-term evolution of the landscape in north-east Scotland, both before and during the Quaternary ice ages.

MOSS OF CRUDEN

A. M. Hall

Highlights

The Moss of Cruden is a key locality for a suite of flint gravels of pre-Quaternary origin. Like the quartzite gravels at Windy Hills, the syn- and post-depositional sedimentary characteristics of the flint gravels are a unique source of evidence for interpreting the history of landscape evolution in north-east Scotland during the late Tertiary and Quaternary.

Introduction

The Moss of Cruden site (NK 028403) occupies an area (0.85 km^2) at the top of a broad ridge orientated south-west to north-east, approximately 10 km south-west of Peterhead. The ridge, which reaches a maximum altitude of 139 m OD is the most important locality for the Buchan Ridge Formation, part of the Buchan Gravels Group (McMillan and Merritt, 1980). These gravel deposits are notable for:

1. the presence of Chalk flints;
2. a highly distinctive lithology of flint and quartzite clasts with a matrix of kaolinitic sand;
3. the advanced degree of post-depositional alteration.

Flint gravels in Buchan were first described by Christie (1831) and subsequently generated considerable scientific interest (Ferguson, 1850, 1855, 1857, 1877, 1893; Salter, 1857; Jamieson, 1858, 1865, 1874, 1882b, 1906; Wilson, 1886; Flett and Read, 1921). Despite much recent work (Koppi and FitzPatrick, 1980; McMillan and Merritt, 1980; Kesel and Gemmell, 1981; McMillan and Aitken, 1981; Merritt, 1981; Gemmell and Kesel, 1982; Hall, 1982, 1983, 1984c; Merritt and McMillan, 1982; Saville and Bridgland, 1992), the age and origin of the Buchan Gravels remain controversial, but there is no doubt that these deposits are of key importance for understanding Tertiary and early Pleistocene environments in north-east Scotland. Recent and continuing excavations at Moss of Cruden (Hall *et al.*, unpublished data) have added to the interest of the site by the discoveries of a small outlier of sandstone of probable Devonian age adjacent to the flint gravel margin and two masses of weathered Lower Cretaceous sandstone, apparently *in situ* and underlying the Buchan Ridge gravels.

Description

The Buchan Ridge Formation comprises deposits of flint gravel found at altitudes of 75 m to 150 m OD discontinuously capping the summits of a broad ridge running south-west from Den of Boddam (NK 115415) to Hill of Dudwick (NJ 979378). These gravels probably reach their maximum extent at Moss of Cruden, where a thickness of at least 25 m has been recorded (McMillan and Aitken, 1981). Present exposures, however, are poor and infrequent.

The deposit at Moss of Cruden comprises white, clay-bound, coarse gravels with minor sandy and silty units. The gravel ranges from granule to boulder size and is composed mainly of flint with metaquartzite and vein quartz. Flint and metaquartzite clasts are generally well-rounded and bear numerous chatter marks. The deposits originally contained small numbers of less siliceous clasts, which have decomposed to balls of white, kaolinitic, sandy clayey silt (McMillan and Merritt, 1980).

Sandy units are composed of quartz and flint with seams of muscovite. Both sand and gravel units are bound and, in places, supported by white, sandy clayey silt consisting of well-ordered kaolinite with minor illite (Hall, 1982). The base of the gravels rests on kaolinized granite and gneiss (McMillan and Merritt, 1980; Hall, 1983, 1987; Hall *et al.*, 1989a).

Recent excavations (A. M. Hall *et al.*, unpublished data) on the north-western edge of the

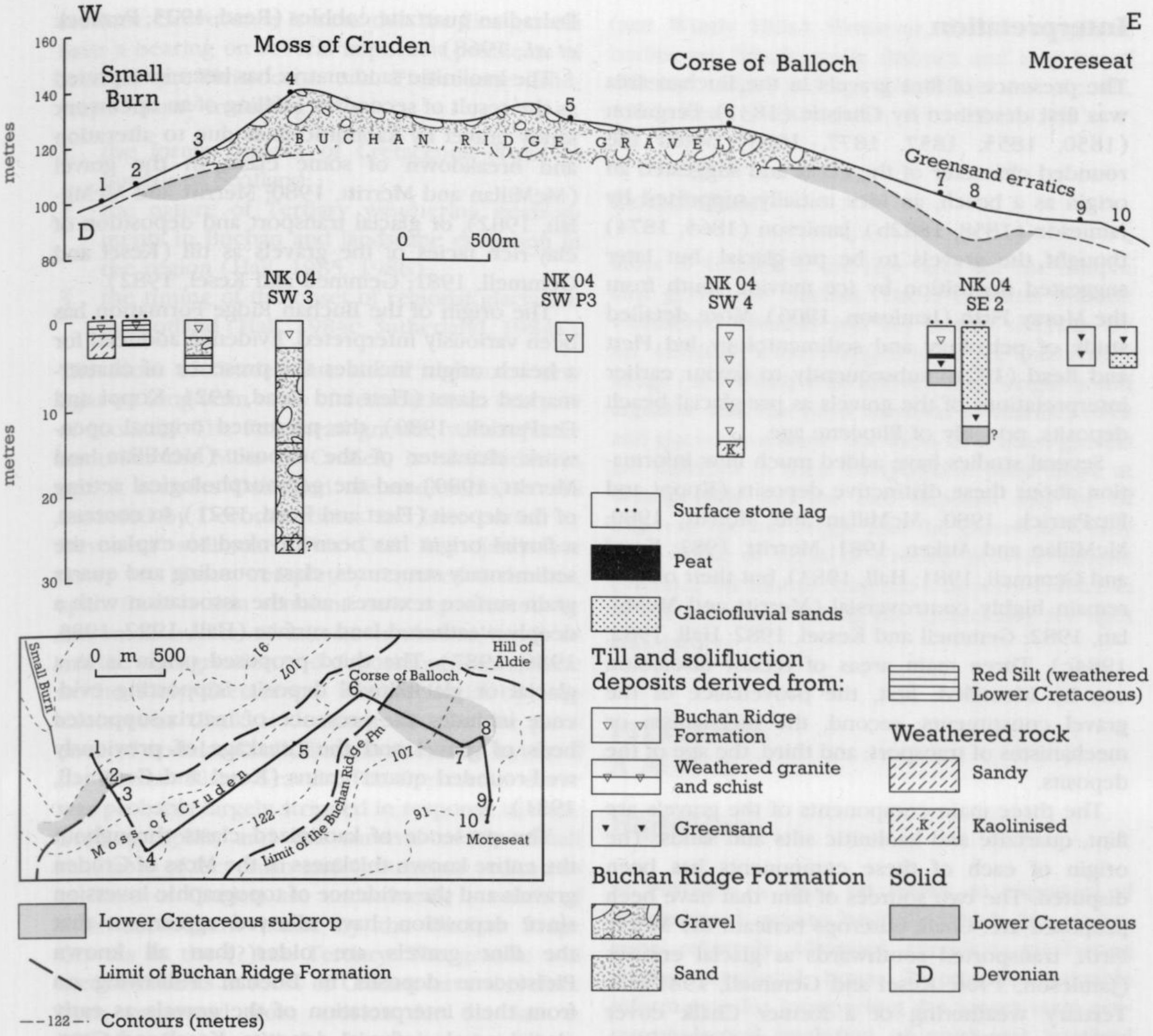


Figure 8.2 Schematic cross-section through the Moss of Cruden ridge. Borehole and pit data are from McMillan and Aitken (1981), Hall and Connell (1982) and A. M. Hall *et al.* (unpublished data).

ridge have shown that the flint gravel margin approaches to within a few hundred metres of a small, concealed outlier of red-brown arkosic sandstone of probable Devonian age. The Moreseat locality on the south-eastern margin of the ridge is famous for the occurrence of large masses of Lower Cretaceous greensand, previously interpreted as erratics transported to the site by ice from the Moray Firth (Jamieson *et al.*, 1898; Hall and Connell, 1982). Recent work has revealed, however, that the Lower Cretaceous sandstones are more extensive beneath the lower slopes of the Moss of Cruden than previously thought, and that these rocks are probably *in situ*. Evidence for this interpretation includes the manner in which mottled, red silts, representing highly weathered Lower Cretaceous sediments, pass below the north-west margin of the Buchan Ridge gravels north of Smallburn (NK 019407).

On the crest of Moss of Cruden, the Buchan Ridge Formation is overlain by a variable thickness of white to grey, gravelly till incorporating occasional erratics of fresh Peterhead granite (Figure 8.2). To the north of the ridge, a sheet of soliflucted flint gravel, up to 2 m thick, extends well downslope on to sandy, weathered granite. North of Moreseat, recent excavations have shown that the gravels are locally overlain by two tills, which are separated by a peat of interglacial or interstadial origin.

Interpretation

The presence of flint gravels in the Buchan area was first described by Christie (1831). Ferguson (1850, 1855, 1857, 1877, 1893) noted the rounded character of the clasts and suggested an origin as a beach, an idea initially supported by Jamieson (1858, 1882b). Jamieson (1865, 1874) thought the gravels to be pre-glacial, but later suggested deposition by ice moving south from the Moray Firth (Jamieson, 1906). More detailed study of petrology and sedimentology led Flett and Read (1921) subsequently to favour earlier interpretations of the gravels as pre-glacial beach deposits, possibly of Pliocene age.

Several studies have added much new information about these distinctive deposits (Koppi and FitzPatrick, 1980; McMillan and Merritt, 1980; McMillan and Aitken, 1981; Merritt, 1981; Kesel and Gemmell, 1981; Hall, 1983), but their origins remain highly controversial (Merritt and McMillan, 1982; Gemmell and Kessel, 1982; Hall, 1982, 1984c). Three main areas of recent discussion can be identified: first, the provenance of the gravel constituents; second, the mechanism or mechanisms of transport; and third, the age of the deposits.

The three main components of the gravels are flint, quartzite and kaolinitic silts and sands. The origin of each of these components has been disputed. The two sources of flint that have been proposed are: Chalk outcrops beneath the Moray Firth, transported southwards as glacial erratics (Jamieson, 1906; Kesel and Gemmell, 1981); or Tertiary weathering of a former Chalk cover (Wilson, 1886), with concentration into later fluvial (Hall, 1982, 1983) or marine gravels (Koppi and FitzPatrick, 1980; McMillan and Merritt, 1980). The recent discovery of little-worn, nodular flint in gravels at the Moss of Cruden indicates that some of the flints are not far-travelled and is consistent with reworking of a nearby remanié flint deposit. This interpretation is also consistent with the discovery that the gravels locally rest on Lower Cretaceous sandstone.

According to Flett and Read (1921), the quartzite clasts are distinct in character from the Dalradian quartzites of north-east Scotland, but recent mineralogical study has demonstrated many similarities (Kesel and Gemmell, 1981). An overlooked possible additional source is the Old Red Sandstone (Hall, 1984c), whose basal conglomerates contain large amounts of well-rounded Dalradian quartzite cobbles (Read, 1923; Peacock *et al.*, 1968).

The kaolinitic sand matrix has been interpreted as the result of secondary infilling of an openwork sandy gravel by kaolinitic fines due to alteration and breakdown of some clasts in the gravel (McMillan and Merritt, 1980; Merritt and McMillan, 1982), or glacial transport and deposition of clay-rich facies of the gravels as till (Kesel and Gemmell, 1981; Gemmell and Kesel, 1982).

The origin of the Buchan Ridge Formation has been variously interpreted. Evidence adduced for a beach origin includes the presence of chatter-marked clasts (Flett and Read, 1921; Koppi and FitzPatrick, 1980), the presumed original openwork character of the deposit (McMillan and Merritt, 1980) and the geomorphological setting of the deposit (Flett and Read, 1921). In contrast, a fluvial origin has been invoked to explain the sedimentary structures, clast rounding and quartz grain surface textures, and the association with a deeply weathered land surface (Hall, 1982, 1983, 1986, 1987). The third proposed origin is as a glacial or glaciofluvial deposit. Supporting evidence includes the presence of matrix-supported beds of gravel and the breakage of previously well-rounded quartz grains (Kesel and Gemmell, 1981).

The presence of kaolinized clasts throughout the entire known thickness of the Moss of Cruden gravels and the evidence of topographic inversion since deposition, have allowed agreement that the flint gravels are older than all known Pleistocene deposits in Buchan. Following on from their interpretation of the gravels as early glacial or glaciofluvial deposits, Kesel and Gemmell (1981) suggested a Pliocene or early Pleistocene age. Flett and Read (1921) also originally proposed a Pliocene age based on long-range height correlations with marine deposits in southern England. McMillan and Merritt (1980) suggested that the degree of post-depositional weathering indicates prolonged alteration under warm climates in the middle to late Tertiary; Hall (1982, 1983, 1985) proposed a Neogene age based on comparisons with types of deep-weathering cover recognized by him in Buchan. However, firm dating of the flint gravels is not yet possible from the evidence available.

The Buchan Ridge Formation is a unique deposit in Scotland. The review above reveals that many questions about the provenance, origin and age of these gravels remain unanswered, and further advances may await the opening of deep sections. However, it is clear that the flint gravels have a bearing on several important problems of Scottish pre-Pleistocene and Pleistocene landscape history including:

1. the former extent of Cretaceous cover in north-east Scotland;
2. the nature of Tertiary weathering environments in Buchan and landscape evolution in the region (Hall, 1985, 1986);
3. the timing of the onset of regional glaciation in Scotland (Hall, 1984c; Sutherland, 1984a).

The Moss of Cruden site sheds important new light on long-term rates of denudation in this part of Scotland. The Peterhead granite, which partly underlies the Moss of Cruden, is of Caledonian age; it intrudes Dalradian metasediments. It was unroofed by Devonian times and later buried by Devonian sediment. This Old Red Sandstone cover was almost completely removed at the site, apart from a thin remnant now represented by the small outlier of arkosic sandstone, prior to marine transgression and deposition of sandstone in the Early Cretaceous. Further burial by Late Cretaceous Chalk is demonstrated by the presence of nodular Chalk flints in the basal layers of the Buchan Ridge Gravels. The Cretaceous cover was probably largely stripped in response to early Tertiary uplift, and the survival of the small remnants of Devonian and Cretaceous sediments at Moss of Cruden are undoubtedly a result of their subsequent burial by the Buchan Ridge Gravels in the (?)late Tertiary. The granite and metasediments at Moss of Cruden have therefore been protected from erosion for the last *c.* 350 Ma. It is unlikely, however, that these igneous and metamorphic rocks were ever deeply buried and this allows the possibility of a highly complex weathering history in these rocks.

The only outcrop of the Buchan Ridge Formation of comparable dimensions to the Moss of Cruden deposit lies beneath the Hill of Aldie (NK 059414), but exposure is extremely poor. Fieldwork there suggests the existence of a flint gravel deposit extending over an area of about 1 km^2 and reaching depths of at least 17.8 m (McMillan and Aitken, 1981). Smaller deposits occur at Whitestones Hill (NJ 979389), Sandfordhill (NK 115416) and Den Muir (NK 105406), but the possibility of glacial and periglacial disturbance is much greater, particularly at the last two localities.

The Windy Hills Formation consists of quartzite gravels with occasional flints and shows many similarities with the Buchan Ridge Formation (see Windy Hills). However, these two gravel bodies are lithologically distinct and may be of different origin and age (McMillan and Merritt, 1980; Kesel and Gemmell, 1981; Hall, 1983).

Conclusion

Moss of Cruden is the type area for the unique flint gravels of Buchan. These deposits include weathered material and are locally overlain by till. Although acknowledged to be pre-Quaternary in age (see Windy Hills above), their origin is still arguable and has been ascribed to marine, river and glacial processes. The Moss of Cruden gravels are different in their composition from those at Windy Hills and the two deposits may be of different age and origin. Like the gravels at Windy Hills, those at Moss of Cruden provide unique evidence for interpreting the long-term evolution of the landscape during the Quaternary ice ages and earlier.

PITTODRIE

A. M. Hall

Highlights

At Pittodrie, a small pit shows an exposure of decomposed granite bedrock which has undergone relatively advanced chemical weathering during pre-glacial times. It provides valuable information for interpreting the longer-term geomorphological evolution of north-east Scotland and shows the limited effects of glacial erosion in this area.

Introduction

The site at Pittodrie (NJ 693245), 30 km north-west of Aberdeen, is a small exposure at *c.* 180 m OD at the foot of Bennachie, a granite hill with good examples of tors at its summit (518 m OD). It shows kaolinized granite containing a hematite/layer-silicate clay mineral, macaulayite, known only from this locality (Wilson *et al.*, 1981, 1984). The weathering of the granite probably occurred during the late Tertiary (Hall, 1985; Hall *et al.*, 1989a). Additional interest in the site is provided by the excellent examples of downslope flaring of bedrock structures as a

Figure 8.3 Weathered granite at Pittodrie overlain by solifluctecl deposits. (Photo: J. E. Gordon.)

result of mass movement under former periglacial conditions.

Description

The section is up to 4 m high and shows 3–4 m of friable weathered granite overlain by 1–2 m of stoney and sandy solifluction deposits, on which a podsolic soil profile has developed (Figure 8.3).

The parent rock at the site is a leucogranite consisting of quartz, K-feldspar and subsidiary mica. The rock has generally weathered to a friable, clayey, silty sand in which bedrock structures, such as joints and quartz veins, are still clearly visible. The weathered granite is usually white to light brown, but also shows striking zones of bright red mottling. Kaolinite and illite are the dominant clay minerals and the rock is strongly depleted of more soluble bases but retains approximately 3.0% K_2O owing to the survival of partially altered grains of K-feldspar. Occasional patches of harder rock coincide with zones of relatively quartz-rich granite.

In situ weathered rock is overlain by about 0.5 m of banded growan (cf. Brunsden, 1964) in which vertical bands of white, pink and red weathered granite have been bent or flared downslope in response to former solifluction. This layer is overlain by up to 1.5 m of dark-brown, soliflucted till. The soliflucted till has a high content of basic igneous clasts, indicating original deposition by ice impinging on the hill from the west.

Interpretation

The Pittodrie site was mentioned as an example of weathered rock of pre-glacial age by FitzPatrick (1963) and Glentworth and Muir (1963). However, the only detailed descriptions of the exposure are those by Wilson *et al.* (1981) and Hall (1983).

Wilson *et al.* (1981, 1984) demonstrated the existence of a previously undescribed swelling hematite/layer-silicate complex, now formally named as macaulayite, in rubefied zones in the weathered granite. They suggested that the mineral formed in pre-glacial or interglacial times, when iron was complexed at higher, subsequently eroded, levels in the weathering profile and passed down joint planes to be oxidized at depth.

Hall (1983) and Hall *et al.* (1989a) described the site in more general terms and gave data on granulometry, geochemistry and clay mineralogy. Hall allocated the Pittodrie site to his 'clayey grus weathering type', a type of intense kaolinitic weathering found at only a few sites in north-east Scotland. Comparisons with the mineralogy of North Sea drill holes (Karlsson *et al.*, 1979) suggests that the clayey gruses are of Miocene to middle Pliocene age (Hall, 1985; Hall *et al.*, 1989a).

The possibility that the observed weathering features are a result of hydrothermal alteration has still to be fully considered. This origin is suggested by the brief reference of Wilson and Hinxman (1890) to a 'segregation vein' in the granite in the vicinity of Pittodrie.

The intensity of weathering at Pittodrie is far in excess of that usually found in weathered granites in north-east Scotland. Comparable kaolinitic alteration is currently exposed at only a small number of other sites in Buchan, where it is generally confined to quartz schist parent rocks (Hall, 1983; Hall *et al.*, 1989a).

Deep weathering of granite and other rocks is widespread in north-east Scotland (Phemister and Simpson, 1949; FitzPatrick, 1963; Hall, 1985, 1986, 1987; Auton and Crofts, 1986; Munro, 1986; Hall *et al.*, 1989a) and is generally ascribed to a pre-glacial or interglacial origin. The degree of preservation of deep weathering despite multiple glaciation is remarkable and is matched in only a few other formerly glaciated areas around the North Atlantic (Hall, 1984b, 1985). The weathering has considerable geomorphological significance:

1. The survival of weathered rock has been used as evidence of minimal glacial erosion in north-east Scotland (Clayton, 1974) and to identify local variations in the intensity of such erosion (Hall, 1983, 1985; Hall and Sugden, 1987; Sugden, 1989). Such studies have significant potential for elaborating the basal processes and dynamics of former mid-latitude ice-sheets (Sugden, 1989).
2. Analysis of the mineralogy of the weathered rock has provided important information on former weathering environments (Basham, 1974; Wilson and Tait, 1977; Hall, 1983; Hall *et al.*, 1989a).
3. The characteristics and distribution of the weathering have been used to investigate long-term landscape evolution in the region (Hall, 1983, 1986, 1987, 1991).

North-east Scotland, particularly the Buchan district, has therefore become an important area for the study of weathering and landform development in formerly glaciated regions (see Hill of Longhaven Quarry). Pittodrie provides a rare example of rubefied and kaolinitic weathered granite and it has supplied important information on pre-glacial or interglacial weathering environments. Pittodrie is also the only known locality for the clay mineral macaulayite.

Conclusion

Pittodrie is a reference site for deeply weathered bedrock, one of the characteristic features of the geomorphology of north-east Scotland. It shows a relatively intense type of weathering in granite represented at only a few sites in the area, and it is the only known location for a particular type of clay mineral. The decomposed bedrock, considered to be the product of pre-glacial weathering, is important for interpreting geomorphological processes during the landscape evolution of north-east Scotland. Its preservation is also significant in demonstrating a relatively low degree of glacial erosion in this area during the Quaternary ice ages.

HILL OF LONGHAVEN QUARRY

A. M. Hall

Highlights

The disused quarry at Hill of Longhaven shows an exposure of granite bedrock that has been heavily decomposed through granular disaggregation and limited chemical weathering. It is a particularly good example of this type of phenomenon which is widespread in north-east Scotland.

Introduction

Hill of Longhaven Quarry (NK 083424) is excavated at an altitude of 110 m OD, near to the summit of a broad west–east ridge which extends almost to the North Sea coast. It provides good exposures of weathered granite typical of the granular disintegration to grus accompanied by a relatively low degree of chemical alteration that is found at many locations in north-east Scotland (Hall, 1985; Hall *et al.*, 1989a). The nature of the weathering contrasts with that, for example, at Pittodrie (see above), where the alteration to clay minerals has been much greater. The only account of the Longhaven site is by Hall (1983), who gave data on granulometry, geochemistry and clay mineralogy (see also Hall, 1985; Hall *et al.*, 1989a).

Description

The lithological succession at the site is simple and continuous along 100 m of quarry face. Extending down from the surface and through a thin humic soil is a layer of cryoturbated till up to 0.3 m thick and containing abundant flint clasts. Beneath this lies up to 5 m of weathered granite, which is locally incorporated into the overlying deposit. The parent rock is typical pink, coarse-grained Peterhead granite, which has disintegrated to a uniform gravelly sand in which original rock structures, such as joint systems and thin quartz veins, are perfectly preserved (see Chorley *et al.*, 1984, plate 8). Corestones up to 1.5 m in diameter are found on the quarry floor, but no fresh rock, apart from occasional aplite veins, occurs in the quarry faces. The basal surface of weathering is locally exposed at the quarry floor by several whaleback-shaped rock 'risers'.

Weathering elsewhere in the Peterhead granite is described by Edmond and Graham (1977) and Moore and Gribble (1980). In an engineering study for Boddam power station, Edmond and Graham (1977) note that weathering in the Peterhead granite:

1. reaches a depth of 56 m in a fault zone;
2. decreases in intensity with depth, thereby indicating that subaerial, rather than hydrothermal alteration is the main cause of weathering;
3. includes thin seams of white and red clay along vertical joint planes, which may reflect minor hydrothermal activity.

Moore and Gribble (1980) gave geochemical data for a 10 m deep weathering profile in Stirling Hill Quarry (NK 123415), approximately 4 km east of the Longhaven site. Kaolinite and illite are the main clay minerals present and the amount of geochemical change is shown to decrease with depth, again supporting the idea of subaerial weathering.

At Hill of Longhaven, the content of fines is unusually low (<6%) and the granite has disintegrated to a gravelly sand (Hall, 1983). Average losses of CaO, Na_2O and MgO are also low (5.9%). Samples relatively enriched in clay, taken from joint planes, are dominated by illite with kaolinite and halloysite. Chlorite is present as a green coating on certain joint surfaces and may reflect slight alteration by hydrothermal solutions. Hall noted that the incorporation of previously weathered granite into the overlying cryoturbated till demonstrates that the period of rock weathering pre-dates at least one glaciation.

Interpretation

A puzzling feature of this site is that an apparently very low degree of chemical alteration has produced such deep and thorough disintegration of the rock. Hall (1983) suggested that some form of mechanical disintegration in response to buttressed expansion (Folk and Patton, 1982), or even ice-sheet loading and unloading (Carlsson and Olsson, 1982), may have been involved. The site has considerable research potential in this respect.

Hill of Longhaven Quarry provides a large exposure in weathered granite showing many features typical of weathering in coarse-grained granites in north-east Scotland. The site also has potential for research into the causes of rock breakdown in the initial stages of chemical alteration.

Other good exposures in similar weathered granites in north-east Scotland are found at Mill Maud (NJ 566067), Glen Cat (NJ 574949) and East Den (NK 082443). The degree of weathering at these sites is slightly greater than at Hill of Longhaven, but other features are broadly similar. Deep weathering in finer-grained granites is well-exposed at Redhouse (NJ 577203), Cairnlea (NJ 901537) and Cairngall (NK 053471).

Deep weathering of granite and other rocks is widespread in north-east Scotland and its geomorphological significance is outlined above (see Pittodrie). The weathering is widely regarded as pre-glacial or interglacial in origin (FitzPatrick, 1963; Basham, 1974; Wilson and Tait, 1977; Hall, 1983, 1985; Hall *et al.*, 1989a). In view of the low degree of alteration at the Longhaven site it is likely that this profile is of interglacial origin (see Hall, 1985; Hall *et al.*, 1989a). Its survival beneath a relatively exposed hilltop site is evidence of the inefficiency of glacial erosion in the Peterhead area, a characteristic feature of the geomorphology of this part of Scotland (Hall, 1983, 1985; Hall and Sugden, 1987; Sugden, 1989). It is also interesting to note that stripping of the weathered bedrock would reveal a hummocky bedrock topography resembling certain types of ice-moulded terrain. The site may thus have further research potential in elucidating the origins of certain classic landforms of glacial erosion, such as roches moutonnées and 'knock-and-lochan' topography (areal scouring) (Linton, 1959).

Conclusion

Hill of Longhaven Quarry demonstrates a particularly good example of weathered granite. It is representative of a type of weathering that shows granular disaggregation of the rock and a relatively low degree of chemical modification. In contrast to the more intense (?Tertiary age) chemical alteration seen at Pittodrie, the weathering at Hill of Longhaven Quarry may have occurred during one or more interglacial climatic phases in Pleistocene times. It is important for interpreting the geomorphological processes that have shaped the landscape of north-east Scotland.

KIRKHILL

A. M. Hall and J. Jarvis

Highlights

The sequence of deposits formerly exposed at Kirkhill Quarry, and proved by boreholes and pits to extend beneath adjacent fields, provides the longest and most complete record of Quaternary events in Scotland. It is a unique locality of the very highest importance for Quaternary studies, providing evidence of multiple glacial, interglacial and periglacial episodes.

Introduction

Kirkhill Quarry (NH 012529) is located 14 km north-west of Peterhead. The interest of the site lies in the variety of environments recorded by a succession of sediments which spans a large part of Middle and Late Pleistocene time. The succession includes:

1. Two interglacial soils of possible Ipswichian and Hoxnian age.
2. Organic sands of possible late Hoxnian age.
3. Tills which record at least three separate phases of glaciation in this part of Buchan.
4. Evidence for at least four separate periglacial phases, two of which pre-dated the last interglacial and three of which involved soil development.

The site represents the most complete Middle Pleistocene sequence known in Scotland and is of key importance in the controversy over the extent and timing of Devensian glaciation in north-east Scotland (Hall, 1984b; Sutherland, 1984a). The sediments have been described in a series of papers by Connell, Hall and co-workers (Connell *et al.*, 1982; Connell, 1984a, 1984b; Connell and Romans, 1984; Hall, 1984a; Connell and Hall, 1987; Hall and Connell, 1991); Lowe (1984) has critically reviewed the available pollen data. The quarry is now filled, but the succession has been proved beneath the fields to the south and east (Hall *et al.*, 1989b) and at Leys Quarry, 0.6 m south-west of Kirkhill (Hall and Connell, 1986).

Description

The sediment succession is up to 10 m thick and occurs in a number of bedrock channels or basins. The lithostratigraphy is summarized in Figure 8.4. Terminology is after Connell and Hall (1987).

Deposits below the Lower Buried Soil

The base of the sequence is composed of blocky talus and gelifluctate deposits derived from frost shattering of the channel margins. These sediments comprise Gelifluctate Complex 1 and are overlain by, and interstratified with, up to 4.5 m of bedded sand and gravel of fluvial or glaciofluvial origin. The gelifluctate and the base of the sand and gravel contain occasional erratic pebbles, which suggest, together with the existence of bedrock channels probably carved by meltwater, an early phase of glaciation at this site.

Recent work at nearby Leys Quarry indicates that the Kirkhill Lower Sands and Gravels rest on,

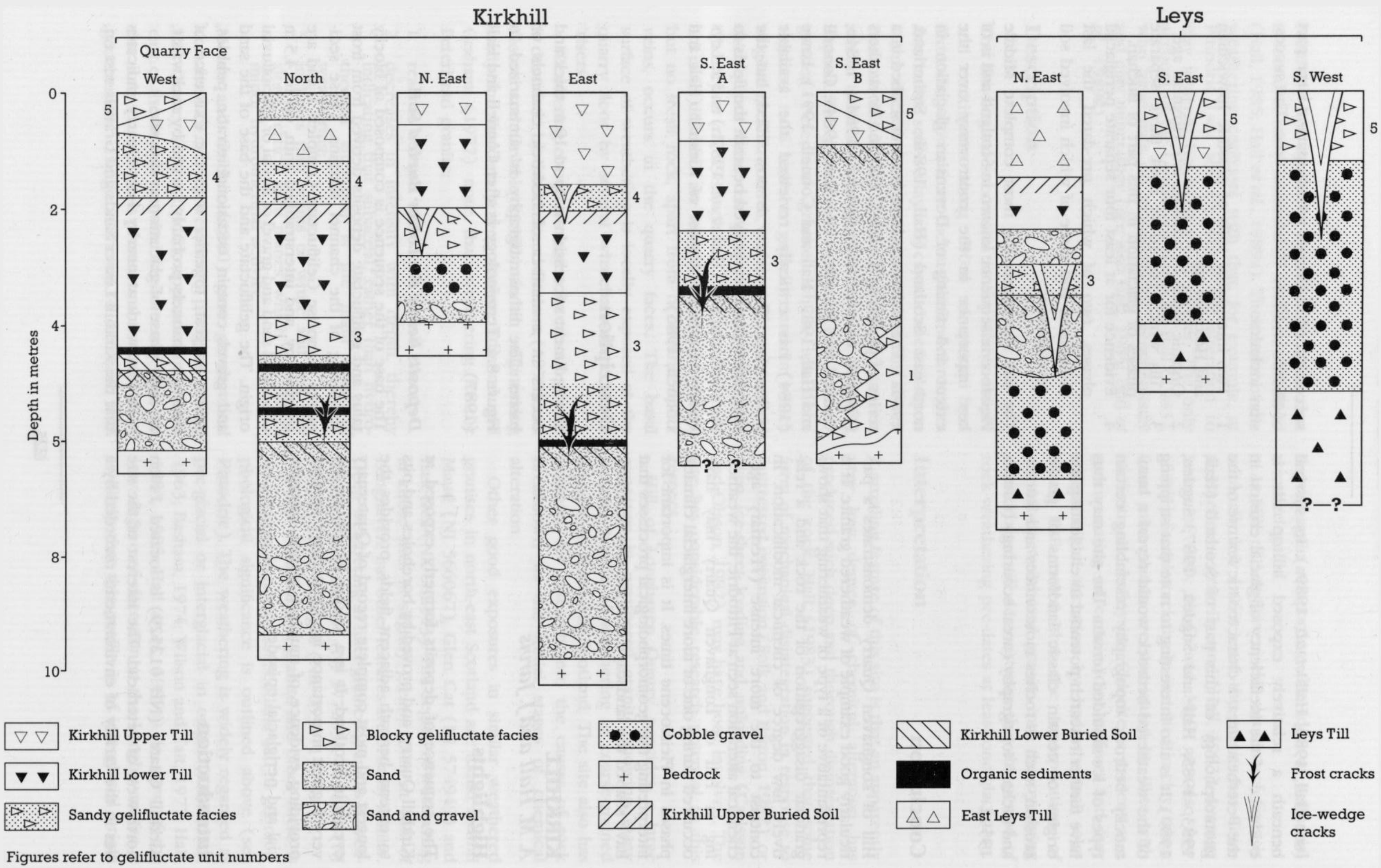


Figure 8.4 Kirkhill and Leys: lithostratigraphy.

or are a facies of the bouldery Leys Gravels, carried by meltwater from the east (Hall and Connell, 1986). Beneath the latter and resting on bedrock lies a further till, the Leys Till, derived from the west. The erratics in the Lower Sands and Gravels are presumably derived from the Leys Till.

The Lower Buried Soil

The lower deposits are truncated by an erosion surface on which is developed the Lower Buried Soil. The soil comprises a distinctive, upper, light-grey, bleached horizon and a lower, grey-brown, mottled horizon, with a basal iron pan (Figure 8.5). Analytical data are given in Connell and Romans (1984). The Lower Buried Soil is of podsolic type and it developed under humid temperate conditions (Connell *et al.*, 1982), but micromorphological evidence of silt droplet fabrics indicates subsequent climatic deterioration (Connell and Romans, 1984).

Deposits between the Lower and Upper Buried Soils

The Lower Buried Soil is truncated and draped by a 0.02 m thick layer of laminated organic mud, deposited in shallow ponds. The mud contains pollen of Gramineae, together with a marked arboreal component of mainly *Pinus* and *Alnus* (Connell *et al.*, 1982). Initial radiocarbon dating of the organic mud gave finite radiocarbon dates for three samples of 45,630 +1740/−1430 BP (SRR–1635), 44,900 +1580/−1320 BP (SRR–1637) and 33,810 +630/−590 BP (SRR–1636), but contamination was suspected (Connell *et al.*, 1982). Later dating of a much larger sample (Connell, 1984b) gave a date of >47,360 BP (SRR–2416) and confirmed that the sediments are beyond the range of radiocarbon dating (Hall, 1984b).

The organic mud is succeeded by 0.1–0.7 m of poorly-organic sands containing frost cracks. Pollen analysis shows a reduction in arboreal pollen and an increase in grasses and *Calluna*, possibly reflecting the establishment of an open, treeless environment. The organic sediments indicate erosion and recycling of organic deposits, possibly including the upper horizons of the Lower Buried Soil, from neighbouring slopes under deteriorating climatic conditions. The organic sands are overlain by sediments belonging to Gelifluctate Complex 3 and then by the Lower Till, containing erratics transported from the north-west.

The Upper Buried Soil

The Upper Buried Soil is developed on the Lower Till. Diagnostic features of soil development include mottling, clay translocation, alteration of clasts and down-profile changes in colour and clay mineralogy (Connell and Romans, 1984). The Upper Buried Soil bears many similarities with Holocene gleyed brown-earth profiles in north-east Scotland and is therefore considered to have formed during an interglacial. Countable pollen dominated by *Alnus* was recovered from one sample in the weathered till but its significance is uncertain.

Deposits above the Upper Buried Soil

The A horizon of the Upper Buried Soil is missing due to erosion. The truncated soil surface is cryoturbated and overlain by Gelifluctate Complex 4. This depositional surface then stabilized, ice wedges developed and periglacial soil formation began. Renewed glaciation then took place across the permafrost surface, with deposition of the brown Upper Till, derived from the west. Of interest is the discovery of a single Norwegian erratic in the Kirkhill Upper Till. In the northern part of the quarry the Upper Till underlies a large erratic mass of dark grey silty clay containing Jurassic and Cretaceous dinoflagellate cysts, which was originally derived from the Moray Firth. West of the quarry, excavations have shown that this material grades into dark tills at least 5 m thick in places and containing fragments of shell (the East Leys Till). The Kirkhill Upper Till and the East Leys Till are overlain by glaciofluvial sands and gravels and by periglacial slope deposits of Kirkhill Gelifluctate 5. This is the last depositional event recorded at the site prior to Holocene soil development.

Interpretation

Kirkhill Quarry contains an extraordinary range of sediments, which provide an unrivalled record of Quaternary environmental change in Scotland. The site is considered to include evidence of two interglacials, at least three glacial phases and at least four periglacial phases. No firm dates, however, exist for sediments in the Kirkhill

Figure 8.5 Kirkhill Quarry, south-east face B (1984). Developed in the Kirkhill Lower Sands and Gravels is the Kirkhill Lower Buried Soil, with its striking bleached horizon. The soil is truncated and overlain by laminated organic muds and sands, and then by periglacial slope deposits of Kirkhill Gelifluctate 3. These rubble layers have been partly reworked to form the Kirkhill Upper Till. The section is about 6 m high. (Photo: J. Jarvis.)

sequence. The simplest view is that the Upper Buried Soil represents the Ipswichian and that the Lower Buried Soil represents the Hoxnian. On this basis, the glacial and periglacial sediments above the Upper Buried Soil would be Devensian, there was one period of regional glaciation preceded by periglacial conditions between the Ipswichian and the Hoxnian, and the latter interglacial was preceded by one period of glaciation as well as periglacial conditions of unknown duration.

Kirkhill Quarry clearly has great potential as a regional reference site, but this potential has not yet been realized owing to the shortage of age determinations and the lack of firm stratigraphic correlations with Pleistocene sediments elsewhere in north-east Scotland. Sands and gravels below the Lower Buried Soil have been tentatively correlated with gravels at Leys Quarry (Hall and Connell, 1986), but no other deposits of comparable age are known in Buchan (Hall and Connell, 1991). Equally, the Lower Buried Soil currently stands alone in the regional stratigraphy as a presumed pre-Ipswichian deposit. The Lower Till may correlate with other weathered pre-Devensian tills of inland derivation at Kings Cross, Aberdeen (Synge, 1963) and Boyne Quarry, Portsoy (see below) (Peacock, 1966). If these correlations are justified, then these tills represent a major advance of inland ice (Hall and Connell, 1991). Acceptance of an Ipswichian age for the Upper Buried Soil invites correlation with the weathered tills above and with the buried interglacial soil at Teindland (FitzPatrick, 1965; Sutherland, 1984a).

The deposits below the Upper Buried Soil point to a complex sequence of pre-Devensian events in Buchan. An early, possibly Anglian ice-sheet transported the erratics in the basal Gelifluctate Complex 1 and deposited the basal till at Leys. Subsequently, ice-sheets covered this area at least in two later, separate periods, probably during a pre-Ipswichian cold period and during the Devensian. In addition, the sediments record at least two pre-Devensian periglacial phases, and the thickness of periglacial sediments in the sequence suggests important periglacial slope modification in the Middle Pleistocene (Connell and Hall, 1987). Finally, the Lower Buried Soil and the overlying organic sediment appear to represent an interglacial phase and a subsequent climatic deterioration. This interglacial was probably the Hoxnian. The only other organic sediments in Scotland for which a Hoxnian age has been claimed are from Fugla Ness, Shetland (Birks and Ransom, 1969; Lowe, 1984) (see above), and Dalcharn near Inverness (Merritt, 1990a) (see above).

The Upper Till has been correlated with other tills of inland derivation, the Inland 'Series' (Hall, 1984b), which represent the last glaciation of central Buchan. The Upper Till at Kirkhill provides an upper limiting age of post-Ipswichian for the Inland 'Series'. At Crossbrae, Turriff, a peat containing pollen of interstadial character and with radiocarbon dates of 26,400 ± 170 BP (SRR–2041a) and 22,380 ± 250 BP (SRR–2041b) rests on till correlated with the Inland 'Series' and is overlain by periglacial solifluction deposits (Hall and Connell, 1991). The combined evidence from Kirkhill and Crossbrae indicates that the last glaciation of central Buchan was during the Early or Middle Devensian and that an ice-free area existed there in the Late Devensian (Sutherland, 1984a; Connell and Hall, 1987). The Kirkhill site thus has crucial bearing on the problems of the timing, number and extent of Devensian glaciations in Scotland (Clapperton and Sugden, 1977; Hall, 1984b; Sutherland, 1984a; Bowen *et al.*, 1986; Hall and Connell, 1991).

The details of the stratigraphic succession at Kirkhill seem assured after over a decade of sediment logging. The quarry is now infilled with refuse, but geophysical and trial pit investigations (Hall *et al.*, 1989b) indicate that the sequence extends to the east of the former quarry, and recent work at Leys Quarry has further expanded the basic stratigraphic sequence established at Kirkhill. Several problems remain outstanding, however: the status of the Lower Buried Soil is not yet resolved (Connell and Romans, 1984) and published pollen data are scanty (Lowe, 1984). Crucially, also, the sediments at Kirkhill are not yet firmly dated. None the less, the Kirkhill succession is the longest known in Scotland and offers potential for correlations, both on land and offshore.

Conclusion

Kirkhill is a unique site of the highest importance for Quaternary studies in Scotland. Its sequence of deposits provides evidence for two interglacial phases, three separate glaciations and at least four periglacial episodes. Kirkhill has the longest succession of Quaternary deposits in Scotland (extending back over approximately 450,000 years) and is therefore a critical reference site for establishing a better understanding of the sequence and timing of glacial and non-glacial climatic episodes.

BELLSCAMPHIE

A. M. Hall and J. Jarvis

Highlights

Deposits exposed in the disused railway cutting at Bellscamphie include three distinct tills, two of which are believed to pre-date the Late Devensian. The sequence provides important evidence for interpreting the glacial history of north-east Scotland and the patterns of ice-movement associated with different glacial events.

Introduction

The section at Bellscamphie (NK 019338) lies 7 km north-east of Ellon in a railway cutting, now disused, and was described by Jamieson (1906) from his observations during the original excavation for the railway in the late 19th century. The site is important for a sequence of three superimposed tills, which include the 'indigo boulder clay' of Jamieson (1906). The tills, the Bellscamphie Upper, Middle and Lower Till Members, may mark three separate phases of glaciation, two of which pre-date the Late Devensian. The Bellscamphie Middle Till (the indigo boulder clay of Jamieson) was originally described at three sites, but is now accessible only at Bellscamphie. The Bellscamphie Lower Till has not been previously described in the literature and has no known correlative deposits in the Ellon area. The Bellscamphie site is therefore of great importance in the study of the Pleistocene history of Buchan. The only published work on the site is that of Jamieson (1906), but it has recently been reinvestigated by Hall (1989b).

Description

Jamieson (1906) described the following succession which had a total thickness of 16 ft (4.9 m):

6. Red clay, a few feet thick, of the Red Clay 'Series'.
5. Gravel, containing pebbles of yellow limestone and sandstone and shell fragments of Crag affinities. Similar in lithology to the gravels forming the Late Devensian Kippet Hills esker, 2.5 km to the south.
4. Sand, fine, clean-washed.
3. Red Clay, similar to bed 6.
2. Indigo boulder clay, with small fragments of schist and granite. No more than a few feet thick.
1. Bedrock, schist.

No other descriptions were produced as the section was soon obscured by vegetation, but numerous references to the site and Jamieson's description exist in the literature (for example, Bremner, 1916b, 1928, 1934a; Synge, 1956; Hall, 1984b; Sutherland, 1984a).

Jamieson (1906) also described the indigo boulder clay at two other sites:

A. Craigs of Auchterellon (NJ 952308). The indigo boulder clay was discovered at a depth of 14 m in wells dug east of the rock knoll of Craigs of Auchterellon, apparently preserved in the lee of the bedrock high. The site is now covered by housing.
B. 'A railway cutting a few miles south of Ellon'. Jamieson's description is vague and the location of the site was not precisely recorded. Consequently, this site has not been relocated.

Excavations in 1988 (Hall, 1989b) revealed a different stratigraphy at Bellscamphie (Figure 8.6) to that described by Jamieson (1906):

5. Grey gravels and sands (Bellscamphie Gravels and Sands).
4. Interbedded red diamictons (Bellscamphie Upper Till).
3. Dark grey diamicton – the indigo boulder clay (Bellscamphie Middle Till).
2. Brown diamicton (Bellscamphie Lower Till).
1. Dalradian psammites.

The Bellscamphie Lower Till is a brown, sandy, silty, massive and overconsolidated diamicton. At the time of the original railway excavations this unit would have lain largely concealed below the cutting floor and this is probably why the unit was not described by Jamieson (1906). The Bellscamphie Lower Till is dominated by clasts of local metamorphic rocks. It rests in shallow hollows on the surface of the Dalradian.

The Bellscamphie Middle Till is a dark grey, clayey silty, massive and overconsolidated diamic-

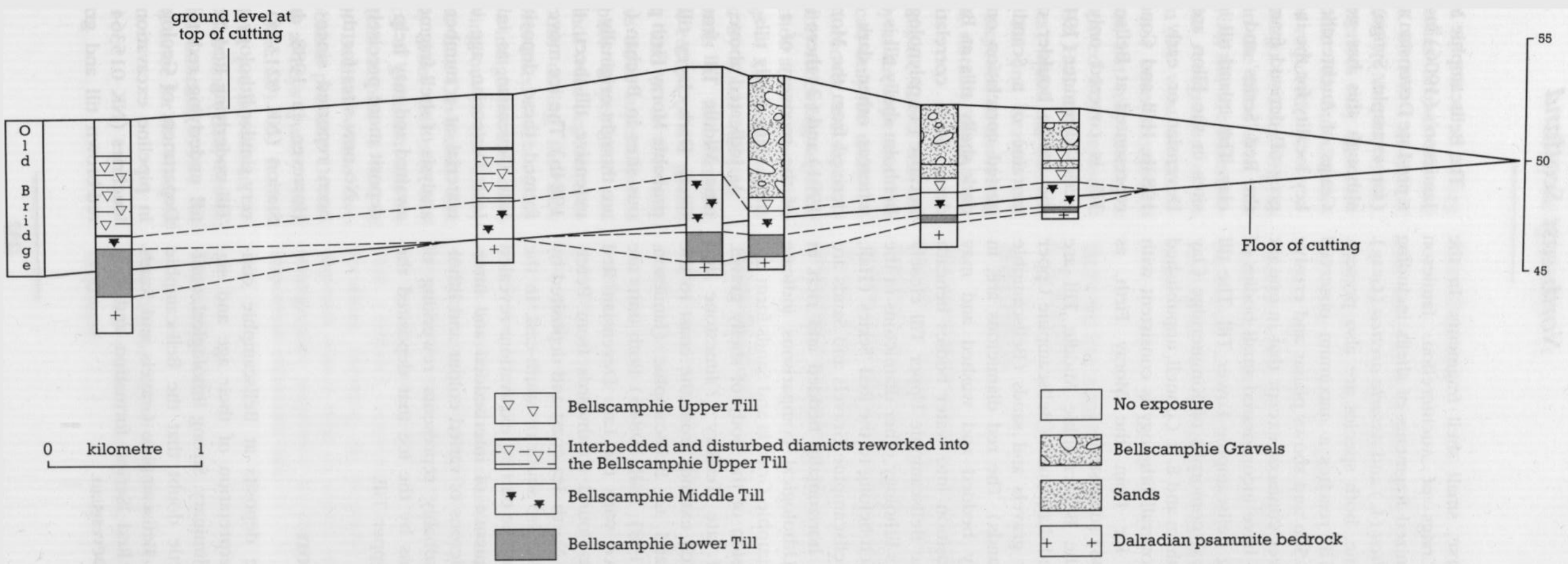


Figure 8.6 Sediment logs and stratigraphy in the disused railway cutting at Bellscamphie.

ton with sparse, small shell fragments. In the deposit at Craigs of Auchterellon, Jamieson (1906) recognized fragments of shells including *Arctica islandica* (L.) and *Astarte arctica* (Gray). At Bellscamphie, both species are also present. The Middle Till reaches a maximum observed thickness of 2.5 m and shows planar and erosive upper and lower contacts, except that in one pit it was seen to have incorporated small bodies of the underlying Bellscamphie Lower Till. The till incorporates palynomorphs of Kimmeridge Clay affinity (W. Braham and E. R. Connell, unpublished data), and its overall lithology is consistent with transport by ice from the Moray Firth, as Jamieson (1906) suggested.

Overlying the Bellscamphie Middle Till are interbedded red diamictons (Bellscamphie Upper Till) and grey gravels and sands (Bellscamphie Gravels and Sands). The red diamictons are, in places, crudely bedded and washed and may represent deposition into water bodies beneath glacier ice. The Bellscamphie Upper Till closely resembles in its lithology other diamictons in the Ellon area, which belong to the Red 'Series' (Hall, 1984b). The Bellscamphie Gravels and Sands are poorly sorted, horizontally bedded and rich in shell debris. Lithological comparisons indicate that the Bellscamphie Gravels and Sands form the western extension of the body of shelly gravel, with clasts of late Tertiary (?)limestone and mudstone, which extends from the coast to the Kippet Hills and to Bellscamphie (Jamieson, 1906; Merritt, 1981; Hall, 1984b). Both units are to be correlated with the Late Devensian Red 'Series' deposits found southwards from Peterhead along the North Sea coast and deposited by ice moving from the south or south-east. In the north-east part of the cutting, excavations revealed a complex sequence of interbedded and interdigitating diamictons of varied colour and lithology, which probably represents reworking of older diamictons by the ice that deposited the Bellscamphie Upper Till.

Interpretation

Analysis of the deposits at Bellscamphie continues and interpretation of their age and significance is preliminary. Strong lithological similarities leave little doubt that the Bellscamphie Upper Till and Bellscamphie Gravels and Sands belong to the Red 'Series' formation and date from the Late Devensian.

The Bellscamphie Middle Till is correlated with Jamieson's (1906) indigo boulder clay, for which a pre-Late Devensian age has been widely accepted (for example, Synge, 1956; Sutherland, 1984a), although this has yet to be demonstrated. At Craigs of Auchterellon, however, originally the key locality for the indigo boulder clay, there is a grey till derived from the west which underlies the Red 'Series' and overlies the indigo boulder clay. This inland till is known from several other sites in the Ellon area and is probably of Early Devensian or early Late Devensian age (Hall, 1984b; Hall and Connell, 1991). This till is not represented at Bellscamphie, where the Middle Till is covered only by deposits of the Red 'Series'. Bremner (1916b, 1928, 1934a) regarded the indigo boulder clay as part of the ground moraine of a Scandinavian ice-sheet and suggested correlation on lithological grounds with dark shelly tills at Burn of Benholm and Aberdeen. Such correlation is dubious, however, because (1) palynological work indicates that the Benholm shelly till is derived from the North Sea, whereas other dark shelly tills in Buchan are derived from the Moray Firth (Hall and Connell, 1991) and (2) there is only one doubtful record of the recovery of a Scandinavian erratic from these dark shelly tills (Hall and Connell, 1991).

As indicated above, transport of the Bellscamphie Middle Till from the Moray Firth seems likely. Dark clayey tills and Mesozoic erratics of probable Moray Firth provenance occur at numerous sites in Buchan (Hall, 1984b, figure 3) and are thought originally to have been part of a more extensive till-sheet, the 'Mesozoic Drift' (Hall, 1984b). The ice movement or movements which formed these deposits probably pre-dated the Late Devensian, as inland tills of Early or early Late Devensian age incorporate masses of this material at a number of localities. Amino acid analysis of shell fragments from the Middle Till is awaited and may help to establish the age of this deposit more precisely.

No new sites for the indigo boulder clay have been reported since the turn of the century. However, in 1988 drainage ditches at Pitlurg Station (NK 021344) exposed a diamicton of very similar lithology to the Bellscamphie Middle Till underlying Red 'Series' deposits. A dark grey till underlying red till was also logged by the Department of Geology, University of Aberdeen, in pipeline excavations at Eastertown of Auchleuchries (NK 015364). Dark grey till underlies red-brown till and gravel in British Geological

Survey (BGS) borehole NK 03 SW 5 at Pitlurg (NK 02633312) and underlies brown till and gravels in BGS borehole NK 03 NW 1 at Hill of Auchleuchries (NK 00573649) (Merritt, 1981). Some or all of these occurrences may correlate with the Bellscamphie Middle Till, but detailed lithological comparisons are required.

Jamieson regarded the indigo boulder clay as the oldest glacial deposit in the Ellon area, but the discovery of an underlying till, the Bellscamphie Lower Till, forces the recognition of an earlier ice movement from the west or north-west. The Lower Till has not been recognized elsewhere in the Ellon area, but may correlate with the weathered till derived from inland at Kirkhill (Connell *et al.*, 1982; Hall, 1984b).

Deposits of the Red 'Series', which are directly comparable to the Upper Till and Gravels and Sands at Bellscamphie, are exposed at numerous localities in the Ellon area, notably around the Kippet Hills.

In summary, the Bellscamphie Lower Till has so far been recognized only at the type site. The Bellscamphie Middle Till can only be easily re-exposed at Bellscamphie. Moreover, the superimposition of three tills probably reflecting separate phases of glaciation is matched at only one other site in the Ellon area, Craigs of Auchterellon, and this site has been fossilized by house building.

The sequence of deposits at Bellscamphie provides a key stratigraphic record of the glacial history of the Ellon area and it is the only accessible site which shows three superimposed till units. The Bellscamphie Upper Till and interbedded Gravels and Sands were deposited by ice moving from the south during the Late Devensian and are well represented at other sites. The Middle Till (Jamieson's indigo boulder clay) was deposited by ice moving out of the Moray Firth, probably prior to the Late Devensian. The Lower Till is known only from this site and represents the oldest period of glaciation known in this part of Buchan. Bellscamphie is one of only two sites known in Buchan where two superimposed tills of probable pre-Late Devensian age occur; the other is at Leys Quarry (Hall and Connell, 1986; see Kirkhill). As Buchan contains the most complete pre-Devensian sequence known on land in Scotland (Hall, 1984b; Sutherland, 1984a; Hall and Connell, 1991), the site is also of national importance for the study of Pleistocene stratigraphy.

Conclusion

The deposits at Bellscamphie provide evidence for three separate phases of ice movement in north-east Scotland, two of which pre-date the last (Late Devensian) glaciation. Such a sequence is rare in Scotland, so that Bellscamphie is a valuable reference site for studies of Quaternary history and for interpreting the patterns of ice movement across the landscape. It is also a type locality for two of the individual ice-deposited till units.

BOYNE QUARRY

J. E. Gordon

Highlights

The superficial deposits exposed at Boyne Quarry include a sequence of multiple tills and ice-marginal lake deposits. These provide important evidence for interpreting the glacial history of the Moray Firth coastal area and the associated depositional environments.

Introduction

Boyne Quarry (NH 613659), *c.* 7.5 km west of Banff, is important for a succession of deposits demonstrating the glacial stratigraphy of the southern coast of the Moray Firth. Two, or possibly three tills occur (Peacock, 1966), and the basal one has been correlated with pre-Devensian weathered tills known elsewhere in north-east Scotland. The exposure is a comparatively recent one and does not appear in the extensive early literature on the glaciation of the Moray Firth coast; the only published references are by Peacock (1966, 1971a) and Connell and Hall (1984b). However, as one of the few localities showing an extended succession of deposits which help to clarify the controversial stratigraphic sequence in the region, it is an important reference site.

Description

The Boyne Quarry section was described by Peacock (1966) and comprises the following sequence:

6. Peaty soil 0.6 m
5. Horizontally bedded silt, sand and gravels 0–1.2 m
4. Grey, silty till with gabbro boulders derived from the Huntly basic complex 1.5 m
3. Dark grey, clayey till with shell fragments 3.0–4.6 m
2. Dark grey, shelly silt and clay, in part till-like and in part laminated, with pockets of shelly gravel especially at the base 1.5–3.7 m
1. Light-brown till 0–3.7 m

The till of bed 1 is considerably decomposed in comparison with the deposits above it. It comprises subrounded pebbles and cobbles of quartzite, with lesser amounts of granite, calc-schist and gabbroic rocks, in a gritty, clayey matrix. Apart from the quartzites, most of the clasts are decomposed. According to Connell and Hall (1984b), the weathering profile is truncated and the till surface covered by a thin (0.02 m) layer of brown silt, and by fine sand and gravel infilling shallow depressions. Subsequent examination (J. D. Peacock, unpublished data) has, however, shown that the till also includes fresh cobbles and boulders of gabbro and that the weathered appearance may partly reflect the incorporation of weathered bedrock. Such weathered bedrock was formerly seen below bed 1 on the south side of the quarry.

Further work has shown that the clay (bed 2) contains Foraminifera, and that the crushed mollusc shells reported earlier are single valves of *Nuculana pernula* (Müller) (J. D. Peacock, unpublished data). Connell and Hall (1984b) have suggested that bed 2 can be subdivided into a lower unit of sheared and interbedded layers of red and brown silt and fine sand, and an upper unit of dark grey, clayey till. Peacock (1966) also noted that the site was apparently unaffected by solifluction.

Interpretation

The glacial deposits of the Moray Firth coast have a long history of investigation, which provides the context for interpreting the sequence at Boyne Quarry. Early accounts drew attention to the presence of anomalous beds of clay containing Jurassic fossils (Christie, 1830; Prestwich, 1838a, 1840; Brickenden, 1851) and exposures of shelly stratified sands, gravels and clays, notably at Gamrie (see Castle Hill) and King Edward (Prestwich, 1838b, 1840; Chambers, 1857).

Martin (1856) described many of the characteristics of the glacial drift of the area and attempted to explain it in terms of debris transported by sea ice during a great submergence. From his observations on the distribution of erratics and patterns of striae, Mackie (1901) deduced ice movement initially from the interior towards the north-east, but it gradually became diverted towards the east and south-east by ice in the Moray Firth, in the first instance by ice from the Northern Highlands then by ice from Scandinavia.

The most significant early contribution, however, was that of T. F. Jamieson, who, in the course of his investigations of the glacial phenomena of Scotland, described many of the exposures and characteristics of the Moray Firth drift and pieced together a stratigraphic sequence for the area (Jamieson, 1858, 1865, 1866, 1874, 1882b, 1906, 1910). His more important observations included:

1. detailed descriptions of the King Edward and Castle Hill sections and identification of arctic shell assemblages (Jamieson, 1858, 1865, 1866, 1906);
2. confirmation of Chamber's (1857) report of a dark grey boulder clay overlying the shelly silts and sands at King Edward (Jamieson, 1866, 1906);
3. identification of a dark, bluish-grey shelly clay between Cullen and Banff, with erratics derived from westerly sources and Jurassic material from the Moray Firth sea floor (Jamieson, 1866, 1882b, 1906);
4. the eastwards continuation of the dark shelly clay to Peterhead and its interdigitation with the red clay of the east coast of Aberdeenshire (Jamieson, 1866, 1906);
5. the inference, from erratics and striae, that ice moved from west to east (Jamieson, 1866, 1906).

From these observations, and work elsewhere in Scotland, Jamieson (1865, 1906) deduced the glacial succession in the Moray Firth area as: (1) early glaciation from the north and west (based on evidence in the Ellon area only), (2) main glaciation with ice from the west succeeding ice moving down Strathspey, (3) as the ice melted away, submergence of the coast and deposition of the dark shelly clay and shelly sands contemporaneous with the red deposits of eastern Aberdeenshire, and (4) less extensive glaciation from the west, responsible for boulder clays (on top of the shelly clays and sands), and equivalent to the Aberdeen moraines (see Nigg Bay).

Unfortunately, Jamieson's interpretations were constrained by a rigid conceptual model requiring all 'clays' with shells, including those which he definitely recognized as boulder clays, to be deposited in glaciomarine or glaciolacustrine conditions during a great submergence of the coast at the end of the main glaciation. This seems to have arisen from a failure to distinguish between true marine clays and shelly boulder clays. Although Bell (1895a, 1895b, 1895c, 1895d) had clearly questioned the evidence for submergence to explain many of the deposits, his arguments went unheeded in Jamieson's later work (Jamieson, 1906, 1910).

In the Geological Survey Memoir, Read (1923) published a comprehensive review of the field evidence and proposed a fourfold division of the glacial stratigraphy of north Banffshire and north-west Aberdeenshire (sheets 86 and 87):

4. Lateglacial sands and gravels.
3. Upper or northerly drift deposited by ice moving out from Central Banffshire as the south-easterly ice withdrew.
2. The 'Coastal Deposits' (see Castle Hill) comprising a suite of sands, clays and gravels, including those at King Edward and Castle Hill, formed in a lake as the south-easterly ice withdrew.
1. Lower or south-easterly drift moving onshore out of the Moray Firth and including the shelly drift and the drift with Jurassic fossils.

This succession, which was based on stratigraphic evidence, striae and erratics, hinged on stratigraphic interpolation since no single exposure showed all the elements of the succession to be superimposed. An important facet of Read's interpretation was that the entire sequence related to a single period of glaciation.

Bremner (1916b) noted the pattern of cross-striations on the south coast of the Moray Firth. Later he agreed with Read's interpretation of two separate ice movements, from the north-west and south, but argued that they represented two distinct glacial periods (his first and second glaciations) (Bremner, 1928, 1934a, 1938, 1943a). Moreover, he proposed the existence of a third ice-sheet, moving from the north-west after deposition of the northerly drift. In support he cited supposedly marginal meltwater channels, evidence from two sections near Rothes and one near Cullen, and glaciofluvial deposits resting on the northerly till and extending from Inverness to Buchan. Bremner (1928) also disputed Jamieson's correlation of the blue shelly till with the red till of the east coast of Aberdeenshire, relating them to separate glaciations.

Charlesworth (1956) supported Bremner's view that the last ice in the Moray Firth area came from the north-west (his Highland Glaciation), and related the 'Coastal Deposits' to the final stages of retreat of this ice.

Synge (1956) also accepted that the last ice came from the north-west. However, a problem with Bremner's scheme was that this ice did not leave an extensive till cover, which Synge thought was improbable. Therefore, he proposed that Read's sequence of deposits was inverted and that the lower drift in fact related to the last ice-sheet. Read's upper drift might not be *in situ* but could have been soliflucted on to the 'Coastal Deposits' in the very few sections where it was seen to overlie them. Synge suggested that the 'Coastal Deposits' might be the equivalent of the Lateglacial gravels (of Read, 1923), noting that the two were never seen in a section together. He concluded, therefore, that the drifts of Banffshire could all be explained in terms of a single glaciation, the last or Moray Firth – Strathmore Glaciation. Erratics from the south were probably incorporated from an earlier drift.

The deposits at Boyne Quarry have an important bearing on these earlier interpretations. Peacock (1966) considered that the weathered till (bed 1) was the relic of a very early glacial episode and that it had undergone prolonged subaerial weathering before deposition of the overlying sediments. It may be of pre-Devensian age (Jardine and Peacock, 1973) and may correlate with the weathered tills reported from Kirkhill (Connell *et al.*, 1982; Hall, 1984b) and Kings Cross, Aberdeen (Synge, 1963). However, further work is required to establish the extent to which the apparent weathering reflects the incorporation of previously decomposed bedrock into the till, rather than being *in situ* weathering of the till itself (J. D. Peacock, unpublished data). Peacock (1966) interpreted bed 2 as an erratic and considered it to be the source material for bed 3. Bed 3 appeared to correspond to the shelly till of Banffshire and the 'lower or south-easterly drift' of Read (1923). The till of bed 4 was probably part of Read's 'upper and northerly drift'. Bed 5 formed part of the 'Coastal Deposits'.

The Boyne Quarry section as recorded by Peacock (1966), thus apparently established that Read's till succession was correct at least there, and not inverted as Synge suggested. However, 'Coastal Deposits' did not intervene between the tills, and Peacock (1971a) showed elsewhere that they were probably deposited in freshwater lakes during the melting of the last ice-sheet (see Castle Hill).

The apparent confirmation of Read's till succession was subsequently rejected by Peacock (1971a), who reinterpreted the uppermost till unit (bed 4) as simply a separate facies of the immediately underlying shelly till; a view supported by the gradational contact between the two units. Peacock (1971a) favoured the interpretation that the gabbro boulders in the top till had been incorporated from an earlier till-sheet derived from the south, so that the sequence of deposits above the basal weathered till, comprising beds 2 to 5, was the product of the last ice-sheet flowing from the north-west. An early north to south or south to north ice movement is shown by striations formerly seen on the bedrock surface, but their relationship to the strata in the adjacent drift section could not be ascertained (J. D. Peacock, unpublished data).

The age of the deposits at Boyne Quarry is uncertain. Peacock (1966) considered that the uppermost till (bed 4) and the overlying 'Coastal Deposits' (bed 5) were the product of Late Devensian ice-sheet advance and retreat, and the reinterpretation of Peacock (1971a) indicated that all the deposits except the weathered till (bed 1) were of Late Devensian age. This was also implied by Clapperton and Sugden (1975, 1977) in their consideration of the glaciation of north-east Scotland. Sutherland (1984a), however, suggested that the Late Devensian ice-sheet may have terminated to the west of the site and that hence the last glaciation of this area was pre-Late Devensian. This view was not accepted by Hall (1984b), who preferred a Late Devensian age for the last glaciation of the southern Moray Firth coast. Amino acid ratios on shells from sand and gravel horizons immediately overlying the weathered till and from the shelly till imply a Devensian age for the glaciation, but do not yet allow a fuller resolution of the chronological problems (D. G. Sutherland, unpublished data).

Boyne Quarry is a key stratigraphic site demonstrating the much-debated Pleistocene succession on the south coast of the Moray Firth, including the two till units and the 'Coastal Deposits' which have formed the basic field evidence for reconstructions of the glacial history of the area. Current interpretations suggest that most of the deposits were produced during a single glacial episode of Devensian age. Boyne Quarry is also particularly significant for one of the few exposures in Scotland of a till which has been considered to be of pre-Devensian age. From a sedimentological viewpoint, Boyne Quarry is also notable in providing a good illustration of the complex sequence of deposits which may be associated with a single glaciation, including a raft of marine clay within shelly till. Finally, Boyne Quarry has significant research potential (Connell and Hall, 1984b). This relates to:

1. the pedological characteristics of the weathered till (bed 1), their origins and the possible correlations with weathered tills elsewhere in north-east Scotland (cf. Kirkhill Quarry),
2. the sedimentary characteristics of the deposits in bed 2 and the process responsible for their origin,
3. the significance of the gradational contact between the tills of beds 3 and 4, and the interpretation of these deposits.

Conclusion

Boyne Quarry is a reference site for the ice-deposited sediments of the south coast of the Moray Firth. The sequence includes two, or possibly three tills, one of which may pre-date the Devensian, and demonstrates the main deposits that have been described from the area. Boyne Quarry is therefore important for establishing the pattern of ice movements across the area and also for studies of the formation of the glacial sediments.

TEINDLAND QUARRY

D. G. Sutherland

Highlights

The sequence of deposits at Teindland Quarry includes a palaeosol which has yielded pollen of both interglacial and interstadial affinites. Sites which preserve such evidence are rare, and

Teindland is a key locality for interpreting the Quaternary history of Scotland.

Introduction

Teindland Quarry (NJ 297570) is located in Teindland Forest in lower Strathspey, 5 km southwest of Fochabers at an altitude of approximately 100 m OD. It is one of a few known sites on the Scottish mainland where organic deposits older than the Late Devensian have been both radiocarbon dated and analysed for pollen. Since its original description by FitzPatrick (1965), the site and its interpretation have proved controversial (Edwards *et al*., 1976; Romans, 1977; Sissons, 1981b, 1982c; Caseldine and Edwards, 1982; Lowe, 1984). Despite the significance of the site, no detailed description has yet been published of the full succession.

Description

The section originally described by FitzPatrick (1965) showed 1.8–2.4 m of sandy till and outwash gravel overlying an iron podsol developed on glaciofluvial outwash (Figure 8.7). A radiocarbon date of 28,140 +480/−450 BP (NPL–78) was obtained from the soil.

More data were provided by Edwards *et al.* (1976), particularly with respect to the pollen content of the sediments. They described a more complex succession than was recognized by FitzPatrick (1965) (cf. Figure 8.8):

5. Humified modern soil layer. *c.* 0.56 m
4. Yellow sand. *c.* 1.11 m
3. Sandy till. *c.* 0.74 m
2. Interbedded sequence of grey and yellow sands and black organic layers. *c.* 0.31 m
1. Fossil podsol developed in a sequence of yellow and grey sands with an iron-rich horizon *c.* 0.17 m below the top of the unit. at least 0.56 m

Six pollen assemblage zones (Figure 8.8) were recognized by Edwards *et al.* (1976), although the upper two (T–5 and T–6) related to the present soil horizon (bed 5) and a single pollen spectrum (T–4) was from a sandy horizon in the till which was considered to have been reworked from the sands beneath (bed 1). Within the basal sands below the iron-rich horizon, Edwards *et al.* identified a pollen assemblage zone (T–1) that contained high proportions of *Alnus*, Gramineae and *Plantago lanceolata*. Also present were low frequencies of *Betula*, *Quercus* and *Corylus* pollen. One sample had up to 50% Filicales spores. The iron-rich horizon yielded a single pollen spectrum (T–2), markedly different from that in the sand below (zone T–1) with little *Alnus*, high values of *Pinus* pollen, a significant level of *Calluna vulgaris* pollen and a reduced percentage of Gramineae. Above this, and coinciding with the interbedded sequence of sands and organic horizons, pollen counts (zone T–3) were dominated by Gramineae and there was a low representation of tree pollen and an erratic component of *Calluna vulgaris*.

Romans (1977) added the further observations that the A horizon at the top of the buried soil was composed of heavily charred organic material together with coniferous charcoal and that the deposition of this material was contemporaneous with the development of frost cracks in the soil.

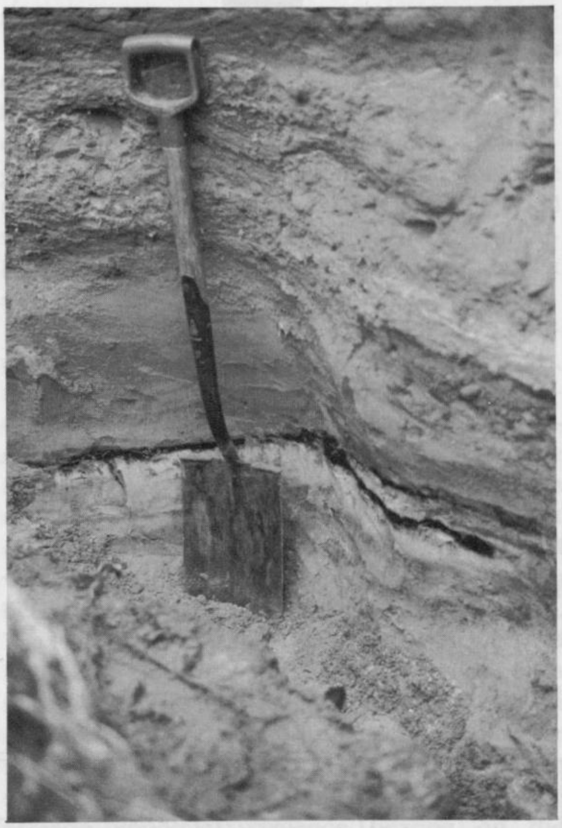
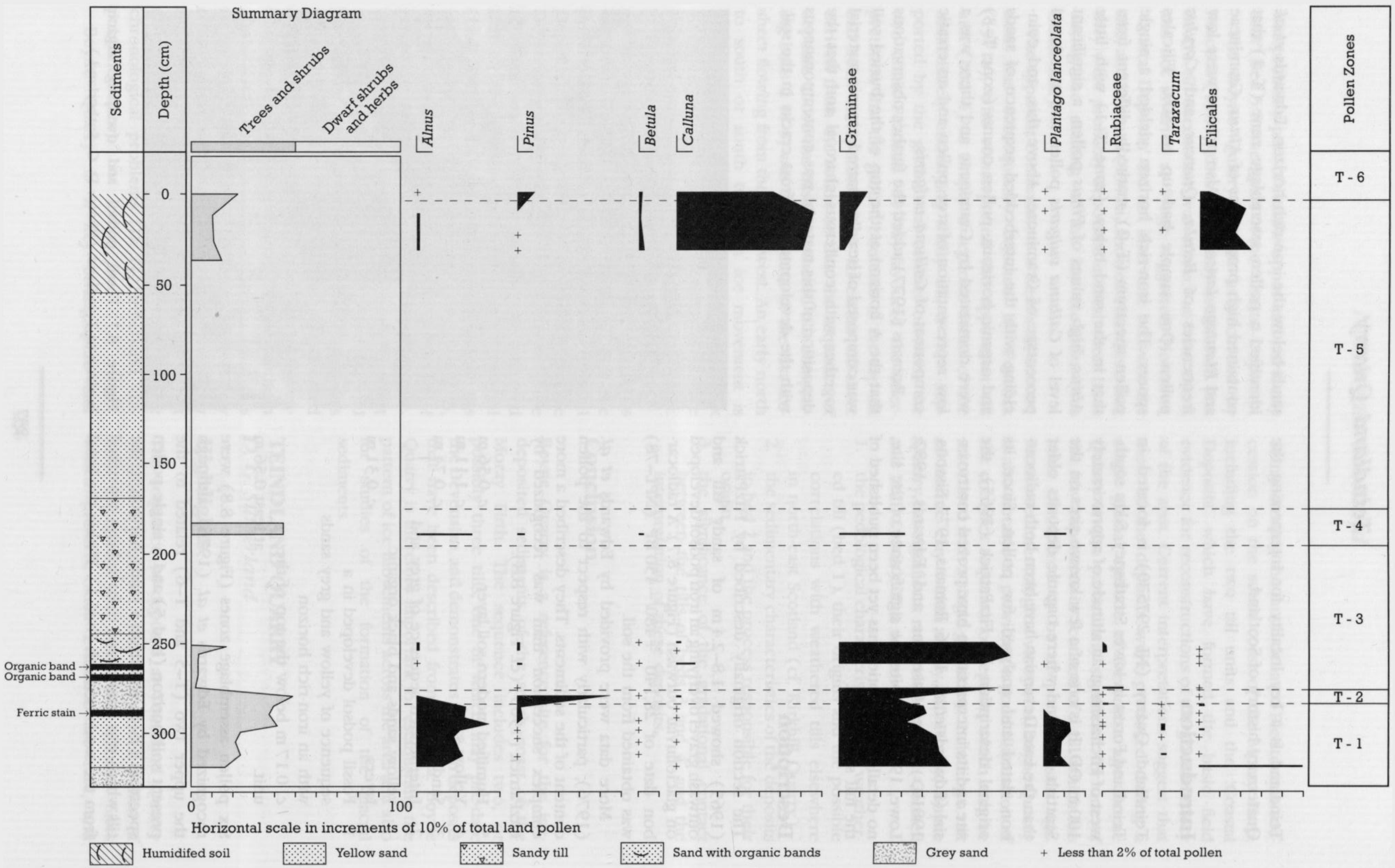


Figure 8.7 Fossil podsol and overlying organic horizon at Teindland. (Photo: D. G. Sutherland.)


Sediments
Depth (cm)
Summary Diagram
Trees and shrubs
Dwarf shrubs and herbs
Alnus
Pinus
Betula
Calluna
Gramineae
Plantago lanceolata
Rubiaceae
Taraxacum
Filicales
Pollen Zones
T - 6
T - 5
T - 4
T - 3
T - 2
T - 1
0
50
100
150
200
250
300
Organic band
Organic band
Ferric stain
0
100
Horizontal scale in increments of 10% of total land pollen
Humidifed soil
Yellow sand
Sandy till
Sand with organic bands
Grey sand
+ Less than 2% of total pollen

Interpretation

FitzPatrick (1965) considered that the degree of soil development was the product of interglacial conditions and cautioned that the radiocarbon date on the soil should be regarded as minimal because of the lack of alkali pre-treatment. The site therefore apparently revealed evidence for a period of glaciation followed by an interglacial (?Ipswichian) then periglaciation and further glaciation (?Late Devensian).

Interpretation of the pollen data was made difficult by the possibilities of reworking during erosion of the palaeosol, differential pollen preservation in soils and downwashing of pollen grains through the sandy sediments. These difficulties notwithstanding, Edwards *et al.* (1976) suggested that zone T–1 represented the vegetation of an interglacial, and drew attention to the similarities in the pollen spectra dominated by *Alnus* and *Plantago lanceolata* and pollen assemblages from the later part of certain interglacial sequences assigned to the Ipswichian in East Anglia (see Phillips, 1976). The sole spectrum comprising zone T–2 was considered most probably to represent the closing phase of the interglacial represented by zone T–1, possibly coinciding with the period of podsol formation.

Zone T–3 was more complex and more difficult to interpret. Edwards *et al.* thought that the basal spectrum in this zone might either indicate cold climatic conditions immediately following the interglacial, or it was part of the sequence of interbedded sand and organic horizons that produced the remainder of the samples in zone T–3. These last were considered to relate to an interstadial phase and, accepting the radiocarbon date of FitzPatrick (1965), this interstadial was assigned a Middle Devensian age. The overlying sediments (bed 3) were considered to be the product of a glacial episode, the fabric of the sandy till indicating ice movement from S60°E to S61°E.

This last interpretation was disputed by Romans (1977), who considered that there was no till exposed at Teindland, but rather that the sediments overlying the buried soil were emplaced by solifluction. He therefore argued that the site had not been glaciated during the Devensian, and inferred a very cold climate during the final phase of soil development from his observations of frost cracks in the soil.

The problem of using the radiocarbon date to infer a Middle Devensian age for part of the sequence was raised by Sissons (1981b). In response, Caseldine and Edwards (1982) provided new radiocarbon age estimates of 40,710 ± 2000 BP (UB–2121) and 38,400 ± 1000 BP (UB–2209), the material for which had been subjected to both acid and alkali pre-treatment. However, as with other interstadial or interglacial sites (for example, Kirkhill and Fugla Ness), finite radiocarbon dates are not on their own sufficient evidence to assign a deposit to the Middle Devensian (Sissons, 1982c). Sissons went on to suggest that, if indeed the Teindland site did contain evidence for interglacial and subsequent interstadial conditions, then it would be possible to interpret the interstadial as having occurred during the Early Devensian during the period immediately after the last interglacial, a suggestion that had previously been partially advanced by Edwards *et al.* (1976) for the basal sample in their pollen assemblage zone T–3.

Lowe (1984) also raised a number of questions concerning the interpretation of the pollen data from Teindland, considering it necessary to obtain more information before either an interglacial or an interstadial interpretation could be unequivocally upheld. In addition, the published sections for the site are greatly simplified (Sutherland, 1984a, unpublished data) and a complex sequence of sediments overlies the soil horizon.

Despite the controversy surrounding the interpretation of the Teindland Quarry sediments, they hold great potential for providing information on Devensian and possibly earlier environments. The site is one of the very few accessible interstadial or interglacial sites on the Scottish mainland (see for example, Clapperton, 1977). It is one of only a small number of sites in Scotland with deposits to which an interglacial origin has been ascribed (see Kirkhill, Sel Ayre, Fugla Ness, Toa Galson in North-west Coast of Lewis and Dalcharn) and the only site at which both interglacial and interstadial deposits have been interpreted as occurring in superposition. Further research should result in clarification of the stratigraphy and it is apparent that the site should provide important evidence bearing on the question of both Early and Late Devensian glaciation of Scotland (Sutherland, 1984a).

Figure 8.8 Teindland: relative pollen diagram showing selected taxa as percentage of total land pollen (from Edwards *et al.*, 1976; Lowe, 1984).

Conclusion

Teindland Quarry is a site of great importance for Quaternary studies in Scotland. The sequence includes organic deposits which pre-date the last (Late Devensian) glaciation. They appear to comprise sediments formed in both interstadial and interglacial climatic phases (that is, respectively, in a warmer interlude within an ice age (glacial) and a warmer phase between two separate glacials), but their ages are not yet unequivocally established. As one of only a few sites where such deposits are accessible, Teindland is a key locality for further research to amplify the Quaternary history of Scotland. The origin of the sediments overlying the organic deposits is also controversial and has a bearing on the argument about whether parts of north-east Scotland were not covered by the last ice-sheet.

CASTLE HILL

D. G. Sutherland

Highlights

Deposits exposed in the coastal section at Castle Hill include a complex sequence of glacial, glaciolacustrine and possibly marine sediments. Organic remains, including shells of marine molluscs and pollen, are also present in some of the beds. Although the importance of the site for interpreting the Quaternary history and changing sedimentary environments of the Moray Firth coast is firmly established, the full details of the record await further investigation.

Introduction

Castle Hill (NJ 794643), a coastal section at Gardenstown, demonstrates an important sequence of Pleistocene sediments, the interpretation of which is fundamental to an understanding of the timing and mode of the last glaciation of the north coast of Buchan. The site has been described in most detail by Jamieson (1906), Read (1923) and Peacock (1971a), and Jamieson (1865) provided a list of marine shells collected at the locality. A progress report of current research was given in Sutherland (1984b). There is, however, no overall agreement as to the stratigraphy of the site, nor is the chronology of the events recorded at Castle Hill established.

Description

Jamieson (1906) recorded a basal layer of partly worn clasts mixed with earthy debris that was overlain by a sequence of shelly sands and clays, which he considered to be a marine deposit. He did not report any till in the sections. Read (1923), however, noted a sequence comprising a basal layer of 'gravelly material', red till and, above, a series of sands and clays Peacock (1971a) recorded a basal till overlain by a sequence of shelly sands, gravels and clays, the last being pebbly and till-like in one bed. Overlying the shelly sediments was a bed of dark grey silt and the section was capped by around 17 m of fine-grained non-fossiliferous, micaceous, yellow sand. A radiocarbon date of >39,500 BP (Birm–191b) was reported by Peacock (1971a) from the shelly horizons, but this failed to resolve the age of the deposits.

The full succession was not observed by Sutherland (1984b), but he identified the following sequence:

11.	Silts, sands and minor clays.	*c.* 17 m
10.	Dark grey, laminated silts and fine sands.	?
9.	Red-brown till.	?
8.	Gap.	10 m
7.	Bedded, medium sands and silts.	?
6.	Shelly gravel.	0.1 m
5.	Irregularly bedded and disturbed, yellow, medium sands and massive, grey clays.	*c.* 2 m
4.	Dark grey, massive clay.	*c.* 1.5 m
3.	Organic sand.	0.2–0.6 m
2.	Angular, platy clasts of Dalradian metasediments in a loose sandy matrix with occasional bedded sand lenses.	0.8–2.0 m
1.	Weathered Old Red Sandstone bedrock.	

The clasts in bed 2 comprise Dalradian metasediments indicating derivation from the slopes immediately to the west of Castle Hill. The upper part of bed 5 was thought to be slumped. Sutherland was uncertain as to whether the organic sand (bed 3) was part of the slumped material or whether it represented an interstadial deposit. The bedding in bed 7 indicated deposition of the sands by a west to east current. No clearly *in situ* beds were reported by Sutherland in the gap in the section, but minor exposures revealed very shelly gravels, sands and massive, grey clays. Bed 9, the only till encountered at Castle Hill, formed a bench around the hill and was similar to till on the neighbouring hill slopes. One sample from bed 10 had an organic content of 14% and a sparse pollen assemblage, dominantly of *Pinus* grains; the upper part of the silts was involuted and cracked. Cross-bedding in the lower 2–3 m of bed 11 indicated deposition by a current flowing from N35°W, and in the upper part, dewatering structures were present.

Sutherland (1984b) also provided additional information on the age of the deposits: amino acid analyses (D-alloisoleucine : L-isoleucine ratios) of two shell fragments of *Arctica islandica* (L.) from the shelly gravel below the till suggested that the shells were of Ipswichian to Devensian age. The details are:

Laboratory No.	Ratio	
	Free	Total
BAL–309B	0.333	0.097
BAL–309C	0.366	0.176

Information on the Castle Hill fossil shells has been summarized as follows by J. D. Peacock (unpublished data). The Castle Hill locality was examined by Miller (1859, p. 333) and shells of marine molluscs in the Hugh Miller Collection in the Royal Museum of Scotland labelled 'Glacial shell beds, Gamrie, Banff' were almost certainly collected from this site (J. D. Peacock, unpublished data). They include paired valves of *Macoma balthica* (L.), *M. calcarea* (Chemnitz) and *Tridonta montagui* (Dillwyn) as well as fragments of *Timoclea ovata* (Pennant). These are partly enclosed in a matrix of coarse-grained, slightly clayey sand. *Arctica islandica* (L.) occurs only as umbonal fragments. The bed from which the shells were collected probably corresponds to bed 7 of Jamieson (1906), bed 5 of Peacock (1971a) and bed 6 of Sutherland (1984b). Jamieson (1906) listed 25 species of mollusc from this locality, many occurring as entire shells. The fauna as a whole is of high-boreal to low-arctic aspect and the excellent preservation of the paired valves suggests that the bed itself is either *in situ* or was transported and deposited by ice *en masse* without significant deformation (see Boyne Quarry).

Interpretation

Read (1923) assigned the sands and clays that he described to his Banffshire 'Coastal Deposits', which he considered to pre-date the last glaciation (from the south) of this coastal area. The shelly deposits described by Peacock (1971a) were considered by him to be the product of the last glaciation (from the north-west) of the area, and the upper sequence of grey silts and yellow sands he assigned to the Banffshire 'Coastal Deposits' which, he argued, had been deposited in an ice-dammed lake during the retreat of the last (Late Devensian) ice-sheet. This lake drained southwards along the Afforsk meltwater channel (NJ 790623).

The Castle Hill sequence is important for resolving the problems of the last glaciation of the eastern Moray Firth coast. Most workers are agreed that the last till to be deposited along this coastline was the product of glaciation from the north-west (Jamieson, 1906; Synge, 1956; Hall, 1984b; Sutherland, 1984a; Hall and Connell, 1991). Both Read (1923) and Bremner (1928, 1934a) advocated later glaciation to explain the movements of erratics and the sequence of meltwater channels but, with the exception of a few sections, no till has been ascribed to this later glaciation. Those sections originally considered to show an upper till have been reinterpreted as either due to complex glacial deposition (Simpson, 1955) or solifluction (Synge, 1956; Peacock, 1971a). The till (bed 9) at Castle Hill identified by Sutherland (1984b) is therefore considered to have been deposited during this period of glaciation from the north-west.

Debate, however, surrounds the date of the glaciation that deposited the till at Castle Hill. The majority opinion is that the last glaciation of this area was during the Late Devensian (Synge, 1956; Peacock, 1971a; Clapperton and Sugden, 1977; Hall, 1984b), but Sutherland (1984a) has suggested that the Late Devensian ice limit may have lain to the west and that the last glaciation here was an Early Devensian event (see also Sutherland, 1981a). The available dating evidence from Castle Hill does not allow these two conflicting interpretations to be resolved.

The sediments overlying the till at Castle Hill (beds 10 and 11) are most probably glaciolacustrine sediments, as envisaged by Peacock (1971a), but the possibility of an organic cryoturbated horizon in these deposits, as reported by Sutherland (1984b), may indicate a more complex history than the brief existence of an ice-dammed lake during a period of deglaciation. The sediments underlying the till are of uncertain origin. They may represent a period of lacustrine sedimentation during ice advance or possibly, in part, marine sedimentation, as suggested by Sutherland (1981a).

Castle Hill has one of the thickest and most complex sequences of Pleistocene sediments along the north Buchan coast. The site is important for elucidation of the glacial chronology of this area, and with possibly two organic horizons within the sequence and abundant marine mollusc shells in certain strata, including one bed possibly *in situ*, there is considerable potential for dating the events represented by the sediments. More widely, the site will ultimately provide evidence relevant to the debate on the extent of the Late Devensian ice-sheet and the possibility of ice-free areas remaining in north-east Scotland at the maximum of that glaciation.

Conclusion

Although the sequence of deposits at Castle Hill has a long history of research, the ages and origins of the different beds are not yet fully established. The site is nevertheless important because of the dating potential provided by the organic contents of the deposits. Further research at Castle Hill should help significantly to resolve the question of the timing of the last glaciation of the eastern Moray Firth coast and the detailed sequence of geomorphological changes that occurred both before and after that event.

KIPPET HILLS

J. E. Gordon

Highlights

The landforms and deposits at Kippet Hills include an excellent assemblage of glaciofluvial features formed during the melting of the Late Devensian ice-sheet. They are also noted for their erratic content and shells of Early Pleistocene marine molluscs, derived from sources offshore. The locality provides important evidence for interpreting ice movements and the pattern of deglaciation in the coastal lowlands north of Aberdeen.

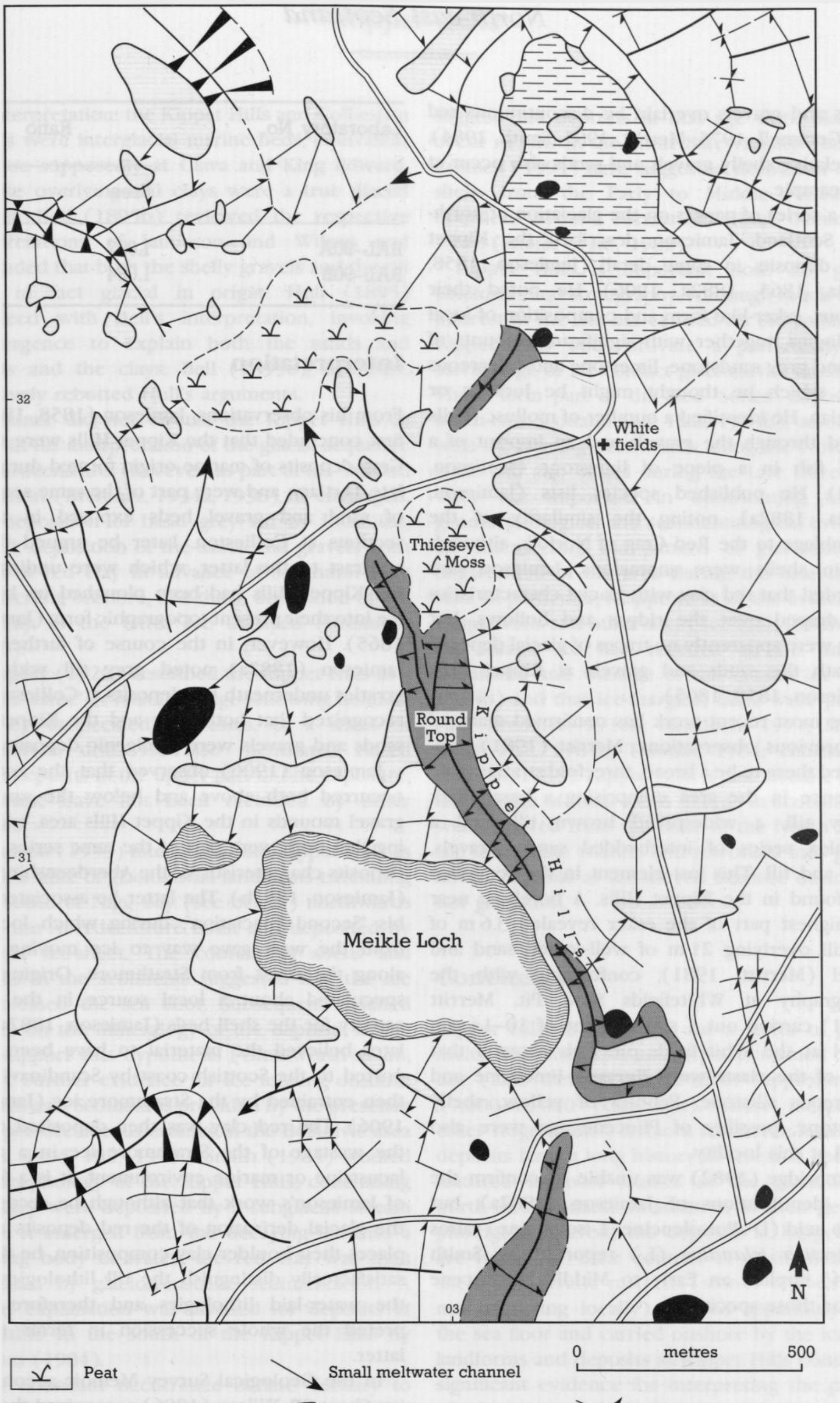
Introduction

The Kippet Hills (NK 030315) are located 7 km east of Ellon and comprise an esker ridge and an area (*c.* 10 km^2) of hummocky, ice-contact glaciofluvial deposits associated with the onshore movement of ice during the Late Devensian. Several kettle holes are present, including the impressive example now occupied by Meikle Loch. In addition, the deposits are noted for an assemblage of fossil shells similar to that of the Red Crag of East Anglia, believed to have been picked up from the floor of the North Sea and incorporated into the deposits by the ice. The locality has featured frequently in the literature on glacial studies in north-east Scotland, notably in the work of Jamieson (1858, 1860a, 1865, 1882a, 1906), and considerable attention has been focused on the origin of the deposits and the source of the shells (Wilson, 1886; Bell, 1895b, 1895c; Hull, 1895; Gregory, 1926; Simpson, 1955). The most recent work on the site is that of Gemmell (1975), Merritt (1981), Cambridge (1982) and Smith (1984).

Description

Extensive sand and gravel deposits in the Kippet Hills area form a striking assemblage of ice-contact glaciofluvial landforms (Gemmell, 1975; Merritt, 1981; Smith, 1984). These comprise a 3 km long esker ridge up to 15 m high (the Kippet Hills) and associated kames, kettle holes and terraces (Figure 8.9). The esker ridge continues northwards into an undulating, triangular-shaped feature (*c.* 0.3 km^2 in area), interpreted by Smith (1984) as a kettled delta. On the west side of the esker, the basin occupied by Meikle Loch forms a large kettle hole some 800 m long. Exposures in Whitefields Sand Pit (NK 032321) have revealed up to about 12 m of

Figure 8.9 Geomorphology of the Kippet Hills (from Smith, 1984).



White fields
Thiefseye Moss
Round Top
Kippet Hills
Meikle Loch
32
31
03
N
0 metres 500
Peat
Terrace surface
Flattish area
Kettle hole
Small meltwater channel
Esker
Break of slope
Road
Ridge
Large meltwater channel

sands and gravels overlain by discontinuous red till (Gemmell, 1975; Merritt, 1981; Smith, 1984). Correlative shelly gravels and sands also occur at Bellscampie.

In a series of papers on the glaciation of north-east Scotland, Jamieson described the Kippet Hills deposits in some detail (Jamieson, 1858, 1860a, 1865, 1882a, 1906). He noted their sinuous, esker-like form and composition of local lithologies, together with significant amounts of red and grey sandstone, limestone and calcareous shale which he thought might be Jurassic or Permian. He identified a number of mollusc shells mixed through the gravels and an imprint of a fossil fish in a piece of limestone (Jamieson, 1858). He published species lists (Jamieson, 1860a, 1882a), noting the similarity of the assemblage to the Red Crag of Norfolk, although certain shells were anomalous. Jamieson also recorded that red clay with glacial characteristics was draped over the ridges and hollows, but there were apparently no traces of glacial deposits beneath the sands and gravels at Kippet Hills (Jamieson, 1858, 1865).

The most recent work has confirmed many of the previous observations. Merritt (1981) considered there to be a broad, threefold stratigraphic sequence in the area comprising a basal, dark clayey till, a widespread brown till, and a complex series of interbedded sands, gravels, clays and till. This last element in the sequence was found in the Kippet Hills. A borehole near the highest part of the esker revealed 3.6 m of red till overlying 21 m of well-sorted sand and gravel (Merritt, 1981), conforming with the stratigraphy at Whitefields Sand Pit. Merritt (1981) carried out a stone count of 10–14 mm gravel at the Whitefields pit. This showed that 41% of the clasts were ?Jurassic limestone and calcareous siltstone. Pebbles of yellow, shelly sandstone, possibly of Pliocene age were also found at this locality.

Cambridge (1982) was unable to confirm the shell identifications of Jamieson (1882a), but amino acid (D-alloisoleucine : L-isoleucine) ratios on *Arctica islandica* (L.) reported by Smith (1984) implied an Early to Middle Pleistocene age for those specimens:

Laboratory No.	Ratio	
	Free	Total
BAL–90A	1.097	0.537
BAL–90B	1.084	0.586

Interpretation

From his observations, Jamieson (1858, 1865) at first concluded that the Kippet Hills were ***in situ*** Crag deposits of marine origin formed during the late Tertiary, and were part of the same sequence of sand and gravel beds exposed in coastal sections at Collieston. Later he argued that in contrast to the latter, which were undisturbed, the Kippet Hills had been ploughed up by land ice into their present topographic form (Jamieson, 1865). However, in the course of further work Jamieson (1882a) noted grey till with local erratics underneath the deposits at Collieston and recognized that both they and the Kippet Hills sands and gravels were glacigenic deposits.

Jamieson (1906) observed that the red clay occurred both above and below the sand and gravel mounds in the Kippet Hills area, concluding that both were part of the same series of red deposits characteristic of the Aberdeenshire coast (Jamieson, 1882b). The latter he associated with his 'Second Glaciation', during which local ice from the west gave way to ice moving north along the coast from Strathmore. Originally he speculated about a local source in the Ythan estuary for the shell beds (Jamieson, 1882a), but later believed the material to have been transported to the Scottish coast by Scandinavian ice then entrained by the Strathmore ice (Jamieson, 1906). The red clay was then deposited during the wastage of the Strathmore ice in a glaciolacustrine or marine environment. It is a feature of Jamieson's work that although he recognized the glacial derivation of the red deposits and in places their boulder clay composition, he did not satisfactorily distinguish the till lithologies from the water-laid lithologies and therefore interpreted the whole succession in terms of the latter.

In the Geological Survey Memoir accompanying Sheet 87, Wilson (1886) recognized the same sequence of deposits as Jamieson, but reversed the interpretation: the Kippet Hills and Collieston gravels were interglacial marine beds, equivalent to those supposedly at Clava and King Edward, and the overlying red clays were a true glacial deposit. Bell (1895b) reviewed the respective interpretations of Jamieson and Wilson and concluded that both the shelly gravels and the till were in fact glacial in origin. Hull (1895) disagreed with Bell's interpretation, invoking submergence to explain both the sands and gravels and the clays. Bell (1895c), however, effectively rebutted Hull's arguments.

Bremner did not discuss the Kippet Hills in detail in his interpretation of the glacial sequence in Aberdeenshire. However, as part of his 'Second Glaciation' (Bremner, 1934a, 1938), he envisaged, first, deposition of basal grey till by local ice, second, deposition of the sands and gravels with bands of red clay in advance of Strathmore ice encroaching onshore, and third, deposition of the red clay as the latter ice decayed (Bremner, 1916b).

Gregory (1926) described the Kippet Hills as a 'pseudo-kame' or residual ridge following denudation, by unspecified processes, of a sheet of glaciofluvial drift. He also mentioned raised beach deposits in the upper part of one exposure, but these have not been recorded by other authors.

Simpson (1955) interpreted the Kippet Hills as part of a suite of glaciofluvial landforms extending from south of Nigg Bay (see below) northwards along the Aberdeenshire coast and deposited by the last ice-sheet. The content of shells and erratics in the sediments suggested that the ice had crossed the sea floor. Subsequent detailed studies on the mineralogy of the deposits in the area support this hypothesis (Glentworth *et al.*, 1964). Further evidence for ice moving onshore in north-east Scotland is provided by the presence of Upper Cretaceous erratics in the Belhelvie area (Gibb, 1905; Hill, 1915). Smith (1984) studied the morphology of the Kippet Hills, concluding that they were deposited by a subglacial stream where it emerged from the decaying ice into a standing body of water; the red clay was then deposited by glaciolacustrine sedimentation. A similar explanation was invoked for deposits at Strabathie to the south of the Kippet Hills by Thomas (1984).

The abundant occurrence of late Tertiary to Early Pleistocene erratics in a limited area around the Kippet Hills led Sutherland (1984a) to suggest that deposits of that age were likely to occur *in situ* in the immediate vicinity. Hall and Connell (1991) have suggested derivation of the shells from the Early to Middle Pleistocene Aberdeen Ground Formation, which occurs offshore (Stoker *et al.*, 1985).

Kippet Hills is important both for glacial landforms and stratigraphy. Although much of the interest in the site has centred on the sediments, Kippet Hills does provide a particularly fine assemblage of ice-contact glaciofluvial landforms. These form part of the Red 'Series' deposits in north-east Scotland (see Hall, 1984b), associated with ice moving northwards along the North Sea coast and also inland during the Late Devensian. They are important in contributing to the geomorphological and sedimentological evidence for interpreting the pattern of glaciation and deglaciation of the area during the Late Devensian. In particular, it appears from the evidence at Kippet Hills and other sites (see Hall, 1984b) that the inland ice had receded at the time of expansion and wastage of the coastal ice (Hall, 1984b) and that ice-marginal lakes were present (see Bremner, 1916b; Murdoch, 1977; Merritt, 1981; Hall, 1984b; Thomas, 1984; Thomas and Connell, 1985). Kippet Hills is also notable for an assemblage of fossil shells unique in Scotland that were derived from the floor of the North Sea in the immediate vicinity and reworked into glaciofluvial deposits as ice moved onshore during the last glaciation.

Conclusion

Kippet Hills is important for a series of glacial meltwater landforms and deposits formed by the last (Late Devensian) ice-sheet (approximately 17,000–16,000 years ago). These include an esker ridge, kames, terraces and kettle holes. The deposits have a long history of research and have featured in most studies of the glaciation of north-east Scotland. In addition to their geomorphological interest, the deposits at Kippet Hills are noted for their content of fossil molluscan shells and erratic material (stones of rock types not occurring locally) derived apparently from the sea floor and carried onshore by the ice. The landforms and deposits at Kippet Hills contribute significant evidence for interpreting the pattern of glaciation and deglaciation in this part of Scotland.

MUIR OF DINNET

J. E. Gordon

Highlights

The landforms at Muir of Dinnet include an assemblage of meltwater channels, eskers and related deposits. These are important in demonstrating the mode of deglaciation of the Late Devensian ice-sheet and the effects of topographic controls on the pattern of ice wastage. In addition, pollen and plant macro-fossils preserved in the sediments that infill the floor of Loch Kinord provide a detailed record of vegetational history and environmental changes during the Lateglacial and Holocene.

Introduction

The Muir of Dinnet site (centred on NJ 430000) occupies an area (*c.* 22.9 km^2) in the south-west corner of the Howe of Cromar, one of a number of major topographic basins in north-east Scotland, and part of the River Dee valley east of Ballater. It is important on three main accounts: first, for its fine assemblage of glaciofluvial landforms demonstrating the progressive downwastage of the Late Devensian ice-sheet (Clapperton and Sugden, 1972; Sugden and Clapperton, 1975); second, in a historical context as the site of the supposed Dinnet Readvance ice limit (Synge, 1956); and third, for the Lateglacial and Holocene pollen and plant macrofossil records preserved in the sediments of Loch Kinord (Vasari and Vasari, 1968; Vasari, 1977). The geomorphology of the area has a long history of investigation (Jamieson, 1860b, 1874; Barrow *et al.*, 1912; Bremner, 1912, 1916a, 1920, 1925a, 1931; Charlesworth, 1956; Synge, 1956; Sissons, 1967a; Clapperton and Sugden, 1972; Sugden and Clapperton, 1975; Maizels, 1985).

Glacial and glaciofluvial landforms

Description

The main glacial landforms of the area were described by Bremner (1931), Clapperton and Sugden (1972) and Sugden and Clapperton (1975). They include eskers and meltwater channels in the River Dee valley between Milton of Tullich and Cambus o'May and on the eastern flank of Culblean Hill, an extensive area of dead-ice topography comprising kames and kettle holes around Lochs Davan and Kinord, and spreads of outwash gravels extending eastwards from Cambus o'May across the Muir of Dinnet and eastwards from the two lochs (Figure 8.10). Additional landforms of note are the roches moutonnées on Cnoc Dubh, and river terraces are present along the margins of the River Dee. Palaeochannels are extensively developed on terrace surfaces (Bremner, 1931) and also down-valley to the east of Dinnet (Maizels, 1985; Maizels and Aitken, 1991). Various sections are present in small pits in the glaciofluvial deposits but have not been described in detail, and in sections along the River Dee the glaciofluvial deposits are seen resting on till.

Interpretation

Jamieson (1860b) first described gravel mounds in the Dee Valley east of Ballater and a great spread of water-rolled gravel extending across the Muir of Dinnet. Initially he explained the deposits as the product of marine processes (Jamieson, 1860b), but later reinterpreted them as moraines and an outwash spread representing a halt stage in the gradual retreat of the last ice-sheet from a limit on the coast at Aberdeen (see Nigg Bay) into the centre of the Cairngorms (Jamieson, 1874).

Barrow *et al.* (1912) noted Jamieson's observations and the gravelly nature of the moraines. They related the moraines and the associated outwash spread to a valley glacier debouching from the constriction of the Dee Valley at the Muir of Dinnet during a phase of local valley glaciation after the ice maximum episode.

Bremner (1912, 1920, 1931) subsequently described the deposits between Ballater and Dinnet in greater detail, concluding that they represented a distinct stage of valley glaciation equivalent to Geikie's Fourth Glacial Stage (Geikie, 1894). He based this conclusion on the interpretation of certain landforms, such as lateral moraines and marginal meltwater channels along the valley sides, moraines in the valley floor that were fresher than those down the valley and contrasts in the lithology and composition of two superimposed 'tills'. However, there was no conclusive evidence to suggest complete deglaciation or an interglacial period immediately prior

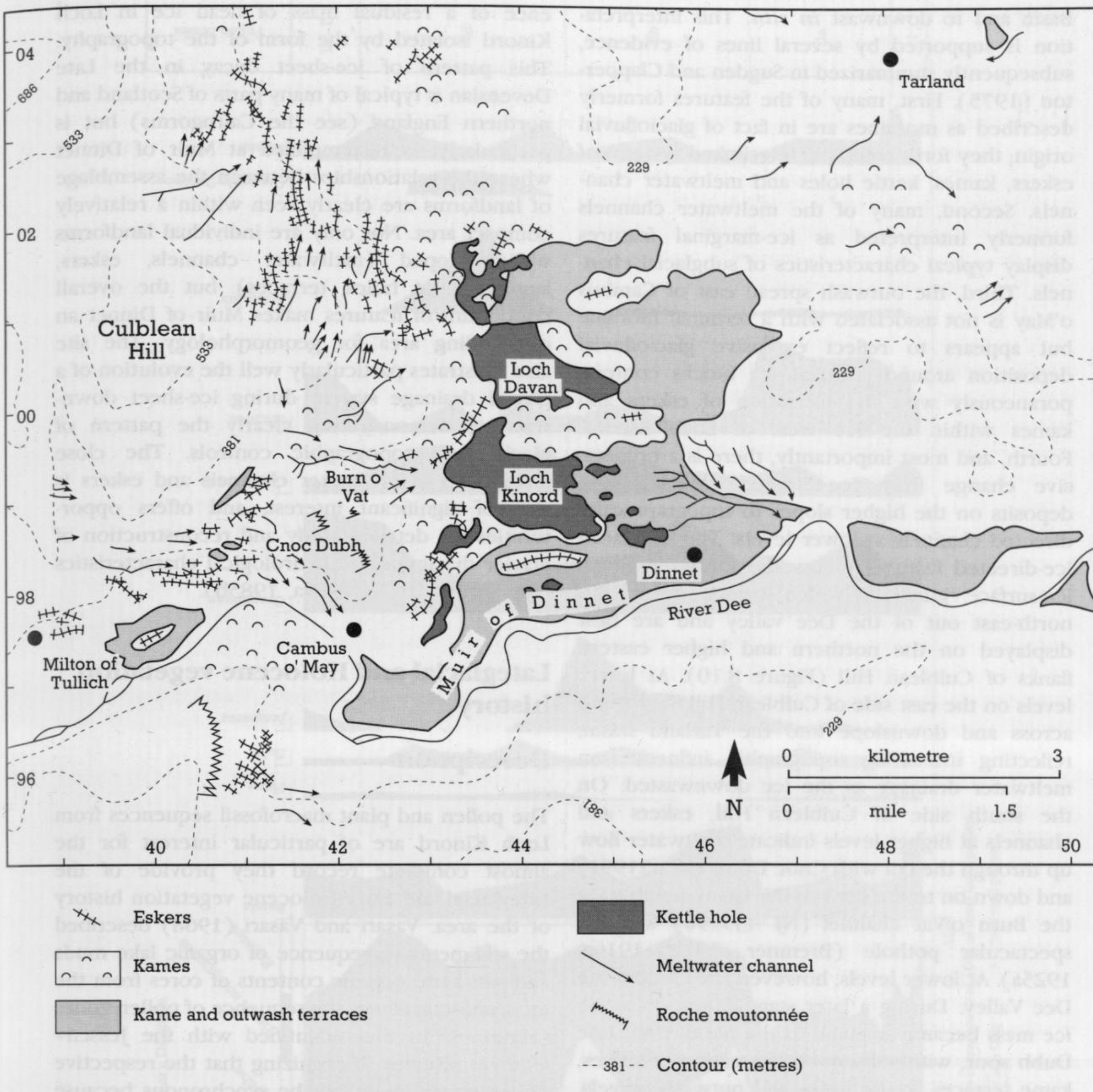


Figure 8.10 Geomorphology of the Muir of Dinnet (from Clapperton and Sugden, 1972).

to the valley glaciation.

Charlesworth (1956) believed the Dinnet deposits and landforms marked the local limit of his Stage M, a Lateglacial ice readvance equivalent to the Loch Lomond Readvance of Simpson (1933). Synge (1956), too, reached the conclusion that 'a massive terminal moraine' at Dinnet marked the limit of what he called the Dinnet Readvance, the local equivalent of the Loch Lomond Readvance. Sissons (1965, 1967a), however, correlated the Dinnet deposits with the Perth Readvance. He suggested they reflected the rapid downwasting of ice leading to stagnation and the formation of dead-ice topography following this readvance.

Subsequent detailed mapping in the Dinnet area by Clapperton and Sugden (1972) led them to dismiss the idea of an ice readvance in the Dee Valley. Instead, they related the assemblage of landforms and deposits to meltwater drainage in a progressively downwasting ice-sheet, concluding that their remarkable concentration near Dinnet was explained by the topography of the area, which allowed a large mass of ice to become isolated from the main ice-sheet in the Tarland

Basin and to downwast *in situ*. This interpretation is supported by several lines of evidence, subsequently summarized in Sugden and Clapperton (1975). First, many of the features formerly described as moraines are in fact of glaciofluvial origin; they form complex, interlinked systems of eskers, kames, kettle holes and meltwater channels. Second, many of the meltwater channels formerly interpreted as ice-marginal features display typical characteristics of subglacial channels. Third, the outwash spread east of Cambus o'May is not associated with a terminal moraine but appears to reflect extensive glaciofluvial deposition around stagnant ice blocks contemporaneously with the formation of eskers and kames within the ice west of Loch Kinord. Fourth, and most importantly, there is a progressive change from ice-directed channels and deposits on the higher slopes to topographically directed channels at lower levels. The subglacial ice-directed features follow the former regional ice-surface gradient, which trends north and north-east out of the Dee valley and are best displayed on the northern and higher eastern flanks of Culblean Hill (Figure 8.10). At lower levels on the east side of Culblean Hill they trend across and downslope into the Tarland Basin, reflecting increasing topographic influence on meltwater drainage as the ice downwasted. On the south side of Culblean Hill, eskers and channels at higher levels indicate meltwater flow up through the col with Cnoc Dubh (NJ 421991) and down on to the floor of the basin, notably via the Burn o'Vat channel (NJ 435996) with its spectacular pothole (Bremner, 1912, 1916a, 1925a). At lower levels, however, they follow the Dee Valley. During a later stage of ice decay an ice mass became stagnant in the lee of the Cnoc Dubh spur, with subsequent formation of kames, kame terraces, kettle holes and outwash gravels. Lochs Davan and Kinord are two particularly impressive kettle holes associated with this final stage of ice decay, being about 0.6 km and 1 km in diameter, respectively. Complete deglaciation had occurred at least by 11,520 ± 220 BP (HEL–418), the oldest date obtained from a core taken from Loch Kinord by Vasari (1977), and probably much earlier, since the Loch Builg area farther to the west is inferred to have been deglaciated before 12,000 BP (Clapperton *et al.*, 1975).

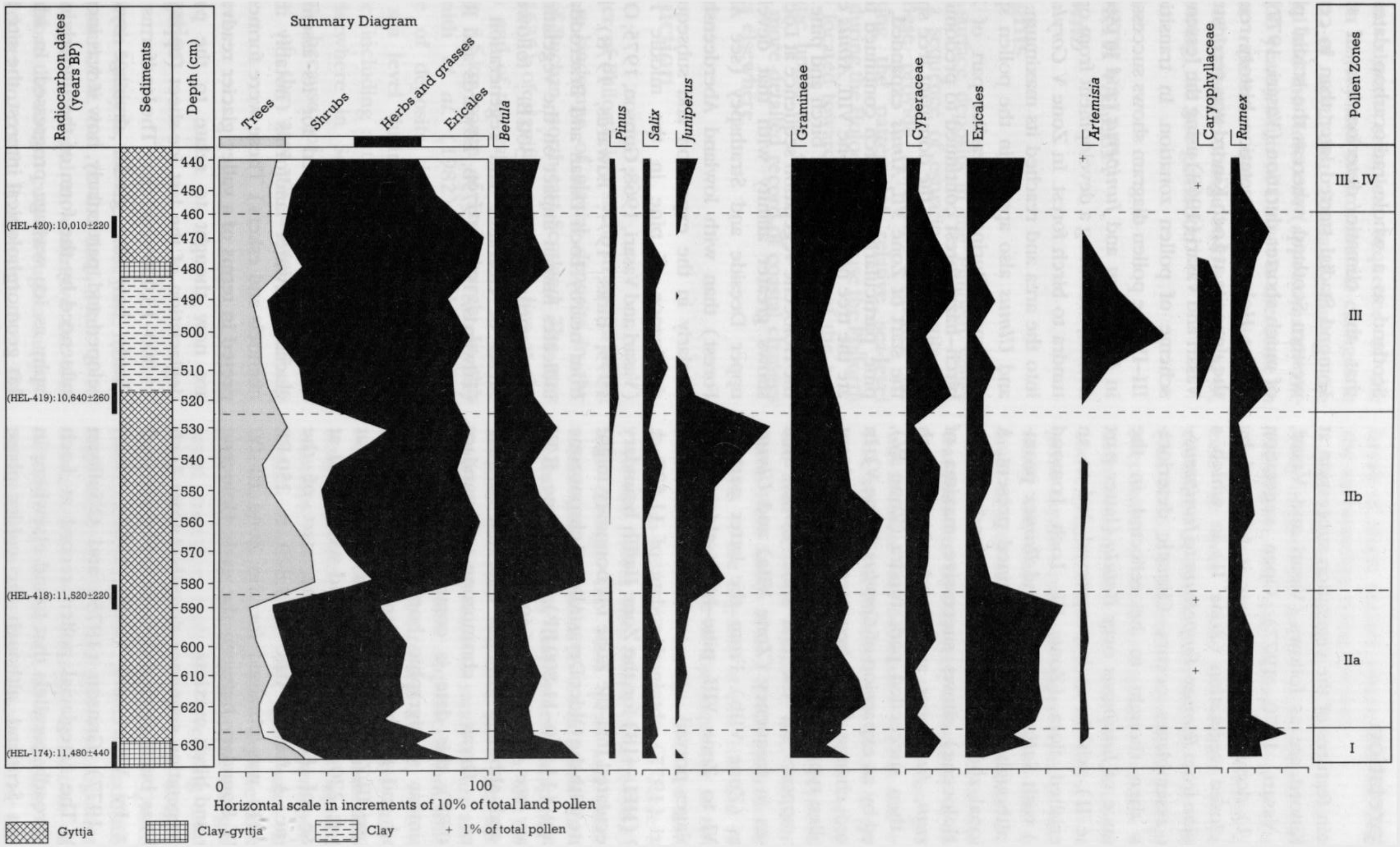
In the context of this latest interpretation of events in the Dinnet area it should be noted that Bremner (1920) had, much earlier, recognized the evidence for downwasting ice and the presence of a residual mass of dead ice in Loch Kinord isolated by the form of the topography. This pattern of ice-sheet decay in the Late Devensian is typical of many parts of Scotland and northern England (see the Cairngorms) but is particularly well-exemplified at Muir of Dinnet where the relationships between the assemblage of landforms are clearly seen within a relatively compact area. Not only are individual landforms well-developed (meltwater channels, eskers, kames, kettle holes, terraces), but the overall continuum of features makes Muir of Dinnet an outstanding area for geomorphology. The site also illustrates particularly well the evolution of a glacial drainage system during ice-sheet downwastage, demonstrating clearly the pattern of glacial and topographic controls. The close association of meltwater channels and eskers is also of significant interest, and offers opportunities for detailed study and reconstruction of glacier dynamics and hydrological characteristics (see Shreve, 1972, 1985a, 1985b).

Lateglacial and Holocene vegetation history

Description

The pollen and plant macrofossil sequences from Loch Kinord are of particular interest for the almost complete record they provide of the Lateglacial and early Holocene vegetation history of the area. Vasari and Vasari (1968) described the sediments (a sequence of organic lake muds and silts) and organic contents of cores from the loch, and correlated the sequence of pollen zones (Figure 8.11) they identified with the Jessen–Godwin scheme. Recognizing that the respective pollen zones might not be synchronous because of regional variations in environmental factors, Vasari (1977) obtained radiocarbon dates (HEL–174, and HEL–418 to HEL–421) to provide a geochronometric framework for the Lateglacial stratigraphy of the site. On this basis he was able to correlate the zonation of the Loch Kinord pollen record with the conventional British scheme and also with the continental sequence of chronozones.

Figure 8.11 Loch Kinord: relative pollen diagram showing selected taxa as percentages of total land pollen (from Vasari, 1977).



Radiocarbon dates (years BP)
Sediments
Depth (cm)
Summary Diagram
Trees
Shrubs
Herbs and grasses
Ericales
Betula
Pinus
Salix
Juniperus
Gramineae
Cyperaceae
Ericales
Artemisia
Caryophyllaceae
Rumex
Pollen Zones
(HEL-420):10,010±220
(HEL-419):10,640±260
(HEL-418):11,520±220
(HEL-174):11,480±440
III - IV
III
IIb
IIa
I
Horizontal scale in increments of 10% of total land pollen
Gyttja
Clay-gyttja
Clay
+ 1% of total pollen

Interpretation

The main features of the vegetation succession at Loch Kinord are as follows (Vasari and Vasari, 1968; Vasari, 1970, 1977). Open vegetation (Zone I) dominated by *Rumex* is followed by more closed vegetation (Zone II) in which a succession from *Rumex–Empetrum* to *Juniperus–Betula* assemblages occurs. Climatic deterioration is then thought to be reflected in the dominance of *Juniperus* over *Betula* (latter part of Zone II), which, as it progressed, led to an impoverished flora (Zone III; Loch Lomond Stadial) with *Salix*, *Artemisia* and *Rumex* prominent, although tree birch remained present. A transitional zone (III–IV; Loch Lomond Stadial–early Holocene) shows successive maxima of *Empetrum*, *Juniperus* and *Betula*. Light birch forests then succeeded park tundra (Zone IV), followed by an expansion of *Corylus* (Zone V). In a marked change *Pinus* becomes the dominant tree pollen type in the latter part of Zone VI, and *Ulmus* appears for the first time. *Alnus* then increases in frequency (Zone VIIa) and *Ulmus* declines (Zone VIIb). From the latter part of Zone VI to Zone VIII, pine–birch–alder forest assemblages prevail.

Vasari (1977) obtained a date of 11,520 ± 220 BP (HEL–418) for the Zone IIa/IIb boundary and speculated that the Zone I/II boundary might correlate with the Older Dryas/Allerød chronozone boundary (11,950–11,800 BP). The Zone II/III boundary was dated at 10,640 ± 260 BP (HEL–419), and although younger than the Allerød/Younger Dryas chronozone boundary (11,000 BP), this date is comparable to dates from similar stratigraphic horizons at sites in Scotland and northern England (Vasari, 1977). The Zone III/Zone III–IV boundary was dated at 10,010 ± 220 BP (HEL–420) and was placed at the rise of *Empetrum* at the start of the Holocene. A further date of 9,820 ± 250 BP (HEL–421) was obtained for the Zone III–IV/Zone IV boundary between the early Holocene juniper and birch maxima.

The vegetation sequence described from Loch Kinord has been discussed in its wider regional context by Vasari and Vasari (1968), Vasari (1970, 1977), Gunson (1975) and O'Sullivan (1975). The Lateglacial pollen record at Loch Kinord broadly parallels that found elsewhere in north-east Scotland, although the colder phase interrupting the Lateglacial Interstadial at several other sites is absent at Loch Kinord. In north-east Scotland as a whole radiocarbon dates suggest that the climatic deterioration of the Loch Lomond Stadial started later than in central and western Scotland, whereas the stadial phase was of much shorter duration (Vasari, 1977).

The Holocene vegetation history recorded in the deposits at Loch Kinord was reconstructed by Vasari and Vasari (1968) using the Jessen–Godwin scheme of pollen zonation. In transition Zone III–IV, the pollen diagram shows successive peaks in *Empetrum* and *Juniperus*, and in Zone IV, in *Betula*, indicating a development from open park-tundra to birch forest. In Zone V *Corylus* spread into the area and reached its maximum; *Quercus* and *Ulmus* also appear in the pollen spectra in this zone. During the earlier part of Zone VI, birch–hazel forest continued to predominate, but later *Pinus* became the dominant tree species. At the start of Zone VII, *Alnus* expanded, although pine, particularly, and birch continued to dominate the tree pollen. In Zone VIII, *Alnus* expanded further at the expense of birch and pine. Overall, the Holocene vegetation sequence at Loch Kinord shows greater affinity with that developed in upper Deeside and Strathspey (see Abernethy Forest) than with lowland Aberdeenshire, particularly in the expansion and subsequent predominance of pine in the middle Holocene (Vasari and Vasari, 1968; Gunson, 1975; O'Sullivan, 1975; Birks, 1977; Edwards, 1978). Evidence from nearby Loch Davan and Braeroddach Loch indicates human impact on the vegetation of the area starting around 5300 BP, followed by a series of clearance and regeneration episodes (Edwards, 1978, 1979b; Edwards and Rowntree, 1980).

Conclusion

Muir of Dinnet is noted for its assemblage of glacial meltwater landforms (notably meltwater channels and eskers). These were formerly interpreted in terms of a valley glacier readvance, but are now thought to relate to the pattern of deglaciation of the last ice-sheet (approximately 14,000–13,000 years ago). The landforms illustrate clearly how the glacial drainage system developed and, particularly, how it was increasingly influenced by the form of the underlying topography as ice wastage progressed. In addition to this geomorphological interest, the site is important for the pollen and larger plant remains preserved in the sediments of Loch Kinord. These record an almost complete sequence of the vegetation history and environmental changes in this area of north-east Scotland during the Lateglacial and the Holocene (approximately the last 13,000 years). Muir of Dinnet is therefore an important reference area for interpreting the patterns of landscape change both at the end of, and following, the last glaciation.

PHILORTH VALLEY

D. E. Smith

Highlights

The sub-surface deposits in the Philorth Valley include a sequence of estuarine sediments and peat. These provide important evidence for interpreting the pattern of relative sea-level changes during the Holocene. Because the Philorth Valley is located towards the margin of the area of isostatic uplift, the deposits there have preserved a more detailed record of coastal changes than sites elsewhere.

Introduction

The Water of Philorth is a small stream draining through a landscape of glacial deposits in the district of Buchan, north-east Scotland. The area (NK 011635) of significant interest lies at the northern end of the valley, west of the farm of Milltown, 3.5 km south of Fraserburgh. In this area, Smith *et al.* (1982) have identified a sequence of deposits that record changes in relative sea level during the middle and late Holocene, including a transgressive episode not found elsewhere in Scotland. This record is important because of its location near the periphery of the area of isostatic uplift in Scotland.

Description

The Philorth Valley is, for the most part, narrow and unremarkable, but in the final 3 km of its course it opens out and an extensive flat area occurs before the stream cuts through a rampart of sand dunes to reach Fraserburgh Bay. The surface of the flat area is largely composed of a brown, silty clay with some areas of sand. A sharp break of slope occurs where this surface meets the surrounding rising ground.

The area was studied by Smith *et al.* (1982). They mapped the surface deposits and found that the brown, silty clay surface lies at a consistent altitude of between +2.2 m and +3.2 m OD, but rises to over +5 m OD where it becomes restricted at its southern margin, near The Neuk (NK 002624). Boreholes across the area proved a succession of sands and gravels overlain by peat, then brown, silty clay, and discontinuous sand above (Figure 8.12). Within the peat two minerogenic layers occur, an upper layer of micaceous sandy silt, which tapers up-valley and a lower layer of grey sand, irregularly distributed (Figure 8.12). The surface of the micaceous sandy silt was found to be relatively consistent in elevation at +1.22 m to +2.26 m OD, but the grey sand was found to vary between −1.15 m and +1.80 m OD; at Mains of Philorth, two layers of grey sand were recorded near the side of the valley.

The sequence of deposits is best represented in the area between Milltown and Philorth Home Farm. Here Smith *et al.* (1982) undertook pollen analysis of the deposits at one site and radiocarbon dates on part of the sequence at two sites. Radiocarbon dates were also obtained from a site further up-valley (Figure 8.12 and Table 8.1).

At the pollen site, Smith *et al.* (1982) found that through the basal peat and intervening minerogenic horizons to 0.4 m below the surface of the brown, silty clay, where sampling ended, the vegetational sequences span the early to middle Holocene. The basal peat, grey sand, and peat below the micaceous sandy silt are associated with early Holocene sequences indicating scattered stands of *Betula* and *Pinus*, with *Corylus* and *Salix* in the general area; the valley floor being subject to a fluctuating water table, with sedges, grasses, and a variety of aquatic communities including *Lemna*, *Potamogeton* and *Typha angustifolia*. The grey sand layer is associated with a temporary decline in aboreal pollen. The top of the peat above the grey sand layer, together with the overlying micaceous sandy silt and much of the peat above it, are associated with increasing values of *Quercus* and particularly of *Alnus*; the silt is associated with high values of *Pinus* and *Quercus*, together with a concentration of *Plantago maritima* and significant representation of freshwater aquatics, notably *Lemna* and *Potamogeton*. The top of the peat and the overlying brown, silty clay yielded pollen indicating *Betula–Quercus* woodland,

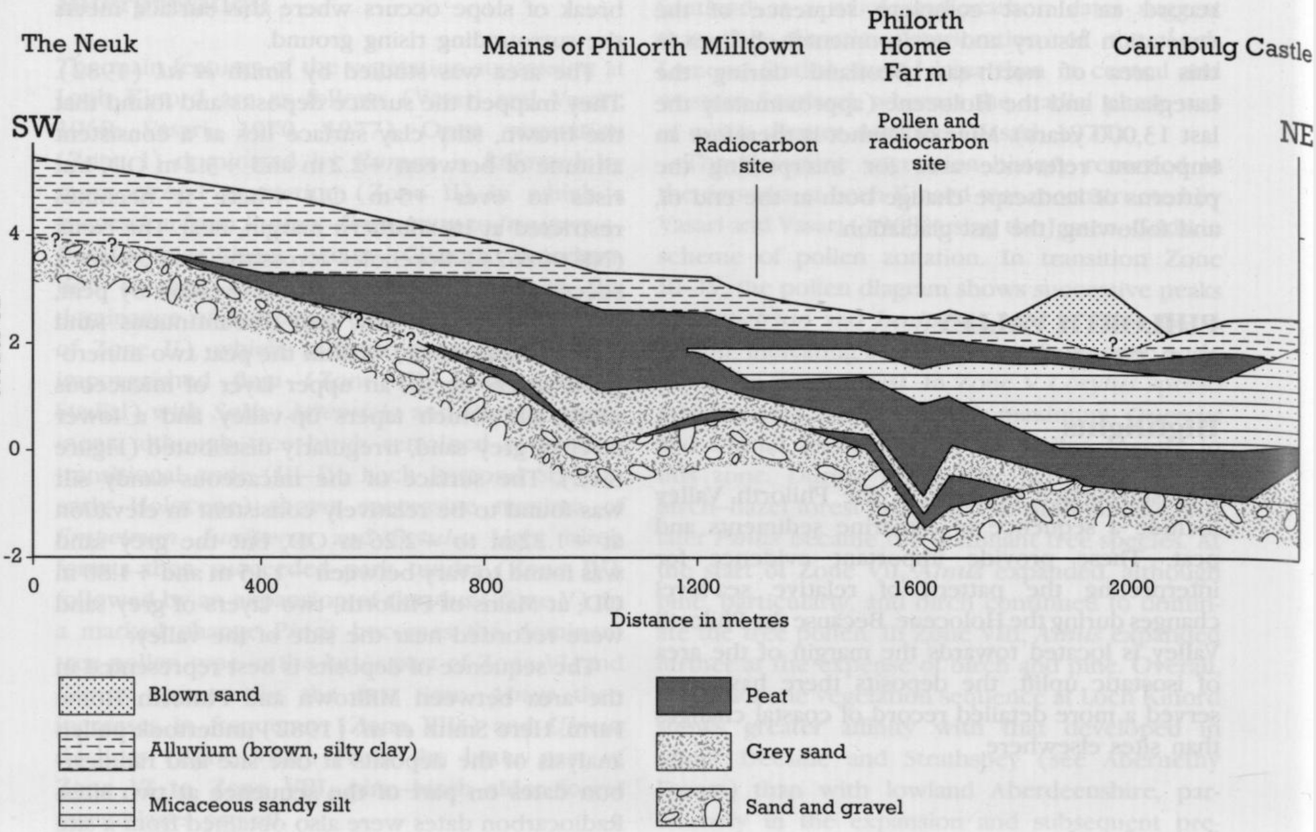


Figure 8.12 Section along the length of the Lower Philorth Valley showing the sequence of sediments (from Smith *et al.*, 1982).

with *Alnus* and local freshwater aquatic communities.

At the pollen site (Philorth Home Farm) and Milltown, peat above and below the micaceous, sandy silt was dated. At Mains of Philorth the sampling site was beyond the up-valley limit of the micaceous, sandy silt, and dates were obtained on peat from below the brown, silty clay and above and below two layers of grey sand (Table 8.1).

Interpretation

Both the pollen analysis and radiocarbon dates of Smith *et al.* (1982) indicate that the deposits which fill the lower end of the Philorth Valley accumulated during the Holocene. It seems likely that the grey sand layer is the deposit of a series of tsunami waves that struck the east coast of Scotland some 7000 years ago (e.g. Dawson *et al.*, 1988). In recent work (1990) the layer has been traced up-valley as far as The Neuk, where it tapers out at an altitude of 2.4 m OD. The two grey sand layers dated at Mains of Philorth lie at the side of the valley and may include colluvial material. One of them (the upper one) may equate with the extensive grey sand layer, but their provenance is uncertain.

The age and provenance of the micaceous sandy silt are better known. Both the pollen and the radiocarbon dates concur in indicating a middle Holocene age. The association of *Plantago maritima* pollen with the layer, together with the increase in representation of *Pinus* and *Quercus*, characteristic of a littoral depositional environment (Traverse and Ginsberg, 1966), indicate that the layer is of marine–estuarine origin, and Smith *et al.* maintain that this is the local expression of the Main Postglacial Transgression. They interpret the radiocarbon evidence as showing that the transgression was under way in the area by 6300 ± 60 BP, that it culminated after 6096 ± 75 BP, and that peat growth on the surface of the resulting deposit (the micaceous sandy silt) had commenced by 5700 ± 90 BP.

Table 8.1 Radiocarbon dates from sites in the Philorth Valley (after Smith *et al.* 1982)

Location	Details of sample	Altitude (metres OD) of sample at contact with minerogenic layer	14C date (years BP)	Laboratory number
Philorth Home Farm	Bottom 2 cm of peat above micaceous sandy silt	1.48	5700 ± 90	SRR–1660
Philorth Home Farm	Top 2 cm of peat below micaceous sandy silt	0.82	6300 ± 60	SRR–1661
Milltown	Bottom 2 cm of peat above micaceous sandy silt	1.82	5140 ± 60	SRR–1686
Milltown	Top 2 cm of peat below micaceous sandy silt	1.11	6095 ± 75	SRR–1687
Mains of Philorth	Top 1cm of peat below brown silty clay	2.59	4760 ± 60	SRR–1655
Mains of Philorth	Bottom 2 cm of peat above grey sand	1.51	6150 ± 250	SRR–1656
Mains of Philorth	Top 2 cm of peat below grey sand	1.47	6885 ± 90	SRR–1657
Mains of Philorth	Bottom 2 cm of peat above grey sand	1.40	7510 ± 120	SRR–1658
Mains of Philorth	Top 2 cm of peat below grey sand	1.34	8465 ± 95	SRR–1659

The brown silty clay present at the surface of the area is today often partially inundated during high tides, and would be even more so affected were it not for dykes along the lower Philorth. Smith *et al.* (1982) suggest that this deposit began to accumulate at about 4760 ± 60 BP as the result of a rise in relative sea level, and that it is still accumulating in places. The silty clay is essentially an estuarine deposit which becomes increasingly alluvial up-valley.

The deposits of the lower Philorth Valley contain evidence of tsunami activity dated at *c.* 7000 BP, and two major marine incursions, the Main Postglacial Transgression and the later one, after 4700 BP, that formed the surface mudflats. The earlier marine incursion in which the micaceous, sandy silt was deposited, culminated between 6096 ± 75 BP and 5700 ± 90 BP. It appears to have been the Main Postglacial Transgression, but is somewhat younger than that event further south, where ages of about 6200 BP in the Tay estuary (see Pitlowie) (Smith *et al.*, 1985b) and around 6800 BP in the Western Forth Valley (see below) (Sissons, 1983a) have been proposed. The Philorth dates, therefore, may be evidence for a time-transgressive shoreline (Smith *et al.*, 1983). Such diachroneity would accord with theories on the formation of relict shorelines in isostatically affected areas. Altitudes on the surface of the micaceous sandy silt (about +2 m OD) demonstrate the decline in altitude of the Main Postglacial Shoreline from the maximum altitudes of over 14 m OD at the head of the Forth Valley, near the centre of isostatic uplift (see Sissons, 1976b). In a recent publication, Cullingford *et al.* (1991) have identified detailed isobase patterns for the Main Postglacial shoreline in eastern Scotland. They place the Philorth Valley below the 2 m isobase and therefore close to the margins of Holocene isostatic uplift.

The second marine incursion identified in this area, in which the brown, silty clay was deposited, took place about 4760 ± 60 BP. It is unlikely to be found in many areas of Scotland. The pace of isostatic uplift over most of Scotland during the late Holocene would probably have exceeded regional sea-level rise. Only areas towards the periphery of the uplifted area would register the more minor fluctuations of the sea surface after the Main Postglacial Transgression. The Philorth Valley site is therefore uniquely valuable for studies of Holocene relative sea-level change in Scotland, and will repay further scientific enquiry.

Conclusion

The sediments in the Philorth Valley record sea-level changes in north-east Scotland during the Holocene. They show that a major coastal flood occurred about 7000 years ago and that there were two subsequent episodes when sea level was relatively higher than at present. This evidence allows comparisons with sites elsewhere in Scotland and contributes towards establishing the wider pattern of sea-level changes during the Holocene. The particular significance of the Philorth Valley lies in its location towards the margin of the area of isostatic uplift (the recovery of the Earth's crust following its depression by the weight of the ice-sheet); as such it preserves a more sensitive record of sea-level change than more central areas that have undergone greater uplift (where the ice was thicker) following the melting of the last ice-sheet.