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LIMITED MODIFICATION OF MID-LATITUDE LANDSCAPES BY ICE SHEETS: THE CASE OF NORTHEAST SCOTLAND

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ABSTRACT

The paper uses a case study in Scotland to examine the amount and processes of landscape modification by Quaternary ice sheets. There is an inverse correlation between the distribution of landforms of glacial erosion and pre-glacial landscape remnants in northeast Scotland. The implication is that in places ice sheets can preserve a pre-glacial landscape unscathed, while elsewhere they remove the pre-glacial weathered rock. The location of glacial protection or erosion is strongly influenced by the topography and its influence on former ice sheet flow and basal thermal regime. The classic glacially eroded landscape of areal scouring can be produced by the removal of only 10–50 m of weathered rock. Furthermore rock basins, often regarded as the hallmark of glacial erosion, may be directly inherited from the pre-glacial pattern of deep weathering.

KEY WORDS Glacial erosion Glacial protection Quaternary ice sheets Tertiary landforms Gruss Scotland

INTRODUCTION

The aim of this paper is to use a case study in Scotland to shed light on the amount and nature of landscape modification by Quaternary ice sheets. It is important to study the long-term effects of ice sheets on their beds in order to understand the rates and processes of ice sheet erosion and in order to appreciate the scale of sediment re-distribution both within an ice covered area and from land to sea that occurs during a glacial age. Direct estimates of the amount of erosion have been bedevilled by the difficulty of reconstructing the form of the pre-glacial topography in areas affected by glacial erosion and, as a result, different studies have yielded widely different estimates (Sugden, 1976). Indirect estimates of Quaternary ice sheet erosion have been made on the basis of sediment volumes presumed to have accumulated during glacial periods, for example in the western North Atlantic off Greenland and North America (Laine, 1980). As valuable as such indirect studies may be, they cannot on their own be expected to provide accurate information on the amount and spatial distribution of erosion beneath an ice sheet.

Northeast Scotland offers an exceptional opportunity to study the pattern and process of landscape modification by ice sheets directly and in considerable detail. There is a transition for a little modified, intricately preserved Miocene land surface to a fully modified glacial landscape within a distance of 30 km, which offers the opportunity to study progressive modification of a landscape by ice. The transition takes place on a lowland which is underlain by metamorphic rocks: this means that two important variables affecting ice sheet erosion, topography and lithology, may be held constant and attention focussed on the glaciological variables involved.

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The pre-glacial land surface is best preserved in central Buchan where it is marked by extensive deep weathering and the presence of Miocene river gravels (Figure 1). The deep weathering in northeast Scotland affects all rock types to varying degrees. At scales of less than 1 km^2, weathering depths are often highly variable, with juxtaposition of fresh outcrops with deep shafts and troughs of weathering. At scales of 1–10 km^2, however, rockhead profiles commonly show a succession of low risers and basins. The high ground of central Buchan preserves a highly kaolinitic weathering type, clayey gruss, and patches of kaolinized flint-rich river gravels of Neogene age. Over the rest of the area, however, the saprolites are of the less-mature gruss weathering type. Grusses formed under humid temperate environments and deep profiles developed during the Pliocene and early Pleistocene (Hall, 1985). Shallow profiles may be the truncated portions of deep profiles or a product of renewed interglacial weathering after stripping of earlier saprolites. That grusses antedate the last glaciation is shown by widespread incorporation of saprolitic material into Devensian tills.

Landforms of glacial erosion are common near the coast and in the Dee valley in the south and relate to ice sheets which crossed the area from the Scottish uplands in the west onto the coastal lowlands. The earliest recognized glacial event is an advance to an icefront in the west central North Sea in the early Middle Pleistocene (Stoker and Bent, 1985). At least two pre-Devensian glacial phases are recognized in Buchan (Hall, 1984) and during the Wolstonian cold stage Scottish ice extended at least 120 km northeast of Fraserburgh (Sejrup *et al*., 1984). Devensian ice was more restricted in extent, with a maximum limit *c*. 40 km east of the present coastline (Stoker, Long, and Fyfe, 1985). Extrapolations from the various ice limits in the west central North Sea using Nye's (1952) formula indicate ice thicknesses of 300–600 m in the study area, with greatest thicknesses during the Wolstonian cold stage. These calculations are intended only to provide a rough approximation of likely former ice thicknesses.

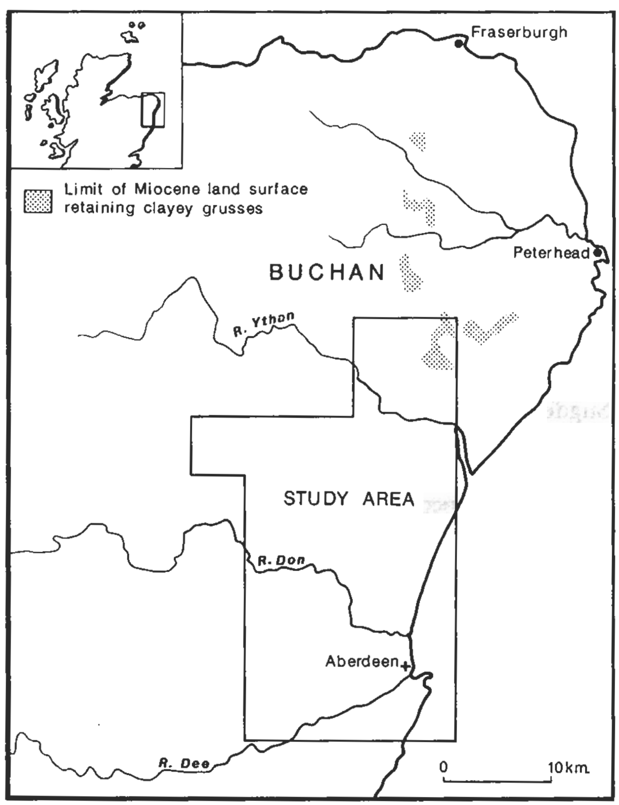

Figure 1. Northeast Scotland showing the location of the little modified Miocene land surface, the main rivers, and the study area

The methodology employed in this paper is to select a 40 × 20 km transect extending from the Miocene surface of central Buchan to the glaciated landscape of the Dee valley and to compare the distribution of landforms of glacial erosion with those of pre-glacial relicts along the transect. If there is an inverse correlation between the two distributions, i.e. the glacial landforms occur in areas with few pre-glacial relicts and vice versa, then it is reasonable to infer that the transect represents progressive modification of a pre-existing landscape by ice. If so then it is possible to tackle further questions. By adopting the ergodic device of substituting space for time, one can view different degrees of landscape modification along the transect as stages in the modification of the landscape by ice. This is an important way of approaching a study of the processes of ice sheet erosion and discovering, for example, whether it is the hills or valleys that become modified first. A second important question concerns the amount of erosion involved. If one can establish the depth of weathered rock in the unmodified area then the identification of weathered rock remnants in the glacially-modified areas places limits on the total amount of rock removed.

The study area consists of an undulating coastal lowland with broad basins at an altitude of 50–100 m overlooked by rounded hills with summits at 100–270 m. The prominent summits of Bennachie and Hill of Fare rise abruptly to 400–450 m 10 km west of the study area and form the eastern outliers of the extensive plateau country of the Eastern Grampians. Of the three longest rivers that cross the study area the Dee and Don originate in the uplands to the west of the study area, while the Ythan rises in central Buchan. The geology of the study area comprises Dalradian metamorphic rocks, dominantly pelitic and semi-pelitic, into which have been intruded Caledonian granitic and basic igneous masses (Figure 2). Old Red Sandstone sediments occur in fault-bounded basins at Aberdeen and Belhelvie and extend offshore. Dominant structural trends are SW–NE and SE–NW (Munro, 1986a).

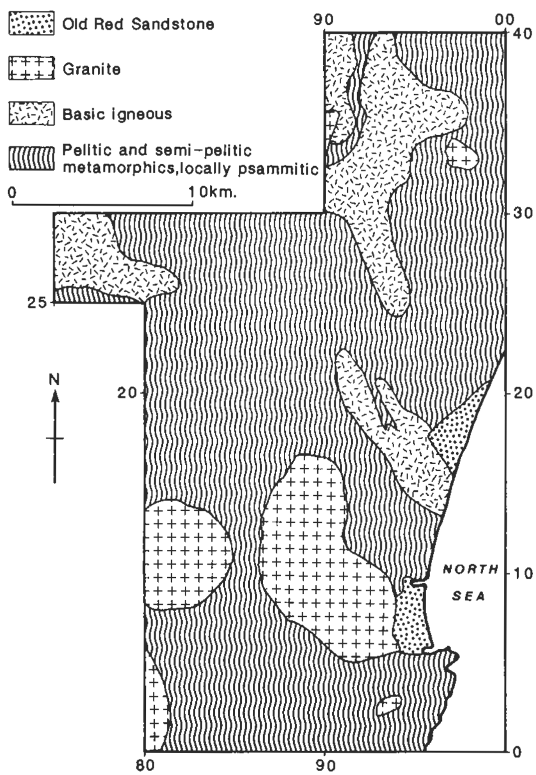

Figure 2. The bedrock geology of the study area

LANDFORMS OF GLACIAL EROSION

Methods

Figure 3 shows the type and distribution of landforms of glacial erosion in the study area. The map was constructed on the basis of fieldwork and air photograph interpretation in 1986. Areas of thick drift along the coast and along the major valleys as well as built up areas were excluded from consideration and their extent is shown in Figure 3. The greatest errors are likely to occur in the areas covered by tree plantations where the extent of glacial features may be somewhat underrepresented. However the overall wooded area is less than 10 per cent and any errors are unlikely to modify the basic pattern materially.

Several groups of glacially eroded landforms were identified. Glaciated rock knobs are shown where a bedrock bump occurs and displays either or both a smoothed stoss slope and/or a jointed, plucked lee slope. In a few cases striations are still visible on the smoothed stoss slope. Bedrock slabs which are exposed at the surface but do not show stoss/lee features are shown separately. There are two types of streamlined hill. One type involves a relatively narrow ridge in the lee of an exposed bedrock bump. The dimensions of the ridge vary with the dimensions of the bedrock bump, but are usually 100–500 m long, 50–100 m wide, and 5–15 m high. Although some ridges may consist of till, there are cases where the ridge has been excavated in bedrock and as a result all such streamlined features are included. The second type of streamlined hill occurs on a large scale and may be described as a rock drumlin. Typically the hill consists of a broad swell, blunt and broad in the west, and tapering smoothly to the east. The limits of individual hills grade smoothly into the surrounding lowland and the dimensions are therefore difficult to measure. However a height of 5–20 m, a length of 0·4–1·5 km and a breadth of 0·2–0·4 km at the broadest point seem characteristic. Streamlined hills at this scale are difficult to identify unambiguously in a lowland landscape with many smooth and gentle slopes and so a feature was only accepted as glacially streamlined if it satisfied the following conditions: (1) the hill is represented on 1:25,000 scale topographic maps by regular smooth contours without indentations and (2) its length is at least twice its width. Such a definition excludes a number of features which could well be glacially streamlined but it does have the merit of objectivity. A glacial origin for the hills so mapped is supported by the aerofoil plan-form typical of drumlins, the conformity of the direction of streamlining with other evidence of glacial movement (see later), and the lack of conformity with structural trends (Munro, 1986). It is uncertain to what extent the hill form reflects the underlying bedrock. In several cases till thickness of at least several metres is known to occur along the eastern flanks. However, shallow pipeline excavations have revealed bedrock on enough tapering eastern slopes to demonstrate that the main form of at least several streamlined hills is moulded in bedrock. In parts of the study area clear rock-cut meltwater channels are intimately associated with areas of bedrock bumps. In these cases the main channels are shown.

Results

Inspection of the morphology and distribution of the landforms of glacial erosion shown in Figure 3 allow two important initial conclusions to be drawn. First, the ice that produced the landforms flowed from WSW to ENE. This conclusion is borne out by the direction of streamlining, the pattern of stoss/lee topography on individual bedrock bumps, the orientation of both striations, and meltwater channels. Second, the ice flowed across the lines of the underlying topography, including the highest hill in the area, Brimmond, at 266 m. This implies ice sheet flow from the Scottish mainland offshore into the North Sea basin.

There is a clear contrast in both the type and density of landforms of glacial erosion along the transect. The variety and density of features is greater near the Dee valley in the south than in central Buchan in the north. In order to describe the features it is helpful to divide the transect into three.

1. South of the latitude of Brimmond Hill almost every hill is affected by glacial erosion. South of the River Dee is the heavily scoured Cran Hill. Here the western flank of the hill over an altitudinal range of 75 m is moulded into the form of rock knobs smoothed on the western flanks and plucked on their eastern flanks. Individual rock hummocks may be 25 m high. The top of the hill is corrugated on a scale of tens of metres with ridges extending eastwards from rock knobs. Rock meltwater channels incise both straight and sinuous courses over the hill. North of the river Dee the moulding is mostly in the form of streamlined hills.

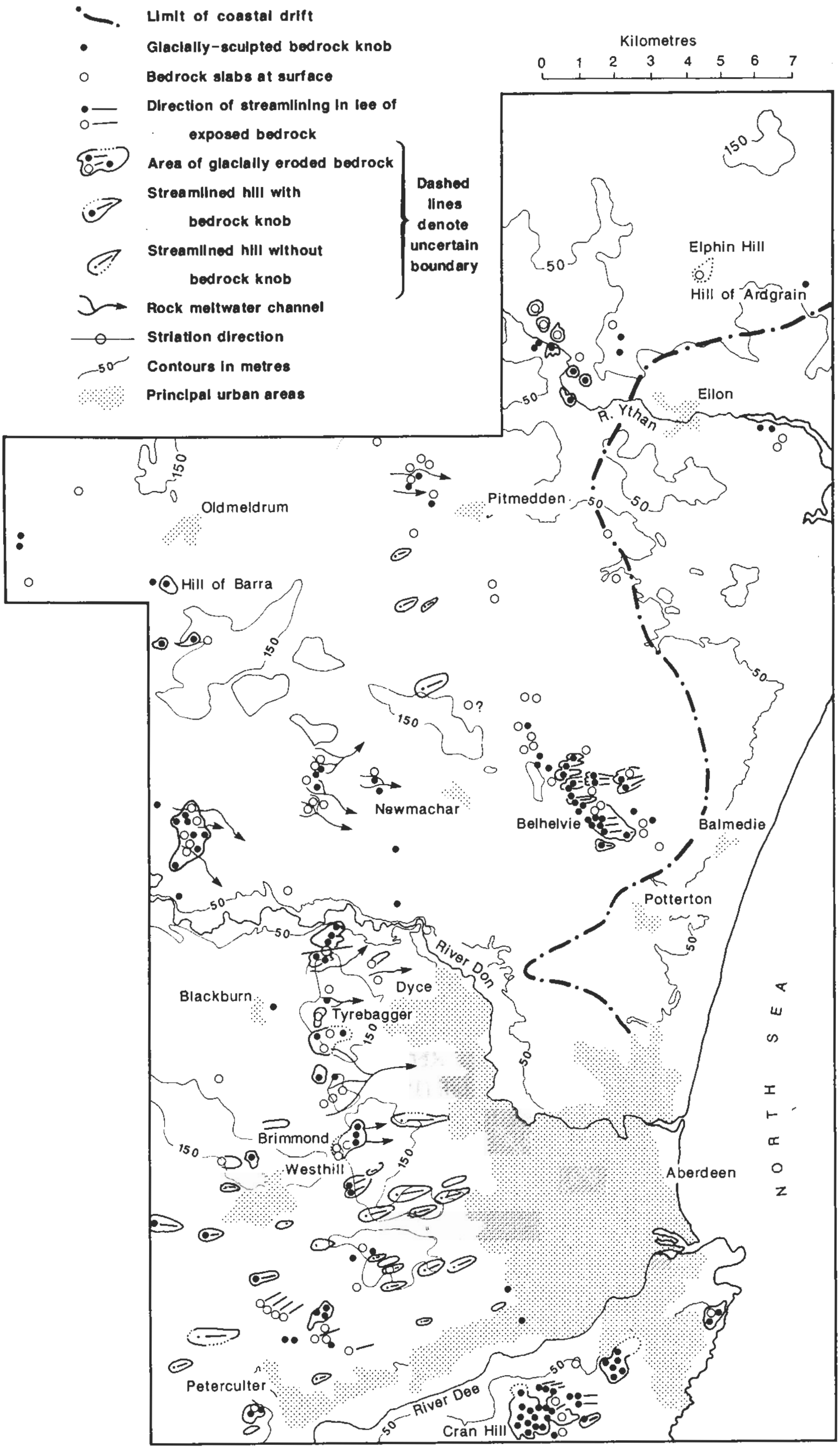

Figure 3. Landforms of glacial erosion in the study area

The criteria for their recognition has already been discussed and it will suffice to note that most of the streamlined hills identified are in this zone and that those shown on the map probably underestimate the number of streamlined features present.

2. In the second area extending north of Brimmond to the Ythan valley, landforms of glacial erosion are associated only with selected hills and cols. Within the area the density of features and the number of locations involved decreases markedly from south to north. There are two characteristic locations for landforms of glacial erosion. The first is the summit of prominent hills, especially the slopes immediately west of the summit. Good examples are the hills of the Tyrebagger and Belhelvie massifs and the sharply upstanding Hill of Barra. The second situation includes cols and valleys associated with meltwater flow from west to east. Commonly a series of rock channels wind through a series of ice moulded rock bumps. Three good examples occur just north of the river Don in the western half of the transect and another immediately north of Pitmedden. The lower Ythan Valley is a large scale example of the same phenomenon.
3. In the area north of the Ythan Valley and its immediate surrounds landforms of glacial erosion are rare or absent. The most northerly possible glacial erosional feature is an exposure of rock slabs on the south-western flank of the Hill of Ardgrain. North of this no glacial erosional landform was seen. Rather, on two hills there were upstanding rock outcrops or tors without evidence of glacial moulding. For example, the tor on Elphin Hill is a joint-bounded and rock mass 3 m high and 8 × 7 m in area.

The description of the landforms of glacial erosion in the transect demonstrates a clear trend from the Dee Valley in the south to central Buchan in the north. Whereas virtually all upstanding hills are moulded by ice in the south, glacial features become increasingly rare towards the north until finally there are none at all. Superimposed on this general north–south trend, is a more local pattern related to geology. Comparison of Figures 2 and 3 shows that characteristic landforms of glacial erosion are best displayed on basic igneous rocks and granites, rather than on metasediments. This is probably because the former are relatively massive with joint-confined blocks whilst the pelitic metasediments are generally fissile (excepting the psammites of Tyrebagger Hill).

PRE-GLACIAL WEATHERED ROCK AND LANDFORMS

Methods

Data on weathering patterns in the study area come from boreholes, continuous pipeline excavations, field surveys, and the literature (Figure 4). About 195 borehole records give information on the condition of bedrock, of which the most important sources are the Department of Geology, University of Aberdeen, aggregate assessment surveys (Merritt, 1981; Auton and Crofts, 1986) and minerals exploration surveys. Pipeline trenches were logged at 1:10,000 scale by members of the Department of Geology, University of Aberdeen under the supervision of M. Munro. Field survey included visits to most pits and quarries marked on the 1:25,000 Provisional Edition topographic maps. References to weathering sites in the study area are widely scattered in the literature and are summarized in Hall (1983). Subsurface information is sufficiently detailed to allow the links between topography and weathering patterns to be established locally.

Results

About 200 weathering sites are recognized from the study area and 40 boreholes record weathering to depths of more than 10 m. The number of weathering sites increases northwards. The density of sites is greatest (1·26 sites km^{-2}) in the area north of the Ythan where landforms of glacial erosion are rare or absent. Densities fall to 0·29 sites km^{-2} in the central zone, and are least in the southern zone (0·11 sites km^{-2}) where landforms of glacial erosion are most widely developed. The depth and continuity of weathering shows a similar trend with the greatest depths of weathering and least frequent fresh outcrops in the Dudwick area in the north and shallow depths of weathering, with a few deeper pockets, a multitude of fresh outcrops, and several major rock quarries in the area south of Brimmond Hill.

Where subsurface information is available, important differences are apparent in the topographic position of the weathering in various parts of the study transect. In the Dudwick area, weathering reaches depths of

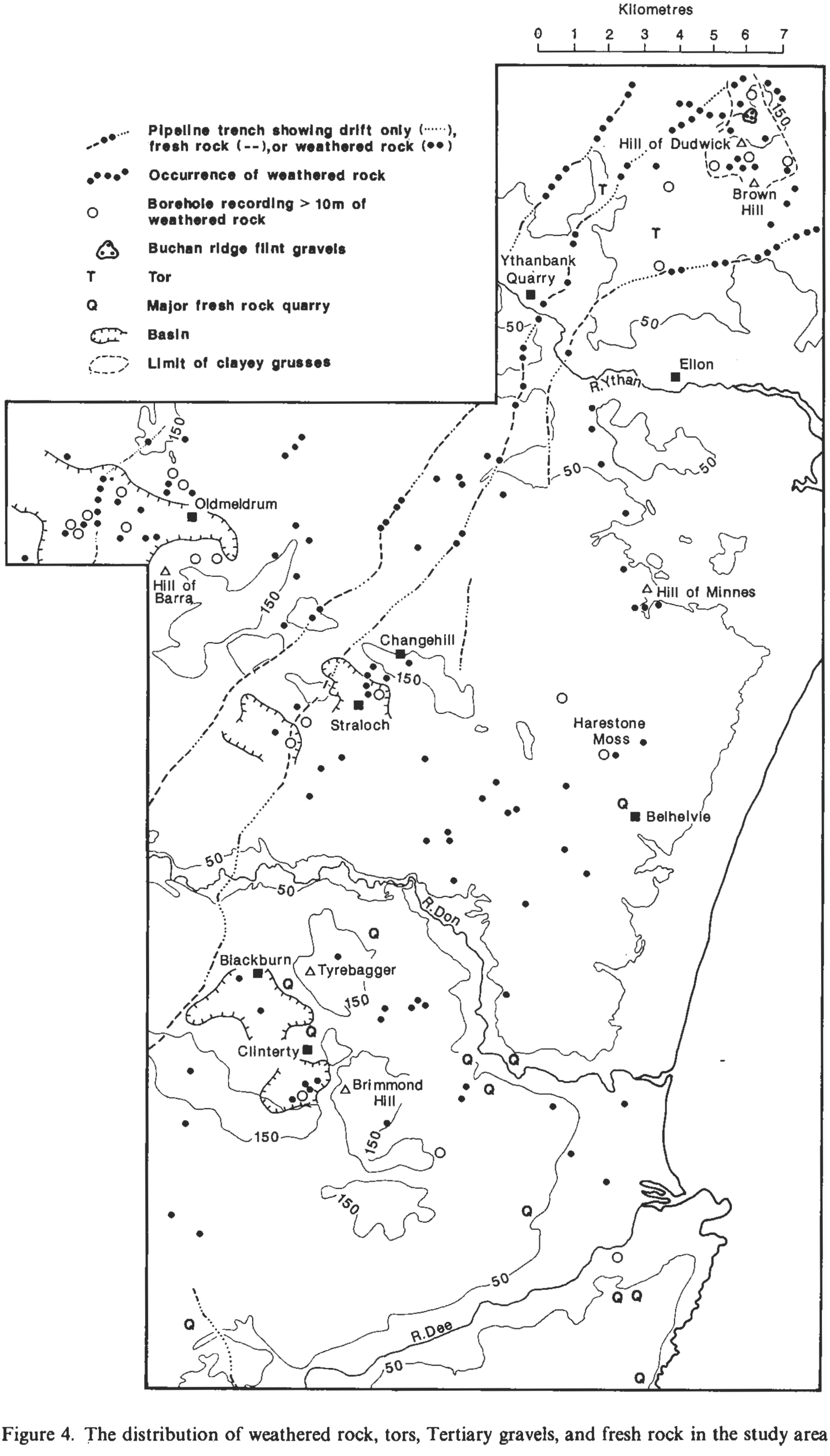

Figure 4. The distribution of weathered rock, tors, Tertiary gravels, and fresh rock in the study area

several tens of metres and fresh rock outcrops are confined to bands of quartzite and to valley floors (Figure 5a). Deep weathering survives on hill summits and a patch of Tertiary flint gravel occurs on Whitestone Hill. Weathering covers become thinner and fresh outcrops become more frequent towards the Ythan Valley, where hills show abundant fresh outcrops on their flanks and summits but with weathering extensively preserved around the base of the hills on both the up-ice and down-ice sides. The hills show a range of structurally-determined orientations and appear to represent resistant rock cores, developed on cordierite-bearing xenolithic basic igneous rocks, which have been exhumed from surrounding saprolites without significant glacial moulding of the hill forms. Closer to the axis of the Ythan valley, ice moulding of hills

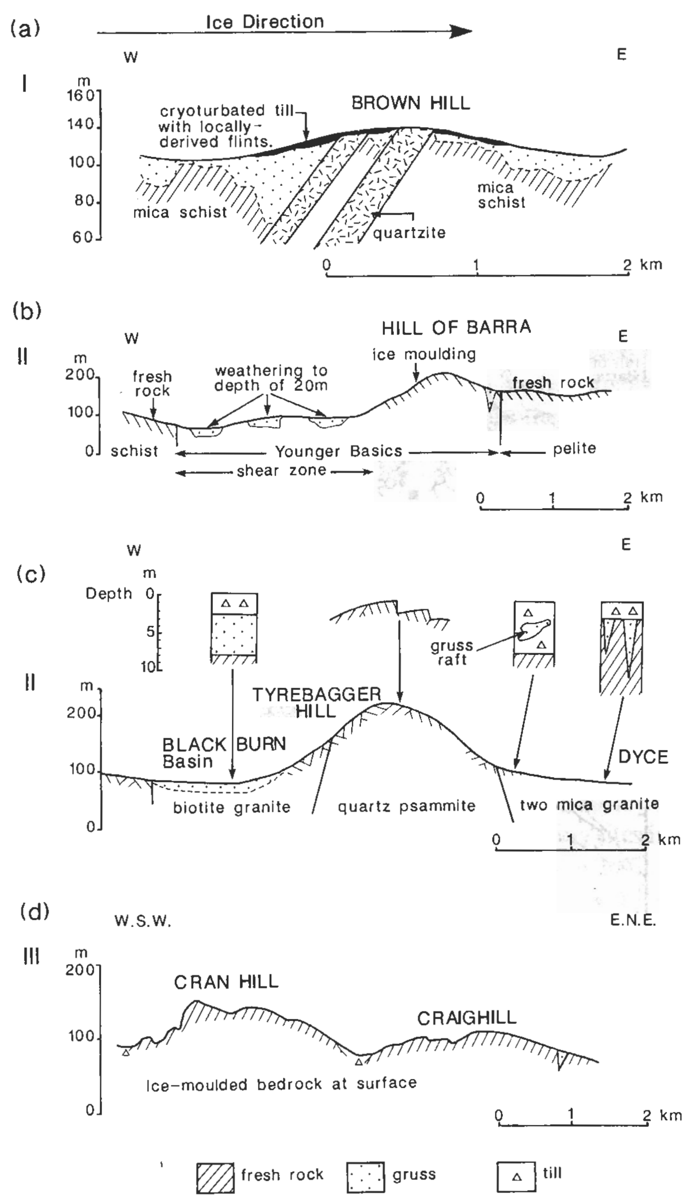

Figure 5. The pattern of weathered and fresh rock in four profiles arranged sequentially from north (top) to south (bottom) within the study area. (a) widespread weathering at Brown Hill, Dudwick, in the region of clayey grusses; (b) weathering in basins and ice moulding on hills, Hill of Barra: (c) weathering in basins up-ice of the ice-moulded Tyrebagger Hill and in pockets down-ice. The raft of weathered rock in till is described by Sugden (1986); (d) ice moulded hills and basins, Cran Hill, south of the River Dee

becomes more apparent and weathering is increasingly confined to protected positions in narrow pockets and lee sites, as at Ythanbank Quarry (Figure 6).

A second area of deep and extensive weathering occurs west of Oldmeldrum (Figure 5b). Here shearing at the eastern end of the Insch mafic intrusion has allowed alteration to depths of 20 m of more (Munro, 1986b) and the opening out of a basin with a floor area of over 15 km^2. This basin is one of a series found along the lower Don valley (Hall, 1983). All these basins appear to be located on zones of low rock resistance and all retain saprolites below till beneath their floors despite being positioned directly facing the up-ice sides of ice-roughened hill masses, such as the hills of Barra, Tyrebagger, and Brimmond (Figures 5b and c).

In much of the rest of the study area boreholes indicate that weathering, where present, is usually 1–4 m deep, although significant numbers of isolated sites with more than 10 m of weathering are also known. The topographic relationships of the weathering may be summarized as follows:

1. Weathering is generally absent from summits, whether ice-roughening is apparent or not.
2. Weathering is often found in the lee of isolated hills and hill masses, as around Dyce (Figure 5c). It is also occasionally found on the stoss side of hills, as at Ythanbank Quarry (Figure 6) and in the midst of glacially-scoured areas, such as at Harestone Moss, Belhelvie, where 10 m of weathered rock lies between and immediately adjacent to ice-moulded rock bumps.
3. Weathering is absent from the floors of major river valleys and most large meltwater channels. At Hill of Minnes, however, a meltwater channel can be shown to have exploited a linear zone of deep alteration.

COMPARISON AND IMPLICATIONS

Comparison of the pattern of glacial erosion with that of deep weathering shows a close inverse correlation (Figure 7). Areas with most evidence of glacial erosion are those with few occurrences of weathered rock. Areas with no evidence of glacial erosion coincide with areas underlain by widespread weathered rock, tors, and, in one location, *in situ* Tertiary gravels. In such areas the widespread occurrence of till confirms the area was covered by ice. In between the two extremes is an area where glacial erosion is confined to certain hills and meltwater routes while weathered rock occurs mainly in low-lying basins. The implication of this close relationship is that the transect does indeed represent the progressive modification of a landscape by ice sheet erosion. At one extreme in the northern Dudwick area of central Buchan, a pre-existing land surface has survived ice sheet glaciation without significant modification; at the other extreme in the vicinity of the Dee Valley, ice sheet erosion has transformed the landscape into one typical of glacial scouring with ice-moulded rock bosses and rock basins.

One possible explanation of this pattern may be a change from a warm-based thermal regime in the south to a cold-based thermal regime in the north (Sugden, 1978). Bearing in mind that critical ice thickness, climatic,

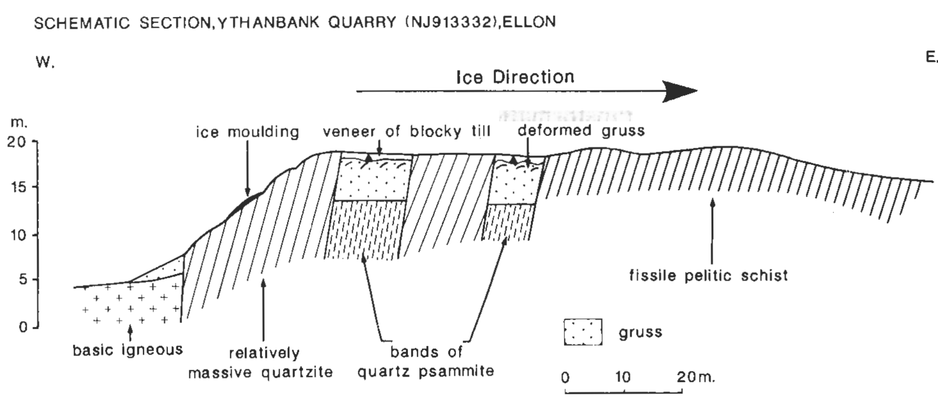

Figure 6. Schematic section of Ythanbank Quarry, Ellon showing the influence of lithology on the local distribution of weathered rock within an area of ice moulding. Weathered rock occurs both up-ice and down-ice of the resistant quartzite

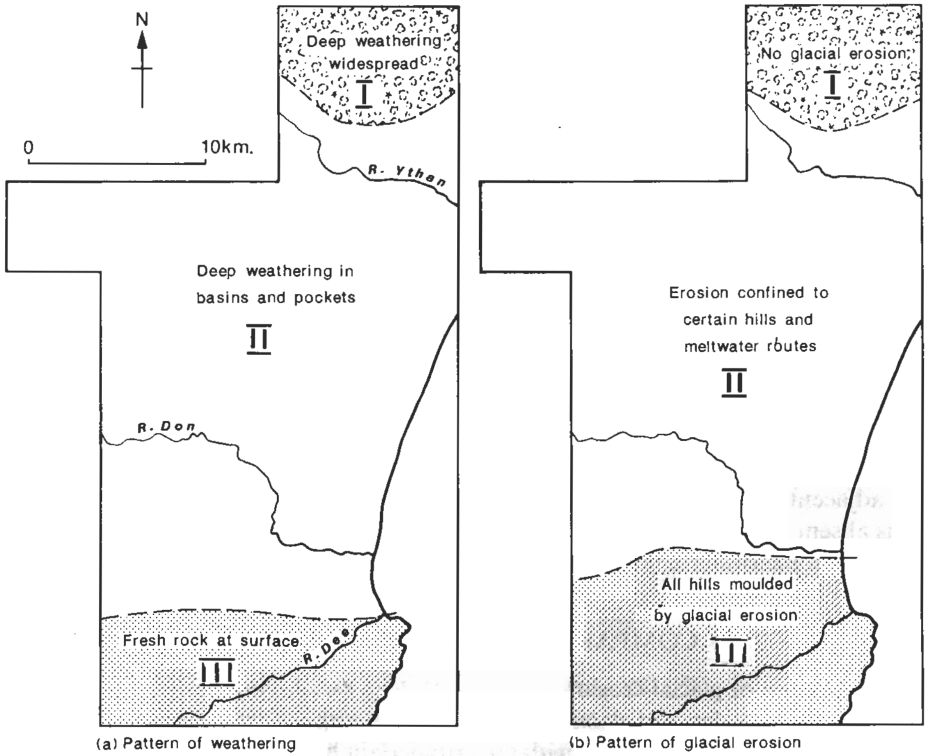

Figure 7. A comparison of the patterns of weathering and glacial erosion, demonstrating a good inverse correlation

and geothermal variables are likely to be similar in two closely adjacent areas, the relationship of former ice flow to topography would have favoured such a contrast in basal thermal regime between the northern and southern extremities of the transect. The Dee valley in the south extends as a low routeway from near the centre of the former Scottish ice sheet and was the conduit of a major ice stream. Also ice from either side of the valley converged into the valley (Clapperton and Sugden, 1977). These factors would have caused high ice velocities, which in turn would have caused sufficient frictional heating to raise basal temperatures to the pressure melting point. In contrast, ice flow over Buchan was divergent and, situated in the lee of eastern Grampian uplands, cut off from direct access to the central Scottish ice dome: this would have favoured low ice velocities, reduced frictional heating, and thus lower basal temperatures.

The presence of a transect from a glacially protected landscape to a classical glacial landscape of areal scouring allows one to substitute time for space and suggest that the sequence also represents the evolution of a glacial landscape over time. The original landscape is represented in the north, intermediate stages of modification in the middle, and major transformation in the south. It can be hypothesized that the profiles in Figure 5 represent these stages of evolution. The original landscape shows widespread deep weathering but fresh chemically resistant bedrock underlying the main hills. The intermediate stages show ice moulding on the up-ice side of some hill summits and in some cols and valleys, but with extensive remnants of weathered rock in basins. The final stage shows exposure of the fresh rock surface and widespread glacial moulding. Weathered rock is rare and confined to small pockets.

The first stages of erosion may be explained in terms of the passage of sliding ice at the pressure melting point. The up-ice side of hill summits, major valleys, and cols are all likely sites for ice to be at the pressure melting point—the hills because of pressure induced melting (Weertman, 1957) and the valleys and cols because of ice convergence. It is worth noting that these sites are also those likely to have had least cover of weathered rock in pre-glacial times so the presence of glacial landforms does not necessarily imply much depth of erosion.

The preservation of weathered rock in the basins is less straightforward and there seem to be several possible explanations—(a) the basins were not covered by ice at the pressure melting point, perhaps because they were enclosed by hills and unaffected by streaming ice flow; (b) they sustained erosion equal to, or more than, the hills but the greater thickness of weathered rock takes longer to be removed; (c) the permeability of the weathered rock reduced sliding at the ice/rock interface because subglacial meltwater drained through the weathered rock; (d) the greater micro-scale roughness of the glacier/bed interface over deeply-weathered rock compared to fresh rock inhibited sliding. These possibilities remain to be investigated in more detail.

In the final stage of glacial modification the weathered rock has been removed to reveal a series of basins and intervening ice-moulded rock hills. Presumably sliding occurred everywhere and was aided by the reduced permeability of the fresh rock substrate.

WIDER IMPLICATIONS

This model of the evolution of the glacial landscape of northeast Scotland has interesting wider implications. The first is that it is possible to create a classic glacial landscape of areal scouring by removing little more than the pre-existing weathered rock and touching up the underlying hard rock surface. Since the unmodified parts of northeast Scotland bear weathered rock mantles commonly over 10 m in thickness but as much as 50 m in favoured locations, one can suggest that the areal scouring in the vicinity of the Dee represents lowering of at least 10 m. On the other hand, where pockets of weathered rock are preserved the lowering is likely to be less than 50 m. The more extensive the weathered rock remnants, the less the lowering accomplished and *vice versa*. Pockets of weathered rock are widely recorded in glaciated shield areas in North America (Bouchard and Godard, 1984) and Europe (Godard, 1962; Lidmar-Bergstrom, 1982) and, so long as these are not hydrothermal or interglacial in origin, then these remnants imply a similar limited amount of glacial lowering of parts of these shields by 10–50 m. This conclusion reinforces a long-held but controversial view of the relatively limited efficiency of glacial erosion in shield areas (Sugden, 1976).

A second implication of the model is that the rock basin, which has long been regarded as a hallmark of glacial erosion (Hobbs, 1945), may owe its main form to the processes of deep weathering in warmer pre-glacial times. The ice has done little more than remove weathered products, as suggested by Hillefors (1969) and by Feininger (1971). In northeast Scotland the basins are related to biotite-rich acid and basic igneous rocks which are susceptible to chemical weathering. It would be interesting to discover whether a similar interpretation applies to other glaciated shield areas.

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