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# Calculating Quaternary glacial erosion rates in northeast Scotland

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## Abstract

Northeast Scotland is an area exhibiting selective erosion by Quaternary ice sheets. In this area both glacial and preglacial landforms exist in close proximity. The depths of erosion which this modification represents are calculated on the assumption of various depths of preglacial weathering. A depth of erosion of between 34 and 62 m per unit area is indicated. Calculated rates of erosion are  $0.021 \text{ mm a}^{-1}$  for the entire 2.3 m.y. of the Quaternary, and between  $0.1$  and  $0.5 \text{ mm a}^{-1}$  on the assumption that glacial conditions existed in this area for 500,000 years and 100,000 years, respectively. These figures are compared to the offshore sedimentary record in the adjacent west-central North Sea. The volume of sediment deposited offshore is equivalent to a depth of erosion of 195 m per unit area, yielding an average erosion rate of  $0.085 \text{ mm a}^{-1}$  over the entire Quaternary. Rates of erosion were low in the preglacial Pliocene ( $0.049 \text{ mm a}^{-1}$ ) and early Quaternary ( $0.063 \text{ mm a}^{-1}$ ). The expansion of ice sheets across the area in the middle Quaternary was associated with a sharp increase in the rates of erosion ( $> 0.13 \text{ mm a}^{-1}$ ) but the last (late Devensian) ice sheet in the area was less erosive ( $< 0.095 \text{ mm a}^{-1}$ ). The estimated rates of erosion represented by the offshore sedimentary record therefore exceed the estimated rates of glacial erosion from the onshore geomorphological reconstruction.

*Keywords:* glacial erosion rates; offshore sediment volumes; geomorphological reconstruction; preglacial landscape; Scotland

## 1. Introduction

Although erosion by former ice sheets and glaciers is widely believed to be a significant component of Quaternary landscape evolution in the northern mid-latitudes, there are few reliable estimates of long-term ( $10^3$ – $10^{-1}$  ka) depths and rates of glacial erosion. The aim of this paper is therefore to calculate the depth and rate of Quaternary erosion across northeast Scotland using geomorphological reconstruction. Specific attention is given to identifying the spatial

variability of Quaternary erosion across the area and to identifying temporal variations in the rates of erosion by comparing these figures with the sediment volumes in the adjacent North Sea basin.

In previous discussions concerning the depths and rates of erosion achieved by former glaciers two main approaches have been used (Bennett and Glasser, 1996): (1) geomorphological reconstruction, in which the preglacial landscape is reconstructed using evidence from landforms, deposits and weathering covers and compared with the present landscape; and (2) sediment volumes, in which the volumes of Quaternary sediments in sedimentary basins are converted into depths of rock erosion in their

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glaciated source areas. In the case of the former Laurentide ice sheet the two approaches give contrasting results. Using mainly geomorphological criteria Sugden (1976, 1978) suggested minimal glacial erosion across the area covered by the former ice sheet, with erosion limited to a maximum of a few tens of metres. In contrast, White (1972, 1988) argued that the exhumation of Precambrian basement from beneath younger cover rocks requires several hundreds of metres of glacial erosion across the Laurentian shield. The sediment volumes on the northwest Atlantic shelf and slope produce an estimated 120–200 m of erosion during the Quaternary (Laine, 1980; Bell and Laine, 1985), lending weight to White's argument (White, 1972, 1988). An explanation for these discrepancies is that there is an inherent problem in making regional estimates of Quaternary glacial erosion, which is that the intensity of glacial erosion is known to vary over space (Linton, 1959) and time (Porter, 1989; Piper et al., 1994). Hence average rates of glacial erosion for basins such as Sognefjord, western Norway (Andersen and Nesje, 1992; Nesje et al., 1992), are not applicable across the full range of glacial landscapes found within the North Sea basin, nor to particular episodes of Quaternary glaciation. Neither are they applicable to landscapes of more limited glacial erosion, such as those found further east in the Norwegian highlands (Kleman et al., 1992). Similarly, in Scotland, depths of glacial erosion are known to vary across the country (Linton, 1959; Clayton, 1974) and within regions (Hall and Sugden, 1987). These variations can be explained by former glaciological and topographical conditions beneath the ice sheets (Gordon, 1979; Glasser, 1995).

The issue of the depths and rates of erosion achieved by former glaciers is related directly to the debate concerning the relative effectiveness of long-term glacial and fluvial erosion in landscape evolution (Harbor and Warburton, 1992a,b). Molnar and England (1990, 1992) have argued that global cooling in the Cenozoic led to an increase in the extent of glaciation in Alpine areas, and that the change to glacial conditions led to increased erosion rates in these areas. Their assumption that the onset of glaciation in Alpine areas is associated with increased denudation rates has since been questioned by Summerfield and Kirkbride (1992). They draw on

the work of Hicks et al. (1990) who calculated denudation rates in glaciated and unglaciated catchments in New Zealand and concluded that there is no significant difference in denudation rates between glacial and non-glacial periods. Clearly there is a need for further estimates of the rates of these processes, especially in those areas formerly covered by mid-latitude ice sheets.

## 2. Study area

### 2.1. General location

The study area is an area of northeast Scotland on the western edge of the North Sea basin (Fig. 1). It comprises an area approximately 140 km in length by 22 km in width. This area was chosen for four main reasons:

(1) It represents a transect from the centre towards the margin of the former Scottish ice sheet, covering a large area of northeast Scotland. The transect encompasses a variety of landscape types, including the coastal lowlands surrounding the North Sea in the east, the high-level plateau of the Cairngorm Mountains in the west and the two major river valleys of the Dee and the Spey (Fig. 2). Modelling of the basal thermal regime of the former ice sheet in this area suggests that this variable topography may be crucial in determining patterns of ice sheet erosion (Glasser, 1995).

(2) The landscape demonstrates classic selectivity of glacial erosion (Sugden, 1968; Clapperton and Sugden, 1977; Hall, 1986; Hall and Sugden, 1987; Sugden et al., 1992). Landscapes of little or no glacial erosion, landscapes of selective linear erosion and landscapes dominated by areal scouring (Sugden, 1974) are all present within the study area.

(3) Remnants of the preglacial landscape survive in this area (Fitzpatrick, 1963; Sugden, 1968, 1989; Hall and Sugden, 1987; Hall and Mellor, 1988; Hall et al., 1989; Hall, 1991; Hall and Connell, 1991; Ballantyne, 1994). These palaeo-features allow the reconstruction of the preglacial relief, an essential pre-requisite for determining the location and depth of erosion by former ice sheets.

(4) Quaternary erosion of the study area has moved sediment to the adjacent North Sea basin,

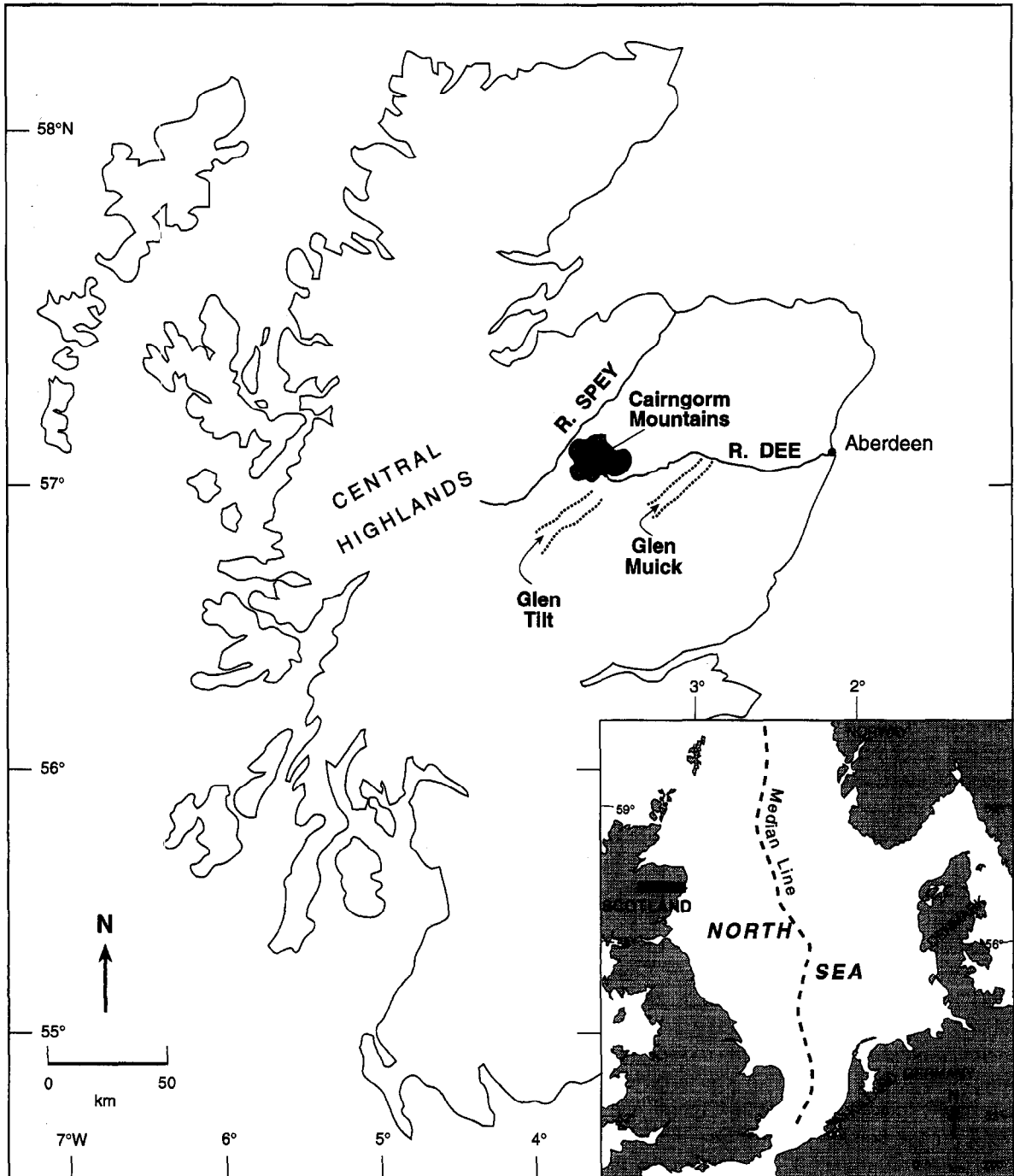


Fig. 1. Location of the study area in northeast Scotland, showing place names mentioned in the text and the relationship to the North Sea basin and to continental Europe (inset). The onshore study area for which depths of glacial erosion are calculated is shown by heavy shading (inset). The area for which sediment volumes have been calculated in this paper is its offshore extension as far as the Median Line in the central North Sea.

allowing calculation of sediment volumes. Offshore sediments also provide important information on Quaternary environmental history in the study area.

## 2.2. *Geology*

The study area is dominated by crystalline rocks, predominantly Dalradian and Moine schists, gneisses and extensive Caledonian granite masses. Elevation of the Cairngorm Mountains and the eastern Grampian plateau occurred in the early Tertiary with uplift probably continuing intermittently through the Tertiary. The main preglacial elements in the relief are erosion surfaces, large topographic basins and valley systems. These reflect the slow etching of the raised basement block by differential chemical weathering under first tropical and then temperate environments during the Tertiary. At the end of the Tertiary, the relief was dominated by etch surfaces, mantled by thick sandy weathering covers and closely adjusted to litho-structural controls (Hall, 1991).

## 2.3. *Quaternary sedimentation in the North Sea basin*

Both glacial and non-glacial erosion during the Pliocene and Quaternary have moved large volumes of sediment offshore into the North Sea basin (Cameron et al., 1987; Gatliff et al., 1994). This provides a chronological and palaeoenvironmental context against which to measure onshore denudation rates and with which to constrain models of landscape evolution. Pliocene sediments in the west-central North Sea are mainly mudstones, with minor sandier units (Gatliff et al., 1994), and the lack of coarse clastic material implies moderate rates of erosion on the adjacent land area. The first ice-rafted debris was laid down in mid-Pliocene times (King, 1983) but is unlikely to have been dropped from icebergs from a Scottish ice sheet since no Pliocene glaciomarine sediments are known from the western North Sea. Although the Plio–Quaternary boundary is formally placed at 1.6 Ma (Aguire and Pasini, 1985), in the southern North Sea the boundary is often placed at around 2.3 Ma, when the first signs of cold climate appear in Dutch sequences (Zagwijn, 1992). In this area of the North Sea, however, this cooling does not appear to be marked by any widespread change in sedimentation. In the northern

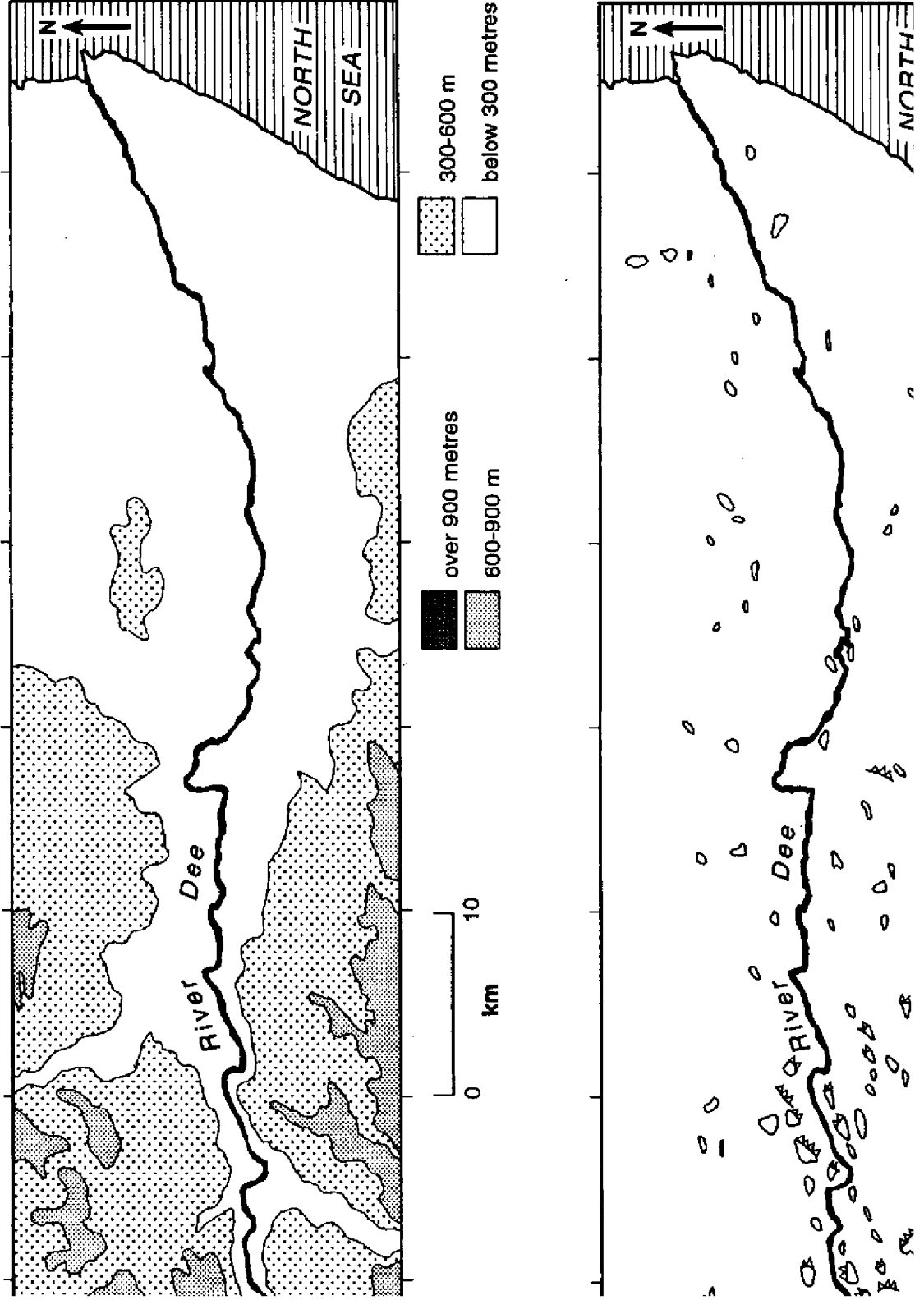
North Sea, a boundary is taken close to the top of the Olduvai palaeomagnetic event at 1.67 Ma. The localised presence of unconformities, with possible boulder lags, at about this level imply erosion prior to or during a marine transgression close to the Plio–Quaternary boundary (Andrews et al., 1990).

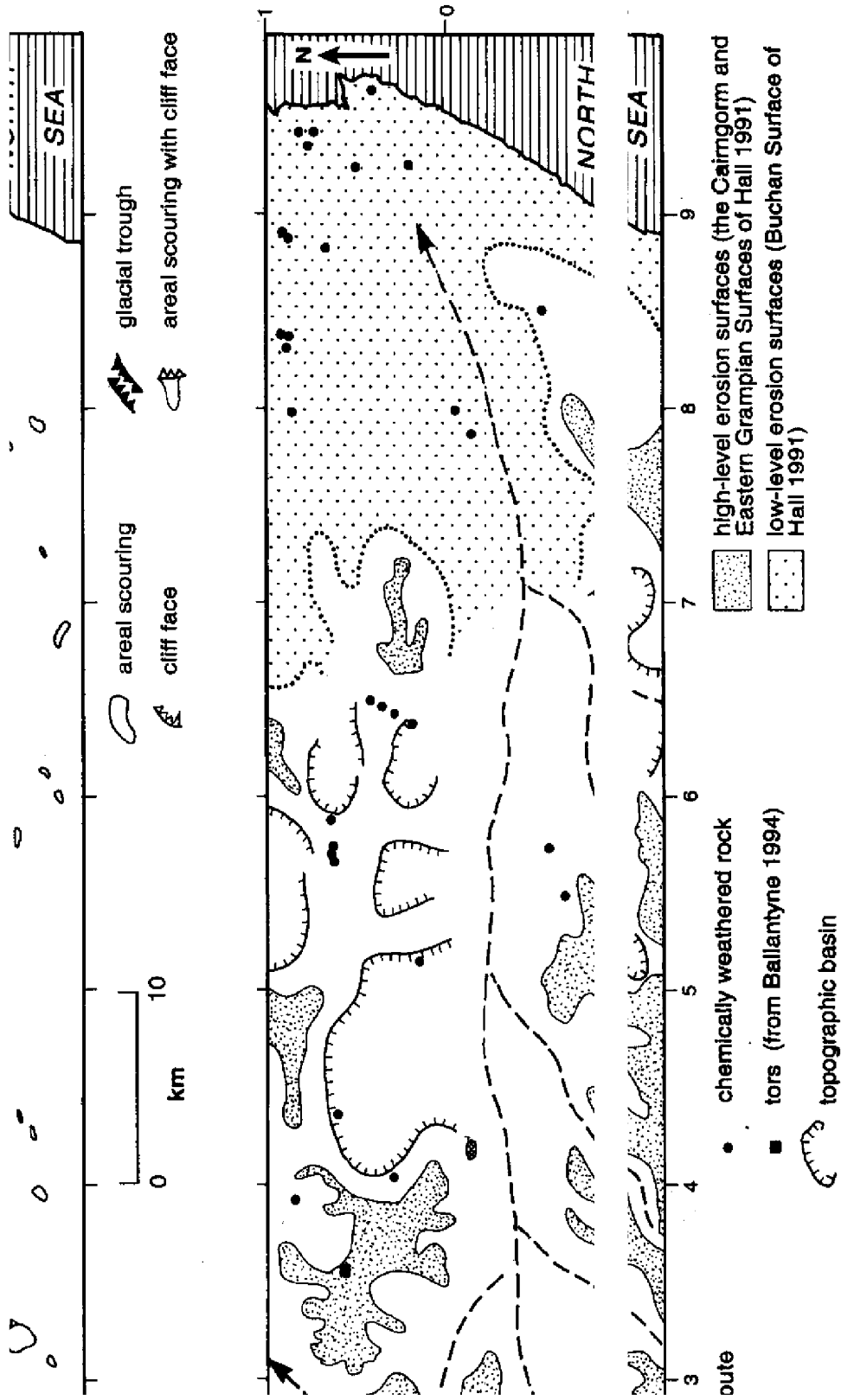
Lower Quaternary sediments consist entirely of the lower part of the Aberdeen Ground Formation. These sediments are mainly muds and form the marine and non-marine parts of a northward-advancing delta complex. Small deltas close to the coast of Scotland and northern England received sediment from these areas (Stoker and Bent, 1987) but most of the sediment was deposited on a much larger eastern delta which prograded northwards from the southern North Sea and which received sediment from the major river systems of the European mainland (Cameron et al., 1987). The early Quaternary sediments accumulated under fluctuating climatic conditions but there is no evidence of direct glacial sedimentation in the basin, although boreo-arctic marine microfauna are recognised as early as ca. 2 Ma (Knudsen and Asbjornsdottir, 1991). Hence it can be assumed that, whilst episodic upland glacierisation had probably begun, the whole of the study area was not glaciated in the early Quaternary. The first signs of ice-proximal sedimentation in the west-central North Sea appear around the early–middle Quaternary boundary, with proximal glaciomarine sedimentation at ca. 0.8 Ma (Sejrup et al., 1987) and the first deposition of lodgement till in the Forth Approaches at ca. 0.75 Ma (Stoker and Bent, 1985). Extensive Elsterian glaciation of the North Sea basin caused widespread erosion. The Elsterian was succeeded by at least two other major glacial phases, the Saalian and Weichselian, but the timing, number and extent of glacial advances in the middle and late Quaternary is unclear (Cameron et al., 1987). Episodic ice sheet glaciation has therefore affected the study area over the last ca. 0.8 m.y.

## 3. *Methods*

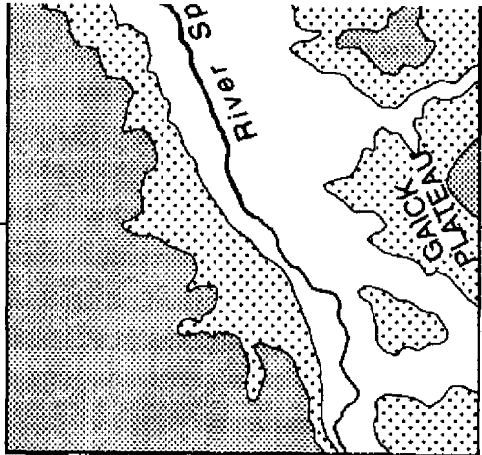
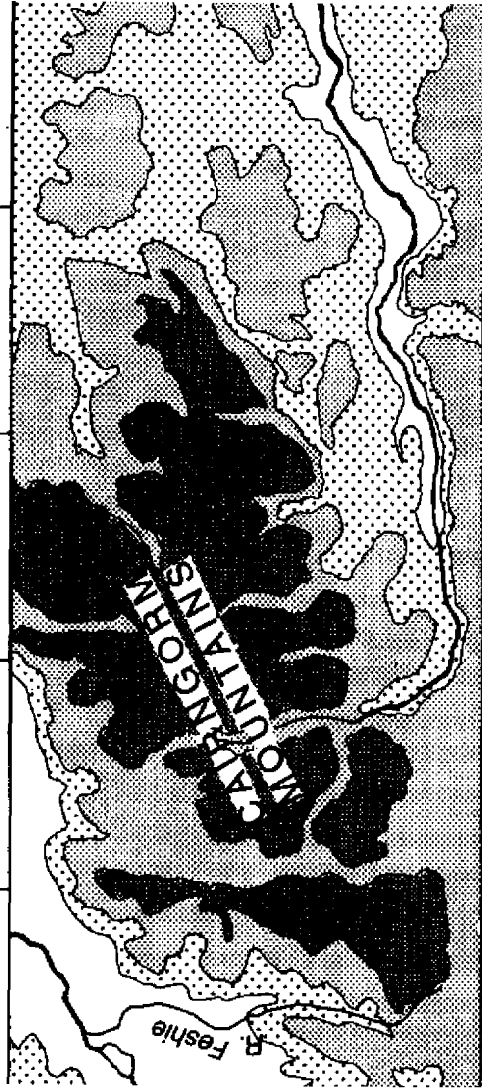
### 3.1. *Geomorphological reconstruction*

In order to calculate the depth and rates of ice sheet erosion it is necessary to establish both the form of the preglacial landscape and the pattern of

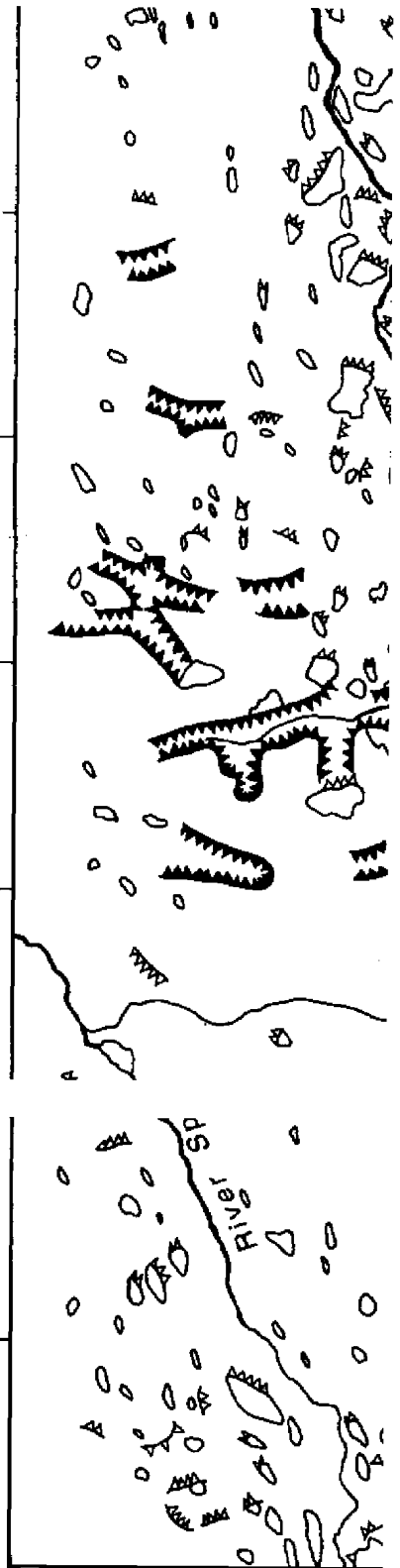




the study area and localities  
 field mapping illustrating the  
 of the rivers Dee and Spey  
 of the preglacial landscape  
 is away from the axes of the



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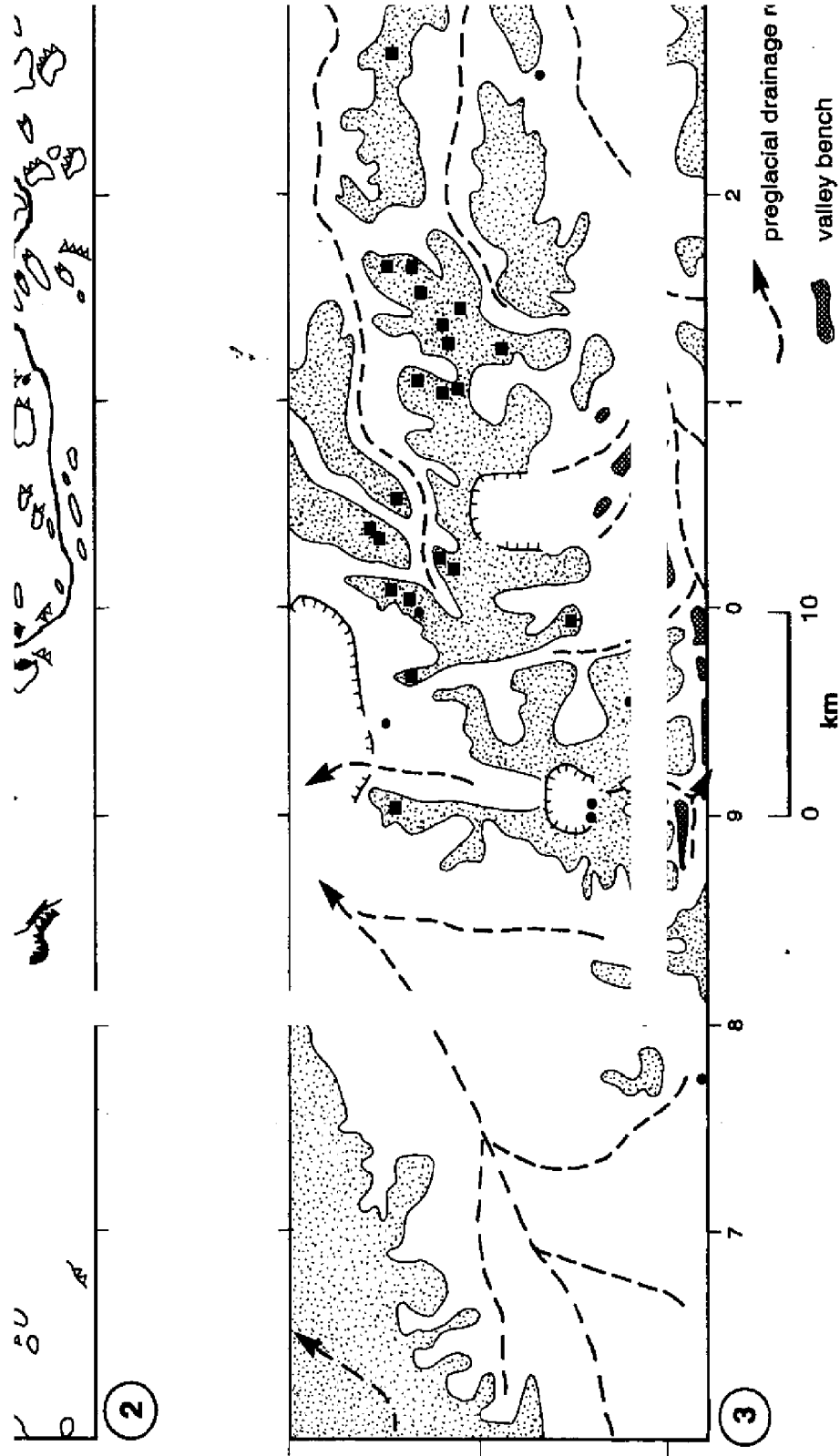


Fig. 2. The distribution of glacial and preglacial landforms in the study area. (1) The present-day topography of mentioned in the text. (2) Geomorphological map of the study area compiled from aerial photography and its pattern of glacial erosion in the study area. Note the contrast between the areal scouring developed along the axes and the lack of evidence of glacial erosion on the interfluvies. (3) Geomorphological map showing the remnants which survive in the study area. Note that the remnants of high-level erosion surfaces and tors are located in areas of rivers Dee and Spey.

ice sheet erosion across the study area. In this study geomorphological mapping and aerial photograph interpretation were used to identify the remnants of the preglacial landscape and to produce a landscape classification for the study area showing the intensity of modification of the landscape by glacial erosion. This allows the study area to be divided into landscape categories reflecting the extent of glacial modification. Detailed field mapping in each of these landscape classes was used to record the occurrence of both glacial and preglacial landforms. The preservation or otherwise of the preglacial landscape then allows calculation of minimum and maximum estimates of the depth of ice sheet erosion for each of the landscape classes. Upper and lower minimum estimates of the depth of erosion are then calculated for the entire study area.

The preglacial landscape (Fig. 2) was identified and reconstructed using the following criteria:

(1) An absence of characteristic landforms of glacial erosion, such as ice-moulded hills and basins.

(2) The presence of major relief elements, such as erosion surfaces, hills, basins and valleys, which form a 'paleic relief' (Gjessing, 1968) that is dissected by the forms of glacial erosion (Sugden, 1968) and which appear to have developed under temperate conditions in the late Tertiary by a combination of differential deep chemical weathering and fluvial erosion (Hall, 1991).

(3) The presence of minor landforms, such as tors (Ballantyne, 1994), small basins floored by weathered rock (Hall, 1986), scarps (Hall, 1986) and valley benches marking the former valley floor (Hall, 1991) which appear to be broadly of preglacial age.

(4) The presence of sheet-jointing parallel to gentle topographic surfaces (cf. Jahns, 1943). The sheet joints are truncated by glacial cliffs (Sugden, 1968; Sugden et al., 1992).

(5) The presence of deeply weathered bedrock. Deep weathering is widespread in northeast Scotland, especially in the Buchan area (Fitzpatrick, 1963; Hall, 1985), and its depth and frequency of occurrence has been shown to be inversely proportional to the intensity of glacial erosion (Hall and Sugden, 1987). Formation of deep sandy weathering profiles has probably spanned most of post-Miocene time but it is likely that only shallow profiles have reformed during Quaternary interglacials (Hall et al., 1989).

A key methodological question for the present study concerns the depth of the weathering profiles which existed at the start of the Quaternary. In many parts of the study area, saprolites are absent or infrequent and one element in estimating depths of glacial erosion is the removal of preglacial weathering profiles. This is a difficult problem as depths of weathering vary widely in northeast Scotland in response to geological, topographical and glaciological controls (Hall, 1986). In central Buchan, however, the presence of Tertiary gravels indicates limited modification of the Tertiary landscape by Quaternary erosion. Here depths of weathering generally vary between 10 and 50 m (Hall, 1985). These figures are taken as estimates of the original thickness of weathering profiles at the start of the Quaternary for the whole of the study area. Central Buchan is a low plateau rising to ca. 150 m OD and the greatest depths of weathering recorded here may not be typical of upland areas in the study transect. The survival of 10–20 m of weathered rock in stream sections on the Gaick plateau (Hall and Mellor, 1988) within the study area suggests, however, that the range of depths is reasonable.

From this discussion it follows that geomorphological reconstruction will yield a minimum estimate of the depth of Quaternary erosion because:

(1) Glacial modification of the preglacial landscape is diachronous. Mountain glacierisation may have occurred at intervals throughout or even before the Quaternary. Hence erosion below the preglacial landscape in areas like the Cairngorms may span at least the last 2.3 m.y. In contrast, the first ice sheet glaciation of the eastern lowlands was at ca. 0.8 Ma and the preglacial landscape was first modified directly by glaciers at this much later date.

(2) The current surface of the paleic relief may lie below its end-Tertiary level due to lowering by non-glacial processes during the Quaternary.

(3) Certain elements taken to be diagnostic of the preglacial relief may sometimes be younger than they seem. For example, isolated occurrences of weathered rock may not be remnants of the preglacial weathering mantle but a result of hydrothermal alteration or, where saprolites are thin, a product of Quaternary chemical weathering (Hall, 1993a). Small tors may have developed by frost weathering and periglacial mass movement during the Quaternary

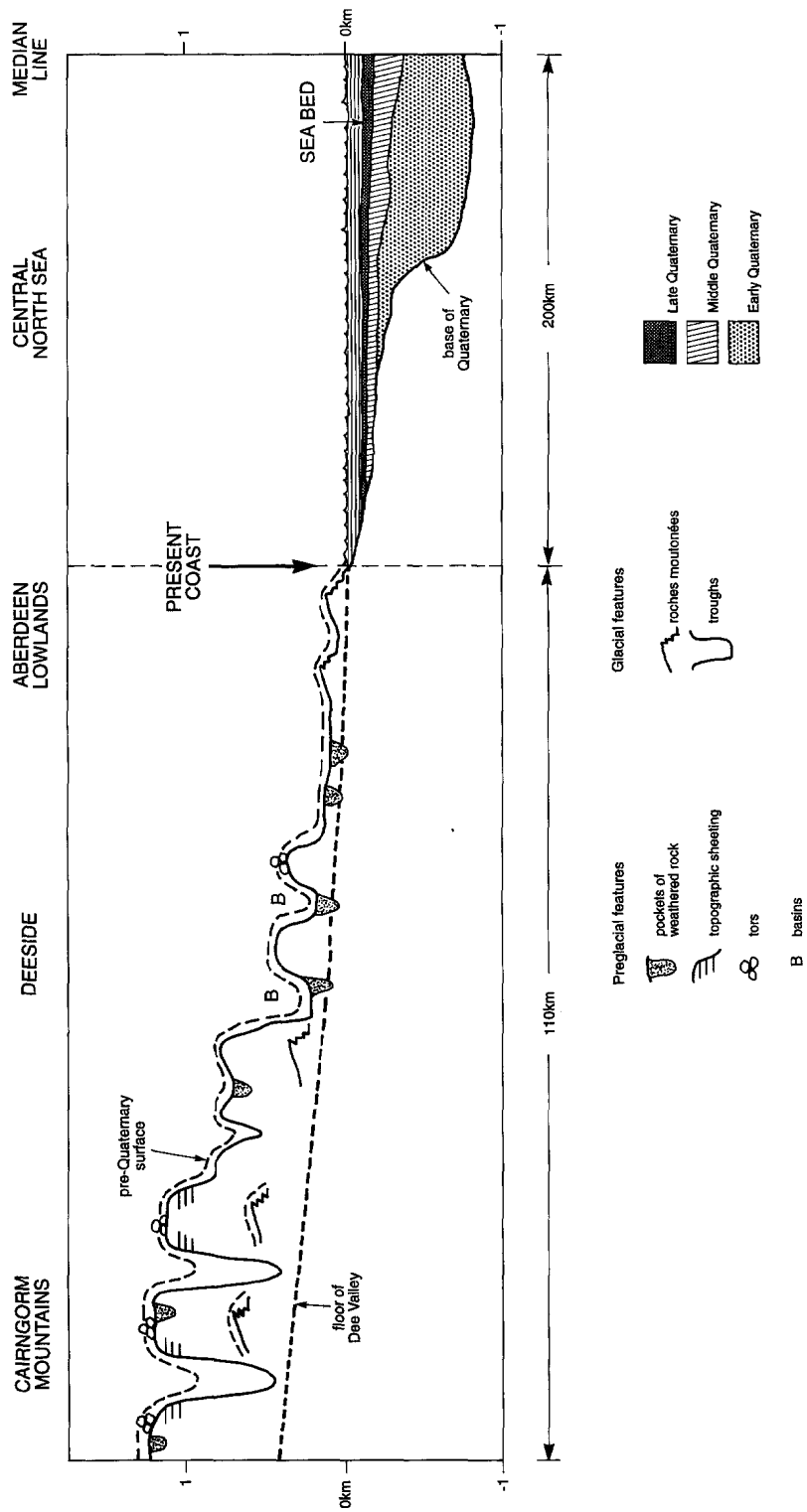


Fig. 3. The spatial relationship between the glacial and preglacial landscapes in northeast Scotland. The area depicted constitutes a transect from the Cairngorm Mountains to the Median Line in the central North Sea. Note the change in horizontal scale between the onshore and offshore areas and that only offshore sediments of Quaternary age are shown.

(Ballantyne, 1994). Sheet jointing may have developed slowly but continuously as gentle rock surfaces were lowered by Quaternary erosion.

(4) In landscapes of areal scouring, glacial lowering of bedrock surfaces may extend many metres below the preglacial basal surface of weathering.

The degree and significance of this underestimation of erosion is discussed later.

### 3.2. Offshore sediment volumes

The volume of sediment was calculated in the offshore extension of the study area in the central North Sea to the Median Line (Fig. 3). Volumes of Quaternary sediment in this area are from Gatliff et al. (1994). Average porosity is assumed to be 55% and average carbonate and organic content 10%, following Laine (1980). Average rates of Quaternary sedimentation are then calculated for the Pliocene, early Quaternary, middle Quaternary and late Quaternary from isopach maps of Pliocene and Quaternary sediments (Gatliff et al., 1994). It is important to note that sediment volumes in the central North Sea cannot be used on their own to estimate depths of erosion in the study area but only as a comparison with the geomorphological reconstruction. This is because the central North Sea has received an unknown volume of sediment from source areas other

than northeast Scotland and because sediment from northeast Scotland has been deposited in parts of the North Sea other than the area now immediately offshore. We acknowledge that the source of sediment in the west-central North Sea remains uncertain and that in the Pliocene the Baltic river system may have contributed material to this area. In addition, in the early Quaternary the sediments of the central North Sea include much material from the rivers of northwest Europe (Gatliff et al., 1994), and in the middle and late Quaternary material from Scotland may have been exported from the study transect boundaries by the more extensive ice sheets and, to a lesser extent, imported by Scandinavian ice sheets. Nonetheless a large, though unquantifiable, part of the offshore sediment must have been sourced from the study area and carried down the axial Dee valley.

## 4. Results

### 4.1. Geomorphological reconstruction

The main elements of the glacial and preglacial landscapes are shown in Fig. 2. The pattern of glacial erosion in the study area can be summarised as follows:

- (1) Large-scale glacial troughs occur only in the

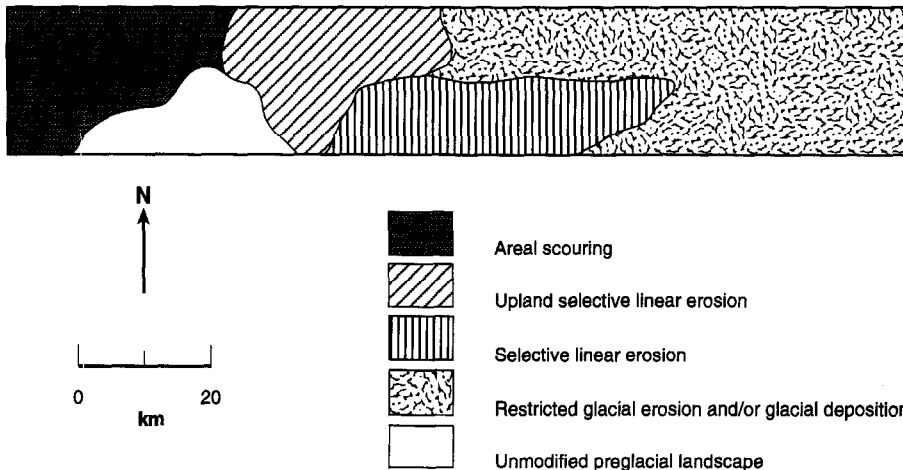


Fig. 4. A landscape classification for the study area, showing the location of zones of areal scouring, selective linear erosion, the unmodified preglacial landscape and landscapes of restricted glacial erosion. The area shown corresponds to the shaded area in the inset of Fig. 1. Boundaries between landscape classes are approximate since the landscapes tend to grade into one another.

centre of the field study area, in and around the Cairngorm Mountains.

(2) Bedrock cliffs occur in numerous locations, especially on valley sides and hill summits, and are most common in western and central areas and rare in the east. Lee-side cliffs occur in conjunction with patches of areal scouring and are most frequent along the Spey and Dee valleys.

(3) Glacial scouring occurs throughout the study area as areal and local scouring and in association with lee-side cliff faces. There is a predominance of areal scouring in the west. Zones of scouring are located along the axes of the two main valleys of the Dee and Spey, especially along the valley floors.

The study area shows a general decrease in the intensity of modification of the landscape by ice sheet erosion from west to east (Fig. 4). The western part of the study area is dominated by landscapes of areal scouring, whilst the central area of the Cairngorms and Dee valley are dominated by areas of selective linear erosion. In the east of the study area there is a zone of restricted glacial erosion and a zone of glacial deposition. This pattern of decreasing modification eastwards is interrupted by an area where the preglacial landscape remains little altered over the Glen Feshie plateau. This pattern of glacial erosion demonstrates a relationship with topography, with the zones of most intense modification centred along the axes of major ice discharge routes. These discharge routes are the locations of zones of basal melting beneath the former ice sheet and the relationship between topography and glacial erosion has been explained with reference to the basal thermal

regime of the former Scottish ice sheets (Glasser, 1995).

The minimum estimates of depths of glacial erosion are based on the assumption that the study area was covered in a weathering mantle 10–50 m deep in preglacial times (Hall and Sugden, 1987). If landscapes affected by ice sheet erosion are dominant, fresh bedrock is widespread and saprolite does not exist, then it is assumed that all of the former weathering regolith has been removed and the depth of erosion is at least 50 m. If saprolite remains at the surface then the depth of erosion is assumed to be less than 50 m, and an approximate value is estimated from the depth and distribution of the saprolite remaining. Subsidiary field mapping of preglacial landscapes, including minor features such as tors and topographic sheeting, and of glacial features such as trough depths and valley floor lowering, allows further refinement of the estimates. In areas where there is widespread evidence for the preservation of the preglacial landscape, it is assumed that minimal glacial erosion of less than 10 m has occurred. These estimates are used to calculate a minimum and maximum figure for the depth of glacial erosion within each landscape class. It is then possible to calculate regional erosion depths in the study area as a whole.

The estimates of minimum and maximum depths of glacial erosion in each of the landscape classes are shown in Table 1, together with their corresponding volume of erosion. The area of upland selective linear erosion, in and around the Cairngorm Mountains, accounts for the greatest depths of erosion with

Table 1  
Minimum and maximum estimates of ice sheet erosion in each of the landscape classes identified in the study area

Landscape class	Estimated ice sheet erosion			
	min. erosion (m)	max. erosion (m)	min. vol. (km <sup>3</sup> )	max. vol. (km <sup>3</sup> )
Selective linear erosion (upland)	108	152	51.3	72.2
Selective linear erosion (lowland)	12	52	6	21
Areal scouring	35	47.5	18.375	25
Restricted glacial erosion	16.4	41.6	16.81	42.64
Preglacial landscape	10	40	2.5	10
Total volume (km <sup>3</sup> )			94.985	170.84

a minimum of between 108 and 152 m of erosion per unit area. Most of the erosion is accounted for by excavation of the deep and extensive glacial troughs as the upper slopes of the Cairngorms have been apparently little modified by ice (Sugden, 1968). Landscapes of areal scouring, which mainly occur along valley routes, account for a minimum of between 35 and 47.5 m of erosion per unit area. In these areas, erosion has been more uniform in its effects on the landscape, although overall depths are not as great as in landscapes of upland selective linear erosion. Landscapes of selective linear erosion in lowland areas account for a minimum depth of erosion between 12 and 52 m. Areas where there is restricted glacial erosion and where there is evidence of widespread glacial deposition may account for a minimum of between 16.4 and 41.6 m. Finally, the little modified preglacial landscape has suffered erosion of between 10 and 40 m in depth.

Summing the values for the landscape classes, the minimum total volume of erosion in the entire study area is calculated to be between 95 km<sup>3</sup> and 171 km<sup>3</sup>. These values correspond to a depth of erosion per unit area of between 34 m and 62 m, equivalent to rates of Quaternary erosion of 0.015 and 0.027 mm a<sup>-1</sup>, respectively. Using the mean depth of erosion per unit area, 48 m, yields a minimum average erosion rate over the 2.3 m.y. of the Quaternary of 0.021 mm a<sup>-1</sup>. These erosion rates increase to between 0.1 and 0.5 mm a<sup>-1</sup> on the assumption that glacial conditions existed during the Quaternary for 500,000 years and 100,000 years, respectively. It

should be noted that these erosion rates represent the minimum estimate of glacial erosion since they do not account for additional deepening of valleys by glacial erosion or by glacial meltwater erosion. These limitations are discussed below.

#### 4.2. Offshore sediment volumes

Quaternary sediments in the central North Sea exceed 700 m in thickness in parts of the Central Graben, with the bulk of these sediments of Early to middle Pleistocene age (Gatliff et al., 1994). Sediment volumes in the central North Sea are shown in Table 2 (based on Gatliff et al., 1994). The average rates of sedimentation which these represent are shown for the Pliocene and for the early, middle and late Quaternary. Erosion rates are lowest in the Pliocene (0.049 mm a<sup>-1</sup>) and rise slightly in the early Quaternary (0.063 mm a<sup>-1</sup>). The maximum erosion rate (0.13 mm a<sup>-1</sup>) is reached during the middle Quaternary. During the late Quaternary the erosion rate falls slightly to around 0.12 mm a<sup>-1</sup>, before dropping further to around 0.095 mm a<sup>-1</sup> during the late Devensian. The Pliocene and early Quaternary sediments are truncated around the western margin of the west-central North Sea but there are no regional unconformities at the boundaries of these sequences in the Central Graben. This suggests that the sequences are largely complete, although the volume of the sedimentary basin may have increased through the Quaternary. The estimated erosion rate for the middle Quaternary is almost certainly an

Table 2

Depths and rates of Pliocene and Quaternary erosion in northeast Scotland implied by the sedimentary sequence in the adjacent North Sea basin

Age	Wet sediment volume (km <sup>3</sup> )	Average accumulation rate (mm a <sup>-1</sup> ) <sup>a</sup>	Volume of rock equivalent (km <sup>3</sup> ) <sup>b</sup>	Erosion per unit area (m) <sup>c</sup>	Average erosion rate (mm a <sup>-1</sup> ) <sup>c</sup>
Pliocene	1320	0.07	533	173	0.049
Quaternary	1480	0.12	600	195	0.085
Early Quaternary	770	0.09	312	101	0.063
Middle Quaternary	600	0.18	243	79	0.13
Late Quaternary	110	0.16	45	15	0.12
Late Devensian	15	0.14	6	1.9	0.095

Note that the rise in erosion rates in this area coincides with the onset of ice sheet glaciation in the middle Quaternary.

<sup>a</sup> Averaged over the offshore study area.

<sup>b</sup> Assuming porosity of 55% and organic and carbonate content of 10% (after Laine, 1980).

<sup>c</sup> Assuming all sediment is sourced from the onshore study area.

underestimate as this sequence contains two regional unconformities associated with the Elsterian and Saalian glaciations (Gatliff et al., 1994) and is truncated around the basin margins. In contrast, the rates for the late Quaternary and late Devensian are probably overestimates as these sequences will include material reworked from older Quaternary deposits in the North Sea and were the last to be deposited.

The high rate of middle Quaternary erosion is consistent with geomorphological evidence from around the North Sea basin. The most extensive seismic reflector in the North Sea Quaternary succession is attributed to erosion associated with the Elsterian glaciation (Stoker et al., 1985). This erosion surface truncates the middle Quaternary part of the Aberdeen Ground Formation and shows large channels which are locally over 100 m deep. Deep glacial erosion and the formation of large channels are also characteristic of the Elsterian glaciation elsewhere in northwest Europe (Ehlers et al., 1991). In addition there is also evidence from further south in Britain, especially around East Anglia and eastern England, that the Anglian glacial phase (equivalent to the Elsterian) was a period of major landscape change with the rearrangement of major drainage systems and the excavation of the Fen basin (Perrin et al., 1979).

## 5. Discussion

Comparison of the results of the geomorphological reconstruction with published estimates of rates of Quaternary erosion indicate that the values of 0.015–0.027 mm a<sup>-1</sup> for northeast Scotland fall within the range of estimates for the Laurentide shield (Bell and Laine, 1985; Kaszycki and Shilts,

1987) but are an order of magnitude less than those for areas of intense glacial erosion such as the Sognefjord basin (Nesje et al., 1992) and Spitsbergen (Svendsen et al., 1989; Table 3). The estimates for northeast Scotland thus appear to be reasonable for an area of moderate relief and selective glacial erosion (Hallet et al., 1996). It was argued earlier, however, that calculation of depths of Quaternary erosion by geomorphological reconstruction will yield a minimum value and therefore tend to underestimate the depths of erosion. We now attempt to quantify the extent of this underestimation in the present calculations.

### 5.1. The timing and duration of glacial periods

In mountains such as the Cairngorms modification of preglacial landsurfaces by glaciers was probably under way by the early Quaternary as faunal evidence from North Sea sediments shows the establishment of boreo-arctic marine conditions as early as ca. 2 Ma (Knudsen and Asbjornsdottir, 1991). Here the preglacial landsurface may approximate in level to the end-Tertiary surface. On the eastern lowlands ice sheet glaciation was probably delayed until ca. 0.8 Ma (Gatliff et al., 1994). The preglacial lowland landsurface thus experienced up to 1.5 m.y. of weathering and erosion in the Quaternary prior to glacial advance. It is impossible to assess accurately the significance of this denudation due to the absence of landforms or deposits of early Quaternary age in the study area. Approximately half of the total thickness of Quaternary sediment in the west-central North Sea is of early Quaternary age (Table 2). Much of this sediment, however, was probably derived from areas to the southeast (Cameron et al., 1987) and only a relatively small part was sourced

Table 3  
Selected published data on rates of Quaternary erosion in glacial and periglacial terrains

Area	Period	Erosion rate (mm a <sup>-1</sup> )	Reference
Spitsbergen	Holocene	0.015	Svendsen et al. (1989)
Spitsbergen	Quaternary	0.4	Svendsen et al. (1989)
Sognefjord	Quaternary	0.24	Nesje et al. (1992)
Laurentide shield	Quaternary	0.05–0.09	Bell and Laine (1985)
Laurentide shield	Quaternary	0.009	Kaszycki and Shilts (1987)

from the study area (Stoker and Bent, 1987). Nonetheless, this sediment is equivalent to ca. 100 m of erosion from an area the size of the study area and even if only 10–20% of this sediment is derived from the study area then this implies 10–20 m of erosion per unit area in the early Quaternary. Although this suggests significant early Quaternary denudation it is not possible to apportion this erosion between the periodically glaciated uplands or the unglaciated lowlands.

### 5.2. *The depth of erosion beneath the weathering surface*

A related problem is that the end-Tertiary surface may have been lowered during the Quaternary whilst retaining the gentle form of the paleic relief. The paleic relief appears generally to be essentially a rock-floored surface with patches of deep weathering. It is therefore possible that this stripped rock surface has been lowered during the Quaternary. Over wide areas, however, the paleic relief shows few classic landforms of glacial erosion such as roches moutonnées, and glacial erosion therefore appears to have been limited. A further difficulty is that glaciers may have achieved significant erosion of fresh bedrock after stripping away the preglacial weathering mantle in zones of areal scouring. Whilst it is known that stripping of the basal surface of weathering can create features akin to ice-moulded glacier bedforms, both in Scotland (Hall, 1993b) and in Scandinavia (Lindstrom, 1988), the presence of roches moutonnées on the floors of deep glacial troughs such as Glen Dee shows that these features may also reflect deep glacial erosion. Ice-moulded bedrock forms are best regarded as equilibrium bedforms maintained during rock surface lowering by a combination of glacial and structural controls. They can also be used to demonstrate that rock surface lowering in the study area is limited to a few metres since west of the present-day coastline the progressive exhumation and moulding of rock cores can be traced in a continuum of forms which have developed without deep erosion of the basal surface of weathering (Sugden, 1989). Similarly, the large roches moutonnées formed on spurs along the Dee valley in places retain the stumps of former tors on their summits. Away from the valley axis, traces of

lee-side plucking disappear (Sugden et al., 1992). We suggest that deep erosion of bedrock has therefore been confined to valley floors.

### 5.3. *Non-glacial erosion of the study area*

It is also possible that significant surface lowering has been achieved by non-glacial processes. The preservation of delicate glacial and periglacial forms in both the mountains and the lowlands, however, suggests that Holocene erosion and transport has been limited to the reworking of late Quaternary sediments. Very limited interglacial denudation is consistent with the observation that 98% of the sediment in the central North Sea dating from the last million years was deposited under arctic or boreo-arctic conditions (Sejrup et al., 1987). It is clear, however, that significant weathering, mass movement and sediment transport took place in both the uplands and lowlands of northeast Scotland under the periglacial conditions of the Younger Dryas or Loch Lomond Stadial (Ballantyne and Harris, 1994). Since similar conditions must have prevailed earlier in the Quaternary, important periglacial modification of the landscape can be inferred but cannot be quantified on existing data. Periglacial erosion rates calculated from the volume of colluvial valley-fills in the Appalachians vary from 0.1 to 0.3 mm  $a^{-1}$ . These rates are for different periglacial episodes of 5–60 ka duration but, if extrapolated, could account for a few tens of metres of ridge-top lowering in the Quaternary (Braun, 1989). In the study area, however, the retention of postglacial debris on slopes and valley floors suggests that successful evacuation to the North Sea basin requires additional glacial or meltwater transport.

### 5.4. *Mapping errors*

Errors in the estimates of the depth of glacial erosion may also result from incorrect identification of the preglacial landsurface. This is not considered as a major source of error in areas such as the Cairngorm and Gaick plateaux, where several lines of evidence are used in its reconstruction. Difficulties may arise, however, where the preglacial landsurface has been more heavily modified and reliance is placed on broad morphology and widely spaced

occurrences of thin saprolites. Misidentification may therefore give localised errors of, at most, a few tens of metres, but is unlikely to give large errors across the whole study area.

### 5.5. Error evaluation

These potential errors need to be seen in the context of the different landscapes of glacial erosion. In landscapes of upland selective linear erosion the minimum average depths of erosion of 108–152 m probably need to be increased to account for 10–30 m of periglacial ridge and plateau lowering, except in areas like the Gaick plateau where the preglacial regolith has not been entirely stripped. In landscapes of areal scouring the minimum average erosion of 35–48 m may not lie far below the true value. Rock lowering below the basal surface of weathering appears to be usually less than 10 m and the preservation of glacial microforms shows that periglacial modification of ice-scoured rock surfaces has been limited in the Lateglacial and Holocene. Total Quaternary erosion may therefore be of the order of 45–60 m. In lowland landscapes of selective linear erosion estimated minimum erosion is 12–52 m. This may need to be significantly increased to account for early Quaternary erosion. The preservation of minor preglacial landforms and patches of weathered rock means, however, that rock surfaces have probably not been greatly lowered by periglacial erosion. Furthermore, the general level of this terrain lies not far below that of adjacent little-modified preglacial landscapes. Total Quaternary erosion may thus have been of the order of 30–60 m. Little-modified preglacial landscapes must also have experienced little more than 10–40 m of Quaternary erosion.

### 5.6. Revision of the estimates of erosion

The original estimates of glacial erosion can therefore be recalculated in order to take into account these possible errors. This recalculation increases the minimum estimate of the volume of erosion in the study area from 95 to 114 km<sup>3</sup> and the maximum estimate from 171 to 201 km<sup>3</sup>. The depths of erosion in the study area expressed per unit area should therefore be increased from between 34 and

62 m to a higher value of between 41 and 72 m. Rates of erosion over the Quaternary (2.3 m.y.) should also be increased slightly from 0.021 mm a<sup>-1</sup> to 0.025 mm a<sup>-1</sup>.

It is only along valleys that there is clear evidence for deep glacial erosion beneath the basal surface of weathering and linear erosion here accounts for between 54% and 60% of the total volume of glacial erosion in the entire study area (Table 1). Over the rest of the study area, average total Quaternary erosion is probably ca. 60 m. A significant proportion of this average erosion, perhaps up to half, is attributed to non-glacial processes. This indicates that glacial erosion was limited in northeast Scotland beneath ice sheets where flow was not tightly constrained by topography but was significantly greater where basal ice flow was channelled along valleys. This is entirely consistent with the sharp lateral contrasts in depths of glacial erosion characteristic of landscapes of selective linear erosion (Sugden, 1968).

Offshore sediment volumes cannot provide data on levels of erosion in northeast Scotland as the sediment in the central North Sea cannot yet be matched to source areas. The main value of the figures for sediment accumulation rates therefore lies in the information provided on variations in rates of erosion during the Quaternary. In the early Quaternary much sediment was received in the central North Sea from the major river systems of the European mainland via a prograding delta system (Cameron et al., 1987). Hence, although northeast Scotland did contribute relatively small volumes of sediment at that time (Stoker and Bent, 1987), the sediment volumes almost certainly overestimate depths of erosion in northeast Scotland. This is significant as half of the total Quaternary sediment volume in the receiving area accumulated in the early Quaternary. Sediment from northeast Scotland was certainly transferred to the central North Sea in the middle and late Quaternary (Stoker and Bent, 1985; Cameron et al., 1987) but some sediment in the receiving area may have been contributed by the Scandinavian ice sheet (Sejrup et al., 1994). That large volumes of sediment were lost from the receiving area in the middle and Late Pleistocene is shown by the repeated truncation of sediment formations by regional erosion surfaces, including deep and broad valleys, by at least three major phases of ice sheet

glaciation in the west-central North Sea (Cameron et al., 1987). On balance, therefore, it is likely that sediment volumes overestimate rates of early Quaternary erosion and underestimate rates of middle and late Quaternary erosion in northeast Scotland.

The doubling, at minimum, of sedimentation rates between the early and middle to late Quaternary indicates that the onset of ice sheet glaciation in northeast Scotland was accompanied by a significant increase in rates of erosion. The figures suggest that middle and late Quaternary sediment accumulation rates were approximately equivalent but it should be remembered that it is likely that the late Quaternary sediment pile is substantially more complete than that of the middle Quaternary. Late Pleistocene sediments rarely exceed 50 m in thickness, and then generally in valleys (Stoker et al., 1985). Hence the data are consistent with the view that early ice sheets, notably the Anglian/Elsterian, achieved significantly greater landscape modification than more recent ice sheets.

## 6. Conclusion

The following conclusions can be drawn:

(1) Geomorphological mapping and aerial photograph interpretation show that northeast Scotland is an area characterised by selective glacial erosion, displaying landscapes of little or no glacial erosion, selective linear erosion and areal scouring. A landscape classification of the area shows that the intensity of glacial erosion decreases from west to east.

(2) Zones of upland selective linear erosion account for the greatest depths of erosion in the study area with a minimum of between 108 and 152 m of erosion per unit area. Landscapes of areal scouring account for a minimum of between 35 and 47.5 m of erosion per unit area, landscapes of selective linear erosion in lowland areas account for a minimum depth of erosion of between 12 and 52 m, areas where there is restricted glacial erosion and where there is evidence of widespread glacial deposition account for a minimum of between 16.4 and 41.6 m, and a zone of little-modified preglacial landscape has suffered erosion of between 10 and 40 m in depth.

(3) Across the entire study area, the minimum total volume of erosion is calculated to be between

95 km<sup>3</sup> and 171 km<sup>3</sup>. These values correspond to between 34 m and 62 m of erosion per unit area. Using the mean of these two values, 48 m, yields an minimum average erosion rate over the 2.3 m.y. of the Quaternary of 0.021 mm a<sup>-1</sup>.

(4) Calculations of the volume of sediment deposited in the central North Sea indicate that early Quaternary accumulation rates (0.09 mm a<sup>-1</sup>) were approximately half those of the middle and late Quaternary (0.16–0.18 mm a<sup>-1</sup>). Sediment volumes give notional erosion rates of 0.063 mm a<sup>-1</sup> and depths of 101 m for the early Quaternary and rates of 0.12–0.13 mm a<sup>-1</sup> and depths of 94 m for the middle and late Quaternary.

(5) Comparison of the two sets of data suggests that calculations of offshore sediment volumes overestimate rates of early Quaternary erosion and underestimate rates of middle and late Quaternary erosion in northeast Scotland. This is because the central North Sea received sediment from source areas other than northeast Scotland in the early Quaternary and because large amounts of sediment were lost from the destination area in the middle and late Quaternary.

(6) The doubling, at minimum, of denudation rates between the non-glacial conditions of the Pliocene and early Quaternary and the glacial conditions of the middle and late Quaternary suggests that the onset of ice sheet glaciation in northeast Scotland was accompanied by a significant increase in denudation rates. This new evidence from the mid-latitudes supports the previous suggestion of Molnar and England (1990, 1992) that glacial periods are characterised by higher denudation rates than non-glacial periods.

(7) The erosion rates indicate that major landforms of glacial erosion may develop over relatively short time spans. Thus, in northeast Scotland, glacial valleys of the order of 10<sup>2</sup> m deep were probably produced over periods of around 10<sup>5</sup> years as predicted by glaciological models such as those of Harbor et al. (1988). It is also possible to suggest that many of the features indicative of glacial erosion in this mid-latitude area were produced during the middle Quaternary cold stages.

(8) The drop in denudation rates between the middle Quaternary and the late Devensian (the last glacial advance in this area) suggests that landscape

modification was greatest beneath the earliest ice sheets in northeast Scotland. This is consistent with other observations from Glen Tilt, Scotland (Sutherland, 1984) and Glen Muick, Scotland (Clapperton, 1986) in that these glacially eroded valleys are primarily pre-late Devensian features. It is also consistent with the conclusion of Sharp et al. (1989) that glacial erosion was limited beneath the last glaciers in Snowdonia, north Wales during the Younger Dryas event.

(9) We suggest that in northeast Scotland the middle Quaternary glaciations caused the most landscape change for three main reasons. (i) The preglacial landscape was deeply weathered and therefore susceptible to ice sheet erosion, whereas the late Quaternary glaciers flowed across what was largely a rock floor. (ii) The earliest ice sheets modified preglacial valleys and created a system of glaciated valleys containing ice-moulded bedforms as the landscape became adapted to ice flow. Ice discharge then followed these new drainage routes in subsequent glaciations because they provided the least resistance to flow. (iii) The Anglian/Elsterian glaciation was the most extensive of the British Quaternary glaciations, implying a relatively thick and rapidly moving ice sheet with high potential for erosion. We conclude from this that later ice sheets had less impact on the landscape, and that this has major implications for the denudation chronologies of mid-latitude ice sheets.

(10) The overall conclusion of this study is that offshore sediment volumes cannot be used to provide data on levels of Quaternary erosion in northeast Scotland because the sediment in the central North Sea cannot be matched reliably to onshore source areas. The main value of data for offshore sediment accumulation rates lies in the information it provides on variations in overall rates of erosion during the Quaternary.

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