Wilson, Stuart B. (2005) *Morphological analysis and mapping of Loch Lomond Stadial moraines using digital photogrammetry and geographical information systems.*

PhD thesis

UNIVERSITY
of
GLASGOW

DEPARTMENT of GEOGRAPHICAL
AND EARTH SCIENCES

Morphological Analysis and Mapping of Loch Lomond Stadial Moraines using Digital Photogrammetry and Geographical Information Systems

Stuart B. Wilson BSc(Hons), MSc

Submitted to the Faculty of Physical Sciences
for the degree of Doctor of Philosophy

September 2005

Abstract

Hummocky moraines, deposited during the Loch Lomond Stadial (Younger Dryas), in the Scottish west Highlands have traditionally been interpreted as having a chaotic spatial pattern attributed to areal stagnation due to rapid climatic amelioration. This has more recently been challenged with the recognition of linear elements in the spatial pattern of moraines, thought to be related to active glacial retreat, incremental stagnation or active retreat with some local ice stagnation.

Morphological analysis and mapping of Loch Lomond Stadial moraines at five key sites, Torridon, Rannoch Moor, Tyndrum and Strath Fillan, the upper Forth Valley and the east Loch Lomond basin has allowed the genetic interpretation and inferences of climatic significance to made. 'Hummocky moraine is found at three of these sites, Torridon, Rannoch Moor and Tyndrum, where they are interpreted as polygenetic in origin.

The spatial organisation and morphology of hummocky features investigated in Torridon allows the differentiation of cross-valley orientated marginal moraines and the more numerous streamlined features with a down-valley orientation interpreted as flutings. As the flutings are superimposed on the cross-valley moraines they are thought to post-date moraine formation. The spatial organisation of glacial landforms in Torridon therefore represents a palimpsest landscape.

Mapping of moraines in the Rannoch Moor basin suggests that this was a major centre of ice convergence rather than accumulation during the Loch Lomond Stadial. Ice mainly accumulated in the corries in the mountains to the west of the moor from where it flowed to coalesce as an upland icefield. Ice is thought to have reached a sufficient volume in the Rannoch Moor basin to flow down valleys as outlet glaciers.

Hummocky features found at Tyndrum and Strath Fillan have a polygenetic origin and include the remnants of eskers, hummocks produced by local ice stagnation, marginal moraines, and lateral moraines which have been modified by paraglacial debris flow. Large terraces at this sites are interpreted as kame terraces with pitted and channelled surfaces. Local ice stagnation is thought to have occurred during a regional pattern of active deglaciation.

Moraines deposited by the piedmont lobes of the south-eastern limits of the Loch Lomond Stadial ice have also provided insights into the nature of deglaciation at the termination of the Loch Lomond Stadial. Moraines in the upper Forth Valley are interpreted as thrust-block moraines produced by glacitectonic processes during surging or fast ice flow. The pattern of moraines suggests at least one short readvance of ice in this area. Short readvances are also inferred by the morphology, spatial organisation and sedimentology of moraines, partly deposited subaqueously, in the east Loch Lomond basin.

Loch Lomond stadial moraines are thought to have been mainly deposited by active glacier retreat with some evidence of local ice stagnation due to high supraglacial sediment cover. Features traditionally interpreted as hummocky moraine, and used as evidence of rapid climatic amelioration are interpreted as polygenetic and therefore cannot be used as evidence of climatic conditions of the Loch Lomond Stadial.

Although digital photogrammetry and GIS were found useful for mapping and spatial analysis of glacial landforms and provided some new insights into the genesis of landforms, the use of images derived from digital elevation models to interpret landforms was found problematic, especially where landforms are located on steep slopes. Problems were also encountered in areas of extensive tree cover. The utility of digital photogrammetry to geomorphological studies is also highly dependent on aerial photograph quality.

Contents

Chapter 1: Introduction

Chapter 2: Literature Review

Chapter 3: Methods

Chapter 4: Torridon

Chapter 5: Rannoch Moor

Chapter 6: Tyndrum and Strath Fillan

Chapter 9: Discussion, Conclusions and Further Research

List of Figures

Acknowledgements

I would like to acknowledge the following people without whom this research would not have been possible. My supervisor Dr. Dave Evans for help and discussion of my work including reviewing this thesis. My second supervisor Dr. Jane Drummond for technical advice relating to GIS and digital photogrammetry. Dr. Doug Benn and Dr. Jim Hansom for comments on the draft thesis. My girlfriend (and my dog) for putting up with me during this project over the last four years and for their help with my fieldwork. Tessa Evans for watching my GPS reference station, which was set up in Tessa and Dave's garden for security reasons while surveying the east Loch Lomond and Forth Valley field sites. The warden at Crianlarich youth hostel for watching my GPS reference station while surveying the Tyndrum and Rannoch Moor sites. Also thanks to people of Shieldaig, Crianlarich and Tyndrum, I met during this research.

I would also like to thank all those who organised and raised funds for the University of Glasgow Iceland expeditions over the last four years, and those involved in the expeditions for the previous four years to Iceland, Canada and Svalbard. The experience and insights into the glacial geomorphology of contemporary glacier margins gained on these expeditions has been invaluable to my knowledge and appreciation of glacial geomorphology. Also thanks the Carnegie Trust and the Royal Scottish Geographical Society and other contributors who helped fund these Expeditions, and to the Carnegie Trust for funding the field research carried out in Scotland for this study.

Thanks to all the staff at the Department of Geography and Geomatics at Glasgow for their help, especially the computer technicians Brian Black and Ian Anthony, and the physical geography technician Pete Chung for help with field equipment including GPS. Thanks to all the postgrad students at Glasgow especially Steve Thomson and Matt Sims for their discussion on glacial geomorphology and Rob Bingham with whom I shared an office for the duration of this work.

I would also like to thank all who organised and attended the Quaternary Research Association field meeting to the western Highland Boundary 2003 and also all the members of the Glacial Landsystems Working Group who attended the meeting in Drymen 2002, and all previous GLWG field meetings. Also thanks to Envirocentre for the use of equipment while editing this thesis.

Declaration

This thesis embodies the results of original research carried out by the author between October 1999 and December 2003. references to existing works are made as appropriate. Any remaining errors or omissions are the responsibility of the author.

Stuart B. Wilson
September 2005

1

Introduction

1.1 Introduction

Following the Lateglacial Interstadial (Windermere Interstadial) glacial conditions returned to the British Isles, during what is termed the Loch Lomond Stadial or Younger Dryas, which has been dated to approximately 11,000 to 10,000 ^{14}C years B.P. Glaciers developed in upland areas especially the Scottish West Highlands and the Lake District. Glaciers also developed in the Cairngorm mountains, the southern uplands, Pennines, Snowdonia and the Brecon Beacons.

The extent of glacial ice during the Loch Lomond Stadial was more restricted than the previous glaciation during which the Lateglacial (Dimlington Stadial) ice-sheet covered most of the British Isles (fig 1.1). Early geomorphological evidence for the Loch Lomond Readvance was found around the south part of Loch Lomond and in the upper Forth Valley (Jack 1874 Renwick & Gregory 1909 Simpson 1933). The term Loch Lomond Readvance was introduced by Simpson (1933).

The extent of glacier ice during the Loch Lomond Stadial was mapped by Charlesworth (1956) and Sissons (1963, 1967a, 1967b, 1973, 1979). Charlesworth gave detailed descriptions of active glacier recession into high mountain valleys and corries but published little geomorphological evidence for this theory. Sissons later proposed more restricted glacial limits compared to Charlesworth using geomorphological evidence such as end moraines, hummocky moraine and the distribution of outwash terraces and periglacial features. Sissons used end moraines to delimit the extent of glacier ice where possible. Where no end moraines were recognisable, Sissons used other evidence especially the existence of hummocky moraine.

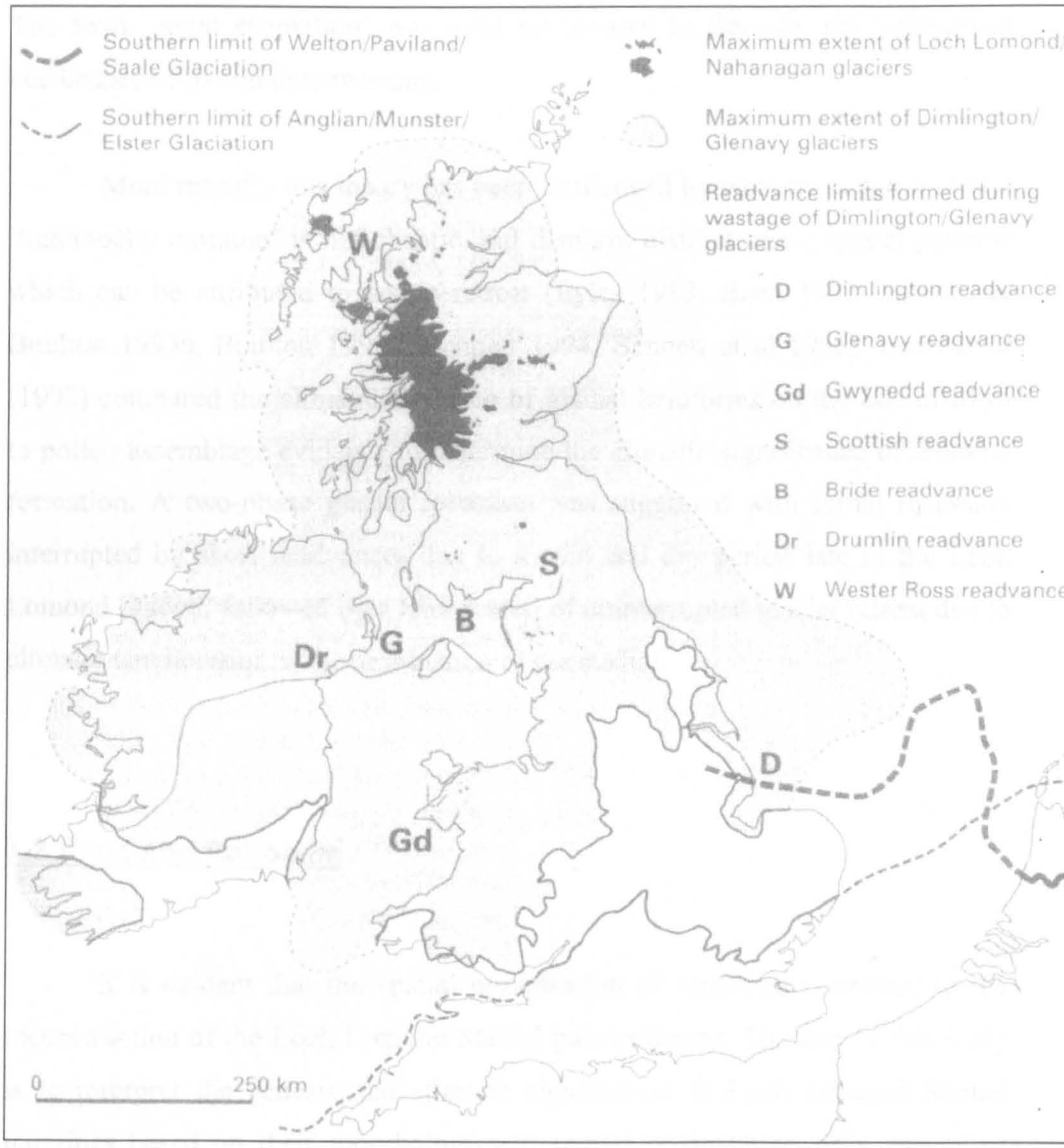


Figure 1.1 Limits of glaciation in the British Isles (Lowe & Walker 1997)

Sissons (1963, 1967a, 1967b, 1973, 1979), based on previous work by Manley (1956) in the Lake District, suggested that hummocky moraine found within the margins of Loch Lomond Stadial glaciers has a chaotic spatial organisation and interpreted this as evidence of in-situ downwasting of glaciers at the termination of the Loch Lomond Stadial, and that glaciers did not recede by active recession as proposed by Charlesworth (1956). The geographically widespread occurrence of 'chaotic hummocky moraine' was used by Sissons to suggest that in-situ downwasting was not due to the local nature of retreat of glaciers but that widespread in situ down-wasting had occurred at the termination of the Loch Lomond Stadial, which he attributed to rapid climatic amelioration.

The term 'aerial stagnation' was used by Sissons to describe the widespread occurrence of in-situ downwasting.

More recently this theory has been challenged by workers suggesting that 'hummocky moraine' is not chaotic, but displays distinct linear spatial patterns which can be attributed to active retreat (Eyles 1983, Benn 1992, Bennett & Boulton 1993a, Boulton 1993a, Bennett 1994, Bennett et al 1998). Benn et al (1993) compared the climatic evidence of glacial landforms on the Isle of Skye to pollen assemblage evidence to determine the climatic significance of moraine formation. A two-phase glacial recession was suggested with initial recession interrupted by short readvances due to a cold and dry period late in the Loch Lomond Stadial, followed by a later period of uninterrupted glacier retreat due to climatic amelioration at the termination of the stadial.

1.2 Aims and Rationale

It is evident that the spatial organisation of moraines is critical to the reconstruction of the Loch Lomond Stadial palaeoclimate. The aim of this study is to interpret the genesis and climatic significance of Loch Lomond Stadial moraines based on their morphology and spatial organisation, at a variety of Scottish sites using digital photogrammetry, digital terrain modelling and geographical information systems (GIS), including the use of three dimensional visualisation techniques. This will include the evaluation of previously published models of Loch Lomond Stadial moraine formation and refining of these models based on a more detailed study of their morphology and spatial organisation, afforded by the digital methods employed. This study will therefore provide a better understanding of the formation of Loch Lomond Stadial glacial landforms and the climatic implications of their morphology and spatial pattern. It will also test the application of digital photogrammetry, GIS and three dimensional visualisation to the study of glacial geomorphology.

This research will include accurately mapping Loch Lomond Stadial moraines using digital photogrammetry and GIS to produce maps of the glacial geomorphology, and digital elevation models (D.E.M.s) for the field sites chosen. Aerial photographs are adversely affected by various distortions, which can be removed by digital photogrammetry. Distortions in uncorrected aerial photographs include height displacement, known as parallax, that result in features appearing to lean away from the centre of the photograph. Also scale is not constant on an aerial photograph with scale reduction towards the photograph edges. Reasons for these distortions are discussed in Chapter 3. Digital images of aerial photographs with distortions removed, known as orthoimages, can be used to accurately map landforms as, unlike aerial photographs, these are geometrically correct and can also be registered to a coordinate system using GIS. This also has the advantage of creating digital elevation models (D.E.M.s), which are necessary to produce orthoimages. D.E.M.s can also be used in various ways to identify and interpret landforms including contouring and hillshading and to produce three dimensional digital models.

Employing the techniques of producing high resolution D.E.M.s, analysing the D.E.MS using three-dimensional visualisation techniques in a GIS and using them to produce maps of the spatial organisation of glacial landforms will give insights into the nature of the morphology and spatial patterns of moraines previously unavailable. The use of digital three-dimensional data rather than conventional aerial photograph interpretation will allow more detailed visualisation of the morphology and spatial organisation of glacial landforms at a number of key sites. This will include assessing and refining previous models of moraine formation, at sites used in previous studies, and the interpretation of the glacial landforms of sites with little previously published literature.

Hummocky moraine complexes known to be of Loch Lomond Stadial age and used in previous geomorphic studies will be investigated including Torridon, Tyndrum and Rannoch Moor. The locations of the southern limits of the Loch Lomond Stadial ice in the upper Forth Valley and east Loch Lomond basin are also included. Evidence which may provide interesting insights into the nature of deglaciation at the termination of the Loch Lomond Stadial have been published for these two sites (Thorp 1991a, Benn & Evans 1996, Philips et al. 2002).

As well as geomorphological reasons for the choice of field sites, sites with varied landscapes have been chosen to assess the effectiveness of the methods in different topographic settings, including the wide lowland valleys of the Forth Valley and Loch Lomond Basin sites, the more restricted upland highland valleys of Torridon and Tyndrum and the open moorland of Rannoch Moor. Vegetation and anthropogenic modification of these landscapes is also varied which will allow assessment of the effect of these variables, especially the use of the techniques in forested and non-forested areas and the effects of buildings and agricultural land-use.

Sedimentological data were collected where possible, including clast shape and fabric analysis. Borehole records are used where available for study areas where sediment exposures are not adequate for clast analysis. This data will be used to investigate the transport and depositional mechanisms associated with the landforms and to correlate this evidence with the interpretation of the geomorphological evidence. The information collected for the proposed sites, including maps, orthoimages, D.E.M.s and sedimentological data are used to construct a GIS project for each site using ESRIs ArcView (3.1) GIS.

1.3 Climatic evidence for the Loch Lomond Stadial (Younger Dryas)

This section will review some of the evidence for a return to cold conditions following the Lateglacial Interstadial, in the period known as the Loch Lomond Stadial, which is coeval with the Younger Dryas chronozone. Evidence reviewed here will include ice-core evidence from the Greenland GRIP and GISP ice cores and evidence of changes to ocean circulation in the North Atlantic. Evidence specific to the British Isles including pollen assemblage analysis, radiocarbon dates, and geomorphological evidence will be discussed in the literature review (chapter 2).

1.3.1 Ice core evidence

The climatic deterioration of the Younger Dryas (Loch Lomond Stadial) can be seen on the graphs below, plotting the paelaeoclimatic indicators of ice accumulation, $\delta^{18}O$, and methane content in the GISP2, Greenland ice core (fig 1.2).

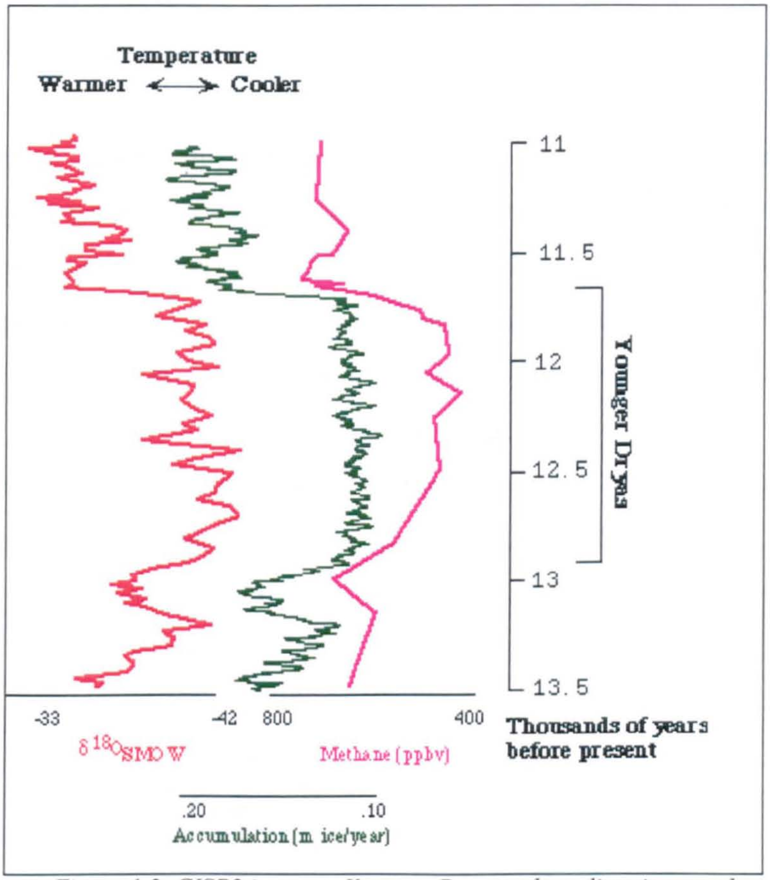


Figure 1.2 GISP2 ice core, Younger Dryas palaeoclimatic record

The colder climate of the Younger Dryas is reflected in the decrease in $\delta^{18}O$, annual ice accumulation and methane, which shows a decrease in temperature from approximately 11,000 to 10,000 ^{14}C years B.P (13 ka to 12.3 ka cal years B.P.). This colder climate continued until around 11.6 ka BP followed by a relatively rapid climate amelioration and the termination of the Younger Dryas. This suggests that the transition from interglacial conditions to the colder conditions of the Younger Dryas was gradual, but the climatic amelioration following the Younger Dryas, apparent in the Greenland ice core record, was more rapid. However, the transition to warmer conditions at the termination of the Younger Dryas was not uninterrupted. A short colder period can be seen on the graph following the period of rapid warming. The abrupt climatic shift at the end of the Younger Dryas was too quick to simply be due to changes in ocean circulation, insolation, atmospheric CO_2, or ice-sheet extent, but may be due to changes around threshold levels in these variables (Alley et al 1993).

The short term cold climatic event of the Younger Dryas is thought to have had a greater effect in northern Europe and Greenland, than in North America (Dansgaard et al. 1989). The cold climate of the Younger Dryas is therefore thought to have been due to changing conditions in the North Atlantic such as rapid changes in sea ice cover. Evidence from the GISP Greenland ice core suggest stormier, drier conditions during the Younger Dryas with higher concentrations of windblown dust and lower $\delta^{18}O$. Dansgaard (1989) suggested that the climate of the North Atlantic became milder and less stormy within a period of 20 years, following the colder period of the Younger Dryas and that in southern Greenland temperatures increased by 7°C within approximately 50 years. Similar climatic patterns can be seen in the DYE3 ice core and the $\delta^{18}O$ record from a lake sediment core, from Lake Gerzen, Switzerland, suggesting that the changes in the climate in Greenland at this time also occurred in continental Europe (Dansgaard 1989).

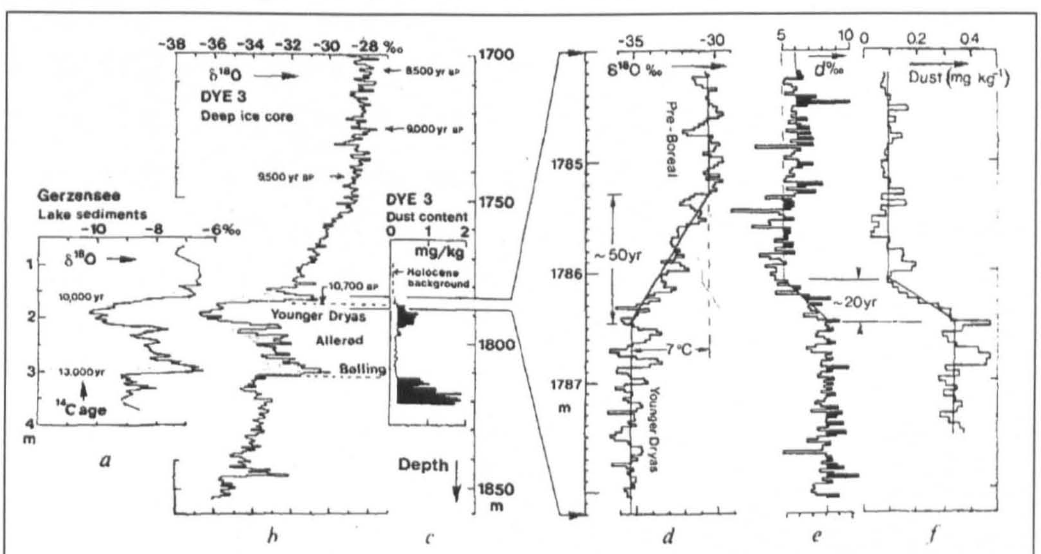


Figure 1.3 DYE3 ice core / Lake Gertzen palaeoclimatic record (Dansgaard et al 1989)

The climate at the termination of the Younger Dryas is also reflected in dust concentration in the ice cores (fig 1.3). Wind blown continental dust increases with storminess and dryness in its source area. Dust concentrations in the ice cores varied in antiphase with $\delta^{18}O$, suggesting dry, very stormy conditions in periods of glaciation such as the Younger Dryas, with a more humid, calm climate during interstadials. The ice core records therefore record a rapid shift in atmospheric conditions at the termination of the Loch Lomond Stadial. $\delta^{18}O$ levels shifted by 5 ‰ within a fifty year period, indicating a temperature rise of 7°C every 50 years.

Dansgaard (1989) suggested that the rapid temperature rise at the end of the Younger Dryas could be due to the northward retreat of the North Atlantic sea ice and the North Atlantic Polar Front from its Younger Dryas position of 55° N. This is thought to reflect large areas of cold surface water opening up and temporarily increasing atmospheric moisture.

The evidence, from the Arctic ice cores, of the climatic cooling of the Younger Dryas is not reflected in ice cores from the Antarctic, suggesting that the Younger Dryas event possibly did not affect the Antarctic Ice Sheet. There are no obvious changes in dust and $\delta\ ^{18}O$ in the Antarctic as can be seen in the ice core record of figure 1.4 (Broecker and Denton 1990).

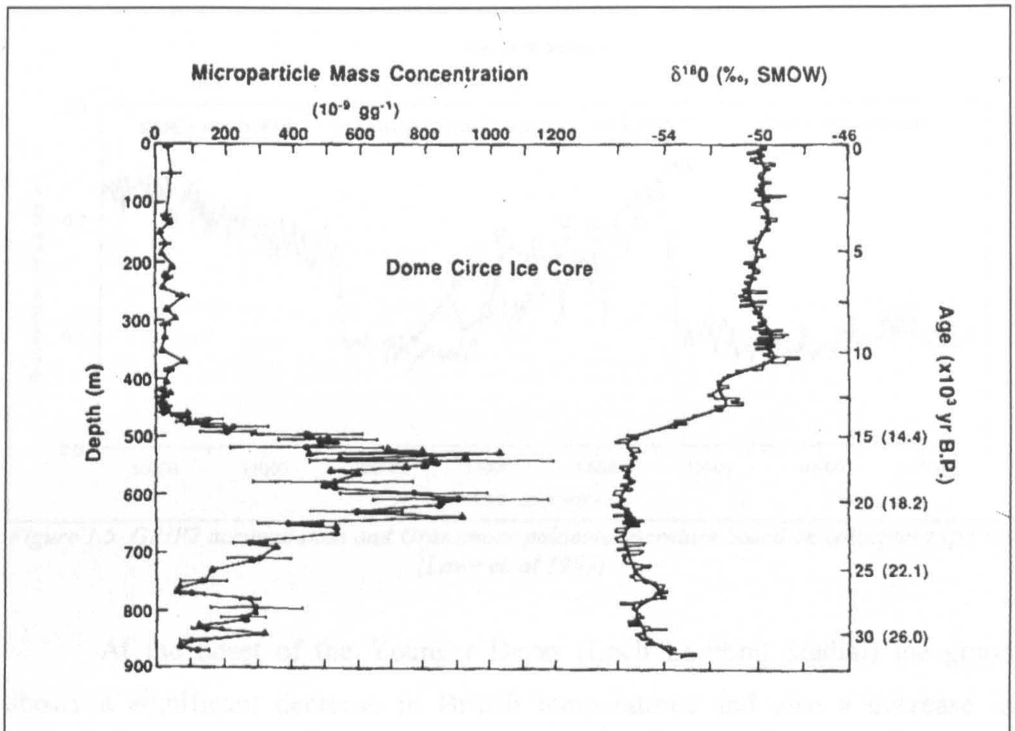


Figure 1.4 Dome Circle Ice Core $\delta^{18}O$ and dust concentration (Broecker & Denton 1990)

Lowe et al. (1995) compared proxy climate data for East England to the snow accumulation records of the GISP2 Greenland ice core. ^{14}C dates were measured from plant macrofossils and coleoptera, collected from a gravel quarry at Gransmoor, East Yorkshire. Temperatures inferred by coleoptera species were combined with the ^{14}C dates to construct a palaeotemperature curve. ^{14}C dates were calibrated to allow comparison with the snow accumulation data. The paelaeotemperature curve, for Gransmoor, was superimposed on the snow accumulation record of the GISP2 ice core (fig 1.5) and demonstrates a similar climate pattern for Greenland and Gransmoor. According the Lowe et. al. discrepancies in the curves are within the error range of both the radiocarbon ages and the ice core record.

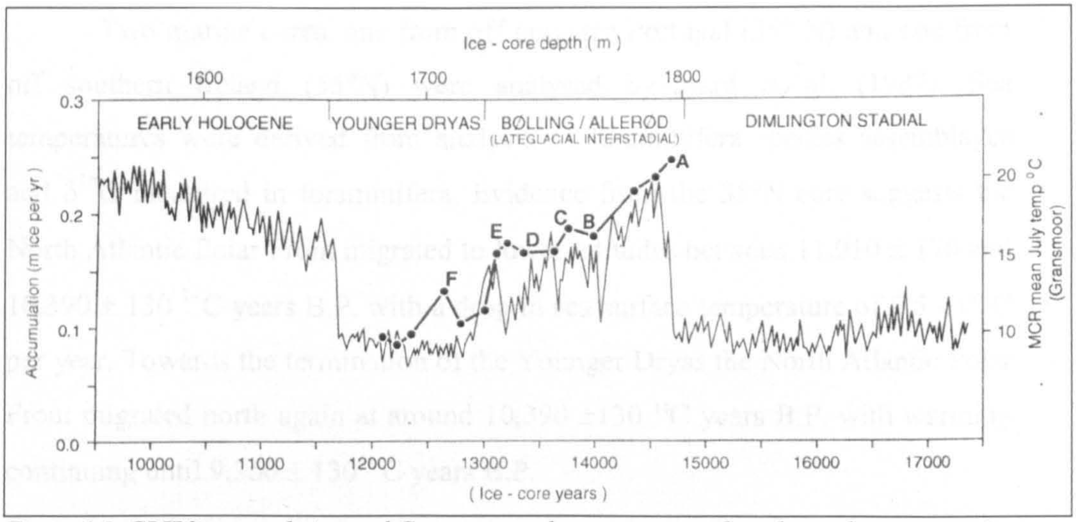


Figure 1.5 GRIP2 accumulation and Gransmoor palaeotemperature based on coleoptera species (Lowe et. al 1995)

At the onset of the Younger Dryas (Loch Lomond Stadial) the graph shows a significant decrease in British temperatures and also a decrease in Greenland snow accumulation. Climatic changes in Britain and Greenland are therefore thought to be in phase, with climatic changes at the beginning of the Younger Dryas occurring around the same time in the British Isles and Greenland (Lowe et al. 1995).

1.3.2 Ocean core evidence

Marine sediment cores from the North Atlantic display evidence of an oscillating North Atlantic Polar Front during the Late Glacial period. The North Atlantic Polar Front shifted north from its southern limit off northern Portugal after 13,500 ^{14}C years B.P., to around the latitude of Iceland. It then shifted south again around 11,000 to 10,000 ^{14}C years B.P. to the latitude of southern Ireland, resulting in dramatic sea surface temperature changes, thought to be responsible for the return to the cold conditions of the Younger Dryas. It is thought that sea surface temperatures in the North Atlantic were kept low due to the influx of meltwater from the Laurentide Ice Sheet from 15,000 to 13,500 ^{14}C years B.P. (Lowe & Walker 1997).

Two marine cores, one from off northern Portugal (35° N) and one from off southern Ireland (55°N) were analysed by Bard et al. (1987). Sea temperatures were derived from analysis of foraminifera species assemblages and $\delta^{18}O$ measured in foraminifera. Evidence from the 35°N core suggests the North Atlantic Polar Front migrated to lower latitudes between 11,010 ± 170 and 10,390 ± 130 ^{14}C years B.P. with a drop in sea surface temperature of 0.5 - 1° C per year. Towards the termination of the Younger Dryas the North Atlantic Polar Front migrated north again at around 10,390 ±130 ^{14}C years B.P, with warming continuing until 9,360 ± 130 ^{14}C years B.P.

^{14}C dates derived from foraminifera from the core off southern Ireland (55°N) date the onset of the Younger Dryas to approximately 10,700 years BP. Dates given for the termination of the Younger Dryas at this location are varied due to effects of bioturbation, but are similar to the dates for the core at 35° N. The difference in dates between the cores at 35° and 55 ° N are within the error margins of the ^{14}C dating methods (Bard 1987). This is thought to reflect rapid southward migration of the Polar Front at the beginning of the Younger Dryas, and a subsequent rapid move north, with a velocity possibly exceeding 5km per year. Figure 1.6 shows the migration of the North Atlantic Polar front, from 16,000 to 10,000 ^{14}C years B.P.

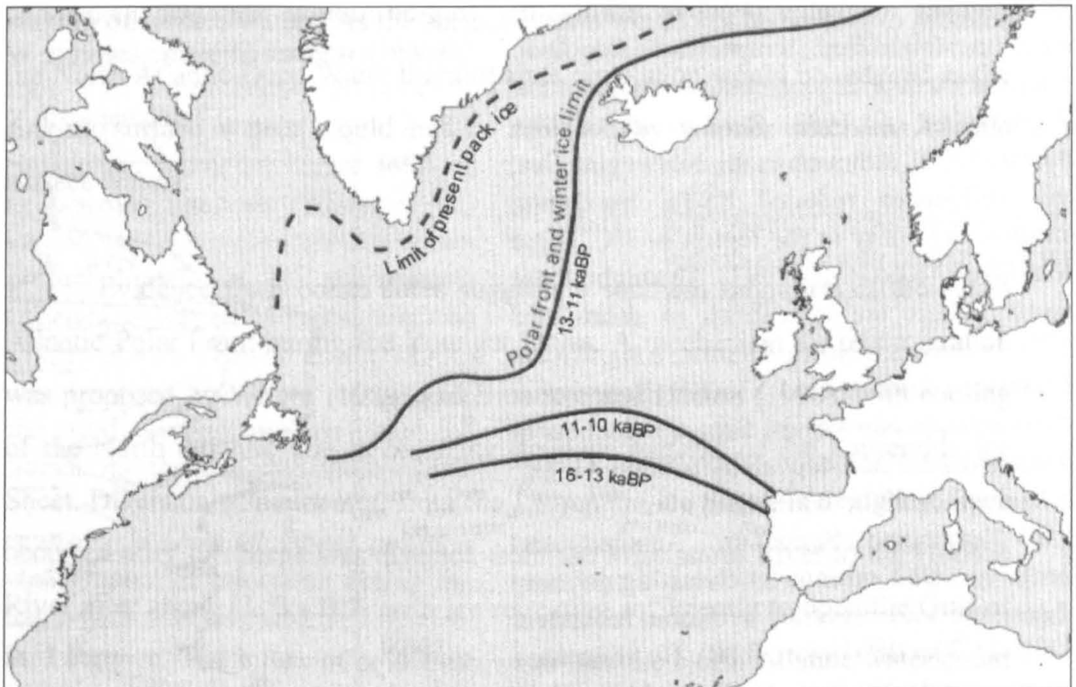


Figure 1.6 Oscillation of the North Atlantic Polar Front 16 to 10 kaBP: Adapted from Ruddiman and McIntyre 1981

Boyle and Keigwin (1997) present evidence from an ocean core from the Caribbean, of a reduction in the formation of the cold North Atlantic Deep Water, at the time of the Younger Dryas. The cold North Atlantic Deep Water is depleted in nutrients and $\delta^{18}O$, and this is reflected in the sediments in the ocean core. However during the period 9,000 to 11,500 B.P. the core shows an episode of nutrient enrichment in the deep ocean water, interpreted as evidence that the production of the North Atlantic Deep Water either ceased or was severely reduced. A mechanism is proposed to explain this period of reduced production of deep water, using the modern analogue of differences in the circulation of the North Atlantic and North Pacific. As the North Pacific is colder than the North Atlantic there is less evaporation of ocean surface water, and the water is therefore less saline. This prevents the sinking of the surface water, as occurs in the North Atlantic, where the more dense cold, highly saline surface water sinks to produce the North Atlantic Deep Water. The less saline water of the Pacific sinks less to form intermediate water. It is suggested that a similar mechanism may have operated in the North Atlantic during the Younger Dryas, with colder temperatures reducing evaporation resulting in lower salinity and reduced sinking of surface waters. As the surface waters would not be sinking to produce the North Atlantic Deep Water thermohaline circulation would be reduced as the sinking surface waters would not be replaced by warmer southern Atlantic surface waters.

Evidence from ocean cores suggests a southern migration of the North Atlantic Polar Front during the Younger Dryas. A mechanism for this migration was proposed by Wright (1989) and Broecker and Denton (1990), with cooling of the North Atlantic due to changing drainage patterns of the Laurentide Ice Sheet. Diversion of meltwater, from the Laurentide Ice Sheet, is thought to have occurred after discharge was diverted from the Mississippi River to the Hudson River after about 11.7ka B.P. with ice retreating sufficiently to open the Gulf of St. Laurence. The influx of cold fresh water into the North Atlantic water could have been sufficient to divert the Gulf Stream, and the warmer water it brings north. This would have allowed cold Arctic water and the icebergs it carried to migrate south, moving the polar front to the south. By 9.5 ka BP. the Laurentide ice sheet had retreated enough to allow drainage via the Mississippi River and the warmer climate at this time would have reduced the cooling effects of meltwater draining via the St. Lawrence River, therefore reducing its effect on the Gulf Stream (Wright 1989, Broecker and Denton 1990).

The abrupt return to cold conditions in the North Atlantic, following the warmer climate of the Lateglacial interstadial, evident from ice and ocean cores resulted in rapid glacier development in the upland regions of the British Isles, especially in the Scottish west Highlands. The cold conditions are also recorded in the glacial geomorphology of the upland areas of the British Isles, with the production 'hummocky moraine' especially being linked to climatic conditions at the termination of the Loch Lomond Stadial (Manley 1956 Sissons 1963, 1967a, 1967b, 1973, 1979). The spatial organisation of moraines has been used as evidence for climatic conditions at the termination of the Loch Lomond Stadial and correlated with other climatic evidence such as ocean and ice core records. Loch Lomond Stadial moraines including 'hummocky moraine' will be investigated at a number of field sites in the Scottish west Highlands to ascertain if their morphology and spatial organisation provide evidence of climatic significance.

1.4 Field Sites

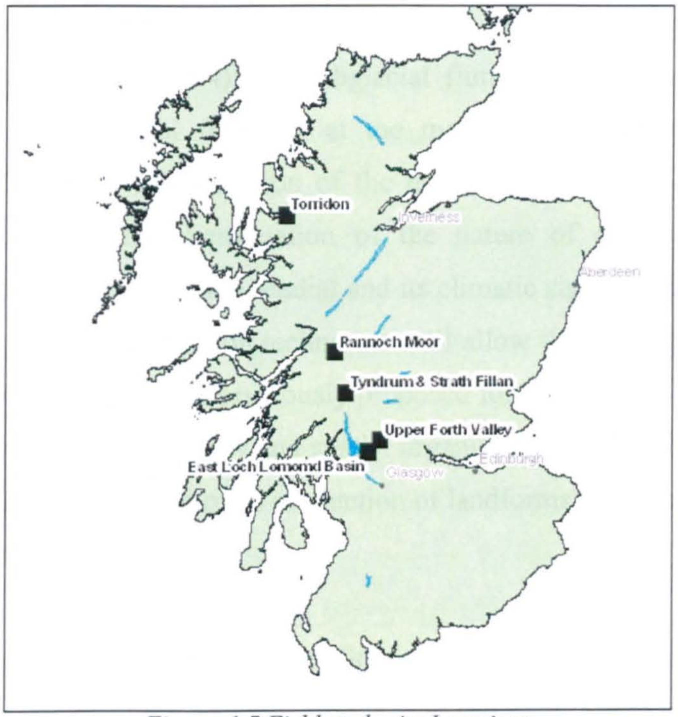


Figure 1.7 Field study site Locations

Five field study sites were chosen at Torridon, Rannoch Moor, Tyndrum, the upper Forth Valley and the east Loch Lomond basin (fig 1.7). Features with the appearance of 'Hummocky moraine' attributed to areal stagnation by Sissons can be found at three of these sites Torridon, Rannoch Moor and Tyndrum. Areal stagnation was thought to have occurred due to the rapid climatic amelioration suggested by ice and ocean core evidence. The remaining two sites in the upper Forth Valley and east Loch Lomond basin were chosen as recent work has been published on the glacial history of these sites that may give interesting insights into the nature of deglaciation at the termination of the Loch Lomond Stadial.

The Torridon field site, situated in the north-west Highlands includes Glen Torridon and the adjoining valleys of Coire a'Cheud Chnoic and Srath nam Poll Dubh. Coire a'Cheud Chnoic is of particular importance as it has been the subject of many previous studies, and in particular, the study of the 'hummocky moraine' found at this site. The hummocky moraines at this site have traditionally been interpreted as evidence of aerial stagnation. However, more recent studies have proposed alternative mechanisms of formation: (1) the product of active glacier recession (Eyles 1983, Bennett & Boulton 1993a, Boulton 1993a, Bennett 1994); (2) subglacial flutings (Hodgson 1982, 1986, 1987); and (3) englacial thrusting at the margins of polythermal glaciers (Bennett et al 1998) . Interpretation of the hummocky moraine at this site is therefore critical to the interpretation of the nature of deglaciation at the termination of the Loch Lomond Stadial and its climatic significance. The use of digital mapping and visualisation techniques will allow the re-assessment of the models of moraine production previously proposed for this site and allow a more detailed study of the morphology and spatial organisation of glacial landforms at this site providing insights into the production of landforms and reconstruction of glacier dynamics at this site.

Rannoch Moor, in the south-west Grampian Highlands is thought to have been the main centre of ice accumulation during the Loch Lomond Stadial, due to high rates of precipitation and the prevailing weather systems from the south-east combined with topography suitable for glacier ice development. Glacier ice is thought to have flowed out from the moor in a radial pattern forming outlet glaciers especially in Glen Orchy, Glen Etive, Glen Coe and Glen Ossian (Thorp 1986, 1991b). However, according to Sissons (1967a), ice volume was not sufficient to produce outlet glaciers from Rannoch Moor. Hummocky moraine is abundant in the Rannoch Moor basin and has a chaotic appearance when viewed from the ground. However, spatial patterns of moraines indicative of active recession have been suggested by Thorp (1986 1991) and Boulton (1992). Analysis of sediments and radiocarbon dates from a sediment core from the Kingshouse area of Rannoch Moor have been used as evidence of active retreat of ice from Rannoch Moor into the surrounding corries (Lowe & Walker 1976).

Despite the importance of this site as the possible main centre of ice dispersal during the Loch Lomond Stadial and its abundant glacial landforms, no maps of the moraines on Rannoch Moor have previously been published. This study will produce the first detailed, accurate maps of the glacial landforms of Rannoch Moor, allowing reconstruction of the complex patterns of ice flow in an area thought to be the main ice shed in the West Highlands during the Loch Lomond Stadial.

The field site at Tyndrum and Strath Fillan is situated approximately 20km south of Rannoch Moor. The geomorphology of this site includes hummocky mounds in the valley bottoms and on the northern slopes of Strath Fillan, and terrace-like features on the valley sides. Very little has been published on the glacial geomorphology of this area, although Sissons (1967a) describes the hummocky features at this site as including chaotic hummocky moraine and some glacifluvial features. These glacial landforms are not thought to mark the maximum extent of glacier ice in the region. The occurrence of glacial landforms continues east of this site in Glen Dochart as far east as the village of Killin suggesting the ice extended as far as the western shores of Loch Tay (Sissons 1967a). The research at this site will allow the interpretation of the origin of proximal moraines and glacifluvial landforms and their relationship with glacial activity in the Tyndrum and Strath Fillan area.

The remaining two field sites are situated at the south-eastern extent of the Loch Lomond Stadial glaciers. The glaciers at these locations, the Menteith and Lomond glaciers, extended beyond the mountains and valleys of the west Highlands onto the lowlands of the east Loch Lomond basin and upper Forth Valley as Piedmont lobes. The landscape and landforms of this site are distinct from the sites further north, with larger scale landforms and low-lying ground with much forest cover and agricultural landuse. These differences will allow a comparison of the application of the methods to differing terrains.

Large moraines extending from the village of Buchlyvie to Arnprior and on the eastern shores of the Lake of Menteith mark the extent of ice in the upper

Forth Valley, which consists mainly of a flat low elevation carse landscape. The carse of the upper Forth Valley has been subject to marine incursion during the Lateglacial (Windermere) interstadial and later during the Flandrian. It has been suggested that these moraines were formed as push moraines (Sissons 1976, Smith 1993) or as thrust block moraines formed by glacitectonic processes due to the rapid advance of ice over unconsolidated estuarine sediments (Thorp 1989). A study of the morphology of the large moraines of the Upper Forth Valley will test the theory that these were formed as thrust block moraines. Mapping the moraines and meltwater channels will allow examination of the relationship between these features. Boreholes were available for the extent of this field site and will be used to analyse the spatial relationship between landform distribution and the subsurface sediments using GIS.

Moraines marking the extent of ice in the east Loch Lomond basin can be traced along the northern slopes of the Kilpatrick Hills, then trending north, in the Blane Valley, to the east of the village of Drymen. These are thought to have been partially deposited in a glacilacustrine environment, where they occur on the lower ground of the Blane Valley. The Blane Valley is thought to have been occupied by an ice dammed lake, Lake Blane during the Loch Lomond Stadial (Rose 1981). Recently published work on the sedimentology of the moraine ridges in the Blane Valley have suggested these were produced during active glacier retreat punctuated by minor readvances, and therefore may provide important insights into the nature of deglaciation at the termination of the Loch Lomond Stadial (Benn & Evans 1996, Phillips et al. 2002). The use of three dimensional visualisation of high resolution D.E.M.s and digital mapping of glacial landforms will allow a study of the morphology of these features relative to the level of the former Lake Blane. This will test if the morphological evidence is consistent with previously published reconstructions of the glacial history of this area.

The varied topography of the five field sites will also allow comparison of the use of digital elevation models to study the morphology and spatial organisation of glacial landforms applied to different topographic settings.

As well as the study of the five sites in Scotland, fieldwork was carried out at a number of contemporary glacier margins in Iceland to investigate the possibility of contemporary analogues for the nature of deglaciation at the margins of Loch Lomond Stadial glaciers in Scotland.

Further discussion of the evidence for glaciation of the west Highlands, during the Loch Lomond Stadial and theories of moraine formation are discussed in the literature review (chapter 2). Further details of the field sites can be found in the relevant field site chapters (chapters 4-8)

2

Literature Review

2.1 Introduction

This chapter aims to provide an overview of the previous research on the palaeoclimate and glacial geomorphology of the Loch Lomond Readvance in the British Isles. Evidence of a return to glacial conditions in upland areas of the British Isles, following the Lateglacial Interstadial, has been recognised since early research into glaciation of the British Isles. Some of the earliest recognised evidence of what was later termed the Loch Lomond Readvance was discovered in the south part of the Loch Lomond basin, especially in the area of Drymen, and the Upper Forth and Blane Valleys. The limit of the ice from this period of restricted glaciation has been traced using geomorphological evidence. This chapter reviews published work on the formation of moraines during the Loch Lomond Readvance and the significance of these moraines for palaeoclimatic reconstruction relating to the Loch Lomond Stadial in the West Highlands of Scotland.

2.2 Palaeoclimatic evidence of the Loch Lomond Stadial

The Loch Lomond Stadial approximately dated to 11,000 to 10,000 ^{14}C years B.P., followed the warmer period of the Lateglacial or Windermere Interstadial of 13,000 to 11,000 ^{14}C years B.P and is coeval with the Younger Dryas cold event that occurred throughout Europe (Lowe & Walker 1997). This cold period has also been recognised in North America, especially in eastern Canada and north-east U.S.A. (Peteet 1993, 1994).

Following the Lateglacial Interstadial, glaciers developed in upland areas of the British Isles, especially in the Scottish west Highlands and the Lake District due to a lowering of temperature by 7-8 °C (Lowe et. al. 1994). Amelioration of the cold climate began around 10,500 ^{14}C years B.P in Europe with a 500 year period of drier climatic conditions as indicated by Artemisia in pollen remains (Lowe & Walker 1997). This was followed by a warmer climate, recorded in the pollen record by woodland replacing steppe/tundra vegetation. Coleopteran studies suggest temperatures similar to present were established by 9,800 to 9,500 ^{14}C years B.P (Atkinson et al. 1987, Coope and Lemdahl 1995).

Donner (1957) related pollen assemblage evidence to glacial readvances including what he termed the Highland Readvance, later termed the Loch Lomond Readvance. Donner recognised six Lateglacial pollen assemblages, the oldest of these, Zone I representing the end of glacial conditions and the beginning of the Lateglacial Interstadial. Zone II correlates with the Lateglacial Interstadial and Zone III with the Loch Lomond Stadial. Zone III is represented in pollen assemblages, taken from small lakes, by a minerogenic sediment layer with very little pollen.

Pollen Zone IV, recording the termination of the Loch Lomond Stadial is described by Donner as having a well defined boundary with zone III, marked by a distinct rise in tree pollen. Zone IV was the first stage represented in sediment samples taken at sites within the limits of the Loch Lomond Readvance, and was used to verify the age of moraines thought to have been produced by the Loch Lomond Readvance. Sissons (1974) found similar pollen assemblages with complete Lateglacial pollen sequences outside the limits of the Loch Lomond Readvance and Flandrian pollen assemblages only within the readvance limits. According to Sissons pollen assemblages suggest rapid climate warming at the end of the Loch Lomond Stadial. Sissons suggests that climate warmed earlier than previously thought with temperatures rising some time before the end of the Loch Lomond Stadial. It is suggested by Sissons that this earlier climate amelioration resulted in in-situ downwasting of the Loch Lomond Readvance glaciers and is recorded in the distribution and characteristics of moraines deposited at this time. The nature of these moraines is discussed later in this chapter.

Lowe and Walker (1976, 1980) examined pollen and radiocarbon dating evidence from a core taken from Kingshouse, Rannoch Moor. A unit from this core containing no pollen is thought to have been deposited during the Loch Lomond Stadial. As no organic material was found in this unit it was not radiocarbon dated. However, organic units above and below this unit were dated to 9,912 ± 200 and 10,290 ± 180 ^{14}C years B.P. Pollen from the organic unit overlying the Loch Lomond Stadial sediments are thought to represent an early stage of vegetation succession on undeveloped soils. As Rannoch Moor is thought to have been the main centre of ice accumulation during the Loch Lomond Stadial this core gives important radiocarbon dates for the termination of the Loch Lomond Readvance, suggesting deglaciation before 10,000 BP. The dates however could reflect a time of reduced glaciation when the Rannoch Moor basin was mainly ice free but ice was still present in the area, especially on the surrounding higher ground. It is suggested that an inorganic unit overlying the organic unit could represent fluctuating climate with climatic amelioration punctuated by short intervals of more severe conditions (Lowe & Walker 1980).

Radiocarbon dates for the deglaciation of Rannoch Moor were compared with dates from the margins of the Loch Lomond Readvance and used to suggest rapid deglaciation over a period of around 500 years (Lowe & Walker 1976, 1980). However, when the radiocarbon dates are calibrated error margins are too large to suggest the time taken for deglaciation. This is due to a plateau in the radiocarbon calibration curve around the period of the Loch Lomond Stadial. Consequently, it is difficult to reconstruct the nature and timing of deglaciation using radiocarbon dates.

Pollen evidence from the Isle of Skye suggests a severe cold climate during the Loch Lomond Stadial (Lowe and Walker 1991). The colder climate of the Loch Lomond Stadial is reflected in a transition from organic rich material to more minerogenic sediment containing tundra type pollen. Pollen assemblage evidence suggests that the conditions for glacier development, of high snowfall, occurred near the beginning of the stadial and that deglaciation likely began in the cold dry conditions of the later part of the stadial, before the climatic amelioration at the onset of the Flandrian. An initial phase of active glacier retreat, in the late Loch Lomond Stadial and during a period of cold dry conditions has also been suggested based on geomorphological evidence (Benn et al. 1992).

Flandrian pollen assemblage sequences are thought to provide some evidence of the nature of deglaciation of the Isle of Skye at the termination of the Loch Lomond Stadial (Lowe and Walker 1991). Pollen assemblage zones found in areas deglaciated early differ from those found in areas deglaciated later. Pollen from the early deglaciated areas on Skye were dated to 9590 ± 90 and 10,220 ± 150 ^{14}C years B.P., suggesting retreat may have began before 10,200 ^{14}C years BP. Most of the ice field had melted by the time Juniperus had colonised Skye, which is thought to have occurred around 9,600 ^{14}C years B.P.

Benn et al. (1992) describe palynological evidence of climate change during the Loch Lomond Stadial and glacier response to this change on the Isle of Skye. According to Benn et al., Skye had a tundra-like vegetation cover outside the glacier limit during the Loch Lomond Stadial. Temperatures at the end of the stadial rose by around 1.7° and 2.6° per century in the early Flandrian (Atkinson et. al. 1987). This rapid warming has been associated with the rapid northward movement of the Atlantic polar front from 35°N and 55°N. There is however some disagreement on how glaciers responded to this rapid climatic amelioration, mainly based on the spatial patterns of moraines. The details of these theories are discussed later in this chapter, including the theory of rapid in-situ downwasting supported by the chaotic nature of some moraines (Sissons 1963, 1967a, 1967b, 1973, 1974, 1977, 1980, Manley 1956) and various theories of active retreat based on patterns of moraines that resemble recessional landforms (Eyles 1983, Benn 1992, 1997, Bennett 1995, 1996, 1994, Bennett and Boulton 1993a, 1993b, Bennett et. al. 1998, Hambrey 1997, Hodgson 1997).

Benn et al. (1992) compared pollen evidence to the climatic conditions suggested by the morphology and spatial pattern of moraines on Skye. In the Kyleakin area, moraines were found to have a down-valley chevron orientation. Additionally evidence of minor readvances was manifest in cross valley pairs of moraines containing sheared and folded sediments, interpreted as push moraines and thought to be indicative of active retreat. Pollen evidence of the abundance of Huperzia found at this site is thought to be indicative of a short lived cooling, which could have resulted in a minor glacial readvance.

Radiocarbon dates for polleniferous sediment at Varragill and Glen Arroch suggest substantial active retreat during the Loch Lomond Stadial. Artemisia found at these sites is used as evidence that this retreat occurred in a cold, arid environment. Cold, dry climatic conditions for the mid to late Loch Lomond Stadial are also suggested by high counts of Artemisia pollen found at other sites in the British Isles such as in the Grampian Highlands, West Highlands, the Lake District and Wales (Birks & Mathewes 1982, Tipping 1985, 1988).

It is thought that a substantial amount of deglaciation can be attributed to a decline in precipitation from the mid to late stadial, occurring before the climatic warming of the termination of the Loch Lomond Stadial. A two stage deglaciation is proposed, with an initial phase of active deglaciation due to cold dry conditions, followed by a final phase of uninterrupted recession with some local ice stagnation due to climate warming, based on the spatial pattern of moraines. Details of this theory are discussed later in this chapter.

2.3 Glacial Geomorphology of the Loch Lomond Readvance

2.3.1 Early research prior to the work of J.B. Sissons

2.3.1.1 Jack (1874)

Jack (1874) interpreted the moraine features of the East Loch Lomond basin and Upper Forth Valley as being deposited at a time when ice retreated from overflowing the Campsie Fells and Kilpatrick and Menteith Hills to a more restricted period of glaciation when the ice was thinner and constrained to the valleys of the Blane and Endrick. Jack also observed silt deposits in the Endrick and Blane Valleys. The silts in the lower reaches of the Endrick Valley were interpreted as being deposited in an enlarged Loch Lomond due to sea levels higher than present. At the time, Loch Lomond was connected to the sea as a fjord. Later, Loch Lomond became a freshwater loch due to isostatic uplift. Marine shells found in the tills of the East Loch Lomond Basin were also used as evidence of Loch Lomond being inundated by the sea. The tills were interpreted as being deposited in a terrestrial environment, deposited directly from glacier ice. The shells were incorporated in the till as glacier ice flowed down the Loch Lomond fjord. The mixing of the shells with striated clasts and sands and gravels was used as evidence that the shells were deposited east of the present shores of Loch Lomond by glacier ice. Below the shelly till, a till with no shells was observed.

2.3.1.2 Renwick and Gregory (1909)

Renwick and Gregory (1909) also observed the two tills in the East Loch Lomond basin. Moraines in Glen Fruin were first attributed to deposition by a glacier from Loch Lomond by Bell (1892). Renwick and Gregory postulated that if the ice expanded into Glen Fruin and the Lowlands at the southern end of Loch Lomond it would also move eastwards into the Endrick Valley and surrounding lowlands. On tracing the evidence for this, the authors found "hummocky drift north and west of Drymen". A ridge interpreted as a moraine was traced from the moorland around Gartmore across the Glasgow - Aberfoyle road to Buchlyvie and Flanders Moss where it continues in a north-south orientation around the east shores of the Lake of Menteith.

The moraine was interpreted as the remnant of a lateral moraine of a glacier that moved onto Flanders Moss from the valley between Ben Lomond to the south and Beinn Choin and Meall Mor to the north. The probable source of this glacier was, according to the Renwick and Gregory (1909), the high ground around Beinn Choin and Meall Mor and not from the main Loch Lomond glacier. It was thought that this moraine, termed the Buchlyvie moraine, was deposited around the same time as the Glen Fruin Moraine. The lake sediments in the Blane Valley were also commented on in this paper and attributed to the blocking of drainage of the Endrick Water by the Loch Lomond Glacier. The moraines of the south-east and south-west of the Loch Lomond basin were described as "Kame like".

2.3.1.3 Simpson (1933)

Simpson (1933) described moraines of two readvances during the retreat of "the last general ice sheet", termed the Perth Readvance and Loch Lomond Readvance. The term Loch Lomond Readvance was used here for the first time. Extensive "morainic deposits west of the Ochil Hills, between the River Teith near Doune and the River Tay at Perth" are attributed to the Perth Readvance. During this readvance, ice is thought to have moved down the valleys of the River Teith and River Earn, which was then diverted to the north-east by the Ochil Hills, terminating east of Perth in the Firth of Tay.

Simpson observed a distinct increase in the number of moraines in the upper valleys, with fewer and more widely spaced moraines in lower valleys. This was explained by more rapid retreat, during the Perth Readvance, of the glaciers in the lower valleys due to the larger surface area of piedmont lobes. Once the ice retreated into the narrower upper valleys they had less surface area and retreat was less rapid. Simpson also suggested that the slowing of the retreat could be due to climate change, or that the valley moraines were deposited during the later readvance recognised in the regions of Loch Lomond and the Lake of Menteith (i.e. the Loch Lomond Readvance).

According to Simpson (1933) the Loch Lomond Readvance, first recognised in the east Loch Lomond and Upper Forth areas (Jack 1874, Renwick and Gregory 1909), occurred at a time when Loch Lomond was a fjord, and was unoccupied by ice in its lower reaches. The Loch Lomond glacier advanced as far as Glen Fruin in the west, near Alexandria in the south, almost to Killearn in the south-east, and up to a considerable height on the Kilpatrick Hills. The limit of the readvance is marked by a terminal moraine, which can be seen for most of the extent of the ice limit. Like Jack (1874), Simpson discussed the inclusion of marine shells in the till within the Loch Lomond Readvance moraines. Outside the terminal moraine no shells were observed.

According to Simpson the inclusion of shells is the only distinguishing feature of tills inside the moraine. The author traced the end moraine from Glen Fruin, across the River Leven and along the north slopes of the Kilpatrick Hills. The altitude of the moraine rises from 30m at Bonhill to 152m at Auchincarrock and to 162m at the trig station on Cameron Muir, 3 km west of Aucheneck House, then falls slowly to the east. Simpson described the end moraines in the Blane and Endrick Valleys as merging with a broader morainic spread. Widespread glacial deposits were described in this area including hummocky mounds, angular debris and spreads of sand and gravel. Concentric ridges within the outer moraine, between Dumfin and Rossdhu, on the west side of Loch Lomond, were interpreted as due to standstill positions of the Loch Lomond glacier during the later stages of retreat. According to Simpson, the till is especially shelly around the area of Finnich Glen, south-east of Loch Lomond, due to the ice having overridden a large area of sea bed.

Simpson (1933) also described the moraine complex in the Upper Forth Valley, which is interpreted as being deposited around the same time as Loch Lomond glacier deposits, by a glacier moving eastwards into the Upper Forth Valley from between Ben Lomond and Ben Venue, and advancing partly into the sea in the Forth Valley. The area covered by the glacier is marked by a well defined moraine at the east end of the Lake of Menteith and a lateral moraine extending from the north side of Torr nam Broc in the west and to Arnprior in the east. According to Simpson, a lateral moraine can also be traced along cliffs north of the Lake of Menteith. The area of the Forth Valley beyond the moraine is free of glacial deposits. A section on the shores of the lake, studied by Simpson, revealed 9m of morainic deposits overlying 3m of clay. Morainic material was observed down to a level of 15m O.D., with peat and Flandrian marine sediments below. A terraced gravel landform to the west of the Lake of Menteith was interpreted as a possible remnant of an outwash plain formed during a standstill of the glacier. The Menteith moraine was reported to overlie 20m of marine clay deposited before the Loch Lomond Stadial.

According to Simpson, the Upper Forth Valley Glacier and the Loch Lomond glaciers were formed contemporaneously. Several streams draining southwards and westwards were diverted by the Loch Lomond Glacier, into the Forth catchment area. An outflow channel of the ice dammed lake, in a broad flat valley near Balfron Station and continuing to Arnprior is located outside and parallel to the Menteith Moraine. This is interpreted by Simpson as evidence that the Loch Lomond and Upper Forth Valley glaciers were present in this area at the same time.

2.3.1.4 Charlesworth (1956)

Charlesworth (1956) described various stages of active retreat of the Loch Lomond Stadial ice, with local patterns of ice receding back into high mountain areas and high altitude corries and valleys. Two main stages of the late-glacial were recognised, the Highland Glaciation and the Moraine Glaciation, with substages A to V. Substages A to L are substages of the Highland Glaciation and M to V substages of the Moraine Glaciation. The map below (fig 2.1) shows the maximum extent of the Moraine Glaciation, termed substage M by the author. Substage M was followed by subsequent retreat (substages N to V) according to Charlesworth.

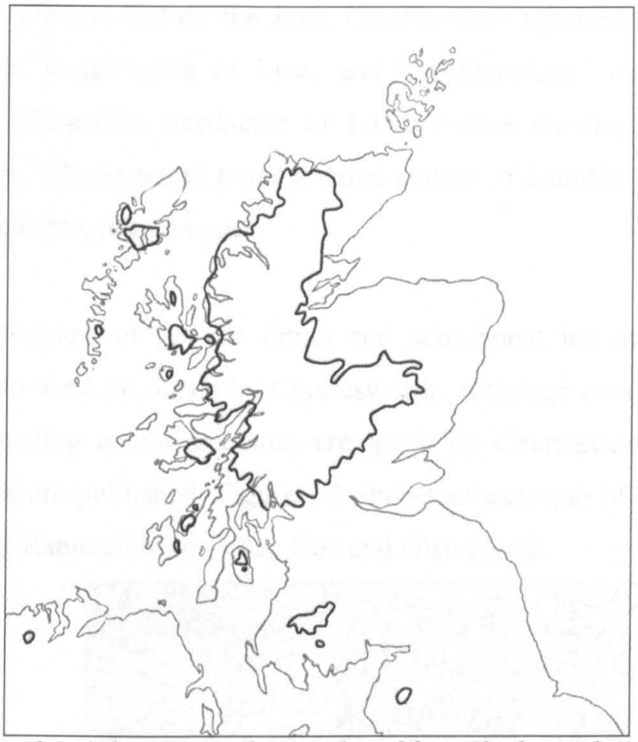


Figure 2.1 Substage M ice limits: adapted from Charlesworth (1956)

The limit of this readvance corresponds with later mapping of the limit of the Loch Lomond Readvance such as Sissons (1980) in the south and west, although Charlesworth suggests more extensive ice limits in the north of the ice field and especially in the eastern Highlands in the areas around the Cairngorms and Deeside.

Glaciers of substage M were correlated with a raised beach Charlesworth termed the "100-foot beach". Glacial sediments overlying the 100-foot beach were used as evidence for the readvance of the Moraine Glaciation stage M, following retreat of the Highland Glaciation ice sheet and marine inundation before rapid isostatic uplift.

In the south Loch Lomond basin Charlesworth reported shells in the glacial deposits. These were used by Charlesworth as evidence of retreat of the Lateglacial ice sheet and marine inundation, following the Highland Glaciation and before the readvance of the Moraine Glaciation in the Loch Lomond area. He also confirmed that shelly glacial deposits are not found outside the limits of the

Loch Lomond glacier. Within the limit Charlesworth reported shells found in glacial deposits as far north as Luss, and "boulder-clays" overlying marine sediments on Inchlonaig, north-east of Luss. Within the limits of the Loch Lomond Glacier, Charlesworth noted a radial pattern of drumlins which does not continue beyond the end moraines.

Detailed maps of the ice limits and subsequent ice margin positions during recession were produced by Charlesworth. Although examples of glacial landforms indicating active recession are given by Charlesworth no maps of these landforms are published. Figure 2.2 shows an example of Charlesworth's maps, including Rannoch Moor, Glen Coe and Glen Nevis.

Figure 2.2 Map of glacier margins in the west-highlands (Charlesworth1956)

Following substage M of the Moraine Glaciation, Charlesworth suggests a substage N of active glacier retreat. This is based on evidence of another raised shoreline termed the "50 foot beach" attributed to rapid isostatic recovery. No evidence of glacial landforms recording this recession is discussed by Charlesworth.

According to Charlesworth, during substage N the Torridon-Gairloch piedmont glacier receded and broke up into smaller valley and corrie glaciers.

The larger piedmont glaciers to the south and west receded considerably with the Loch Lomond Glacier receding north of Luss and the Aberfoyle Glacier (termed the Menteith Glacier in later literature) to south of Loch Chon.

Charlesworth suggests a climatic change and minor readvance of a number of highland glaciers and increased corrie glaciation in south-west Scotland during substage P, although no further details are discussed here.

It is evident that Charlesworth was suggesting active retreat, with localised retreat patterns. A period of restricted corrie glaciation near the termination of the Loch Lomond Stadial is thought to have occurred. A minor readvance is suggested during substage P, with some readvances in the west Highland ice field and increased corrie glaciation in the south of Scotland.

Despite the detailed descriptions and suggested locations of ice margins during each substage of glaciation, Charlesworth published little evidence for the history and nature of deglaciation he proposed. The pattern of deglaciation suggested by Charlesworth is mainly based on the evidence of "100 foot" and "50 foot" raised beaches. If glaciers actively receded back into high valleys and corries, with a period of corrie glaciation near the termination of the Loch Lomond Stadial, this is likely to be evident in the geomorphological record. Possible evidence of active glacier retreat will be investigated, in this study, at the five field sites studied.

2.3.1.5 The Loch Lomond Readvance in the Lake District (Manley 1959)

Glaciation of the Lake District during the Loch Lomond Stadial is discussed by Manley (1959), who relates the spatial organisation of moraines to climatic conditions at the termination of the stadial. Manley proposed that deglaciation in the Lake District was not by active retreat, as suggested by Charlesworth (1956) for the Scottish Highland glaciers, but was due to areal stagnation, caused by an abrupt climate amelioration at the termination of the Loch Lomond Stadial. This theory of areal stagnation due to rapid climate change was later applied to the glacial history of the Scottish Highlands by J.B. Sissons (1963, 1967a, 1967b, 1973, 1979).

According to Manley, large terminal moraines are often absent from the glaciated valleys of the Lake District, which is explained as a result of thin ice-streams wasting rapidly on the bottom of flat-floored valleys. Manley (1959) observed the irregular appearance of hummocky moraine in some valleys, which he attributed to the downwasting of the remains of tongues of dead ice. Raistrick (1926) interpreted hummocky moraine at some locations in the Lake District as due to the fluvial erosion of lateral moraines, however Manley interprets these as ice stagnation features.

Small moraines observed at the lips of tarns were used as evidence of continuing corrie glaciation, after deglaciation of the valleys. Charlesworth (1956) had previously proposed a period of restricted corrie glaciation at the termination of the last glaciation of the Scottish Highlands. Manley also observed evidence of small corrie glaciers in the Pennines, to the east of the Lake District.

2.3.2 The glacial geomorphology of the Loch Lomond Readvance according to J.B. Sissons

2.3.2.1 Delimiting the Loch Lomond Stadial ice

Sissons (1963, 1967a, 1967b, 1973, 1979) suggested less extensive glacier limits than proposed by Charlesworth (1956). Sissons employed a multidisciplinary approach to delimiting ice extent and climate reconstruction for the Loch Lomond Stadial. Sissons approach combined geomorphological evidence (Sissons 1973, 1974, 1979), pollen analysis (Sissons 1973, 1979), radiocarbon dating (Sissons 1967b 1974, 1977, 1979) and palaeontological evidence (1974, 1979). Sissons (1967b) provided a map of the extent of the Loch Lomond Readvance based on radiocarbon dates of material taken from sites interpreted as ice marginal. Radiocarbon dates include 11,700 ± 170 B.P. on shells found in an end moraine near Drymen, east of Loch Lomond and 11,800 ±

170 B.P. for shells found in the Menteith moraine in the upper Forth Valley. The map in figure 2.3 shows the extent of glaciation proposed by Sissons (1967b) and that proposed by Charlesworth (1954) (see inset map).

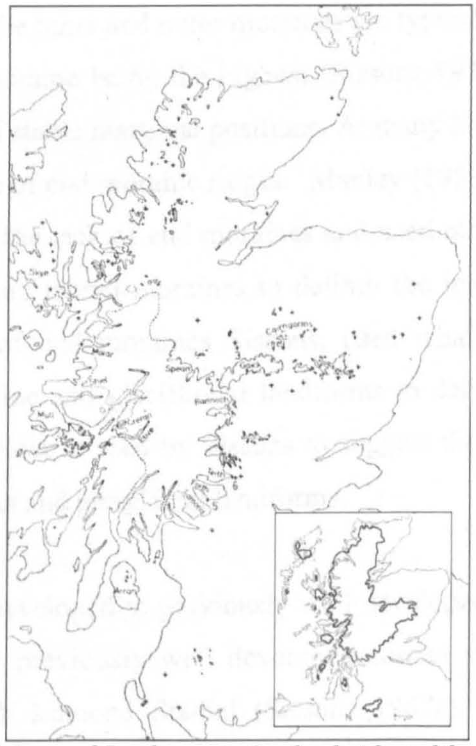


Figure 2.3 Extent of the Loch Lomond Readvance in Scotland, Adapted from Sissons (1974) and (inset)Charlesworth (1956)

Similar to Manley's (1959) study of the Lake District, Sissons suggested a reduction in glacier ice cover towards the east. Glacier ice cover in Scotland was most extensive in the West Highlands due the precipitation gradient (Sissons 1967a). According to Sissons (1967a) glaciers in the West Highlands extended to sea level, whereas further to the east they did not descend to lower altitudes. For example in Glen Dee glaciers descended to 1400 ft (427m) and only to 1600 ft (488m) in the Cairngorms. Sissons found a similar west to east pattern of glacier extent in northern England with glaciers descending to 500 ft (152m) in the Lake District, but only to 1200 ft (366m) further east in the northern Pennines. According to Sissons, (1967a) no large ice sheet developed in the British Isles during the Loch Lomond Stadial, but hundreds of valley and corrie glaciers were produced. In some areas, especially in the West Highlands, corrie glaciers amalgamated to form large valley glaciers. Large areas within the extent of the ice field, however, remained ice free and much of the high ground stood above the ice surface.

According to Sissons, (1977,1979) the best evidence of former glacier limits is provided by end moraines, and is often characterised by two or three suites of end moraines. The inner and outer moraines are typically steep and well defined with the outer moraine being the highest (Sissons 1977, 1979). This is interpreted as evidence of stable marginal positions. At many locations, however, there is no clear evidence of end moraine ridges. Manley (1959), working in the Lake District, also noted the lack of end moraines and used other evidence such as hummocky moraine and lateral moraines to delimit the ice margins. Where there was no evidence of end moraines Sissons, used what he described as "fresh" hummocky moraine and glacifluvial landforms to delimit the extent of former glaciers. Other evidence used by Sissons to suggest the extent of glacier ice included boulder limits and periglacial landforms.

Glaciers mainly developed in previously well developed corries and it is thought possible that all previously well developed corries were occupied by glaciers during the Loch Lomond Stadial (Sissons 1967a). Not all glaciers, however originated in corries, as some valley glaciers may have been fed from snow and glacier ice accumulating on high plateaux. An ice cap is thought to have developed on the Gaick plateau in the central Grampian Highlands where moraines in the surrounding valleys suggest outlet glaciers flowed in a radial pattern from a plateau ice cap (Sissons 1974). Geomorphological evidence also suggests the development of a valley glacier in the Talla Valley in the Southern Uplands. This valley has no corries and the glacier is therefore thought to have been fed by snow from a plateau above the valley (Sissons 1967a).

Ice directions during the Loch Lomond Stadial are thought to have been different to those of previous glaciations. The smaller glaciers would have been more topographically constrained than the Late Devensian (Dimlington Stadial) ice sheet for example. The duration of the Loch Lomond Stadial was too short to allow the accumulation of larger ice sheets or ice caps. Sissons suggests that Rannoch Moor, which had previously been a major ice accumulation centre, was not occupied by an ice cap during the Loch Lomond Stadial, but smaller corrie glaciers descended onto the Rannoch basin from the surrounding high corries, depositing moraines and glacifluvial features on the moor (Sissons 1967a).

The only glaciers on the mainland to advance beyond upland areas were the piedmont lobes of the Loch Lomond and Menteith glaciers, at the southern limits of the ice field (Sissons 1967a, 1974). A piedmont glacier also developed on the Isle of Mull. Ice flow on the islands of Mull, Arran and Skye had a radial pattern with glaciers descending from mountain masses such as the Cuillins in Skye and descending to sea level or near to sea level. The regional pattern of ice flow from previous glacials did not have this radial pattern, due to the more extensive ice cover, and reduced topographic constraint.

The map below (fig 2.4) shows the extent of glacier ice cover in the North-west Highlands according to Sissons (1977). It can be seen from the map that Sissons suggests a more restricted glacier ice cover than found to the south of this area.

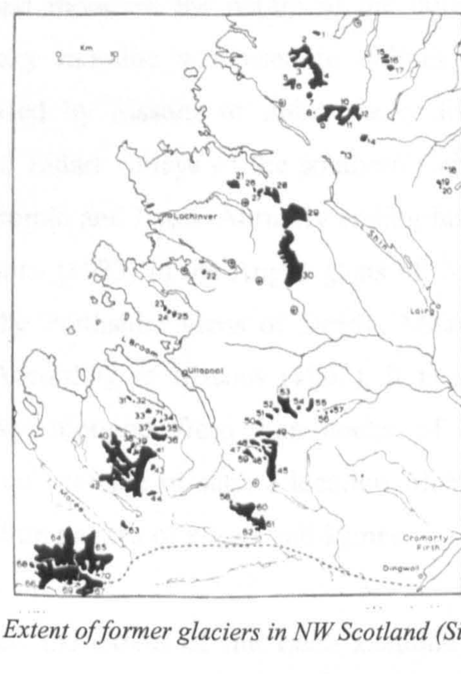


Figure 2.4 Extent of former glaciers in NW Scotland (Sissons 1977)

Sissons noted that in the North-west Highlands the limits of many small glaciers are marked by arcuate end moraines typically 1m to 8m high and littered with boulders. For example in Glen Torridon a small terminal moraine is situated on the floor of the glen at an altitude of 50m and continues, after a small gap, as a narrow bouldery ridge (Sissons 1977).

According to Sissons, the largest ice mass in the north-west Scottish Highlands during the Loch Lomond Stadial was situated south-west of Lochs Torridon and Maree, where there is high ground close to the coast (Sissons 1977). Valley glaciers flowed from icefields supplied by snow avalanching and snow-blow from higher steep slopes. The regional firn line altitude, calculated by Sissons, rises inland due to diminishing snowfall, but there are some anomalies in this pattern due to snow blow onto glaciers.

At other sites, where end moraines are not present Sissons (1973,1974) used the boundary between pitted and non-pitted outwash terraces to delimit the maximum ice extent. The pitting is thought to be due to the melt out or buried glacier ice in the outwash sediments. Where end moraines were observed, outwash terraces outside the end moraines and areas of hummocky moraine can be distinguished from those inside as they are not kettled. In the absence of distinct end moraines the nature of the outwash terraces, and the presence of hummocky moraine was used to delimit the extent of former glaciers. This was used by Sissons to infer glacier limits in many valleys including the Dee and Eidart valleys of the southern Cairngorms, and in glens Garry, Esk, Truim, Tromie and Lyon. Abruptly ending hummocky moraine was also observed by Sissons (1973) in the Angus glens of Mark, Effock, Doll and Caenlochan, and in the Perthshire glens of Diridh, Mhairc, Errochty. Lochay, Turret and Artney. According to Sissons (1967), it is sometimes difficult to distinguish hummocky moraine from hummocks of glacifluvial material. Tyndrum is given as an example of such a location where hummocky moraine has been deposited within an area of eskers and kames.

Sissons mapped the extent of the Loch Lomond Readvance, with the maximum extent of glaciers marked by glacial landforms including end moraines, lateral moraines and glacifluvial landforms. Periglacial landforms were also used to infer the limits of Loch Lomond Stadial glaciers (Sissons 1973, 1974, 1977). Periglacial features, thought to be of Loch Lomond Stadial age, such as solifluction lobes were interpreted as occurring outside the limits of the Loch Lomond Readvance glaciers, with no periglacial features within the areas covered by ice. However, the most significant landform used to infer the Loch Lomond Readvance limits, especially where no recognisable end moraines were found, was hummocky moraine, described by Sissons as having a chaotic spatial pattern. Hummocky moraine was also thought to be a significant indicator of the nature of deglaciation and climatic changes occurring at the termination of the Loch Lomond Stadial.

2.3.2.2 Hummocky Moraine and its climatic significance

Charlesworth (1955) attributed 'hummocky moraine' to the active retreat of Loch Lomond Stadial glaciers as they receded back into their parent corries. Sissons (1977) criticises Charlesworth's work on the basis of a lack of evidence. Charlesworth (1955) did however present some examples of evidence of active retreat, although much of the ice limits he mapped were not supported by published evidence. Sissons (1965, 1974, 1977, 1979) interpreted the widespread occurrence of 'hummocky moraine' as evidence that the Loch Lomond Stadial glaciers downwasted in situ due to rapid climate amelioration (Sissons 1974, 1977, 1979). The spatial pattern of hummocky moraine at various locations was described as chaotic by Sissons. Closed depressions in areas of hummocky moraine were observed and thought to have been formed as kettle holes, formed during meltout of stagnant ice. Actively retreating ice would not deposit large areas of chaotic moraines according to Sissons but would have resulted in end moraines with a cross valley orientation. Sissons did observe glacial landforms with a linear pattern at some sites, described as straight or almost straight ridges of lines of mounds. These are often orientated 30 to 40 degrees to the valley axis, arranged in a V-shaped pattern. Lineations in the spatial pattern of these features were not interpreted by Sissons as evidence of active ice, but as crevasse fill material deposited during ice stagnation. At some sites, especially in the north-west Highlands, Sissons observed a pattern of inset end moraines which he attributed to an early period of active glacier retreat. However, these features do not usually continue far up valley from the interpreted glacier limits, according to Sissons. 'Chaotic' hummocky moraine, interpreted as being formed by ice stagnation, does however continue up valley suggesting that deglaciation was mainly due to in-situ ice stagnation. As features interpreted as hummocky moraine by Sissons were geographically widespread within the limits of the Loch Lomond Readvance, these were attributed to regional climatic conditions rather than local climatic or glaciological conditions.

The term 'areal stagnation' is used by Sissons to describe the widespread occurrence of in-situ downwasting of glacier ice. The geomorphological evidence for rapid climatic amelioration was correlated with other evidence such as ocean core evidence suggesting a rapid shift north of the North Atlantic Polar Front (Sissons 1974, 1979). Pollen evidence from the margins of Loch Lomond Stadial glaciers suggest rapid vegetation colonisation and succession and was attributed to rapid climate change (Sissons 1973). Radiocarbon dates also suggest rapid deglaciation including radiocarbon dates from Callender, at the southern margin of the Loch Lomond ice field, suggesting deglaciation by 10,670 ± 240 B.P. and 10390 ± 240 for Rannoch Moor at the centre of the ice field (Sissons 1979). More recently the theory of areal stagnation has been challenged based on linear patterns recognised in hummocky moraine, suggesting its distribution is not chaotic and is not indicative of ice stagnation as suggested by Sissons (Eyles 1983 Hodgson 1986, 1987, Benn 1992, Bennett & Boulton 1993b, Bennett 1994, Wilson & Evans 2000). These theories of hummocky moraine production are discussed later in this chapter.

2.3.3 Models of Moraine Formation

2.3.3.1 Introduction

After the work of Sissons, the theory of aerial stagnation became generally accepted, but was later challenged by studies concentrating on the patterns of moraines specifically those that highlighted lineation. Lineations in Loch Lomond Stadial moraines have been interpreted as evidence of active retreat of the Loch Lomond Stadial glaciers providing important implications for the history and nature of deglaciation and climatic change. This section will review models of moraine formation proposed by various workers and the palaeoclimatic significance of these theories.

2.3.3.2 Moraines formed by incremental stagnation

Eyles (1983) compared moraines in the Scottish Highlands to moraines formed at the margins of contemporary Icelandic glaciers. According to Eyles, substantial amounts of supraglacial material, derived from severe periglacial weathering of valley sides, is transported to ice margins in Iceland, and that this was also the case in Scotland during the Loch Lomond Stadial. Similar to Sissons, Eyles describes the limits of the Loch Lomond Readvance as often being marked by irregular mounds with no systematic lineation or orientation, and no relation to former iceflow direction. South-east Iceland is used as an analogue for the Scottish Highlands during the Loch Lomond Stadial, which according to Eyles has similar conditions to those that existed in Scotland during periods of substantial ice cover.

According to Eyles (1983), if a glacier is wet based it will fail to incorporate much englacial material derived from the glacier bed due to continual basal melting. Englacial loads are increased by erosion-prone valley sides in accumulation zones, and are also added to by overriding and subglacial shear of decaying ice cores at the contact between active clean ice and stagnant ice cores along the ice margin. This process results in englacial debris bands at the glacier snout. According to Eyles, basal meltout accumulations in south-east Iceland are thin due to karstic destruction of the ice, in relatively high air temperatures of around + 1° C. Meltout accumulations overlying lodgement till in south-east Iceland are typically less than 1m thick and are crudely bedded with a wide variation in matrix content, due to rapid matrix loss during melting. Thicker meltout sequences develop where ice cores are buried under thick outwash, the overlying material insulating the ice cores, and causing slower rates of melting. Continental conditions of continuous or discontinuous permafrost can also result in slower meltout and thicker meltout sequences. During the Loch Lomond Stadial, temperatures in the Scottish Highlands were lower than those presently occurring in south-east Iceland, allowing thicker meltout deposits to develop. Deeper excavation of hummocky moraine may reveal more substantial englacial and subglacial meltout reflecting the more severe climate (Eyles 1983).

Landforms of coarse grained supraglacial diamicts, including latero-frontal moraines and medial moraines with a hummocky, bouldery topography, frequently cover whole valley floors in south-east Iceland. However, in the valleys of outlet glaciers draining Oraefajökull, South-east Iceland, this landsystem is obscured by large areas of hummocky moraine, consisting of diamicton derived from the periglacial weathering of the valley sides, and transported conveyor belt fashion towards the glacier margins. Supraglacial diamicts studied by Eyles in south-east Iceland contained a wide variety of grain sizes due to the mixing of valley side debris of various origins including bedrock, fans, soils, and fluvial sediments transported by supraglacial streams

Medial moraines are deposited as either a thick hummocky non-compact cover which is ice cored during deposition or as a dispersed bouldery cover which is not ice cored at deposition, which may be locally thickened and form dump moraine ridges. Severe compression at the margin can cause increased diamict thickness due to enhanced englacial debris concentrations. Complex stratigraphies in hummocky moraine are attributed to diamict slides into troughs between ice cored highs, including coarse grained outwash sediment and lacustrine sediments.

According to Eyles (1983), during recession diamict covered ice cores are left along the valley floor. Meltout of the ice cores results in hummocky relief. Following several cycles of topographic reversal, due to meltout of the ice cores, an irregular topography develops with steep sided bouldery mounds, ridges and dead ice hollows. Where the supraglacial cover is thinner diamict is shed directly from the ice front and is draped over recently produced subglacial deposits. Thick sequences of diamict and outwash accumulate in the troughs between the glacier and the valley sides, due to net flow towards the valley sides in the ablation zone. Landforms on the valley floor are often destroyed by meltwater streams, with lateral ridges surviving as the dominant landform type.

Facies and landforms studied in Iceland can, according to Eyles, be recognised in Scotland. In many Scottish valleys hummocky moraine extends across the whole valley floor near former glacier margins, reflecting radial flow of ice in the terminal zone and the transport of supraglacial material to latero-frontal positions. Further up valley the distribution of hummocky moraine is more controlled with linear medial moraines along the valleys. Examples of the Gaick Plateau and Glen Torridon are given, where distinct medial and lateral distribution of hummocky moraine can be mapped (Eyles 1983)

Supraglacial diamict is widespread in the West Highland valleys, according to Eyles (1983). This is thought to be due to intense periglacial weathering resulting in large amounts of frost weathered bedrock being deposited on glaciers during the Loch Lomond Stadial. Eyles observed tracts of hummocky moraine that he interpreted as supraglacial diamict deposited by active glaciers. A mechanism of incremental stagnation is proposed to explain these features. Surface ablation at the margin of the glacier exposes debris at the surface. The debris on the ice surface insulates the underlying ice, creating an insulated rim of ice at the margin. The cleaner ice upglacier thins and retreats. The process is repeated as the glacier recedes and more debris is exposed on the surface and consecutive areas of ice cored hummocky moraine are deposited.

This process results in hummocky topography with some transverse lineation due to bulldozing by the clean, more active ice upglacier. Eyles also suggests that these processes and landforms are common at surging margins due to intense compression of active ice. After decay of the ice cores in these moraines there is little evidence left that they were deposited by an active glacier. Similar suites of landforms observed in Scotland and at contemporary glacier margins in Iceland are interpreted as evidence that the widespread hummocky moraine of Loch Lomond Stadial age in Scotland is not a product of wholesale stagnation as suggested by Sissons (1965, 1974,1977, 1979) and Manley (1959), but was deposited during active frontal retreat.

According to Eyles, this interpretation supports Charlesworth's (1956) proposal of active retreat. Differences in the quantity of supraglacial material incorporated on different glaciers would account for variations in the rate of recession in response to climate change (Eyles 1983). This is thought to explain pollen evidence of a complex time transgression of deglaciation across the Scottish Highlands (Gray & Lowe 1977)

2.3.3.3 Moraines deposited by a two-phase deglaciation

In one of the most intensive studies of Loch Lomond Readvance moraines, Benn (1992) observed three spatial patterns in the hummocky moraine on the Isle of Skye. These include transverse, longitudinal and chaotic landforms. The transverse linear patterns are thought to be evidence of active retreat, whereas chaotic hummocky moraine is thought to have formed by the meltout of ice cores buried in sediment but is not indicative of wide scale ice stagnation as suggested by Sissons.

For example, moraines in Glen Arroch, Coire na Cuilean and in the Kyleakin hills are described as some of the most impressive moraines on Skye. The valley floors are filled with moraines, but none exist on the upper slopes of valleys. Most of the moraines consist of sharp crested ridges in chains of hummocks. The largest moraines in the Kyleakin Hills are 12m high, although most are approximately 2 to 3m high. The ridges have a beaded or undulating long profile, especially near the valley floor, giving them a hummocky appearance. Many moraines form cross-valley pairs, with similar size and gradient, which according to Benn is not compatible with Sissons' (1967a) interpretation of lineation being due to crevasse fill, as crevasses splay out downvalley, towards the valley sides. This distribution of moraines, together with sedimentological data, is interpreted by Benn as evidence that deposition occurred as a series of recessional moraines. Exposures in these moraines show loose diamicton interbedded with sands, gravels and silt, thought to have been interbedded as subaerial debris flows or flow tills and water laid sediments. Sediment geometry is complex suggesting reworking. Evidence of glacigenic debris flows, includes erosive channelised bases, sand and silt stringers, and basal traction gravels. Benn also observed some evidence of glacitectonics. Clasts in these moraines predominantly consist of locally derived lithologies. A moraine ridge studied in Glen Arroch contained steeply dipping and folded diamicton units, thought to be of a subglacial origin and rock masses interpreted as rafts quarried from the glacier bed. Bedding in this moraine is parallel to the ridge crest. These structures suggest compression and shear under stress orientated normal to the trend of the moraine, typical of proglacial glacitectonics and the moraines were therefore interpreted as push moraines.

Transverse moraines in Gleann Torra-mhichaig form intermittent parallel chains trending obliquely down valley. Some ridges and chains appear in pairs at similar altitudes and with similar gradients on opposite sides of the valley. These were again interpreted by Benn as the remnants of recessional moraines. The transverse moraines occur on the valley sides, with the valley floor occupied by moraines with a more chaotic distribution. Exposures in the transverse moraines show stacked debris flow units dipping downslope, thought to be due to slope activity during moraine formation. The valley side moraines are used by Benn as evidence of very active slope processes during deglaciation. This activity may have contributed to the dissected, discontinuous appearance of the transverse moraines on the valley sides, leaving them with a hummocky appearance. The interdigitation of glacial and slope material suggests paraglacial activity during deglaciation.

Moraines on the floor of Glean Torra-mhichaig were described by Benn as chaotic conical mounds including some completely enclosed hollows. An exposure in a three metre hummock shows lenses of diamicton interbedded with water sorted sands and gravels. Material in these moraines is interpreted as a mixture of subglacial and supraglacial debris. Sediments in the section studied by Benn consist of interbedded debris flows and glacifluvial sands and gravels, which have undergone syndepositional deformation and reworking. Clast fabric dip angles are parallel to the moraine surface in the lateral parts, while the lower central part is largely structureless. Sands have been deformed into an isoclinal fold, and these structures have been used as evidence that the hummocky moraine was originally ice cored and that the faults and folds and destruction of sedimentary structures in the central part of the exposure are due to the melting of buried ice. The location of the chaotic moraine on the northern part of the valley and transverse moraines on the valley sides was interpreted by Benn as due to actively retreating ice. The chaotic moraine is not necessarily due to extensive stagnation, as proposed by Sissons (1965, 1974,1977, 1979) and Manley (1959), but interpreted as due to small sediment covered ice cores decaying during the final stages of deglaciation.

Chaotic moraine in the Cuillins occurs in association with stepped kame terraces. These are interpreted as being formed during the downwasting of stagnant glacier remnants, and not widespread stagnation. According to Benn, the nature of deglaciation cannot be reconstructed by the presence of chaotic hummocky moraine, but must also include the evidence of adjacent landforms.

An area of hummocky moraine with transverse, chaotic and longitudinal moraines, near Sligachan, was also studied by Benn. These had previously been studied by Harker (1901) and interpreted as ice stagnation features. This area was occupied by a low gradient piedmont glacier during the Loch Lomond Stadial, which paused during retreat, depositing the transverse chains of hummocky moraine. Eskers and small areas of chaotic moraines were deposited by small pockets of stagnant ice. The longitudinal ridges include flutings, megaflutings and small drumlins. A section through a small drumlin contained mainly subglacial till, with stratified debris cropping out on the east flank. Clast fabric analysis at this site showed a strong downglacier orientation, suggesting that the feature was deposited by active and not stagnant ice. The longitudinal moraines in this area are interpreted by Benn as subglacial bedforms, probably deposited by a combination of lodgement and subglacial deformation.

From the above evidence collected at various sites on Skye, Benn (1992) concluded that the hummocky moraine in central Skye is polygenetic. Three sediment-landform associations are proposed, including transverse recessional moraines (including push and dump moraines) chaotic moraines formed by uncontrolled ice margin deposition from stagnant ice, and longitudinal forms including drumlins and flutings. In some valleys two or more of these assemblages were found. Benn disagrees with Eyles' (1983) contention in that hummocky moraine is composed only of supraglacial material. Subglacial material tends to be more common on valley floors, especially where there is erodable material, including unlithified sediment, jointed rocks and minor intrusions. Supraglacial material is more common where the glacier surface was close to sources of debris supply such as cliff faces. Supraglacial entrainment can occur on both accumulation and ablation zones. Both active and passively transported material can therefore be present in hummocky moraine. In all twenty valleys investigated by Benn (1992) recessional moraines, formed at formerly active glacier margins were identified.

Benn suggests the term hummocky moraine should not be used to imply a single set of genetic processes or a specific moraine pattern, however the term remains useful as a descriptive term for many areas of moraine. According to Benn it would be an improvement to use additional genetic terms such as "hummocky recessional moraine".

2.3.3.4 Transverse moraines deposited by active recession only

Lineations in hummocky moraine were also observed by Bennett and Boulton (1993a) and Bennett (1994) and similar to Eyles (1983) and Benn (1992), the linear patterns of hummocky moraines are interpreted as being formed by active recession. According to Bennett (1994), large tracts of hummocky moraine cannot be produced by incremental stagnation during active recession, which was suggested by Eyles (1983) as a mechanism producing hummocky moraine with some cross-valley lineation, as this would require a very large volume of debris concentrated along glacier margins. Lineations in moraine patterns have also been attributed to crevasse fill, deposited during ice stagnation (Sissons 1967a). However, crevasses observed on contemporary glaciers have a rectilinear pattern, which is not true of patterns of down-valley orientated landforms attributed to the Loch Lomond Stadial. The spatial patterns within hummocky moraine are however very similar to patterns found at the margins of actively retreating glaciers (Bennett and Boulton 1993a, Bennett 1994).

Bennett and Boulton (1993a) disagree with Sissons' description of hummocky moraine as chaotic, because when examined more closely, the hummocky moraine displays two patterns of spatial organisation including cross valley concentric ridges or chains of discrete mounds and down valley radial ridges, which are usually continuous. A third pattern of localised chaotic moraines can also be found in some locations. Hummocky moraine was mapped at a scale of 1:10 000, including mapping the crest lines of individual mounds (Bennett and Boulton 1993a). Features interpreted by Bennett and Boulton (1993a) as cross-valley concentric ridges were mapped by joining mounds where they formed a continuous line. The spatial pattern within Loch Lomond Stadial hummocky moraine, mapped by Bennett and Boulton (1993a), is interpreted as being similar to that of contemporary active glacier margins.

Features displaying lineation transverse to ice-flow are interpreted as ice marginal moraines, including push and dump moraines. Down-valley orientated landforms are interpreted as flutings. Ice margins mapped by Sissons are questioned by Bennett and Boulton as many were interpolated from localised evidence and based on the presence of hummocky moraine. Bennett and Boulton (1993a) used the limits of the ice marginal features to produce maps of the regional extent of ice and pattern of deglaciation for the north-west Highlands. Where there was no geomorphological evidence of the ice limit, the limit was interpolated from adjacent valleys. A map of the limits and pattern of deglaciation, in the north-west highlands, according to Bennett and Boulton (1993a), is shown in figure 2.5.

Figure 2.5 Extent of former Loch Lomond Stadial glaciers and their recession in NW Scotland (Bennett & Boulton 1993a)

Bennett (1994) concluded that deglaciation was centred on a few decay centres, with a pattern of deglaciation strongly influenced by topography. Deglaciation centres were located in areas with well connected valley systems. In areas of less well developed valley systems, deglaciation was thought to have occurred with more numerous decay centres. According to Bennett, corries are not important as suggested by Charlesworth (1956) because climate was not severe enough to sustain a period of corrie glaciation at the end of the Loch Lomond Stadial.

Deglaciation is thought to have occurred by the active retreat of glaciers, with chaotic patterns of hummocky moraine confined to deglaciation centres. The pattern of deglaciation suggested is more complex than that proposed by Benn (1992) for Skye. Bennett suggests this is due to a more complex climatic pattern for the mainland than that of Skye. It is suggested that this could be due to the mainland ice cap being large enough to dampen the effects of climatic change. According to Benn (1992) and Benn et al. (1993) climatic amelioration at the close of the Loch Lomond Stadial resulted in a phase of active retreat with some local stagnation of glacier ice. This is contested by Bennett who suggests no local stagnation occurred.

The pattern of deglaciation seems to have varied by location. Bennett (1994) suggests that the term hummocky moraine should be replaced, with landforms previously described as hummocky moraine individually interpreted. Landforms previously interpreted as hummocky moraine include marginal moraines, ice contact fans, flutings, drumlins, kame terraces and stagnation terrain. Interpreting these features can however be problematic due to the superimposition of different landforms, for example supraglacial material draped onto flutings. Although landforms or landform assemblages are difficult to interpret it would, according to Bennett (1994), be better to attempt to interpret individual landforms than to encompass these different forms using the term hummocky moraine.

2.3.3.5 Controlled moraines

Bennett et al. (1998) interpreted the morphology of moraines, found in the Torridon area as being typical of controlled moraines (cf. Benn & Evans 1998), produced by englacial thrusting. Bennett et al. (1998) compared the processes of moraine formation in Svalbard with the hummocky moraines of Coire a'Cheud Chnoic, Torridon. The moraines in Coire a'Cheud Chnoic have previously been interpreted as subglacially streamlined features by Hodgson (1987), as formed by incremental stagnation (Eyles 1983), and as ice marginal moraines formed by pushing and dumping (Bennett & Boulton 1993). Hodgson's interpretation of these features is discussed in section 2.3.4 of this chapter. The term moraine mound was preferred to hummocky moraine in this study. According to Bennett et al., hummocky moraine observed in Svalbard is produced by the melt-out of englacial material. Landforms observed in Svalbard were described as arcuate belts of moraines formed at the Neoglacial maximum, with isolated mounds between these and the present ice margins. Ridges with a down-valley orientation were interpreted as flutings and drumlins.

The arcuate belts of mounds and larger areas of hummocky moraine have been interpreted as due to glacier thrusting using contemporary arctic analogues by Hambrey et al. (1997). Bennett et al. (1998) mapped moraines in Svalbard and Torridon from aerial photographs and measured their profiles using an abney level. The glaciers studied in Svalbard are polythermal, with a cold base at their thinner margins. The moraines consist of mounds a few metres to 10m high and 10 to 100 metres wide and long, and form arcuate broad belts of mounds near the neoglacial maximum. Isolated mounds occur between these belts and the present glacier margin. Mounds described as fresh have a short, straight or gently curved crest aligned parallel to the general moraine ridge trend, but many other morphologies were also observed. Suites of moraines are described as having an imbricate form composed of sheets, inclined in an up-glacier direction. Up-glacier slopes of the moraines have a rectilinear form with slope angles of 20 to 35°, although some have shallower slope angles due to solifluction or mass movement. Distal slopes are steeper and less regular. Facies of the mounds are complex but each mound is interpreted as being composed of a single facies, and are interpreted as terrestrial or glacimarine in origin.

The terrestrial facies are composed of sandy gravels and diamicton, with evidence of shearing and clast characteristics typical of subglacial deposits, including faceted and striated clasts. These sediments are interpreted as basal till and glacifluvial deposits. Supraglacial material does not form a significant proportion of the sediment of the moraines, but forms a drape on the surface of these features. There is little evidence of sediment flow into ice cored troughs or topographic reversal, which would be expected if the material was deposited by in situ meltout. Sediment flows and slumping do however occur on the surface of the mounds, especially on clast poor, mud rich glacimarine deposits, resulting in low conical shaped mounds. Most of the sediments within the moraine mound complexes has not undergone significant post-depositional debris flow.

The moraines observed in Svalbard were interpreted as the products of glacier thrusting. As these moraines do not display evidence of significant sediment flow, previous models of moraine formation such as Eyles

(1983) and Sissons (1965, 1974,1977, 1979) are not applicable to the formation of the Svalbard moraines (Bennett et al. 1998). Thrusts are thought to develop where there is a reverse bedrock slope, at glacier confluences, at polythermal margins or by surging, but are most commonly due to polythermal ice where the faster moving warm based ice is restricted at the margin by cold based ice frozen to its bed. Thrusts rarely reach the glacier surface, but outcrop near the glacier margins due to surface ablation. Melt-out of the debris rich thrusts is thought to produce moraine-mound complexes composed of individual thrust slabs. Sediment is draped over the glacier foreland as the glacier melts, but sediment at the base of the thrust forms a ridge (fig 2.6). According to Bennett et al. (1998), the material at the base of thrusts, which forms these ridges contains very little ice and is therefore not significantly affected by the melt out of buried ice. Similar moraines can also be produced by proglacial thrusting (Bennett et al. 1998).

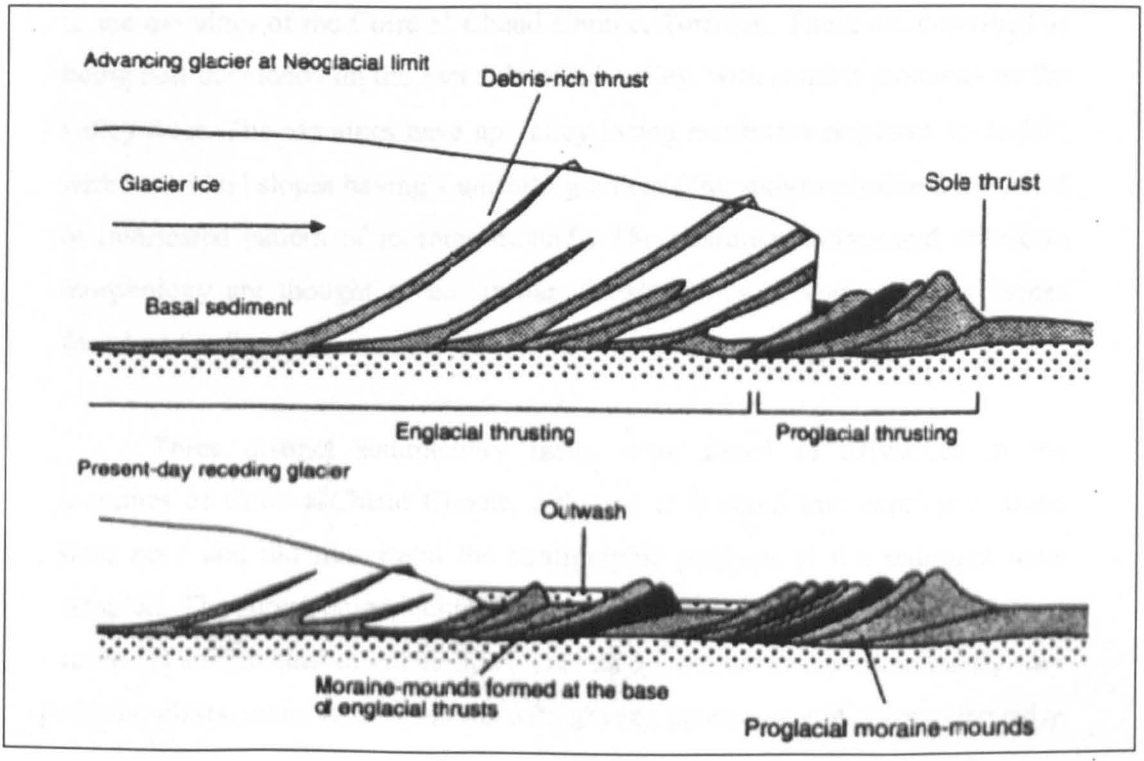


Figure 2.6 Development of controlled moraines by thrusting (Bennett et al. 1998)

The size of the mound left at the base of the thrust relative to the amount of sediment draped over the glacier foreland is a function of the angle of the thrust, with steeper thrusts producing larger ridges and less draped sediment. The morphology of the moraines is also affected by the planform of the thrust, with straight thrusts producing cross-valley orientated ridges and arcuate thrusts producing up-glacier convex ridges. Imbricate mounds reflect imbricate thrust systems. The moraine mound complex is also affected by the number of thrusts outcropping at the glacier surface. If a large number of thrusts reach the glacier surface much of the debris will be incorporated into ice-cored topography. According to the authors, there is a continuum between a moraine mound complex with in situ thrust slabs and one where the topography reflects resedimentation into ice cored troughs. Thrust slabs dominated the glacier margins studied in Svalbard, although there was some evidence of slumping and sediment flow. Morphology of mounds produced by surging and non-surging glaciers are similar, although thrusts formed by surges tend to be steeper.

The moraines studied by Bennett et al. (1998) in Svalbard were compared to the moraines of the Coire a' Cheud Chnoic, Torridon. These are described as being best developed on the east side of the valley, with smaller moraines on the valley floor. The moraines have up valley facing rectilinear slopes of 15 to 30°, with individual slopes having a uniform gradient. The authors observed a stacked or imbricated pattern of moraine mounds. The rectilinear slopes and imbricate morphology are thought to be similar characteristics to that of the moraines found on Svalbard.

Three distinct sedimentary facies were found in exposures in the moraines of Coire a'Cheud Chnoic, although it is noted that exposures found were poor and did not reveal the stratigraphic position of the sediment units sampled. The three facies included a sandy gravel with angular clasts with no striations and no clast orientation, a clast rich diamicton with predominantly sub-angular clasts, many with striations with a weak fabric perpendicular to the ridge crest, and a facies of quartzite sand and gravel. No information on the location of the sample sites of the different facies is given.

Formation by thrusting, similar to the interpretation of moraines on Svalbard, was argued to be the most likely origin of the hummocky moraines in the Coire a' Cheud Chnoic, with well defined rectilinear slopes, a stacked morphology and varied sedimentary composition. It is suggested that the thrust controlled slabs melted out during glacier recession to form the moraine complex. A polythermal ice margin may be required to entrain sediment within the thrusts. It was suggested that some Loch Lomond Stadial glaciers may have been polythermal, especially in the north-west where outlet and valley glaciers may have been cold based near their margins.

The theory that that these moraines were formed by incremental stagnation (Eyles 1983) was rejected by Bennett et al. (1998) as it is thought that incremental stagnation would produce irregular conical shaped mounds whereas the morphology of the 'hummocky moraine' of Coire a'Cheud Chnoic is more uniform with an imbricate pattern of moraines with consistent slope angles. Hodgson's interpretation of the hummocky moraine at this site as being formed subglacially as flutings was rejected, because according to Bennett et al. the moraine crests have a cross-valley orientation, and an irregular spatial organisation, whereas flutings and drumlins at contemporary glacier margins have a more regular down valley orientation. Formation as marginal moraines (Bennett and Boulton 1993) was also rejected due the 'well defined rectilinear faces' of these moraines, whereas moraines formed at the ice margin typically have pitted and irregular ice-contact slopes.

Moraines with similar morphology and internal structure to those in Torridon and Svalbard have been observed by other authors, and interpreted as being formed by processes other than sediment entrainment along thrust planes. Debris bands in the Kongsvegan glacier in Svalbard, studied by Bennett and Hambrey (1998), were recently reinterpreted as crevasse fills (Woodward et. al. 2002). According to Woodward et al., ice deformation would have deformed englacial debris bands as described by Bennett and Glasser (1998), and therefore their structure would not be preserved. The debris bands in Kongsvegan glacier, are interpreted as being formed by the squeezing of saturated sediments into crevasses at the glacier bed. The resultant landforms do not resemble crevasse patterns due to deformation of the sediment bands during surging. Other explanations of debris bands in glacier ice have also been proposed. Sharp (1984) working at Skalafellsjökull, south-east Iceland, interpreted debris bands in moraines as due to the glacier overriding snowbanks. Little supraglacial material was observed on this glacier, therefore moraines are thought to mainly consist of material of a subglacial origin. Also clasts measured in these moraines were predominantly sub-rounded to sub-angular with a high percentage (51%) of clasts being striated, suggesting a subglacial origin. Distal slopes were generally steeper than proximal slopes on the moraines. The moraines are thought to have been formed by the glacier overriding snowbanks and depositing debris rich ice from the glacier sole. If the margin is stable, debris bands will be repeatedly stacked to form the moraine.

Moraines consisting of imbricated slabs of debris were also observed by Krüger (1993). The imbricated slabs were interpreted as consisting of lodgement till. According to Krüger the moraines were formed by the freezing on of previously deposited till as the glacier advanced during the winter. The debris bands are deposited in the summer and if the glacier is stable the process of freezing on and stacking of debris will be repeated. The moraines studied by Kruger increased in size significantly over the period of a three year study. The sediment slabs showed no evidence of glacitectonics. The process of freezing on of sediment at the glacier margin requires cold based ice at the margin, suggesting seasonal freezing. A similar interpretation of moraines formed by stacking of debris was given by Matthews et al. (1995). Moraines at Styggedalsbreen, southern Norway were found to have alternate bands of subglacially derived and glacifluvial debris. Buried ice was common in these moraines. The subglacial debris is thought to be frozen on similarly to that observed by Kruger (1993). The glacifluvial debris is interpreted as supraglacial in origin. Two debris layers are deposited annually, a subglacial layer and a layer of supraglacial, glacifluvial sediment. The supraglacial material insulates the underlying ice, which is thought to account for the occurrence of ice cores within the moraines.

2.3.3.6 Other Moraine types

Landforms described as hummocky moraine are the most common form of moraines found throughout the Scottish Highlands. Most of the ice margins proposed by various authors have been delimited using the location of landforms with hummocky topography, commonly found at the lower end of valleys, especially in the West Highlands. At some sites however more substantial marginal moraines mark the limit of glacial advance, during the Loch Lomond Stadial, especially at the margins of the piedmont lobes of the Lomond and Menteith Glaciers. At both these sites the ice advanced out of the topographical constraints of the dissected mountain regions of the West Highlands and onto low lying, wide valleys. Both the area around the south of Loch Lomond and the Upper Forth Valley had been subject to marine incursion during the Lateglacial Interstadial. The Menteith and Lomond glaciers both advanced over marine sediments, the Clyde Beds, of a Lateglacial age. Marine shells and other biogenic material has been found in the moraines and till deposited by these glaciers.

The south-eastern limit of the Loch Lomond Readvance is delimited by prominent moraines that can be traced along the south side of the Upper Forth Valley from Ballat, on the Glasgow to Aberfoyle road, to Arnprior in the east. The moraines can then be traced in a south to north direction from Arnprior, along the east shore of the Lake of Menteith to Port of Menteith. Moraines are not easily recognised on the north side of the valley, although some small remnants exist. The moraines are discontinuous with numerous meltwater channels punctuating the latero-frontal moraine loop.

These moraines have been described in some of the earliest literature on the Loch Lomond Stadial (Jack 1874, Renwick and Gregory 1907). According to Renwick and Gregory the ridges on the south of the valley were previously interpreted as kames, however they interpret the ridges as lateral moraines. The moraines are recognised as following the south of the Upper Forth Valley, then turning north, to the east of the Lake of Menteith and traceable to Auchyle farm (north-east of the Lake). They are not traceable on the north side of the valley according to Renwick and Gregory. Early literature on these and other sites were discussed previously in section 2.3.1.

According to Simpson (1933) the moraines of the Upper Forth Valley separate an area free of 'morainic drift' from an area strewn with drift, however it is also noted that there is little topographic evidence of glacial landforms and sediments, within the moraine limit. The area within the moraines is generally flat and peat covered. The moraines are described as mainly consisting of angular blocks of highland grits, in the western parts of the Upper Forth Valley, but east of Buchlyvie sand, gravel and unstratified rubble is more common. The moraine on the east shore of the Lake of Menteith is described as being about 100 ft (30m) above the level of the lake with morainic deposits overlying dark grey, fossiliferous clay with fragments of the marine species *Mytilus edulis*. Shells from this moraine were radiocarbon dated by Sissons (1967b) to 11,800 ± 170 B.P. Faunal assemblages found in the moraine by Gray & Brooks (1972) are indicative of a boreal to sub-arctic climate. Channels, observed near Balfron Station, attributed to the Lomond Glacier diverting local drainage, continue in the Upper Forth Valley, outside the limit of the Menteith Glacier, and are used as evidence that the Lomond and Menteith Glaciers were contemporaneous (Simpson 1933).

More recently D.E Smith (1993) interpreted the Menteith Moraines as push moraines, and the channels cut through the moraines as meltwater channels. As well as the moraines on the southern slopes of the valley and across the valley east of the Lake of Menteith, a ridge in the centre of the valley and south of the Lake of Menteith was observed by Smith, who reports that it is composed of bedrock, but is overlain by smaller superimposed ridges of sand and gravel, orientated parallel to the valley axis. These ridges are thought to be crevasse fill ridges. Meltwater channels were mapped on the carse to the east of the larger moraines, but it is suggested that these could have been formed beyond the ice margin or during ice-sheet deglaciation, prior to the Loch Lomond Stadial. Within the limit of the moraines glacial and glacifluvial features including kame terraces, outwash terraces and meltwater channels were recognised. These are thought to have formed during retreat of the Menteith Glacier. Kettle holes in this area are thought to have formed by the melting of stagnant ice detached from the receding glacier. The larger moraine on the east shore of the Lake of Menteith is interpreted as being constructed of material being pushed up in front of the advancing glacier. A meltwater channel through this moraine with an outwash fan on the moraine's proximal side is thought to have formed during glacier recession. According to Smith (1993), there is no evidence that marine water has entered the Lake of Menteith since the Loch Lomond Stadial. Moraines at Easter Garden, north of Arnprior are described as small ridges intersected by meltwater channels. The moraines here consist mainly of sand and gravel and are kettled in places.

Thorp (1991a) attributed the moraines to being produced by fast moving ice with low basal shear stress. As the glacier advanced onto the unconsolidated glacimarine clays of the Upper Forth Valley, high pore water pressures in these sediments would have reduced basal shear strength, leading to rapid basal sliding.

According to Thorp basal shear stress typically increases towards the margins of contemporary glaciers. Basal shear stresses calculated by Thorp for Loch Lomond Stadial glaciers, including the Spean, Ossian, Lyon, Treig and Rannoch glaciers all increased towards the margins. Basal shear stress was however thought to decrease towards the margins of the Menteith, Creran and Lomond glaciers. Thorp (1991) attributed the lower basal shear stress of the Menteith, Creran and Lomond glaciers to the overriding of unconsolidated marine and glacimarine sediments with high porewater pressures. Thorp proposed that the Menteith glacier advanced rapidly, overriding unconsolidated marine and glacimarine sediments, producing large moraines by the glacitectonic reworking of marine and glacimarine material at the glacier margin. Crushed shells found in the sediments of the moraines were interpreted as being crushed by glacitectonic processes (Thorp 1991a). It is noted that other authors such as

Holdsworth (1973) and Dowdeswell (1986) have associated low profile glaciers with surging. Surging is suggested as a mechanism for producing the large moraines of glacimarine sediment in the upper Forth Valley (Thorp 1991a). Alternatively Thorp considered that these features could have been produced by continual rapid basal sliding rather than surging. According to Thorp the low basal shear stress of the Menteith Glacier could suggest the glacier was not polythermal but was warm based.

Evidence of moraines produced by proglacial thrusting of existing sediments have been observed at the margins of contemporary Icelandic glaciers such as Eyjabakkajökull (Croot 1988, Evans and Rea 1999, 2003) Slettjökull (Kruger 1993) and Bruarjökull (Evans et al. 1999, Evans & Rea 1999,2003). Moraines produced by this process have been termed thrust block moraines (Evans & England 1991). According to Evans and Rea (1999) this type of moraine can be found on contemporary glacier forelands in two settings, at subpolar margins in permafrost terrain and at the margins of surging glaciers. Where sediments in glacial forelands are frozen due to permafrost, a rapidly advancing glacier can bulldoze and stack large blocks of frozen sediment (Kalin 1971, Evans & England 1991). However it is also possible to move and stack large blocks of unfrozen sediment in glacier forelands not affected by permafrost, especially sediments with high pore water pressures (Evans & Rea 2003). Sedimentary units likely to have higher pore water pressures such as silt and clay units in sands and gravels can act as decollement surfaces allowing shearing and stacking. Examples of thrust block moraines produced from unfrozen sediments can be seen at Bruarjökull, and Eyjabakkajökull, Iceland. Figure 2.7 shows the thrust block moraines at the margins of Eyjabakkajökull. It can be seen from the map that lakes have formed in the depressions left by the removal of the slabs of sediment, from which the thrust block moraines were produced (Evans et al. 1999).

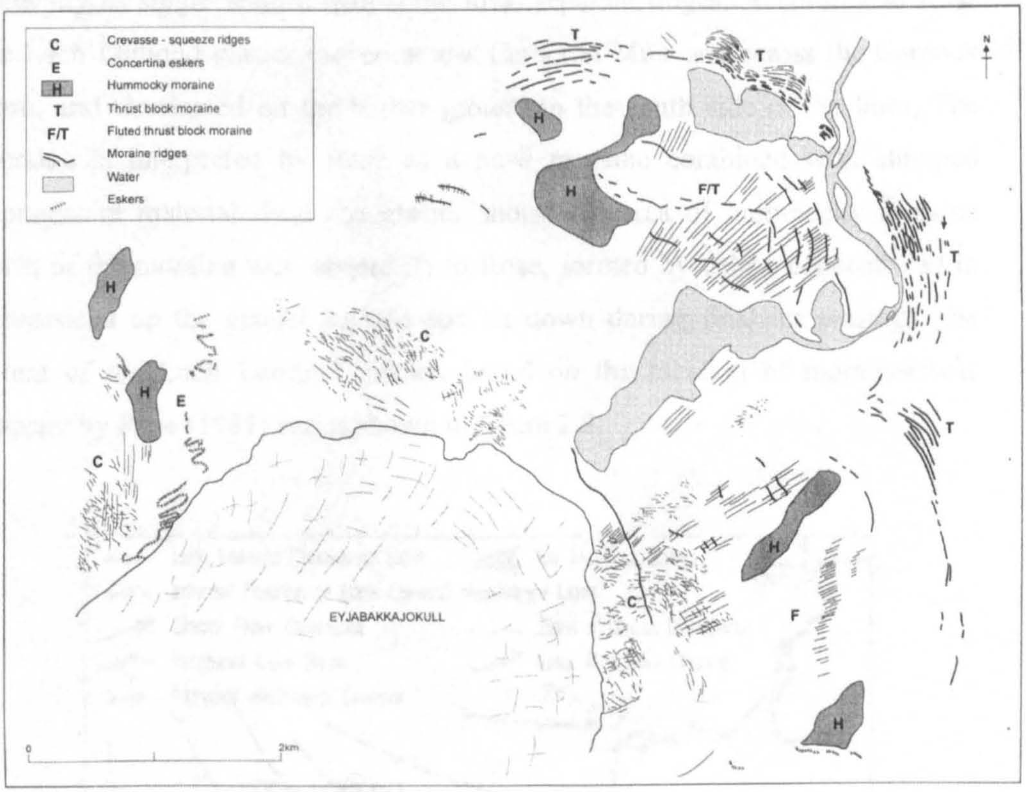


Figure 2.7 Map of Eyjabakkajökull Proglacial Geomorphology(from Evans et al.. 1999)

Moraines marking the limits of the Loch Lomond glacier an be traced from Glen Fruin and Glen Douglas in the west (Bell 1892) to Balloch in the south, along the northern slopes of the Kilpatrick Hills an in the Blane Valley east of Drymen. This study will investigate the genesis of the moraines in the east Loch Lomond Basin, from the Kilpatrick Hills in the south, to north of Drymen. This moraine is thought to have been partly deposited subaerially and partly as coalescing Gilbert-type deltas deposited in an ice dammed lake in the Blane Valley know as glacial Lake Blane. (Rose 1981, Benn & Evans 1996, Phillips et al. 2002). To the north of the Blane Valley, beyond the area of the former lake, moraines were deposited in a subaerial environment

The south-eastern extent of the moraine at Carnock Burn and on Cameron Muir is described by Rose (1981). The moraine at this location is described as a clearly defined feature 5 to 7m high and 40m wide at its base. The ridge is generally as single feature with some local separate ridges. According to Rose the Loch Lomond glacier moved across Cameron Muir and across the Carnock Burn, and terminated on the higher ground to the south side of the burn. The moraine is interpreted by Rose as a push moraine combined with slumped supraglacial material from the glacier snout. An area of hummocky moraine north of the moraine was, according to Rose, formed by debris concentrated in depressions on the glacier surface and let down during final ice wastage The extent of the Loch Lomond glacier, based on the location of moraines was mapped by Rose (1981) and is shown in figure 2.8.

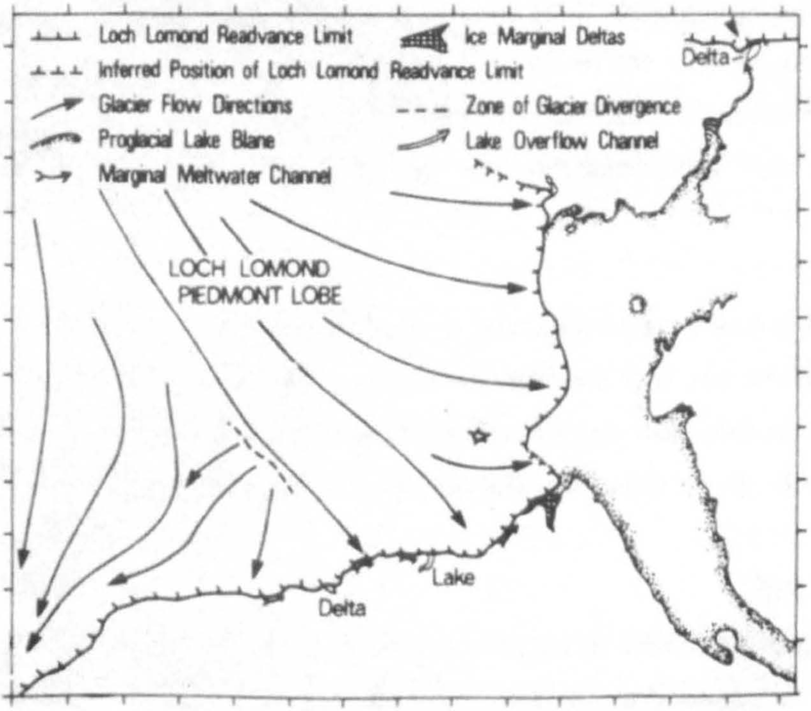


Figure 2.8 South-west margin of the Loch Lomond Glacier (J Rose 1981)

As well as the end moraine, the margin of the Loch Lomond glacier is also marked by a change in the direction of drumlins. Within the limits of the moraine drumlins have a radiating pattern reflecting the ice direction of the Loch Lomond glacier's Piedmont lobe, whereas outside the moraine drumlins have a west to east direction indicating ice direction of the Lateglacial ice sheet. This gives further evidence that the moraine marks the limit of the Loch Lomond glacier during the Loch Lomond Readvance.

Five ridges to the west of Gartness are described by Gordon (1993) as being formed as subaqueous moraines, with each of the ridges interpreted as a standstill position of the receding Loch Lomond glacier.

Good sediment exposures are rare in most parts of the Loch Lomond end moraine. However some very good exposures have been studied in detail, including a river cut section at Gartness (Rose 1981) and at Drumbeg where a large quarry cut into the moraine allowed detailed studies of its stratigraphy by Benn and Evans (1996) and Philips et al. (2001). These studies are discussed here in detail as the details of the sedimentology published in these works will be compared to the mapping and interpretation of the geomorphology carried out for this study. As these studies give detailed analysis of the stratigraphy of the moraine and there are few other exposures in this moraine, it is planned to use the published data rather than collecting new sedimentological data for this study.

Sediments in a river cut exposure in the Loch Lomond end moraine at Gartness are interpreted by Rose (1981) as evidence that the moraine was deposited in a subaqueous environment. The moraine has been subject to glacitectonic processes on its ice proximal side, but not on the distal side according to Rose.

Benn and Evans (1996) described a field site at Drumbeg Quarry, near Drymen giving an interesting insight into the stratigraphy and sequence of events in this area. The quarry cuts through a delta complex deposited in glacial Lake Blane in the early stages of deglaciation of the east Loch Lomond basin during the Loch Lomond Stadial. The delta consists of Gilbert type foresets and topsets, with proximal subaqueous outwash deposits, to the east of the delta. The foresets consist of well sorted sand and gravel. The proximal outwash is more variable with matrix supported gravels and interbedded sand lenses and drapes. Undisturbed areas of this deposit show cross cutting units interpreted as due to repeated channel erosion and filling in a series of subaqueous fans. Sediment at higher levels in the sections, on the ice proximal (west) side of the fans, exhibited evidence of glacitectonic deformation, whereas the ice distal (east) side very little deformation had taken place The top of the exposures studied show the remnants of a till capping, which outcrops extensively to the east. At the western end of the exposure, laminated diamicton is overlain by well jointed clay. The sediments at this location have been subjected to compressional deformation, with asymmetric and overturned folds and thrusts. This is interpreted as possible evidence of a change in the flow of the overriding ice possibly due to a minor oscillation of the margin or due to compression with local perturbations during continuous subglacial shear due to the inhomogeneous nature of the material.

Working in Drumbeg quarry on an exposed section in an ice-contact fan, Phillips et al. (2002) used techniques of structural geology to interpret the glacial history of this feature. According to Phillips et al. the Gilbert-type delta / fan complex was affected by polyphase deformation with four tectonostratigraphic units which correspond to four deformational and depositional events. The glacitectonised sediments exposed in the quarry, are interpreted as evidence of polyphase deformation, of the delta during two minor readvances of the Loch Lomond Glacier, during recession from its Loch Lomond Readvance maximum position. A temporary stabilisation of the ice margin, due to progradation of the delta into glacial Lake Blane, was followed by a minor readvance with a north-east ice flow direction, resulting in thrusting of the deltaic sediments to form a thrust block. The ice then receded and the thrust block was subject to erosion and deposition, by glacial meltwater. Another readvance followed this period with ice overriding the thrustblock/delta deforming the sediments and depositing a till cap over the sequence.

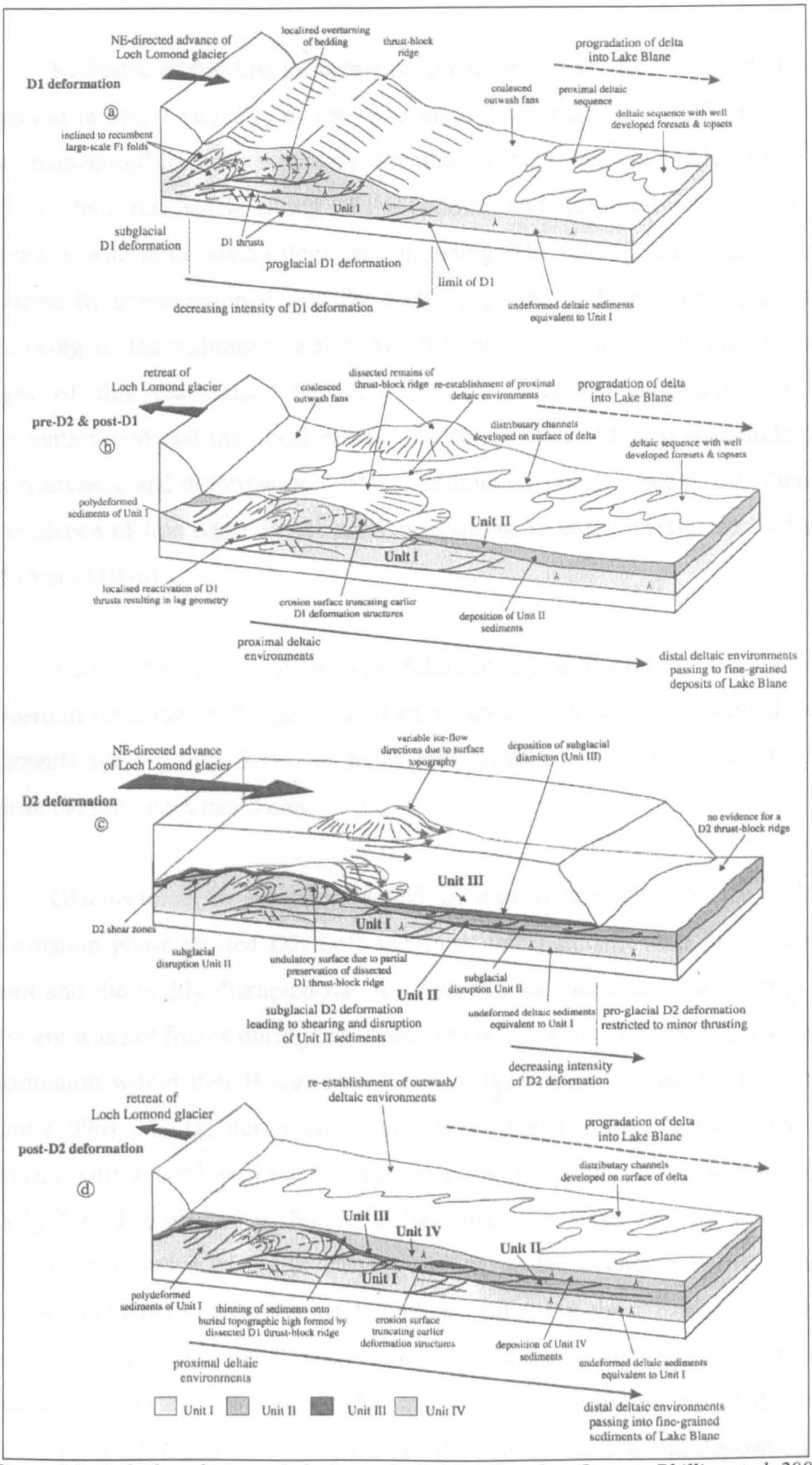


Figure 2.9 Polyphase history of glacitectonised delta, Drumbeg Quarry: Phillips et al. 2002

Evidence of the first deformation event termed D1 by Philips et al. was observed in unit 1 (fig 2.9) of the sedimentary exposure. The ice is thought to have readvanced in a north-easterly direction at this time. The readvance of ice into the delta resulted in tilting of the bedding and tectonic thickening of the sequence, with large scale folding and thrusting. The folding is thought to have occurred by compression during the early stages of readvance and resulted in shortening of the sediments which was followed by thrusting during the later stages of this readvance. Thrusting led to a tectonic thickening of the sedimentary unit and the development of a thrust block ridge. It is thought that this readvance and deformation did not continue beyond this section, as there is no evidence of this phase in the section to the north-east investigated by Benn and Evans (1996)

This initial deformation was followed by a period of erosion and deposition resulting in the production of a subaqueous fan and proximal delta sediments (unit II, fig 2.9) The sands and gravels of unit II unconformably overlie the sand dominated unit.

Glacitectonic structures observed in unit II are attributed to a later deformation phase termed D2. Soft sediment deformation within sand and silt lenses and the highly disrupted nature of unit II was used as evidence that the sediment was not frozen during the second readvance (D2). This highly disrupted deformation within unit II was also found in the section studied by Benn and Evans (1996). The D2 deformation event is attributed to ice overriding the fan complex, with a north-east ice direction resulting in the deposition of a till, unit III (fig 2.9). The till unit is thought to have been deposited contemporaneously with the deformation of the underlying unit II, as the boundary between these two units is marked by a prominent south-west dipping shear zone. Clast fabric analysis indicates that the ice direction changed during deposition of the till, from north-east near the base of the unit to south-east at the top of the unit. Similar to deformation phase D1, D2 is followed by erosion and deposition by meltwater during ice recession. This resulted in a fining upwards sequence of gravel, pebbly gravel and sand, which is overlain by a thin diamicton attributed to subsequent mass flow.

The location of the glacitectonised delta, inside the outer moraine of the Loch Lomond Glacier is used as evidence that the polyphase deformation, sedimentation and erosion occurred during the early stages of deglaciation, as the glacier margin oscillated due to the dynamic nature of the ice margin during deglaciation.

The lowest sedimentary unit of the delta contains shell fragments and is interpreted as subglacially deformed marine sediment of the Clyde Beds. The sediments also include the glacilacustrine sediments of the Blane Valley Silts deposited in the former Lake Blane. These sediments are thought to have been overridden during early advance of the Loch Lomond Glacier into the East Loch Lomond basin and Blane Valley after 12,870 Cal years BP (calibrated age of ^{14}C age of marine shells of the Clyde Beds). Recession of the margin and stabilisation at the location of Drumbeg quarry is thought to have occurred while the glacier was in contact with the deep lake water of Lake Blane. The stabilisation allowed the deposition of the Gilbert-type delta. The polyphase deposition and deformation of the Gilbert type delta is thought to be indicative of active recession at the end of the Loch Lomond Stadial.

2.3.4 Flutings

Some glacigenic features attributed to the Loch Lomond Stadial have been interpreted as flutings or fluted moraines (Peacock 1967, Sissons 1967a, 1974, Hodgson 1986, 1987, Bennett 1995). Flutings generally consist of elongate, sub-parallel ridges, streamlined in the direction of ice flow (Boulton 1976, Rose 1989, Gordon et.al. 1992). The height of flutings ranges from a few centimetres to a few metres. They are usually straight or slightly curving ridges, and usually consist of till, although they can also be formed from other pre-existing sediments (Benn & Evans 1998). Flutings often form downglacier of an obstacle such as a boulder, clast cluster or core of consolidated sediment. They are thought to form in the lee cavity of the initiating boulder or obstacle. Saturated sediment is squeezed into the low pressure cavity by the pressure of the ice and prevents the cavity from closing in the lee of the obstacle. The sediment in the lee cavity can form as a fluting by sediment being added to the downglacier end of the fluting as the cavity is kept open by the ice-flow (Boulton 1976, Benn 1994a). It has also been suggested that they can form by the sediment in the lee of the obstruction being frozen on to the glacier and moved down flow, with the cavity upglacier being filled with fresh sediment (Schytt 1962). According to Benn and Evans (1998) there are two types of flutings. The first has a tapering appearance, becoming narrower downglacier. These have a tapering or herringbone pattern of clast fabric. The other type of fluting is parallel sided, with constant cross-profiles and a parallel or slightly converging clast fabric. Previous studies of flutings in the Loch Lomond Readvance landform record in Scotland are now reviewed.

Peacock (1967) interpreted elongate glacial landforms in Glen Shiel as flutings. These are described as linear features visible on aerial photographs under certain light conditions. They show little deviation in direction and have no relation to the underlying solid geology. They are aligned parallel with glacial striae and comprise low ridges 1m to 3m high and vary from 10m to 100m in length, constructed of stony material with locally derived small boulders. Locally, mounds form chains up to 200m long and usually 10m to 15m apart. Flutings west of Cluanie Inn are described by Peacock as having a linear structure located obliquely across the hillside and consisting of morainic drift a few feet thick with boulders and larger blocks. Generally they are low parallel ridges with some larger mounds. According to Peacock the ridges were constructed from debris derived subglacially from rock knobs.

Landforms with a down-valley orientation were, at some sites, interpreted as fluted moraines by Sissons (1977). Fluted moraines are difficult to map in the field but can be easily recognised on aerial photographs (Sissons 1977). According to Sissons fluted moraines often extend to higher altitudes than hummocky moraine and are frequently found on steep slopes, and are therefore associated with rapid ice movement. In Strath Dionard Sissons observed flutings superimposed on dead ice topography. This was interpreted as evidence that the glacier must have overridden the stagnant ice and deposited the flutings before the stagnant ice downwasted. The flutings are therefore unaffected by the underlying topography as this was produced by meltout of the dead ice after the flutings were deposited. This explanation is consistent with Sissons' interpretation of end moraines suggesting a period of active retreat followed by subsequent in-situ downwasting of glacier ice. However, if the flutings were produced before the meltout of the stagnant ice it is unlikely that they would be preserved after meltout of the underlying ice and the production of stagnation topography. The preserved flutings observed by Sissons therefore do not suggest that the underlying topography was subject to significant melt-out of stagnant ice. This would suggest that either the features interpreted as flutings are not flutings or alternatively the landforms interpreted as 'dead ice topography' were not produced by the melt-out of stagnant ice.

Sissons in his book *The evolution of Scotland's scenery* (1967a) produced a map of the Glen Torridon area showing an ice margin with ice direction mapped from the direction of "fluted moraines", however no reference to these fluted moraines is discussed in the text. Flutings were also observed by Sissons (1974), ranging from less than 1m to 8m in height and from a few metres to a few hundred metres in length. They are usually located in groups, with gently curving patterns. Sissons (1974) interprets these as being formed by fast moving ice and are thought to be "valuable indicators of the last direction of ice movement". Some features previously interpreted as fluted moraines may be lateral or medial moraines according to Sissons (1977).

Hodgson (1986, 1987) interpreted glacigenic features aligned in the direction of ice flow in Torridon as being produced subglacially as flutings. Three sites in the Torridon area were investigated by Hodgson, Coire a'Cheud Chnoic on the south side of Glen Torridon, Strath a'Bhathaich, south of Ben Damh, and An Ruadh-stac, to the north of Glen Torridon.

Some of the fluted moraines in Torridon consist of smooth corrugations in profile, usually less than 1m high and 10 to 20m wide and less than 500m long. These do not have boulders or other initiating obstacles at their stoss ends. More commonly fluted moraines found in Torridon are steep sided ridges with irregular long profiles. The largest features are up to 6m high and occur in the lees of bedrock obstructions such as spurs and nunataks.

Two study sites are discussed in detail by Hodgson (1986), one south-east of An Ruadh-stac and the other in Strath a'Bhathaich. The fluted moraines and striae in the field site south-east of An Ruadh-stac have a convergent north-west to south-east directional pattern. Strath a'Bhathaich is a south-west draining valley surrounded by hills with a number of corries and has a variety of glacial depositional landforms attributed to the Loch Lomond Stadial. The valley is on the western edge of the Moine Thrust, where quartzite crops out on the surrounding slopes, in the corries and on the summit of Beinn Damh. Flutings are well developed, the largest being 400m long and 4m high. A thick spread of quartzite boulders in Strath a'Bhathaich is interpreted as a medial moraine.

Hodgson (1986) studied clast lithologies in the flutings at the above sites, to investigate whether the flutings or the material they were constructed from is of Loch Lomond Stadial age or from a previous glaciation. Valley glaciers in the Torridon area had their sources in areas of the local bedrock lithologies of Torridonian sandstone and Cambrian quartzite. The only Cambrian quartzite is in the high ground to the north-west above 550m. In contrast, the Late Devensian ice sheet flowed westwards into this area carrying erratics of Moine Schist, and other metamorphic and igneous lithologies from further east.

The upper layers of the till show few or no ice sheet erratics, but 50 to 60% quartzite clasts. With increasing depth, the proportion of quartzite diminished with sandstone becoming more dominant. This was used to suggest two tills, an upper till which included quartzite clasts and no erratic lithologies and a lower till mainly of sandstone but with a significant amount of erratic clasts.

The tills are rich in coarse gravel and cobbles with some large boulders and are clast supported with a sandy matrix, forming an unconsolidated diamict. No structure or stratification was observed in the tills, although exposures were poor. Particle sizes in all samples were similar, however, clast sizes were more variable in the upper till. Clast fabrics showed significantly strong preferred orientations parallel to the ridge crests. A secondary north-south fabric was also observed in the lower till.

According to Hodgson, it is possible that the two tills were deposited as a lower tier of subglacial till overlain by supraglacial material. This scenario was rejected because the topography of the flutings is not masked by a blanket of supraglacial material. The strong clast orientation parallel to the ridge crests suggests that the upper till and flutings are genetically related.

Hodgson provides two explanations for the tills. The lower till could have been deposited by the Late Devensian ice-sheet and then overridden by Loch Lomond Stadial ice, which deformed the till and produced the flutings. Alternatively, the lower till was deposited during an early stage of the Loch Lomond Stadial during which local bedrock material and erratics from Late Devensian ice sheet sediments were available for transportation; the ice-sheet sediments were eroded first followed by bedrock. The difference between the two tills in this scenario is due to an exhausted supply of ice-sheet erratics at the time of the deposition of the upper till. The secondary north to south orientation found in clast fabrics in the lower till is thought to show an earlier ice direction, therefore the former explanation of the two tills is more likely.

The evidence from these two sites suggests that most of the till in the area was deposited by the Late Devensian ice sheet, and was later subject to minor reworking and fluting of the surface, along with some bedrock material eroded and deposited during the Loch Lomond Stadial. Significantly for the present study, Hodgson's preferred interpretation indicates that evidence of earlier glaciation survives as a palimpsest beneath Loch Lomond Stadial deposits.

Similar to the sites discussed above, Hodgson (1987) also interprets glacigenic landforms in the Coire a'Cheud Chnoic, Glen Torridon, as flutings. These features reach a height of over 8m, but exposures of bedrock in streams show the till in this area is generally not very thick. The amount of sediment in the valley is thought to be around the equivalent of a 2m thick uniform till cover. The hummocks are often higher at their north side giving the impression that they are conical mounds, with a chaotic distribution, when viewed from Glen Torridon. Mapping of these features by Hodgson showed them to be elongate with a down-valley orientation. Clast orientations were strong and parallel to ridge crests with secondary modes. The secondary clast fabric modes at this site were transverse to the ridge crests. Only two sites out of the twenty sampled did not have preferred orientations. This is used by Hodgson (1986) to suggest that these landforms are not crevasse fillings are proposed by Sissons, but are some form of fluting.

Clast lithologies were sampled at thirty-two sample pits, with samples taken at an interval of 10 to 20cm in depth. A significant increase in ice sheet erratics with depth was found at only three of these sites. This does not suggest there are distinctive lower and upper tills in this valley, as found at other sites by Hodgson (1986). However this may be due to sampling methods as most of the samples were taken from 1m dug pits, on ridge crests. It is possible that a distinctive lower till underlies these sediments.

Lithologies of surface boulders were also sampled in the Coire a' Cheud Chnoic. 100 boulders at 20 locations were sampled. No ice-sheet erratics were found in this valley, and only a small percentage of quartzite boulders were observed, despite the high ground surrounding Coire a'Cheud Chnoic being underlain by quartzite. The highest number of quartzite boulders were found below the mouth of the col between Sgurr Dubh and Sgurr nan Lochan Uaine, on the east side of the valley, suggesting that ice flowed down this col before it was deflected by a larger glacier in the main valley. This col connects the main valley with the corries of Coire Beinne Leithe and Coire na h-Uamha. It is suggested by Hodgson that this could either have occurred during the Lateglacial ice-sheet glaciation or early in the Loch Lomond Stadial.

Hodgson described the elongate landforms in the Coire a' Cheud Chnoic as being similar to roche moutonees, and proposed that they formed by Loch Lomond Readvance ice moving down the main valley in a northerly direction. The valley contained abundant debris from the Lateglacial ice-sheet, and from periglacial activity at the start and end of the Lateglacial Interstadial. During the Loch Lomond Readvance the previously deposited debris was overridden by ice or incorporated into the glacier bed, retarding the ice and being streamlined into the elongate downvalley orientated landforms. Interaction with ice in the main valley of Glen Torridon, flowing from the north, thickened and slowed the glacier in Coire a' Cheud Chnoic. Debris was then entrained, but this caused a negative feedback in slowing the glacier and reducing its ability to transport sediment. The hummocky moraine of Coire a' Cheud Chnoic is therefore interpreted as being produced by subglacial streamlining at the glacier bed where there is abundant availability of existing debris, and is indicative of active ice retreat.

Bennett (1995), working on the north side of Glen Torridon interpreted areas of hummocky topography as flutings, or flutings masked by a drape of supraglacial material, which he termed hummocky flutings. Hodgson (1986, 1987) is acknowledged by Bennett (1995) for suggesting much of the till forming the flutings in the Torridon area was brought into the area by glaciers preceding the Loch Lomond Stadial. However Hodgson (1986,1987) is criticised by Bennett for relying on sedimentary evidence from shallow pits, dug into the surface of the features. This, according to Bennett would not necessarily have been representative of the typical sedimentology of the features, and would be subject to post-depositional modification. Bennett uses morphological variation to interpret the landforms and tests this with a few good sediment exposures.

Four sites on the north side of Glen Torridon were investigated by Bennett (1995). The Coire a' Cheud Chnoic, on the south side of Glen Torridon, where landforms were interpreted by Hodgson (1986,1987) as flutings and later by Bennett and Hambrey (1998) as due to sediment melt-out from thrusting, was not included in the study. Sites chosen included Loch Grobaig, and Glas-tol

Lochan, north of Liathach, and Glen Grudie and Creag Dhubh, north of Beinn Eighe. It is suggested by Bennett that ice flowed in a westerly direction at Loch Grobaig, during the Loch Lomond Stadial. This area has a high density of 1-5m high boulder covered mounds, which seem to have little orientation on the ground but show a distinct east to west pattern on aerial photographs. The direction of these features is not affected by bedrock structures, and is parallel to the ice direction indicated by striations. These are interpreted by Bennett (1995) as flutings, similar to interpretations of similar landforms in Coire a' Cheud Chnoic by Hodgson (1986, 1987). Aerial photographs show a similar pattern of landforms to those in the Coire a' Cheud Chnoic. Three landform types were identified by Bennett at this site and described as megaflutings, irregular streamlined mounds and continuous irregular mounds. The megaflutings consist of long straight ridges up to 5m high and usually less than 70m long. The alignment of smaller flutings suggest these are the remnants of longer megaflutings. These megaflutings occur on top of larger irregular mounds. The irregular mounds are asymmetrical, being steeper and taller on their west side, and have a smooth, boulder free surface. The third type of landform recognised by Bennett (1995) are irregular hummocks separated by enclosed hollows and transverse ridges. Some conical mounds were observed, located between ridges or disrupting the pattern of ridges. This type of terrain is found throughout the Torridon area and was described by Bennett (1994,1995) as 'hummocky flutes'.

At another site, Glas-tol Lochan, investigated by Bennett (1995) the megaflutings have a different morphology from those described above. Here the megaflutings occur in a linear swarm between an area of bedrock and boulder covered moraine hummocks to the east. They are longer and flatter than those observed at Loch Grobaig but some are broken into short lengths. These are difficult to recognise on the ground, but more obvious on aerial photographs. These megaflutings are considered to have been affected by post-glacial modification.

In Glen Grudie flutings were observed on aerial photographs, but were difficult to recognise on the ground due to numerous irregular mounds and ridges. The flutings merge into enclosed hollows and conical mounds. They are shorter than the flutings found at other sites and form chains of ridges.

The flutings studied on Creag Dhubh have a simpler form than the others studied, and are higher and wider, and more widely spaced. Variation in the width of the flutings gives them a beaded appearance. These mainly consist of small boulders with little fine material between. Larger boulders between these flutings are orientated parallel to the flutings.

From these observations Bennett (1995) proposed that the landforms in north Glen Torridon represented three types of fluting: hummocky flutes, regular megaflutes and streamlined mounds. It is suggested that the hummocky flutes are deposited as a composite landform, with the flutings being formed subglacially and later draped with supraglacial material during deglaciation (fig 2.10).

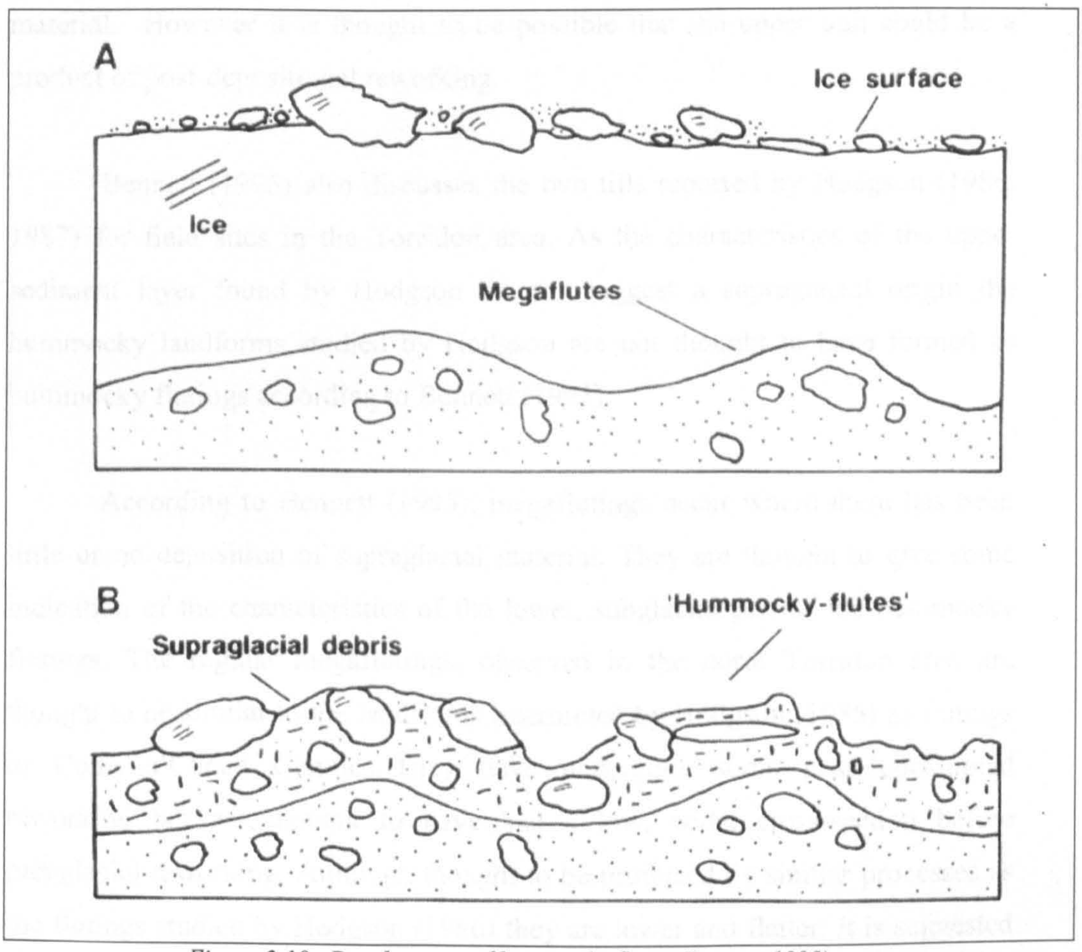


Figure 2.10 Development of hummocky flutes (Bennett 1995)

The size and morphology of the hummocky flutes varies (Bennett 1995), due to variation in the thickness of the supraglacial material draped over the underlying fluted terrain. Where there is more supraglacial material the flutes are more masked and may be difficult to recognise. More obvious flutings are thought to occur where there is only a thin covering of supraglacial material. This is used to explain some of the characteristic variation in morphology of the hummocky flutes such as the irregular variation in height and width. Enclosed depressions observed between the flutings are interpreted as kettle holes produced by the meltout of ice buried by supraglacial material.

Small sediment exposures contained a lower till of compact material with an upper till of larger, looser material with a more varied clast size. This, according to Bennett fits the proposal that the landforms, interpreted as hummocky flutings, are produced subglacially and then buried by supraglacial material. However it is thought to be possible that the upper unit could be a product of post-depositional reworking.

Bennett (1995) also discusses the two tills reported by Hodgson (1986, 1987) for field sites in the Torridon area. As the characteristics of the upper sediment layer found by Hodgson do not suggest a supraglacial origin the hummocky landforms studied by Hodgson are not thought to have formed as hummocky flutings according to Bennett (1995).

According to Bennett (1995), megaflutings occur where there has been little or no deposition of supraglacial material. They are thought to give some indication of the characteristics of the lower, subglacial part of the hummocky flutings. The regular megaflutings, observed in the north Torridon area are thought to be similar to the landforms interpreted by Hodgson (1986) as flutings in Coire a'Cheud Chnoic. They have undergone some post-depositional reworking but are thought to have had a low, wide, cross-section before paraglacial reworking. Although thought to be produced by similar processes as the flutings studied by Hodgson (1986) they are lower and flatter. It is suggested by Bennett that the megaflutings were not produced in subglacial cavities, but by some method of ice flow which concentrated the sediment into flutings. No explanation of this process is discussed.

The streamlined mounds are distinguished from other features by their smooth streamlined, boulder free surface. Bennett (1995) likens these to landforms found in Iceland and Canada, produced by ice overriding existing landforms. It is suggested that these flutings were produced by the same process proposed by Hodgson (1986) for features to the south of the glen. These flutings are interpreted as the product of the subglacial streamlining of debris initially deposited during an earlier glaciation. The existing debris and landforms are thought to either pre-date the Loch Lomond Stadial or represent ice-marginal retreat positions of the Loch Lomond Readvance subsequently overridden by a minor readvance.

Elsewhere in the Scottish Highlands fluted terrain has a similar morphology to the hummocky flutings described in this paper, with irregular shaped mounds and bouldery surfaces, and some pattern of lineation (Bennett 1995). According to Bennett the flutings described by Peacock (1967) in Glen Sheil come under the category of hummocky flutings, although these are generally less continuous and smaller than those in Torridon.

2.4 Digital mapping and visualisation of glacial landforms

It can be seen from previous work on the genesis of glacial landforms of the Loch Lomond Stadial that the spatial organisation and therefore the mapping of these landforms is critical to the interpretation of their origin The studies discussed here have mostly used traditional methods of mapping landforms, including field mapping and the use of aerial photographs. Recently work however has explored the use of digital methods of mapping and visualisation of glacial landforms. This has mainly concentrated on the use of satellite imagery, and the use of digital elevation models (D.E.M.s).

Mapping glacial landforms using digital satellite images is discussed by Boulton and Clark (1990) and Clark (1993, 1994, 1997, 1999). Although aerial photographs provide a useful tool for mapping glacial landforms at a large scale, smaller scale mapping using satellite images was found to provide insights into the spatial patterns of large scale glacial landforms over larger areas. The use of digital images, which can be viewed at varying scales, was found to reveal patterns of landforms. Digital images were found more useful than paper copies of satellite images as used in previous studies, as these can only be viewed at one scale. Satellite images were used by Clark to map mega-scale lineations in North America produced by the Laurentide Ice Sheet. It is noted that the resolution of the Landsat images used limits their potential for mapping smaller scale landforms such as flutings, drumlins and eskers (Boulton & Clark 1990, Clark 1997). However these images are useful for mapping larger scale features which appear on satellite images as a grain rather than individual landforms. Mega-scale features are defined as features measuring 8 to 70km in length and 200 to 1300m wide. The spatial pattern of these landforms is more easily recognised on satellite images than on aerial photographs on which they appear fragmentary (Clark 1993). Mapping lineations in the spatial pattern of mega-scale glacial landforms provided evidence of major shifts in the position of the ice divide of the Laurentide Ice Sheet over time.

GIS was used to combine evidence from digital satellite imagery with other evidence allowing integration of data from various sources. The GIS was also found useful for mapping temporal changes in ice direction based on cross-cutting patterns of landforms. Aerial photographs were found more useful for viewing landforms at a larger scale to determine the relative age of the features. According to Clark (1997), aerial photographs can complement the use of satellite images as they allow more detailed larger scale investigation of landform morphology and spatial patterns.

Clark and Meehan (2001) investigated glacial landforms in Ireland using images derived from digital elevation models. Images were created using hill shading techniques. It is noted that satellite images have the disadvantage of being illuminated from one source only therefore creating a bias in the image.

Digital elevation models however can be hill shaded from varying directions, by changing the source's azimuth and elevation. Although Clark and Meehan found this method useful for recognising lineation in landforms, changing hillshading azimuth can create false landform lineations. Digital elevation models give information on height only and do not give any information on landform shape or breaks of slope and therefore images derived from D.E.M.s may not depict the true morphology of a landform (Clark and Meehan 2001). Non-azimuth based techniques were found to be the most reliable method of depicting landforms (Clark & Meehan 2001). Non-azimuth based hill shading can easily be achieved using three-dimensional visualisation tools available in some GIS (Clark per. comm.)

2.5 Summary and Discussion

Evidence for a return to glacial conditions in the Scottish west Highlands and other upland areas of the British Isles, following the Lateglacial Interstadial includes pollen assemblage evidence, radiocarbon dates and geomorphological evidence. The limits of Loch Lomond Stadial glaciers are recorded by end moraines at some locations especially the south-western margins, delimited by the prominent end moraines of the Lomond and Menteith glaciers (Jack 1874, Renwick 1909, Simpson 1933, Rose 1981, Benn & Evans 1996, Philips et al.. 2002). However, end moraines are absent at many former glacier margins and other evidence has been used to delimit the extent of glacier ice, especially the occurrence of hummocky moraine (Sissons 1963,1967a, 1967b, 1973, 1979, Manley 1956).

Hummocky moraine has been used as evidence of the extent of the Loch Lomond Stadial glaciers and the nature of deglaciation. However, there has been much debate on the processes responsible for the production of hummocky moraine, including the possibility that hummocky moraine is polygenetic. According to Charlesworth (1956), hummocky moraine represents standstill positions or minor readvances during active local retreat of ice back into high corries. Little evidence of the nature of these moraines however was published by Charlesworth and his theories were later challenged, especially by Manley (1956) and Sissons (1963, 1967a, 1967b, 1973, 1974, 1977, 1980) who described hummocky moraine, at various sites in the Scottish Highlands and north England, as displaying a chaotic appearance. The unordered chaotic distribution and enclosed hollows in the moraines were used by Manley and Sissons to suggest that hummocky moraine was produced by in situ downwasting of buried glacier ice. This was used as evidence of widespread or areal ice stagnation, attributed to rapid climate amelioration at the end of the Loch Lomond Stadial resulting in rapid deglaciation. The theory of areal stagnation has more recently been challenged.

Linear spatial patterns within hummocky moraine have been used to suggest these are not ice stagnation features but deposited during active recession. Hummocky moraine has been re-interpreted as push and dump moraines deposited during active retreat (Bennett & Boulton 1993, Bennett 1994), as recessional features with some localised stagnation (Benn 1992), as due to incremental ice stagnation Eyles (1983), as controlled moraines (Bennett et al. 1998) and as subglacial flutings (Peacock 1967, Sissons 1967a, 1974, Hodgson 1986, 1987, Bennett 1995). The interpretation of these moraines and the nature of deglaciation of the south-western margins have important implications for the reconstruction of the palaeoclimate of the Loch Lomond Stadial.

It can be seen from the existing literature that the spatial organisation of glacial landforms has been used to infer the nature of deglaciation and climatic conditions at the termination of the Loch Lomond Stadial. The spatial patterns of glacial landforms within the limits of the Loch Lomond Readvance have previously been mapped using field mapping techniques or from aerial photographs.

More recent work on mapping glacial landforms has employed digital methods including the use of satellite images (Boulton and Clark 1990, Clark 1993, 1994, 1997, 1999), the use of Geographical Information Systems (Clark 1997) and images produced from digital elevation models (Clark & Meehan 2001). The use of satellite images is, however, limited to mapping larger scale features such as mega-scale lineations produced by large ice sheets, such as the Laurentide ice sheet. According Boulton & Clark 1990 and Clark 1997 satellite images are not suitable for mapping smaller scale features such as flutings and eskers. Satellite images are therefore not thought to be suitable for mapping the smaller scale landforms of the Scottish West Highlands, produced during the Loch Lomond Stadial. Other digital methods however could prove useful for mapping and visualisation of landforms of this scale. According to Clark (1997), aerial photographs can be used for more detailed studies of landforms. Although past studies of Loch Lomond Stadial glacial landforms have employed the use of aerial photographs, the use of digital aerial photographs has not previously been investigated. High resolution scanned aerial photographs and the use of digital photogrammetry to produce digital elevation models and geometrically correct orthoimages could provide insights into the morphology and spatial organisation of Loch Lomond Stadial glacial landforms, similar to work on the spatial organisation of larger scale features using satellite images by Boulton and Clark (1990), Clark (1993, 1994, 1997, 1999).

Although digital techniques for terrain visualisation and mapping using aerial photographs have been developed for some time, little application of these techniques has been applied to the study of glacial landforms. This study aims to employ digital mapping and visualisation techniques, using digital elevation models, to reassess models of moraine formation and the spatial organisation and genesis of glacial landforms thought to have formed during the Loch Lomond Stadial. The recognition of spatial patterns of glacial landforms not previously recognised may provide useful evidence of the nature of deglaciation and climatic conditions of the Loch Lomond Stadial. Sedimentological data will also be collected to assist in the interpretation of the landforms mapped in this study.. A discussion of the digital mapping and visualisation techniques and sedimentology techniques employed is presented in chapter three.

3

Methods

3.1 Introduction

This chapter describes the methods used in this research. They include digital methods of map production, digital visualisation techniques and sedimentological analysis, including clast form and fabric assessments and the evaluation of borehole records. The digital mapping techniques used included digital photogrammetry and geographical information systems (GIS). The application of these methods to the study of geomorphology will be discussed and the procedures involved in these techniques will be explained. Technical details of digital photogrammetry and GIS will not be discussed unless relevant to this study. These can be found in text books such as *Elements of Photogrammetry* (Wolf & Dewitt 2000*), Remote Sensing and Image Interpretation* (Lillesand & Keifer 1994), *GIS and Computer Cartography* (C.B.Jones 1997) and *Fundamentals of GIS* (M.N. De Mers 2000).

The morphology and spatial organisation of Loch Lomond Stadial glacial landforms will be investigated by mapping these landforms and using digital three-dimensional visualisation techniques to infer their genesis and significance to palaeoclimatic reconstruction. This will be supplemented with sedimentological data where possible. The techniques of identifying and mapping landforms using aerial photographs has been a common practice for many years. Aerial photographs have been used to interpret landforms since the 1920s (Lo 1976). However, aerial photographs are not geometrically accurate due to scale distortions (Kilford 1970 Kraus 1993 Falkner 1995 Wolf & Dewitt 2000). Mapping landforms from uncorrected aerial photographs will therefore result in some distortion of the spatial organisation and dimensions of features. Scale on an aerial photograph is decreased towards the edges due to features at the edges being further from the camera. Height of the land surface also causes distortion as higher altitude areas are closer to the camera. Height also causes distortion known as parallax, which results in features appearing to lean away from the centre of the photograph. Distortions are also introduced to aerial photographs due to tilt of the aircraft. These distortions can be removed by the processes within photogrammetry. Until recently photogrammetry, including analogue and analytical photogrammetry, was a highly skilled and time consuming process. More recently the development of digital photogrammetry has resulted in less time consuming methods. Digital photogrammetry also has the advantage of producing digital elevation models as well as corrected aerial photographs, which can be used in various ways to study the morphology of landforms. The digital format geometrically corrected aerial photographs are termed orthoimages. This study will employ digital photogrammetry to produce orthoimages, digital elevation models (D.E.M.s) and maps of the geomorphology of the chosen field sites.

Sedimentological data including clast fabric and shape analysis was carried out where possible. Borehole records were obtained from the British Geological Survey and used to analyse the sedimentary record for field areas where sediment exposures were not available. Sedimentological data, the orthophotos, D.E.M.s and maps of landforms, produced photogrammetrically and other relevant data were collated using a geographical information system (GIS).

3.2 Mapping and morphological analysis

3.2.1 Overview

Maps and D.E.M.s were produced for each field site using digital photogrammetry and GIS. The first stage of this was to measure ground control points, which are necessary for the photogrammetric process. This was carried out using a global positioning system (GPS). Orthoimages and D.E.M.s could then be produced for the field sites and landforms mapped using the orthoimages. The maps of the geomorphology were combined with the orthoimage, D.E.M. and data derived from the D.E.M., and sedimentological data in the GIS. This allowed interpretation of the glacial landforms for each field site.

3.2.2 GPS ground survey

GPS was used to provide accurate coordinates for control points, features that could be recognised on the aerial photographs. It is necessary for the photogrammetric process to have previously measured coordinates of features that can be seen in the overlap of at least two aerial photographs. These are used to fix the photographs to a ground coordinate system and to remove photograph distortion. A network of points was chosen for each site to give adequate coverage of control points. It was initially planned to include three control points per photograph, one at the centre (termed the principal point in photogrammetry), one near the centre top and one near the centre bottom of the photograph, providing six control points per stereo pair. This pattern of control points was then amended to take into consideration the availability of suitable features for control and access. The choice of features to use as control points differed depending on the type of terrain being mapped. Anthropogenic features such as a gate post or the end of a wall are usually recognisable on aerial photographs and it is easy to find what part of the feature was used as a control point. Natural features such as boulders are more difficult to recognise on the photographs and it is less easy to find the exact point on the feature that was measured. Anthropogenic features were therefore used where possible and features such as boulders used where this was not possible. Where natural features were used extra points were measured to give a choice of feature to use as control. Boulders have been successfully used as control to photogrammetrically produce maps of glacier margins and landforms (D.Twigg pers com). Details and maps of the control points used are discussed in the field site chapters (chapters 4-9).

The coordinates of the chosen control points were measured using a Leica 500 differential GPS system. Differential GPS requires the use of two receivers, a reference station and a rover station. The reference station is usually set up at the beginning of a day's surveying at a suitable location. The reference station records its location including height, calculated from the position of GPS satellites at set intervals for the duration of the day's survey. The rover station is set up on individual control points for a period of time, the length of which is governed by its distance from the reference station. Data from the reference station is used to adjust the data from the rover station to provide more accurate coordinates. This results in a high degree of accuracy for the control points relative to the reference station. The position of the reference station is usually measured with a high degree of accuracy due to the longer time period of measurement, although it is common for height measured by this method to differ from national coordinate systems by a significant amount. This however does not affect the relative accuracy of the points, and therefore was not thought to be important for the mapping of glacial landforms. It is now possible in the UK to tie a GPS survey into the national grid using the Ordnance Survey network of passive GPS control points, a network of points with markers tied into the national grid. The passive GPS network was however not available at the time most of the surveying for this project were carried out. The only site that was tied into the OS passive GPS system was the Loch Lomond field site as the survey for this site was carried at a later date than other sites. It would have been possible to tie the other surveys into the OS national grid using the coordinates of triangulation points, which are available from the OS. Unlike the GPS network the coordinates of triangulation points were not available free of charge and were therefore too expensive for this research.

3.2.3 Digital Photogrammetry

Aerial photographs were purchased from the aerial photograph library of the Royal Commission for Ancient Monuments Scotland (RCAHMS). Aerial photographs were first examined in the aerial photograph library and decisions made on the extent of photography to be purchased based on the extent of visible glacial landforms on the photographs. Some photographs were rejected due to the quality of the photographs or large areas of the photographs being obscured by shadow or cloud cover.

The aerial photographs purchased were all at an approximate scale of 1:24 000 in 230mm format and as black and white diapositives. For information on the coverage of aerial photographs for each site see the relevant field site chapters (chapters 4-9). The photographs were scanned commercially using a high resolution photogrammetric scanner (Vexcel 4000) at a pixel resolution of 25 microns. Higher resolutions were available but this would have produced extremely large computer files, and considerably increase processing times for the photogrammetry process.

Aerial photographs for each field site were imported into a photogrammetry project. A project in Helava Leica Socet Set contains all the images and data used to create orthoimages and D.E.M.s for a site and the resultant orthoimage and D.E.M. files. The control points, previously measured using GPS, have to be identified on the aerial photograph images by pointing to them on screen with the screen cursor to record their coordinates. Tie points, features recognisable in at least two photographs with no measured coordinates were also measured. These can be measured manually or automatically. Socet Set's automatic point measurement function was initially used to measure tie points. Socet Set has a function for checking if an adequate coverage of ground control points and tie points has been measured known as blunder detect and solve. If coverage of control and tie points is not found to be adequate extra control points can be added manually. After manually measuring control points the blunder detect and solve function can be run again. This procedure can be repeated until an adequate coverage of points is achieved. Aerial Triangulation can then be performed. Aerial triangulation registers the images to a ground coordinate system (in this case the Ordnance Survey National Grid) and registers the images to each other. Accuracy of the triangulation process is recorded in the root mean square error (RMS) values calculated for the ground control points. If these show a poor quality triangulation adjustments can be made by re-measuring the control points, taking out control points that the software is unable to measure accurately and/or adding more tie points.

Once an adequate solution is found the images can be rectified. This is carried out using a stereo pair. The rectification process orientates the images to north and removes scale distortions. Rectification is carried out on the overlap area of each stereo pair and results in two images, a left and a right image, of the overlap area only. These can be viewed in stereo using the stereoscope built into the workstation (fig 3.1)

Figure 3.1 Helava Leica Socet Set on a Unix workstation with built in stereoscope

The rectified images can then be used to extract a digital elevation model. A resolution of 5m was chosen for all the D.E.M.s used in this study. This resolution was found adequate to study the glacial geomorphology of the field sites, which would not be possible with lower resolution D.E.M.s. A higher resolution D.E.M. might be more useful but would create extremely large files, needing large amounts of computer memory and would considerably increase processing times. Digital elevation models produced by the Ordnance Survey are available via the Digimap service for academic research these however have a resolution of 50m which is not thought to be adequate for the interpretation of glacial geomorphology. Figure 3.2 shows a comparison between a 5m resolution D.E.M. produced for this study and a 50m resolution D.E.M. obtained from the Ordnance Survey. The images shown are hillshaded D.E.M.s of part of the Tyndrum field site and were produced by identical methods.

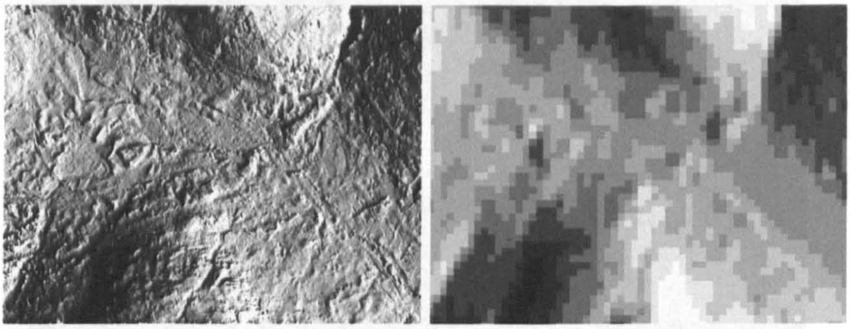


Figure 3.2 Comparison of 5m resolution D.E.M. (left) and 50m resolution D.E.M. (right), Tyndrum

A 5m resolution D.E.M. from previous work at Breiðamerkurjökull, Iceland was compared to a D.E.M. produced in the field by measuring points using a total station (electronic distance measurer and theodolite) to assess the suitability of the photogrammetrically produced D.E.M. and the resolution chosen. The total station has the advantage that the position of breaks of slope and tops of ridges can be chosen manually, so the D.E.M. should give a reasonably accurate reproduction of the land surface. Points in the photogrammetrically produced D.E.M. are measured at a set grid interval. This has the effect of smoothing the topography in the D.E.M.. However, the difference between the D.E.M. produced by photogrammetry (fig 3.4) and the D.E.M. produced by field survey using a total station is not great (fig 3.3). It is therefore thought that photogrammetrically produced D.E.M.s with a resolution of 5m are adequate for the study of glacial geomorphology. Producing D.E.M.s by digital photogrammetry has the advantage of being able to cover large areas relatively quickly, compared to ground survey, allowing a more extensive survey area to be studied (Brown 1998).

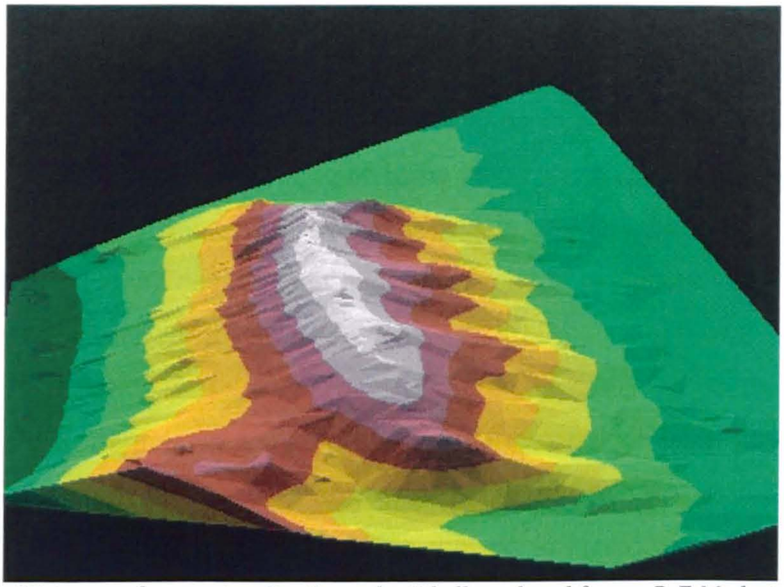


Figure 3.3 3D image of a moraine, Breiðamerkurjökull produced from a D.E.M. derived from a total station survey

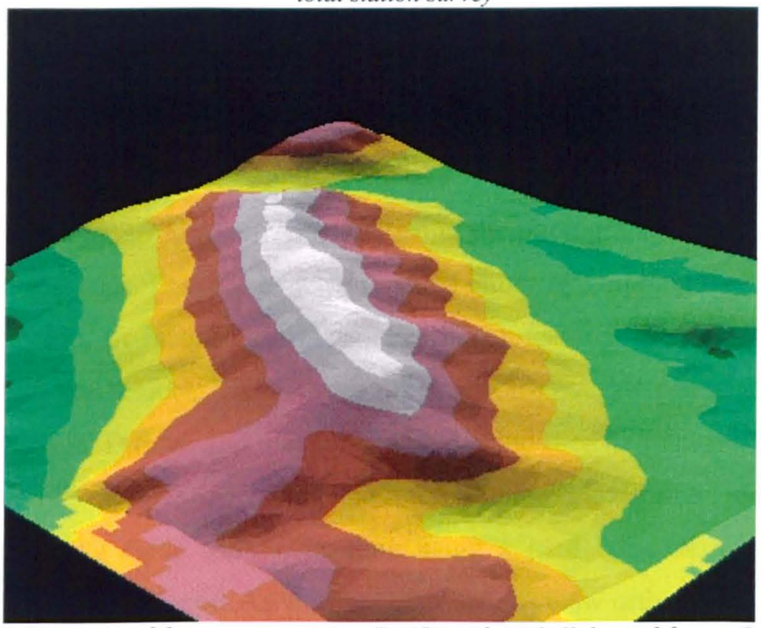


Figure 3.4 3D image of the same moraine at Breiðamerkurjökull derived from a 5m resolution D.E.M. produced by photogrammetry

After creating the D.E.M., orthoimages were produced. This process removes distortion due to the height of features, known as parallax. Before the removal of parallax features on an image appear to lean away from it's centre, with the amount of lean dependent on the height of the feature. (Kilford 1970, Kraus 1993, Falkner 1995, Wolf & Dewitt 2000). Parallax is also important to the creation of the D.E.M. as it is measuring this height displacement that allows the determination of elevation change. Creating orthoimages requires the D.E.M.s and the rectified images, previously produced. The orthoimages were created then mosaiced to create an orthomosaic. The software allows various methods of mosaicing and enhancements. Contrast and Brightness can be balanced across multiple images to give a seamless mosaic. Although mosaicing and enhancing the images can be done using automatic techniques, it was found that manual methods mosaicing two images only and simultaneously gave the best results. The result could be mosaiced with another image until all images for a field site have been added.

As the orthoimages are geometrically correct, unlike aerial photographs, they can be used for accurate mapping of landforms. Removing parallax, however, prevents the image from being viewed in stereo. Stereo viewing of orthoimages can be achieved by creating an image with this distortion re-introduced. These images are termed orthomates. The use of an orthoimage and orthomate in conjunction with the D.E.M. allows viewing and mapping of features in stereo and in their correct geographical position.

Glacial landforms were mapped using the photogrammetric software and built in stereoscope. Landforms were mapped either by mapping their extent as a closed polygon, or in the case of smaller linear features their ridge crest was mapped as a line feature. The features mapped were not interpreted at this stage. The orthoimage, D.E.M. and mapped features could then be imported into a GIS, ArcView 3.1 for further processing and interpretation. Landforms are more easily recognised using these techniques than using a hard copy aerial photograph stereo pair and stereoscope. As well as being able to view ortho-corrected images in 3D other software functions such as height exaggeration, changing scale, contrast and brightness were found useful tools for feature recognition. The advantages of digital images being scale independent (although limited by resolution) was discussed by Clark (1997)

3.2.4 Mapping and Geographical Information Systems

The data from the photogrammetry processes were imported into ArcView GIS and combined with other data such as sedimentological data and

Ordnance Survey data. The D.E.M.s were imported as ASCII files. ArcView converts the ASCII text files to a GIS raster grid with each cell value representing elevation. The orthoimage was imported as a tiff image file. The file of the mapped landforms was imported into ArcView after some processing using ArcInfo. Feature files, can be exported from SocetSet in dxf format. However where landforms were mapped as closed polygons these appear in ArcView as line features. To convert these to polygons the dxf files were converted to ArcView theme files in ArcView then imported to ArcInfo and converted to ArcInfo coverages. This allows the line features to be converted to polygons using ArcInfo. No function exists in ArcView for this process. The files were then exported from ArcInfo as ArcView themes and opened in ArcView.

Ordnance Survey 50m resolution D.E.M.s were also imported into the GIS and used to create contours. Although as previously discussed their resolution is not suitable for analysing glacial geomorphology they provide a greater coverage than the photogrammetrically produced D.E.M.s, allowing the surrounding topography to be taken into account when interpreting the glacial geomorphology of a field site. Digital photographs of landforms were taken in the field and their location recorded using a Garmin handheld GPS. The locations of the photographs were plotted in the GIS and ArcView's 'hotlink' facility used to allow the photographs to be viewed by clicking on the symbols representing their location. This allowed viewing of terrestrial photographs, aerial photographs, maps and D.E.M.s of to assist the interpretation of landforms.

As well as glacial landforms, other features such as streams, lakes, roads and settlements were included in the maps, making it easier to locate the landforms mapped. This was also found useful for producing maps for use in the field. These features were mapped from the orthoimage using the GIS. Place names were also added.

3.2.5 Digital visualisation techniques and Geomorphological interpretation

The 5m resolution D.E.M.s were used to create contours of the field areas. The D.E.M.s were also used to create other visual data useful to the interpretation of the geomorphology including hillshaded D.E.M.s and maps with relief represented with hypsometric colours. It was found particularly useful to create three dimensional images by draping the orthoimage on the high resolution D.E.M.. This was carried out using ArcScene, which is part of ESRI's ArcGIS. The three dimensional viewing facilities of ArcView 3.1 using the 3D analyst extension were not found to give high enough quality images to be of use to the interpretation of the glacial geomorphology. This was attempted as ArcScene was not available at the time of beginning the project.

The use of relief represented by hypsometric colours on maps was not found particularly useful for identifying landforms. This was due to the fact that the glacial landforms studied did not always lie on horizontal surfaces. The contours do not therefore pick out the landforms as they join points of equal elevation rather than follow the shape of the landform. D.E.M.s produced by photogrammetry do not include information on breaks of slope or the boundaries of landforms. If the landforms were on horizontal surfaces the contours would pick out the landform shape as can be seen on the 3D models of the moraine at Breiðamerkurjökull. This moraine was formed on a near horizontal sandur plain, whereas the landforms studied in Scotland in this research were not formed on horizontal surfaces, often being formed on valley sides or steeply sloping valley floors such as those in the Coire a'Cheud Chnoic, Torridon. Contours joining points of equal elevation were found to obscure rather than pick out landforms and patterns of landforms. The use of hillshaded D.E.M.s as used by Clark and Meehan (2001) is therefore thought to be a more appropriate method for recognising landforms and their spatial organisation.

3.3 Sedimentology

3.3.2 Overview

Sedimentological data complemented the geomorphological evidence from the five field sites investigated. The type of sedimentological data used was dependent on the nature of the site. Where adequate sedimentary exposures were available clast shape and fabric analysis was carried out, whereas at other sites borehole records were used, if available. Grain size analysis was also carried out for sites with sediment exposures. Adequate sedimentary exposures were found at the Torridon and Tyndrum field areas. Due to a lack of sediment exposures borehole records were used to investigate the nature of sediments in the Upper Forth Valley. An adequate number and distribution of borehole records, kept by the British Geological Survey, was available for this area. Neither an adequate number of borehole records nor sedimentary exposures were available for Rannoch Moor. Only two sedimentary exposures were found and the only borehole records available were clustered around a bridge on the main road through Rannoch Moor. The borehole records only recorded Flandrian sedimentary sequences and were therefore not relevant to this project. However, published details of sediment cores taken on Rannoch Moor, including detailed descriptions of sediments and radiocarbon dates were available (Lowe & Walker 1976). Extensive and detailed published and unpublished sedimentological data exists for the East Loch Lomond Basin and was utilised for this project, especially Benn & Evans (1996) and Phillips et al (2002). It was not thought necessary to collect new sedimentological data for this site.

3.3.3 Clast shape and fabric analysis

Where sediment exposures were available samples of 50 clasts were measured, including measurement of shape, angularity and fabric. Clast surface features such as striae were noted. Clast lithology was also noted where this was thought to be significant.

Clast form analysis is a widely used and long established technique for determining the transport history of sediments (Holmes 1960, Boulton 1978, Benn & Ballantyne 1993, Benn & Evans 1998). Clast form including shape and angularity reflects both the lithology of the clast and its transport history. The initial form of a clast is affected by its lithology. Clasts of massive coarse grained lithologies such as granite tend to be block shaped, whereas clasts derived from more fissile bedrock such as shales are more elongate due to fracturing along bedding planes (Benn 1990).

Initial clast form can be modified by erosion depending on its transport path. Clasts can originate from above the glacier, mainly by frost-shattering of bedrock, or subglacially due to plucking at the glacier bed. Clasts derived from above the glacier tend to be more angular and less blocky than clasts that have been subject to subglacial transport (Boulton 1978). Subsequent passive transport, including supraglacial and englacial transport have little effect on clast form and therefore clasts retain their original form (Boulton 1978). Clasts with subglacial transport paths are either derived from plucking of the underlying bedrock or from supraglacial material descending into the basal transport zone (Sharp 1960, Lewis 1960, Boulton 1978) (fig 3.5).

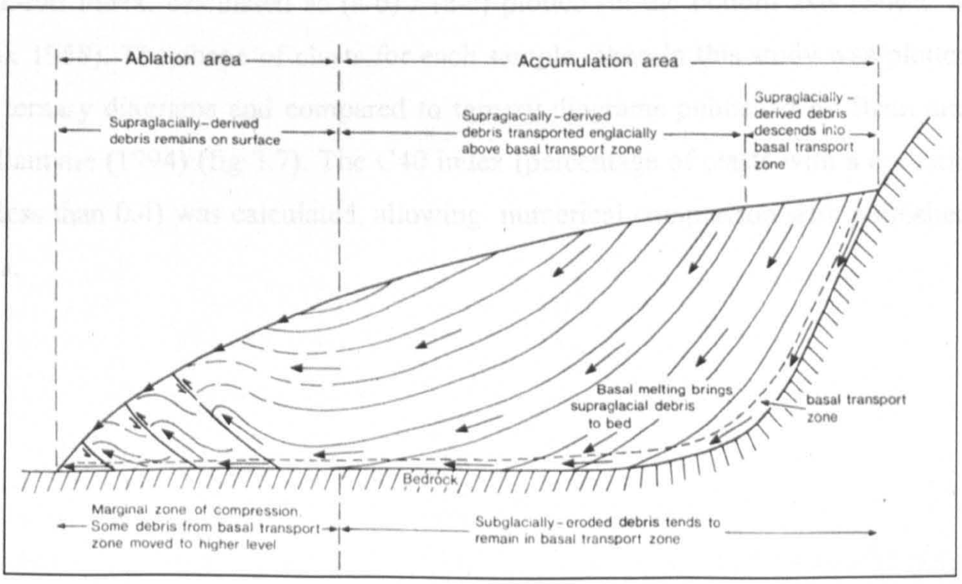


Figure 3.5 Debris transport paths though a glacier (Boulton 1978)

The form of clasts subjected to subglacial transport is modified by erosion of the clast surface. Clasts transported in the basal traction zone come into contact with the bed and with other clasts (Boulton 1978). Clasts also undergo wear during shear in subglacial deformation layers as they are overridden or override other clasts (Benn 1995). Subglacial erosion of clasts results in modification of clast form including edge rounding, striation and polishing of clasts (Boulton 1978, Benn & Evans 1996). It is therefore possible to distinguish between clasts that have undergone active subglacial transport from clasts which are derived from frost-shattering or have undergone passive supraglacial or englacial transport. It is thought that significant clast modification can occur over short transport distances (Flint 1971, Drake 1972, Humlum 1985).

Clast shape can be determined by ratios between the longest (a), intermediate (b) and shortest (c) axes and can be seen as a continuum with three end members, blocks, slabs and elongates. Clast shape can therefore be plotted on a triangular or ternary diagram with the three end members at the corners of the triangle (fig 3.6) (Ballantyne & Benn 1993). Clast shape can be plotted on a ternary diagram using simple ratios. The ratio of the length of the c axis to the a axis is plotted on the left axis (c:a), the b to a ratio on the right axis (b:a) and the disk-rod index, calculated as (a-b) / (a-c) plotted on the bottom axis (Sneed & Folk 1958). The shape of clasts for each sample taken in this study was plotted on ternary diagrams and compared to ternary diagrams published by Benn and Ballantyne (1994) (fig 3.7). The C40 index (percentage of clasts with a c:a ratio of less than 0.4) was calculated, allowing numerical comparison with published data.

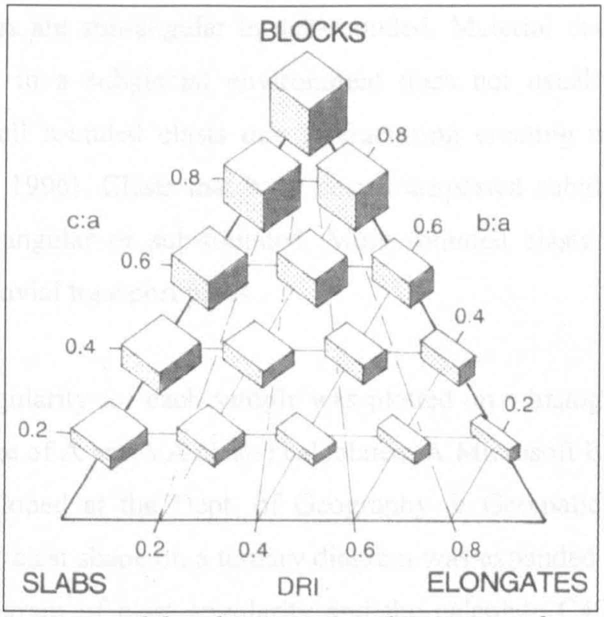


Figure. 3.6 The continuum of clast shape represented on a ternary diagram (from Benn & Ballantyne 1993)

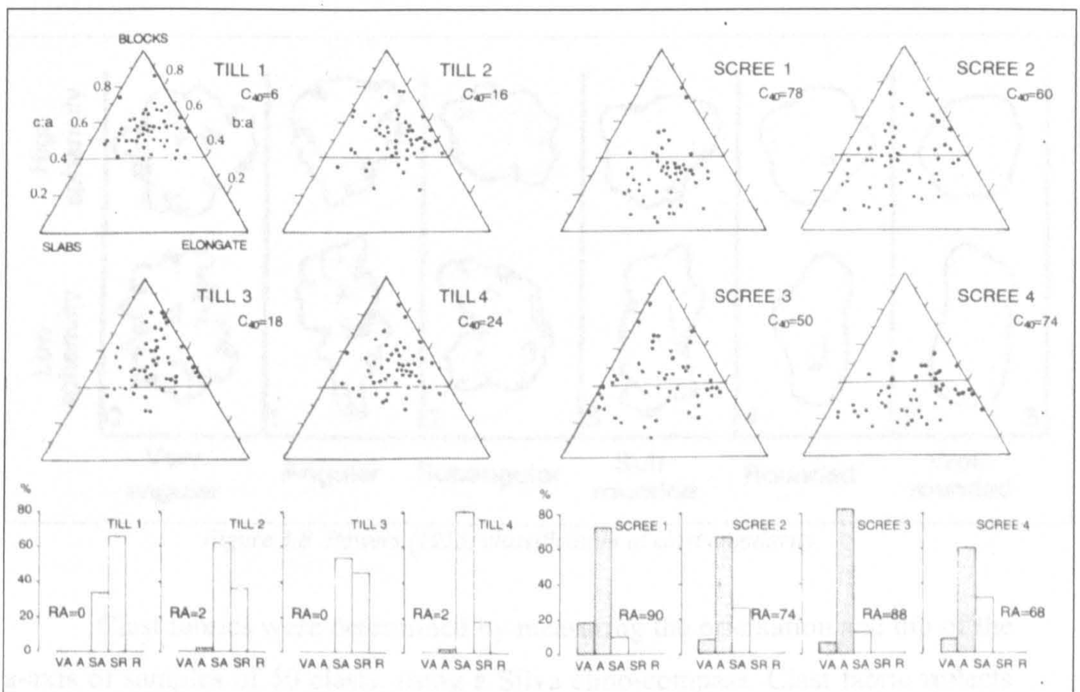


Figure 3.7 Clast shape and angularity of till and scree from Storbreen, Norway (from Benn & Ballantyne 1994)

Clast angularity or roundness describes the degree of curvature of clast edges. The angularity of clasts was categorised using the descriptive categories developed by Powers (1953). Clasts are categorised as well rounded (WR), rounded (R), sub-rounded (SR), sub-angular (SA), angular (A) and very angular (VA) (fig 3.8). It can be seen from the histograms in figure 3.7 that the scree samples tend to be angular to very angular whereas the actively transported clasts from till samples are sub-angular to sub-rounded. Material that has undergone active transport in a subglacial environment does not usually contain many rounded and well rounded clasts due to fracturing creating new sharp edges (Benn & Evans 1996). Clasts that have been transported subglacially therefore tend to be sub-angular or sub-rounded. More rounded clasts usually indicate fluvial or glacifluvial transport paths.

Clast angularity for each sample was plotted on a histogram and the RA index (percentage of A and VA clasts) calculated. A Microsoft Excel spreadsheet previously developed at the Dept. of Geography & Geomatics, University of Glasgow, to plot clast shape on a ternary diagram was expanded to automatically generate a histogram of clast angularity and the calculate C40 and RA index values.

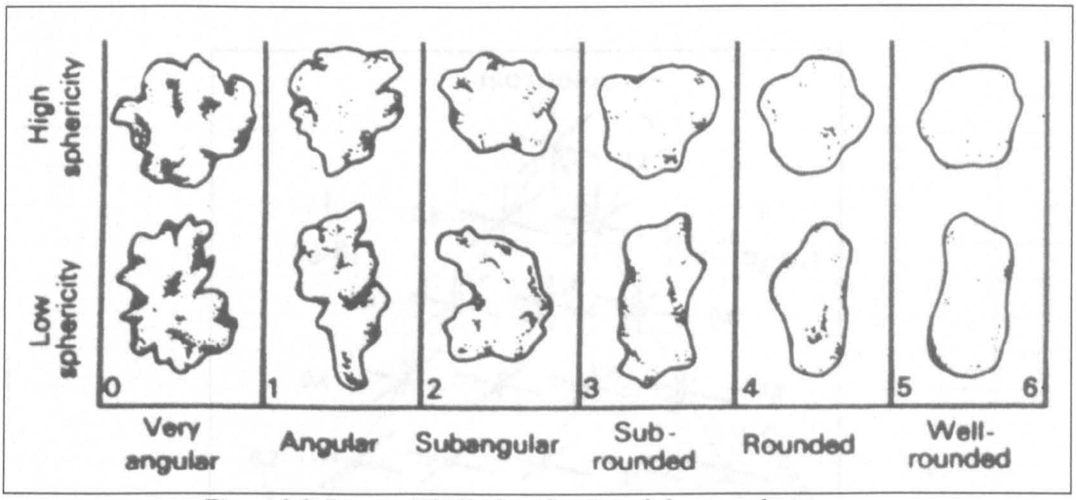


Figure 3.8 Powers (1953) classification of clast angularity

Clast fabrics were determined by measuring the orientation and dip of the a-axis of samples of 50 clasts, using a Silva clino-compass. Clast fabric reflects the direction and magnitude of strain in the sediment when it was deposited. This is an established and widely used technique for inferring the depositional environment of sediments. Clast fabrics were plotted on equal area Schmidt stereonets, allowing the graphical interpretation of the strength of fabrics, their preferred orientation (direction of dip) and dip angles. The stereonets were generated using the computer software package Rockware (version 2.0), using the spherical Gaussian method. The software also calculates the mean azimuth of clast orientations and normalised eigenvectors, which can be used to numerically determine fabric strength. Mean dip was also calculated using Microsoft Excel.

Clast fabric shape can be defined by ratios of eigenvalues, the values of which depend on the vector strength of clast preferred orientation. A continuum of all possible fabric shapes can be represented on a ternary diagram, based on ratios of normalised eigenvalues, with isotropic fabrics plotted at the top of the ternary diagram, girdles at the bottom left and cluster fabrics at the bottom right of the diagram (Benn 1994) (fig 3.9). Eigenvalues λ_1, λ_2 and λ_3 are normalised to give normalised eigenvalues S_1, S_2 and S_3 where the sum of S_1, S_2 and $S_3 = 0$. These represent the degree of clustering of a fabric. The eigenvalues are plotted on a ternary diagram with the isotropy index (S_3/S_1) plotted on the left axis of the ternary diagram and the elongation index ($1-(S_2-S_1)$) plotted on the right axis (Benn 1994).

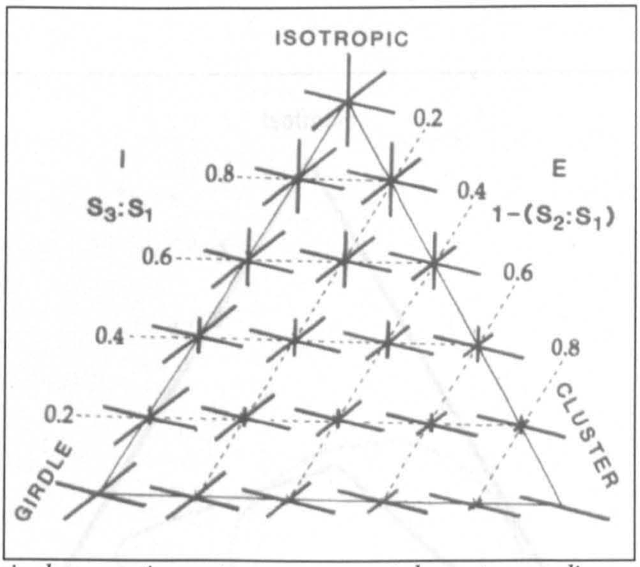


Figure 3.9 Fabric shape continuum ternary represented on a ternary diagram (Benn 1994)

Clast fabric was plotted on a ternary diagram with envelopes enclosing areas of likely clast fabric shapes of particular sedimentary depositional environments. Envelopes were adapted from previously published data (Benn 1994, Benn and Evans 1996) (fig 3.10).

Although the use of clast fabrics as an indicator of the genesis of sediment facies and landforms is well established some recent work such as Bennett et al (1999) has suggested that fabrics within similar sediment facies display a wide variation of fabric characteristics and that fabric is a poor indicator of sediment genesis, even when used in conjunction with other evidence. However statistical analysis, comparing upper and lower till fabrics, of clast samples taken at Breiðamerkurjökull, Iceland by Benn and Ringrose (2001) show that variance between samples from the upper and lower till was generally greater than variance due to random variation, although some overlap of sample characteristics was observed. Caution in the use of clast fabrics is recommended, especially where fabric shapes plot close to the boundaries of facies type envelopes (Benn & Ringrose 2001). Samples of 50 clasts were used and it is thought that as random variance would increase for smaller samples and therefore sample size should be at least 50. Benn and Ringrose (2001) stress that clast fabric should not be used alone to infer the genesis of a sediment.

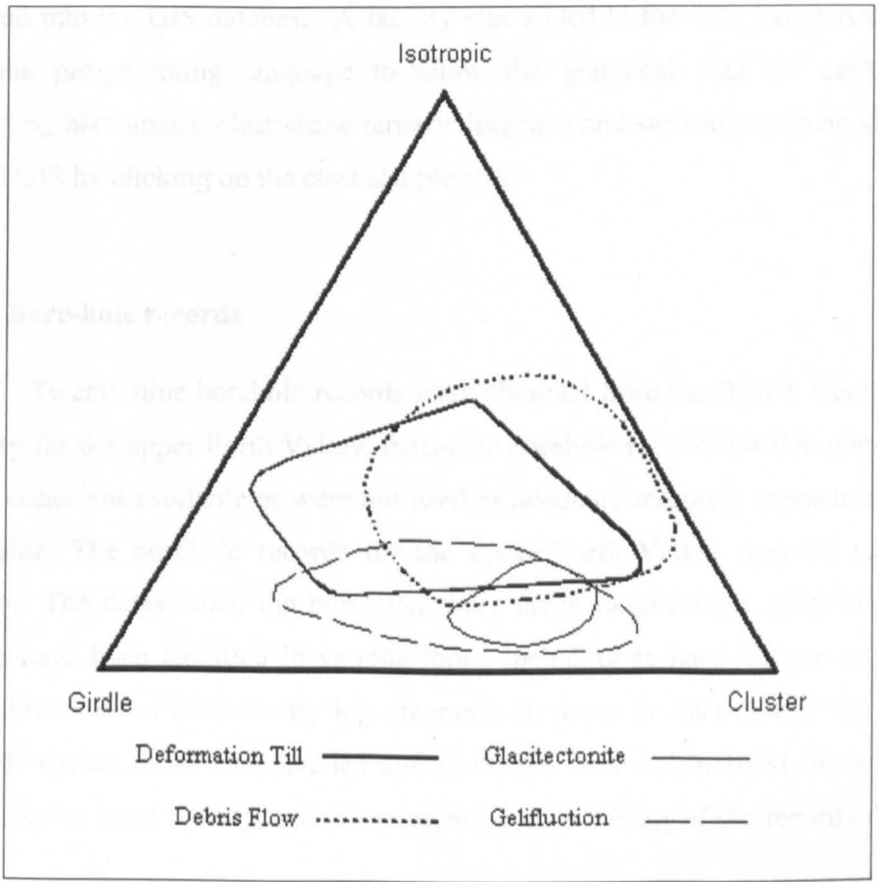


Figure 3.10 Clast fabric ternary diagram with envelopes enclosing likely areas of clast fabric shapes of sedimentary depositional environments (adapted from Benn 1994 Benn & Evans 1996)

Another problem, which can be seen on the ternary diagram (fig 3.10) is that the envelopes for particular sedimentary depositional environments significantly overlap, especially the envelopes for deformation till and debris flow. The problem of distinguishing deformation till from debris flow deposits has been noted by others such as Eyles et al (1988), Eyles & Kocsis (1988), Owen & Derbyshire (1989), Derbyshire & Owen (1990), Owen (1991), Ballantyne & Benn (1996). Deformation tills and debris flows can however often be differentiated by the orientation of clast fabrics (Benn & Ballantyne 1996). Deformation till fabrics tend to be orientated in the direction of ice-flow, usually down-valley, whereas debris flow fabrics are orientated downslope. Debris flows on valley sides therefore are usually not orientated down-valley.

At each sample site descriptions of the site and sediments were noted and the azimuth of the exposure measured. The location of each sample site was recorded using a Garmin hand held GPS. and later plotted onto the GIS for each field area. Numerical clast data such as eigenvalues, C40 and RA index was entered into the GIS database. A facility was added to the GIS, using ArcView Avenue programming language to allow the graphical data for each site, including histograms, clast shape ternary diagrams and stereoplots, to be viewed in the GIS by clicking on the clast sample site.

3.3.4 Bore-hole records

Twenty nine borehole records were obtained from the British Geological Survey for the upper Forth Valley. Adequate borehole records for the other sites were either not available or were not used as adequate sediment exposures were available. The borehole records for the upper Forth Valley were of varying quality. The dates when the boreholes were taken ranged from 1886 to 1986. These have been recorded in various forms including as hand written or typed descriptions or as sedimentary log diagrams on paper or microfiche. The older records tended to be less detailed and problems were encountered interpreting them due to hand writing, archaic terminology and fading of the records due to age. The more recent records included detailed descriptions and interpretations of the sediments and some information on faunal remains found in the sediments.

The borehole record details were noted and used to construct geological cross-profile diagrams and borehole diagrams. Sediment types were generalised to allow correlation of sediment units to construct the cross-profile diagrams. The original descriptions and interpretations from the borehole records are presented in Appendix 4. The location of each borehole was available as ordnance survey coordinates. These were used to plot the borehole locations in the GIS allowing them to be combined with maps of the geomorphology of the area.

3.4 Assessment of Methods

The GIS data for each field site included maps of glacial landforms, orthoimage mosaics, D.E.M.s represented by contours, hypsometric coloured terrain images and hillshaded D.E.M.s. The usefulness of this data was found to be variable depending on the nature of the terrain of the field study site. The terrain of sites varied from the open uplands of Torridon and Rannoch Moor to terrain that has been substantially modified by agriculture, forestry and human settlement, such as the upper Forth Valley and East Loch Lomond basin. In the Torridon study the three-dimensional orthoimages, created using ArcScene were found to provide useful insights into the spatial organisation and morphology of glacial landforms. This was also found to be the case for the Tyndrum site. Images created from the D.E.M. however rely on good quality D.E.M.s. As the D.E.M.s are extracted from aerial photography, using digital photogrammetry, the height of the surface does not necessarily record the height of the ground but the height of any feature in the photograph including forestry and buildings. This is not a major problem where there are few buildings and trees. Heights can be adjusted manually in the D.E.M. using the photogrammetric software. This however is very time consuming especially for field sites where much of the area is covered by forestry or settlements. Also when the height is edited for features covering large areas, such as commercial forestry this does not reveal the true surface of the land below the trees but merely smoothes the D.E.M. to represent an average height of the land surface below the tree cover. This height correction is useful for creating generalised contours as found on topographic maps but would not improve the quality of the D.E.M. with respect to the identification of landforms. It is therefore not possible to identify landforms below commercial forest plantations using digital photogrammetry. It may be possible to create D.E.M.s of the land surface below some forestry using land survey methods, such as the use of total station surveying. This however would not be practical in dense commercial forest.

The use of the D.E.M.s for interpreting glacial geomorphology was therefore found useful for field sites with little forestry, at the time the aerial photographs were taken. However, problems were encountered in the Upper Forth Valley field site where much of the land is forest covered, including forest cover on glacial landforms. The larger glacial landforms however were visible on the orthoimage and the orthoimage was used to map these features. The D.E.M. of the upper Forth Valley was not used for interpretation due to its poor quality. The D.E.M. however was useful as it is necessary to produce a D.E.M. for orthoimage production. It was not thought possible to overcome this problem using photogrammetric or land survey methods, however it may be possible to use D.E.M.s produced by other methods to study areas with dense tree cover. Lidar or aerial laser scanning has the ability to scan the land surface below tree cover and would therefore create more appropriate terrain models to study landforms with dense tree cover (Lillesand & Keifer 1994). This is however beyond the scope and budget of this project. The quality of D.E.M.s, produced by digital photogrammetry, is also affected by the quality of the aerial photographs. Aerial photographs for some areas, especially the East Loch Lomond field site, were of poor quality, possibly due to poor handling and storage of the photographs or due to poor reproduction.

The D.E.M.s and especially the three dimensional images produced by draping an orthoimage on a D.E.M. were found to be particularly useful. The three dimensional orthoimages, produced using ArcScene, can be rotated, tilted and scaled to view any feature from any angle and scale, allowing the image to be moved to the ideal position to view the geomorphology. For location with adequate quality D.E.M.s, this gave insights into the morphology of features that would be difficult to achieve using conventional stereoscope viewing of aerial photographs. Where D.E.M. quality was poor the methods failed to provide a more detailed study of the morphology of landforms than could be achieved by conventional field mapping and aerial photograph interpretation. Comparisons between the different methods of employing the D.E.M.s orthophotos and maps are given in the relevant field site chapters (chapters 4 to 8)

Clast analysis was found to be of limited use for the Rannoch Moor and upper Forth Valley field areas. Exposures are rare and/or inadequate at these sites. Clast analysis did however provide useful data to supplement the mapping and morphological analysis at the Torridon and Tyndrum sites. Clast shape and fabric characteristics were often found to be ambiguous, with more than one possible interpretation of the data. However, clast data was generally found to be useful when combined with geomorphological investigations. This emphasises the need to combine clast analysis data with other evidence to interpret the origin of landforms. The borehole records for the upper Forth Valley provided useful information for the interpretation of landforms and extent of glacier ice in this area.

Although only limited GIS analysis was carried out the GIS was found to be a very useful tool to correlate data from various sources including sedimentological data, maps of the geomorphology, orthoimages, terrestrial photographs and relief visualisation data and therefore aided landform interpretation. GIS functions for the processing and visualisation of the digital elevation models, such as hillshading and contouring, was found useful, but the quality of images varied depending on conditions for each site including the quality of available aerial photographs, local topography and the amount of tree and building cover.

4

Torridon

4.1 Introduction

4.1.1 Location

Glen Torridon is situated in the north-west Highlands, to the east of Loch Torridon and Torridon village, and has an east to west orientation. Two large mountains, Liathach (1,054m) and Beinn Eighe (1,010m), dominate the north side of the valley. The south side of Glen Torridon is flanked by a smaller hill, Seana Mheallan (437m) and the Coire a' Cheud Chnoic. Srath nam Poll Dubh, a valley to the south of Seanna Mheallan, is also included in the study site. Srath nam Poll Dubh runs east to west parallel to the main Glen Torridon, to the south-west of Lochan Neimhe. Figure 4.1 shows the location of the study site. The field site studied in the Torridon area includes the Coire a' Cheud Chnoic (corrie of a hundred hills) (see fig 4.2) and the western part of Glen Torridon from Lochan an Iasgair in the east, to the head of Upper Loch Torridon in the west. This site, especially the Coire a' Cheud Chnoic, has been the site of many previous studies of glacial landforms particularly the "hummocky moraine". Various interpretations of moraine genesis have been proposed for this site. and it is therefore a highly significant location for the study of moraines of the Loch Lomond Stadial.

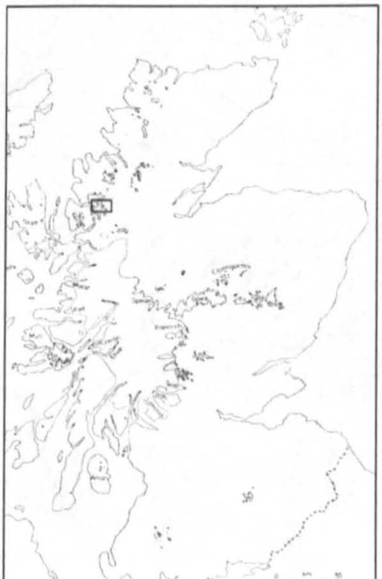


Figure 4.1 Location of the Torridon study area and the Loch Lomond Readvance limit (adapted from Sissons 1976)

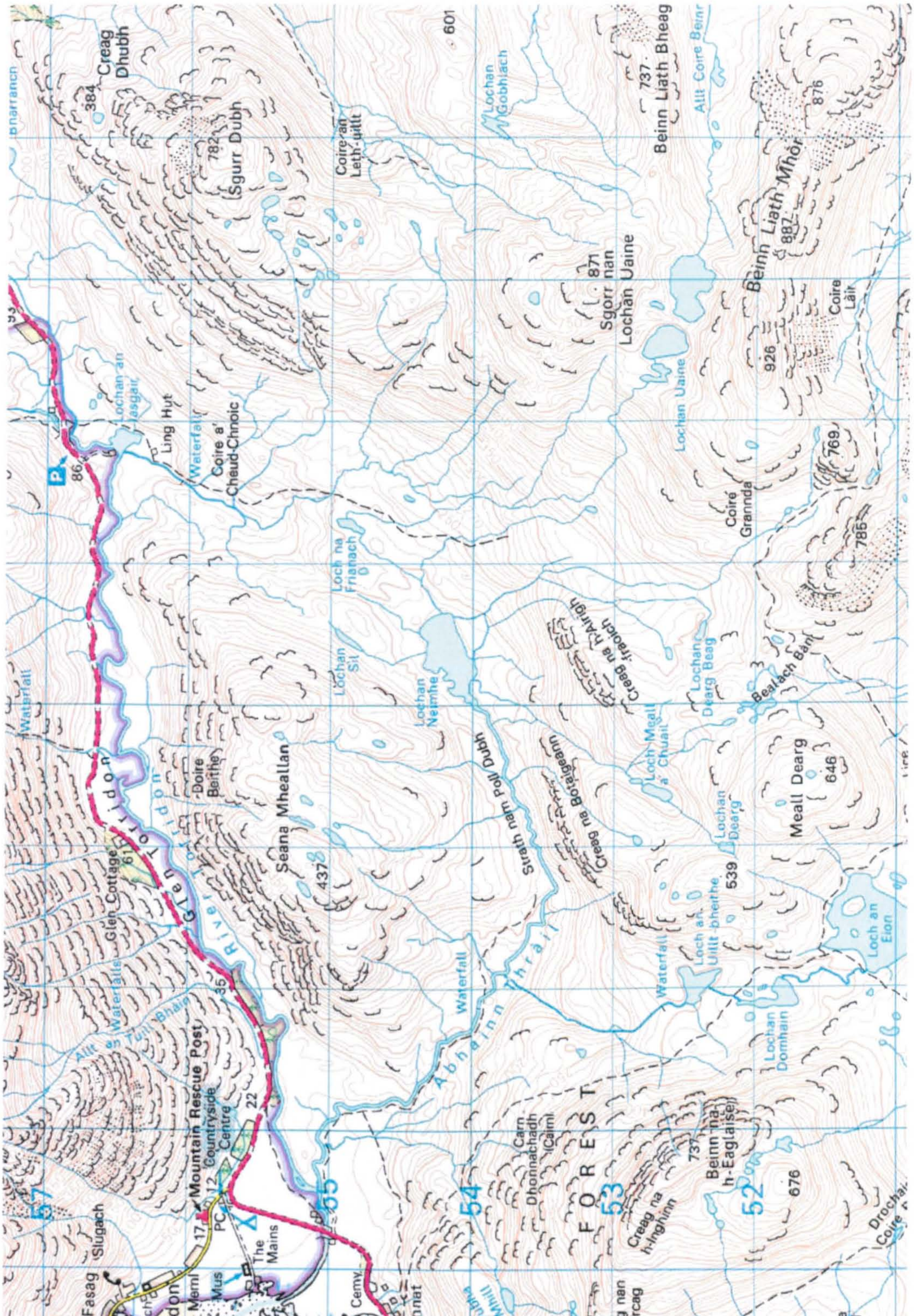


Figure 4.2 Extract from Ordnance Survey Landranger map, Torridon (crown copyright Ordnance Survey)

4.1.2 Geology

The field site lies approximately 5km to the west of the Moine Thrust. The bedrock within the mapped area is mainly Torridonian sandstone. The higher ground surrounding the field area includes areas of quartzite including Sgurr Dubh, Sgorr nan Lochan Uaine and the upper slopes of Coire a' Cheud Chnoic in the east, Meall Dearg and around Lochan Dearg in the south and the summit of Beinn Eighe and Coire an Laoigh on the north side of Glen Torridon. There is also quartzite bedrock on Seana Mheallan. The Torridonian sandstone on the lower slopes and in the valleys of Coire a' Cheud Chnoic, Srath nam Poll Dubh and Glen Torridon are overlain by glacial sediments and landforms. Torridonian sandstone bedrock is generally exposed on the steeper upper slopes of the area, with no overlying Quaternary sediments. Bedrock to the east of the Moine Thrust is predominantly Schist.

4.1.3 Geomorphology

The main site investigated in the Torridon area in this study was the Coire a' Cheud Chnoic (Corrie of a hundred hills), Glen Torridon. The glacier in the coire was probably a small valley glacier rather than a corrie glacier. The geomorphology of the coire is dominated by features traditionally described as hummocky moraine. Viewed from the main part of Glen Torridon the hummocks have the appearance of conical mounds approximately 8m high with a chaotic spatial pattern. The hummocks are often viewed from the viewpoint in the car park, which is in the main part of Glen Torridon opposite the Coire a' Cheud Chnoic (fig 4.3).

Figure 4.3 View of Coire a' Cheud Chnoic from Glen Torridon

Lineations in the hummocky moraine of the Coire a'Cheud Cnioc have been interpreted as being formed in various ways including aerial stagnation, incremental stagnation, marginal push and dump moraines, controlled moraines, shear moraines, and as flutings produced by the streamlining of pre-existing glacigenic sediment.

Early interpretations of Loch Lomond Stadial hummocky moraine (e.g. Charlesworth 1955) attributed them to the active retreat of Loch Lomond Stadial glaciers into their parent corries. However they were later reinterpreted as products of aerial stagnation (Sissons 1965, 1974, 1977, 1979) due to rapid climate amelioration at the end of the Loch Lomond Stadial. This was based on the apparent lack of spatial organisation, and thought therefore to have been produced by the meltout of stagnant ice. Active retreating ice would be expected to produce recognisable lineations or transverse ridges representing successive receding glacier margins.

The chaotic nature of hummocky moraine at various sites in the Scottish West Highlands has been questioned since the identification of cross-valley and down-valley linear spatial patterns. The Coire a' Cheud Chnoic has been the subject of various studies of the spatial pattern of hummocky moraine. Bennett and Boulton (1993) described the moraines as displaying a two fold spatial pattern including cross-valley concentric ridges or chains of ridges and a second pattern of down-valley radial ridges. The cross-valley ridges were interpreted as push and dump moraines deposited during active glacier retreat.

The hummocky moraine of the Coire a' Cheud Chnoic has also been explained as the product of incremental stagnation during active glacier recession by Eyles (1983). According to this theory, melting at the margin exposes englacial material, which insulates the glacier, resulting in slow downwasting at the margin. The cleaner ice up-glacier recedes and the glacier becomes decoupled from the debris covered margin. As englacial material is again exposed the process is repeated. This results in cross-valley moraines with a discontinuous, hummocky appearance. Cross-valley lineations are attributed to bulldozing of the moraines during minor readvances. The moraines deposited at the glacier margin would have been ice cored, with the slow melting of the ice-cores resulting in an apparent chaotic, discontinuous appearance. According to Eyles some of the original cross-valley pattern of moraines is preserved, despite the chaotic appearance from the ground.

Hodgson (1982, 1986, 1987) interpreted glacigenic features aligned in the direction of ice flow in Coire a' Cheud Chnoic as being produced subglacially as flutings. The hummocky moraine in the coire is interpreted as mainly showing a down-valley orientation, and has a streamlined appearance, especially when viewed from aerial photographs. The orientations of the flutings are used by Hodgson as indicators of ice flow during the Loch Lomond Stadial. The flutings include smaller scale features of less than 1m in height and 10 to 20m in length, however larger flutings are more common with heights of up to 6m and single ridges can be traced for up to 500m.

The moraines of the Coire a' Cheud Chnoic have also been interpreted by Bennett et al (1998) and Hambrey et al (1997) as due to thrusting within the glacier. Thrusts are thought to develop with glacier ice due to compression at the margin of polythermal glaciers. Debris is moved from the base of the glacier along shear planes and is deposited on the glacier surface by meltout at the glacier margin. This debris is subsequently lowered into the substrate producing moraines. These cross-valley linear moraines however will be ice-cored and the linear morphology would therefore be subject to alteration during melting of the ice cores, leaving moraines with a hummocky appearance and possibly some remnants of the cross-valley linear pattern (see chapter 2 section 3).

This location has been used by various workers as an example of how landforms traditionally interpreted as 'hummocky moraine' is formed. The various mechanisms suggested for the production of hummocky moraine have very different implications for the use of these landforms for palaeo-climatic reconstruction. It can be seen that interpretation of the morphology and spatial organisation of landforms is critical to previously published theories on the mechanisms of production of the hummocky topography in the Torridon area, and especially Coire a' Cheud Chnioc. This study will assess these theories by using digital photogrammetry and G.I.S. to create maps and three dimensional models of landforms, allowing insights into the morphology and spatial organisation of these landforms not previously available.

4.2 Methods

4.2.1 Geomorphology

The glacial geomorphology of the Torridon area was mapped using digital photogrammetry and G.I.S. Three aerial photographs, arranged in one strip, were required to give stereo coverage for the western part of Glen Torridon and Coire a'Cheud Chnoic. A network of control points needed for the photogrammetric process was measured using differential G.P.S. A suitable point for the reference station was found on the edge of a car park in Glen Torridon, opposite the Coire a' Cheud Chnoic.

An adequate number of GPS control points was measured (fig 4.4). This included three points per photograph, resulting in six points in the overlapping area or each stereo photograph pair. Some extra points were also measured, as some of the features used may be difficult to recognise in the aerial photograph. Difficulties were found in finding and measuring suitable control points as the area has relatively few features distinctive enough to be accurately located on the aerial photographs. Most of the control points consisted of large boulders, which were visible on the aerial photographs. A similar technique has been used to photogrammetrically map glacier margins in Iceland, and was found to be satisfactory (D. Twigg pers. comm.)

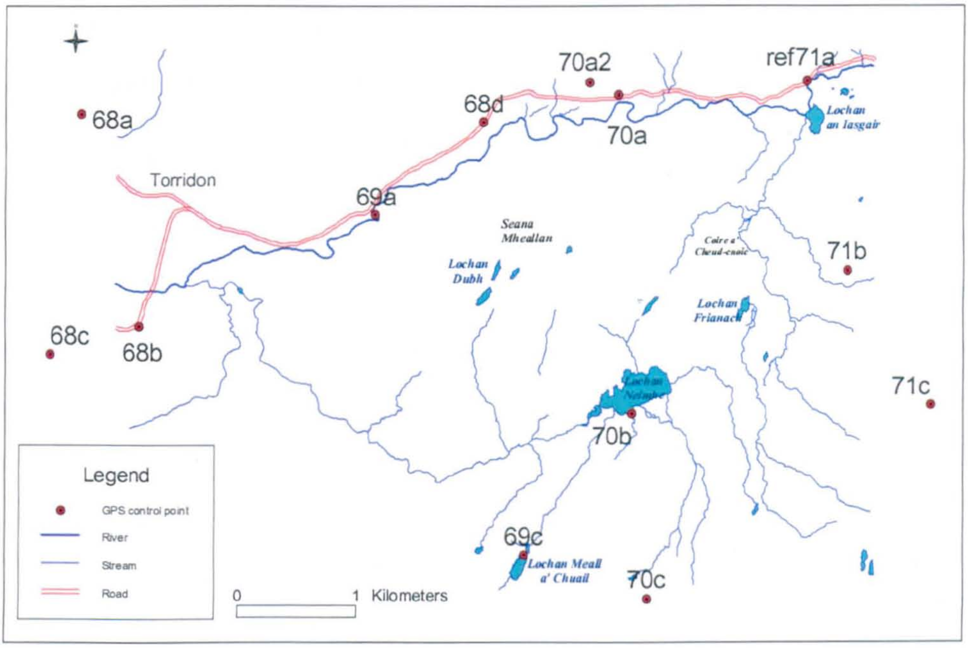


Figure 4.4 Torridon GPS control points

A digital elevation model and orthophoto mosaic were produced for the area of the aerial photographs with stereo coverage. Glacigenic ridges in the Torridon area were mapped using line symbols to represent the features crests. Closed shape symbols (polygons in GIS terminology) could have been employed by digitising the outlines of the features, however the landforms are small and numerous, with some merging features. Digitising the outline of these features would therefore be problematic as it would be difficult to define their extent. Plotting the features using line symbols gave good representations of the length, position and orientation of features. It was therefore decided that mapping the features as linear ridges was more accurate and more appropriate to this study. Larger moraines, located near the head of Upper Loch Torridon were mapped as enclosed polygons. This work was carried out using the photogrammetric software, Helava Leica Socet Set, which has the facility of on-screen three-dimensional viewing of orthophotos combined with digital elevation models.

The mapping, digital elevation model and orthophoto were transferred to the GIS (ArcView), for further processing and interpretation. Three dimensional digital techniques within the GIS software were employed to visualise the digital elevation model and interpret the glacial landforms. This work was carried out within the ArcView GIS system including the 3D Analyst extension. Various techniques of three-dimensional visualisation were experimented with, including hillshading, contouring (including the use of hypsometric colours to represent height), creating aspect maps and draping the orthophoto over a digital elevation model. Two digital elevation models were produced for this work including a 5m resolution model for the whole of the site and a 1m resolution model for part of the Coire a' Cheud Chnoic to allow a more detailed study of the geomorphology of that area. A 1m resolution digital elevation model could have been produced for the whole study area, however it was found that this created a very large file and was not practical to use due being too slow to process or navigate in the GIS.

The three-dimensional images below (figs 4.6 to 4.16) depict the eastern part of the Coire a. Cheud Chnioc. These were created from the 1m resolution D.E.M. The location and extent of the 1m resolution D.E.M. can be seen in figure 4.5. This will also give an approximate scale of the three-dimensional images. The scale of the three-dimensional images is not constant.

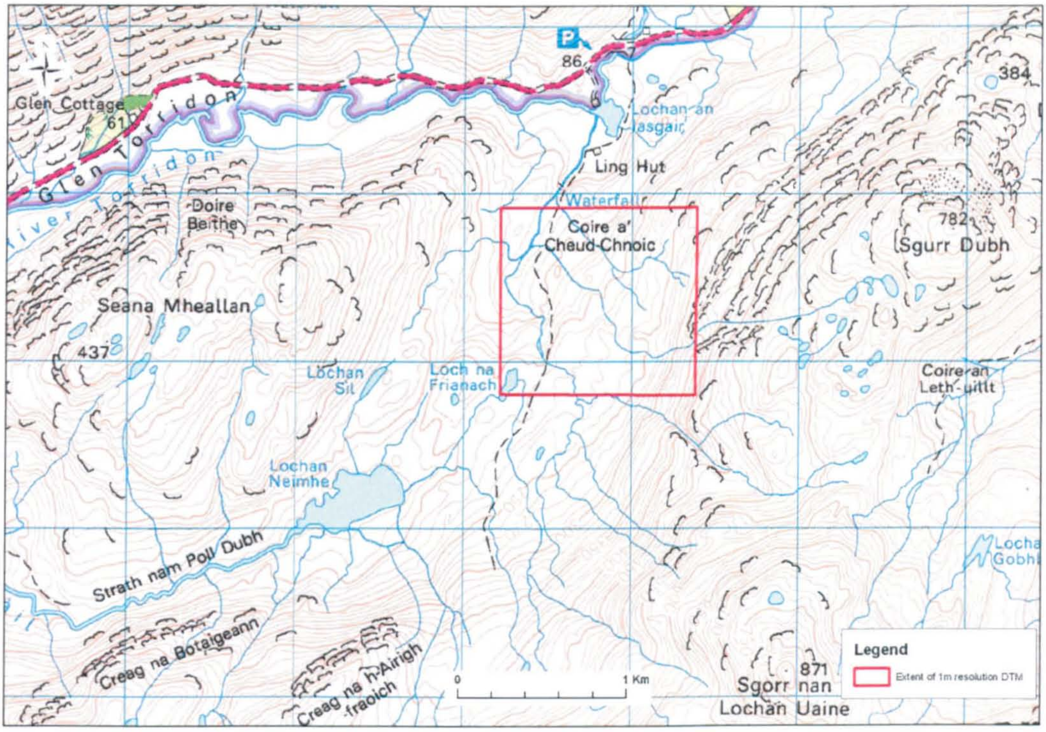


Figure 4.5 Extent of 1m resolution D.E.M. , Coire a'Cheud Chnoic

Contours with an interval of 5m were created from the D.E.M. and can be seen overlaid with the mapped crests of glacigenic ridges (red lines) in figure 4.6.

It can be seen from the 3D image (fig 4.6) that the contours do not show the pattern of landforms as mapped from the orthophoto. This can be viewed more clearly in the orthophoto, draped over the D.E.M. (fig 4.7). The ridges can be clearly seen in the orthophoto with the contours giving no indication of the pattern of the geomorphology.

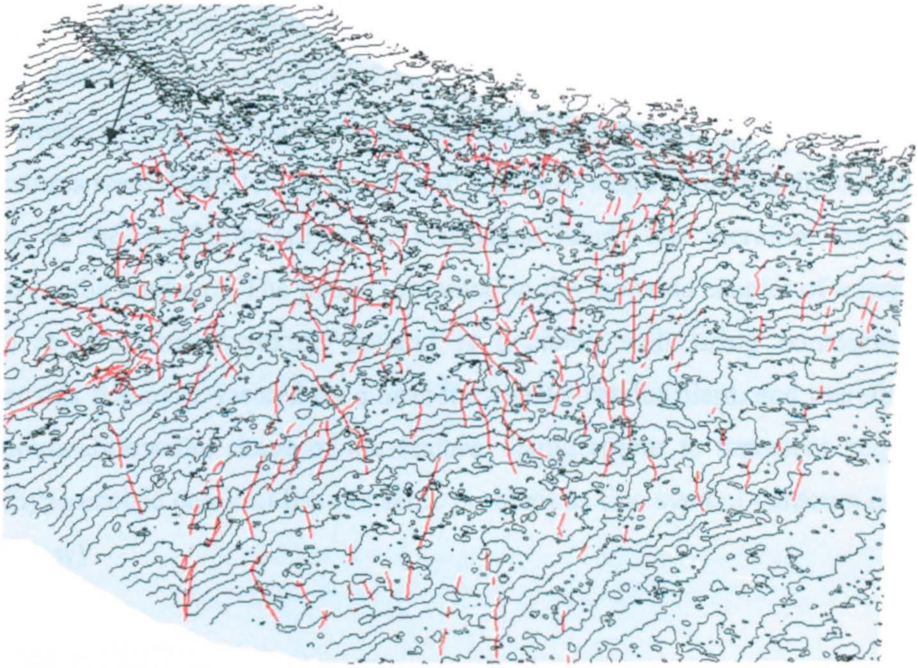


Figure 4.6 Coire a' Cheud Chnoic, north-east, with 5m contours and mapped crests of glacial landforms

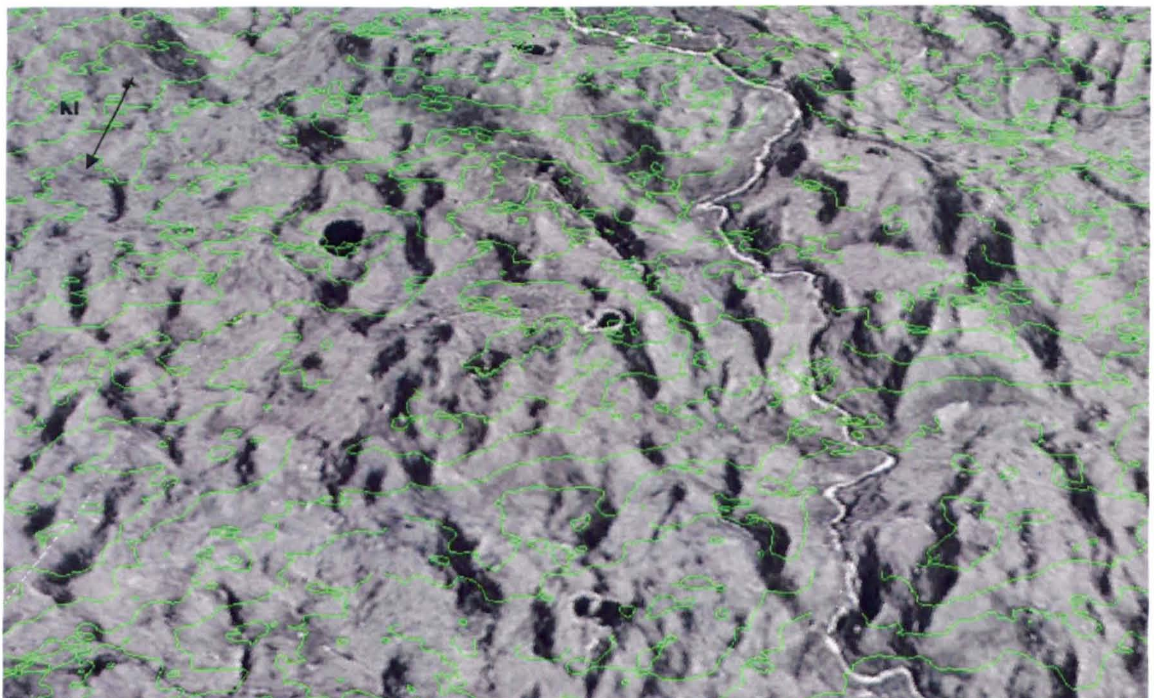


Figure 4.7 3D image showing orthophoto and 5m contours, Coire a'Cheud Chnoic.

The contours can clearly be seen on this image crossing the ridges. This is due to the contours joining points of equal height above datum and do not pick out the breaks of slope of landforms as the landforms are not on a flat plane. As these features were deposited on a slope the breaks of slope including the outline and crest of the landforms are not at a constant height and therefore are not followed by the contours. The image presented in the methods chapter of a large moraine at Breiðamerkurjökull, Iceland is depicted well using contouring. However this feature is located on a near flat coastal sandur plain, and therefore the contours follow the shape of the feature. Using colour to represent height values (hypsometric colours) has the same problem as line symbol contours (see fig 4.8 below)

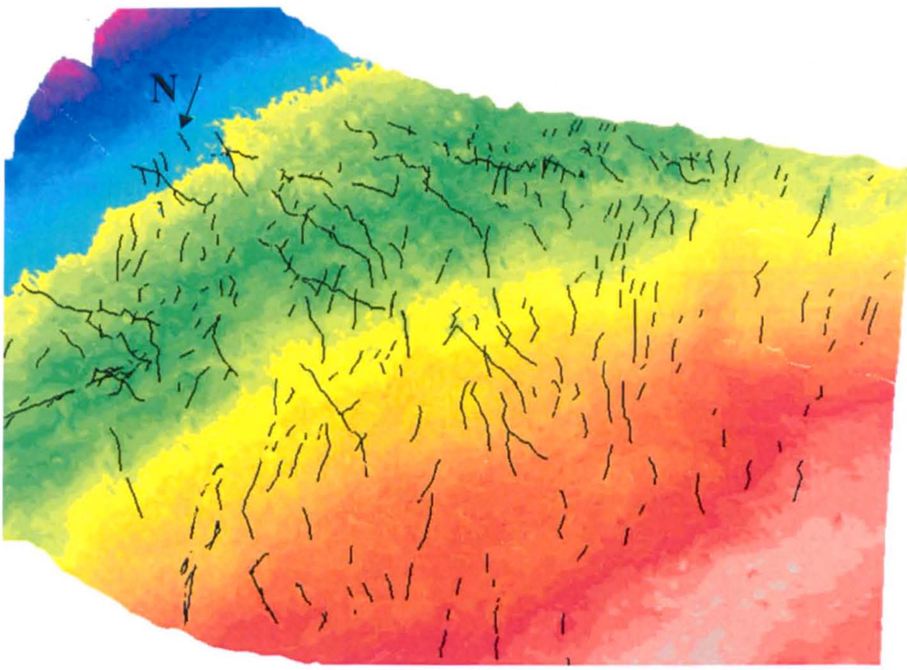


Figure 4.8 Hypsometric colour map, Coire a' Cheud Chnoic.

Patterns of landforms were however visible on the D.E.M. using hillshading techniques. This method of landform visualisation was used by Clark & Meehan (2001) to identify subglacial landforms in Ireland. Shading the D.E.M. in the GIS allows manipulation of the D.E.M. by changing the angle and azimuth of the light source. Although different patterns of landforms can be recognised by changing the azimuth of the light source the images produced have to be interpreted with some caution as the direction of the light source can introduce a bias into the image. The most reliable method of shading D.E.M.s is therefore with the light source set to directly above the image. This is achieved by setting the light source angle to 90 degrees (C. Clark pers. comm.).

The images below (figs 4.10 to 4.14) show the D.E.M. shaded with varying light source azimuth. Figure 4.9 shows the glacigenic ridges mapped in 3d using the photogrammetric software as a comparison. Although it is difficult to recognise individual landforms the shaded D.E.M. allows some interpretation of the geomorphology with the pattern of landforms appearing as a grain rather than clearly defined landforms. This can be compared to work by Boulton & Clark (1990) and Clark (1997) who describe larger scale landforms such as drumlins and megaflutings as appearing on satellite images as a grain. The grain in these images was successfully used to infer paeleo-iceflow directions of large ice-sheets by Boulton & Clark (1990) and Clark (1997). The use of lower resolution satellite images to detect larger scale landforms is comparable to this study which uses higher resolution D.E.M. derived images to detect smaller scale features.

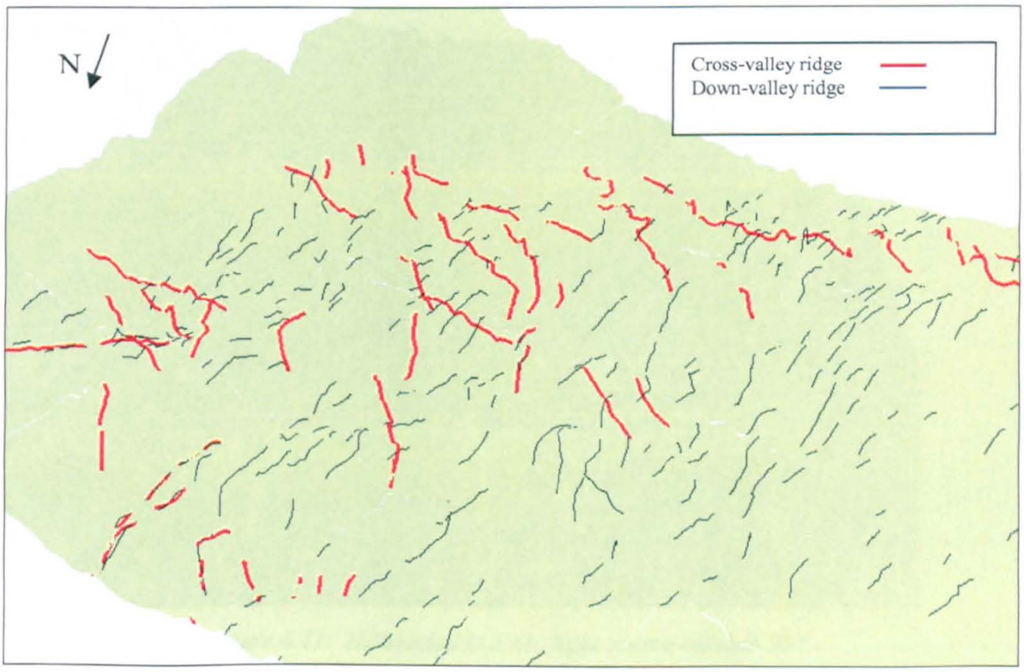


Figure 4.9 Down-valley and cross-valley orientated glacigenic ridges.

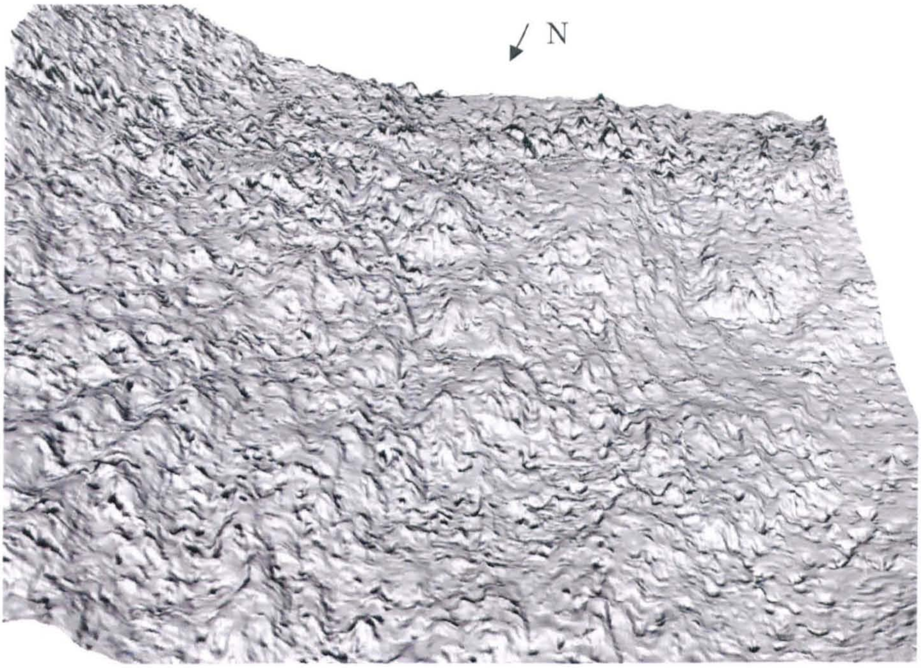


Figure 4.10 Hillshaded D.E.M., light source azimuth 0°

Figure 4.11 Hillshaded D.E.M., light source azimuth 90 °

Figure 4.12 Hillshaded D.E.M., light source azimuth 180 °

Figure 4.13 Hillshaded D.E.M., light source azimuth 270 °

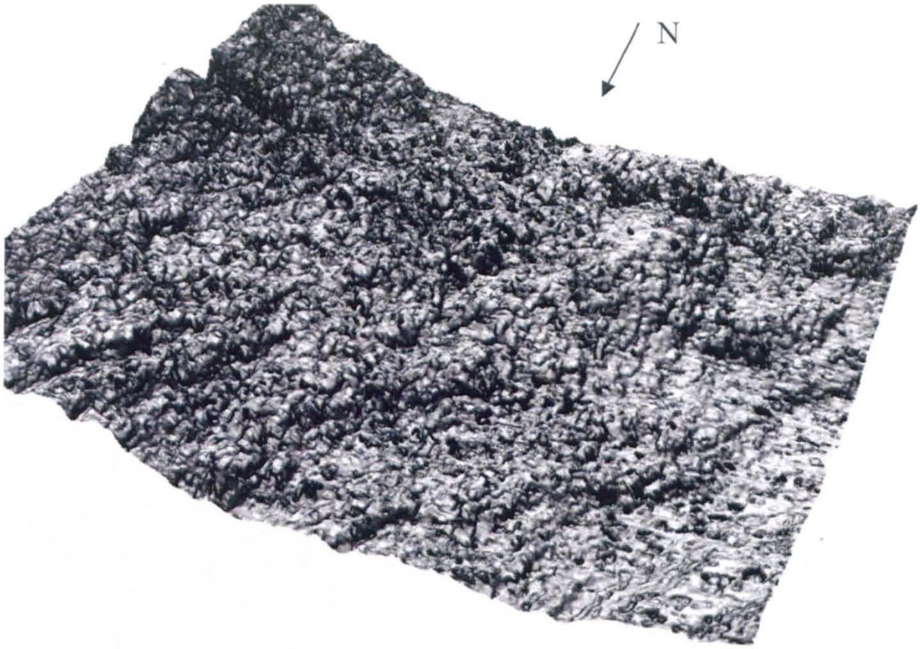


Figure 4.14 Hillshaded D.E.M., unbiased

Although grains in these images show some linear pattern of landforms the pattern and morphology of features is not clear. This may be due to the small scale of the landforms at this location and the fact that the D.E.M.s do not include any information on breaks on slope. A D.E.M. produced by field survey can include points at the breaks of slope, however field surveys are very time consuming and therefore it would only be practical to survey a small sample area. D.E.M.s produced by photogrammetry have the advantage of allowing larger areas to be surveyed relatively quickly.

Another technique of visualisation of the digital elevation model, creating an aspect map was also experimented with (fig 4.15). This gave better results than the above methods but it is still difficult to recognise the morphology of landforms. The image did however reveal lineations in the landform pattern and allows the recognition of two spatial patterns of landforms, one down-valley and one cross-valley, similar to the pattern picked out by the three dimensional mapping using the photogrammetric software. The morphology of the larger cross-valley features can be recognised quite easily in this image (coloured blue). The smaller down-valley features can be seen superimposed on the cross-valley features (coloured red). However the morphology of the smaller features is not visible.

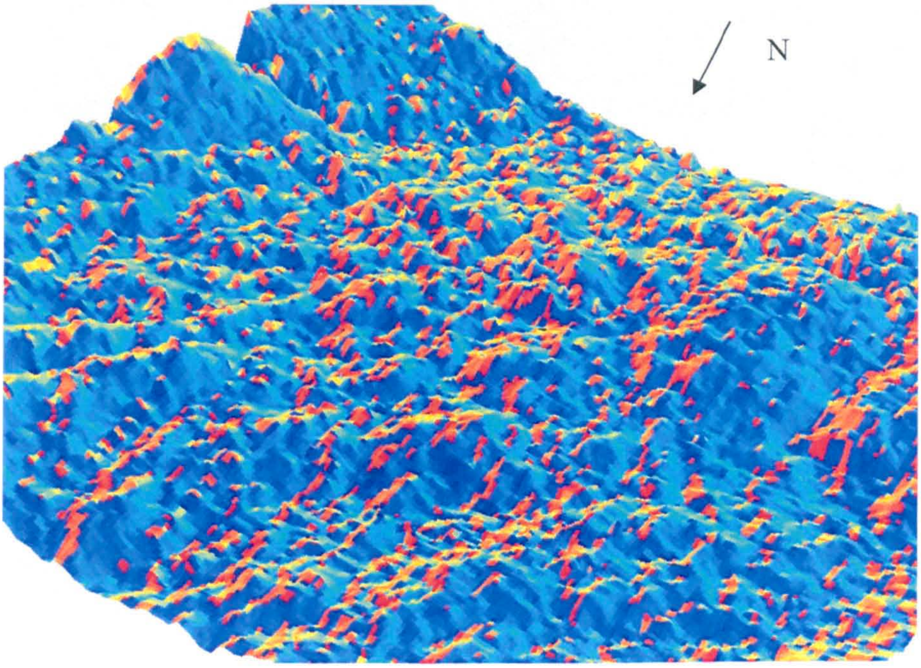


Figure 4.15 Aspect map, Coire a'Cheud Chnioc

Key (azimuth in degress)

0 - 20	
20.00000001 - 40	
40.00000001 - 60	200.0000001 - 220
60.00000001 - 80	220.0000001 - 240
80.00000001 - 100	240.0000001 - 260
100.0000001 - 120	260.0000001 - 280
120.0000001 - 140	280.0000001 - 300
140.0000001 - 160	300.0000001 - 320
160.0000001 - 180	320.0000001 - 340
180.0000001 - 200	340.0000001 - 360

The morphology of the landforms of the Coire a' Cheud Chnoic can however be seen more clearly on the orthoimage draped on the D.E.M. (fig 4.16) This has the advantage of combining 3D visualisation with an image of the geomorphology as depicted on the aerial photograph. This can be seen as a combination of digital 3D visualisation techniques with traditional landform interpretation from aerial photographs. As this technique gave the best results the images presented and discussed for this site were produced by this method.

Figure 4.16 Orthophoto draped over D.E.M.

4.2.2 Sedimentology

Sedimentological data collection was carried out at this site including clast fabric and shape analysis. Notes were also recorded on the lithology of clasts in order to ascertain if the material in the hummocky moraine consists of schists and quartzite brought into the area during pre-Loch Lomond Stadial glaciations, as proposed by Hodgson (1982, 1986, 1987). Stratigraphic studies of the sediments were found to be problematic due to a lack of adequate exposures, however exposures were large enough for clast fabric and shape data to be collected. Figure 4.17 shows the locations of clast sample sites studied in the Coire a' Cheud Chnoic and Glen Torridon.

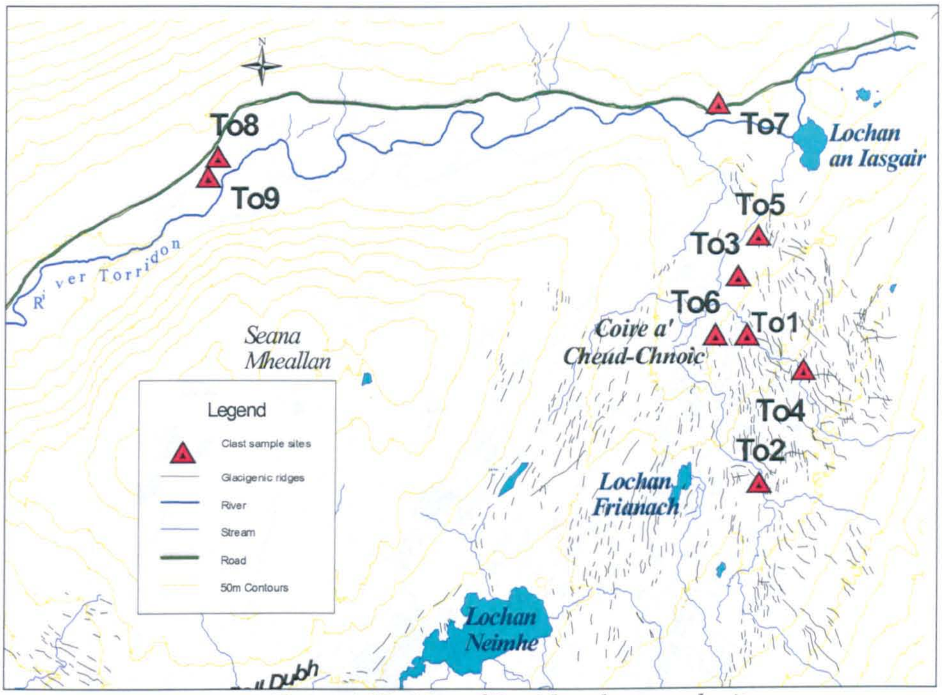


Figure 4.17 Map of Torridon clast sample sites

4.3 Results and interpretation

4.3.1 Geomorphology

Glacigenic ridges in the Coire a' Cheud Chnoic show both cross-valley and down-valley orientated spatial patterns. The more numerous down-valley orientated features are subparallel and extend further up valley than the cross-valley features (figs 4.18, 4.19). The down-valley valley orientated, features are narrow and sharp crested. They have consistent orientations with shorter ridges forming chains, which are interpreted as being formed as longer ridges. These characteristics are typical of flutings (Boulton 1976, Rose 1989, Gordon et.al. 1992). The down-valley orientated landforms in Coire a'Cheud Chnioc have previously been interpreted as flutings (Hodgson 1986, 1987). The orientation of the flutings is thought to reflect ice flow direction during the Loch Lomond Stadial. Similar features were also mapped in the north side of Glen Torridon, on the slopes of Beinn Eighe, and in Srath nam Poll Dubh, to the south of Seana Mheallan. The consistent orientation of the flutings suggest they were produced by ice flowing in one direction. No evidence of cross-cutting fluting was found. The overriding is therefore likely to have occurred as one event.

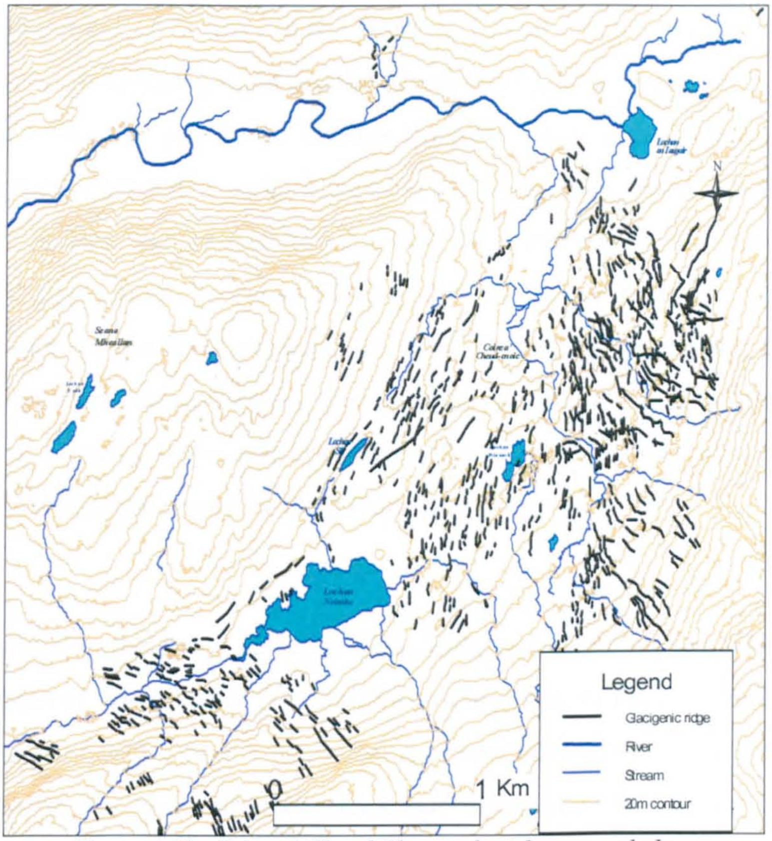


Figure 4.18 Coire a' Cheud Chnoic glacial geomorphology

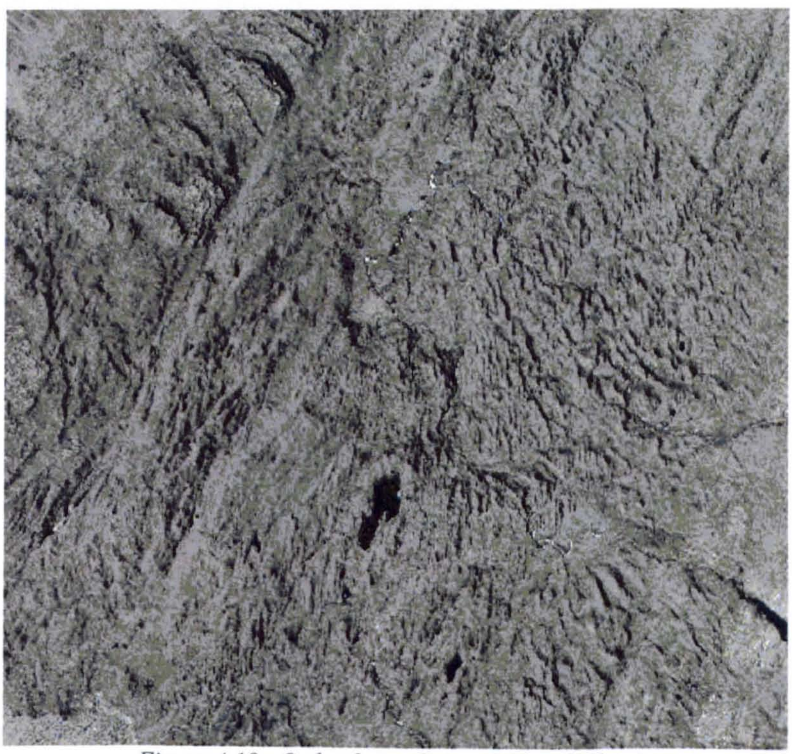


Figure 4.19 Orthophoto, Coire a' Cheud Chnoic

The pattern of flutings in the Coire a' Cheud Chnoic is indicative of ice flowing from the higher ground around Meall Dearg, Coire Lair and Beinn Laith Mhor (fig 4.18). The pattern of flutings suggests ice diverged round the higher ground of Seana Mheallan with ice flowing north into the Coire a' Cheud Chnoic and Glen Torridon and ice also flowing west along Srath nam Poll Dubh towards the head of Upper Loch Torridon. Flutings can also be traced on the north side of Glen Torridon on the south-western slopes of Beinn Eighe, trending south-west along the northern slopes of Glen Torridon, suggesting the glacier issuing from the Coire a' Cheud Chnoic was confluent with another glacier flowing from the slopes of Beinn Eighe, possibly from Coire an Laoigh.

As well as the down-valley orientated flutings there is a second cross-valley pattern of ridges (fig 4.21) The cross valley chains of ridges are found in the lower part of the Coire a' Cheud Chnoic. Especially when viewed in 3d the flutings can be seen as continuous ridges superimposed on the cross-valley orientated features (fig 4.22). This morphology of cross-valley, discontinuous ridges with smaller superimposed ridges suggests that the underlying cross-valley ridges are older than the smaller overlying ridges. Patterns of glacial landforms with differing orientations have previously been relatively dated using aerial photographs and stereo viewing to determine the relationship and relative age of two or more orientations of landforms (Clark 1997). The relative age of these features suggested by their morphology is consistent with Hodgson's interpretation of the down-valley ridges as flutings.

Figure 4.20 Aerial photograph stereo pair of flutings and moraines, Coire a' Cheud Chnoic

The cross-valley chains of ridges are therefore interpreted as a series of recessional moraines pre-dating the production of the flutings. As these pre-date the flutings they can be relatively dated as either early Loch Lomond Stadial or Late Devensian (Dimlington Stadial) in age. The cross-valley orientation can be seen on aerial photographs although the moraines have been substantially dissected and fluted. Figure 4.21 shows cross-valley moraines in the Coire a'Cheud Chnoic, which have been overridden by glacier ice, and their surface remoulded into flutings and partially dissected. Dissection most likely took place during final ice wastage. The images were extracted from a three-dimensional image of the field site created by draping an orthoimage over a 5m resolution D.E.M.. For the location of these images see fig 4.5. Due to the reworked nature of the cross-valley moraines there is little evidence to allow interpretation of their mechanisms of deposition.

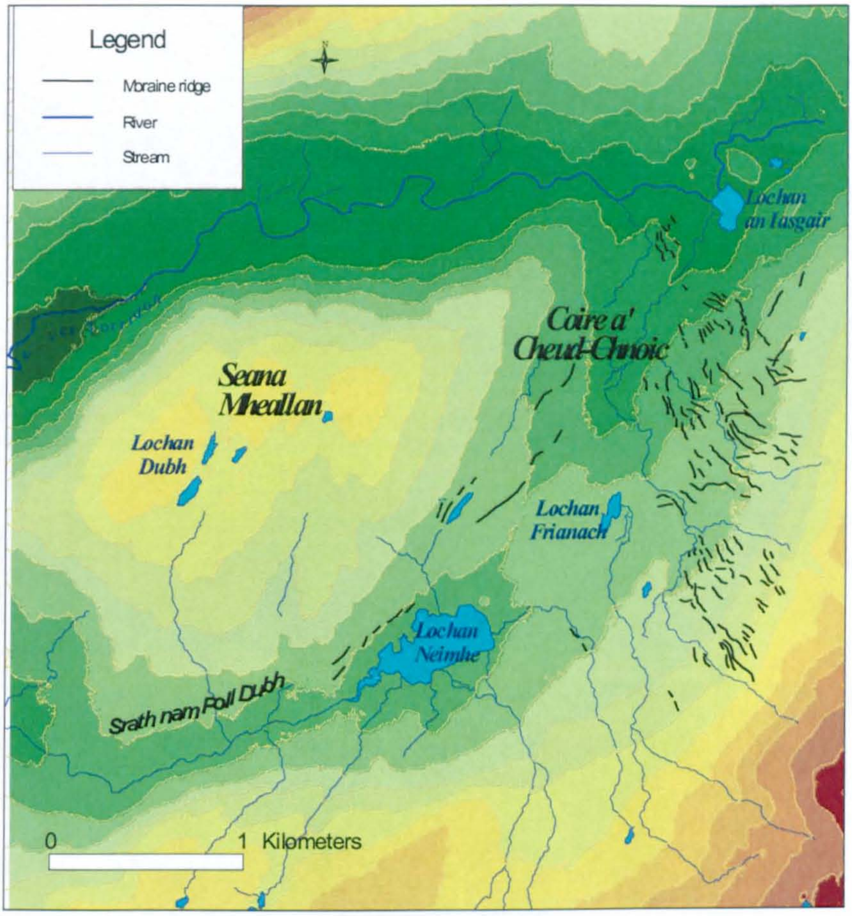
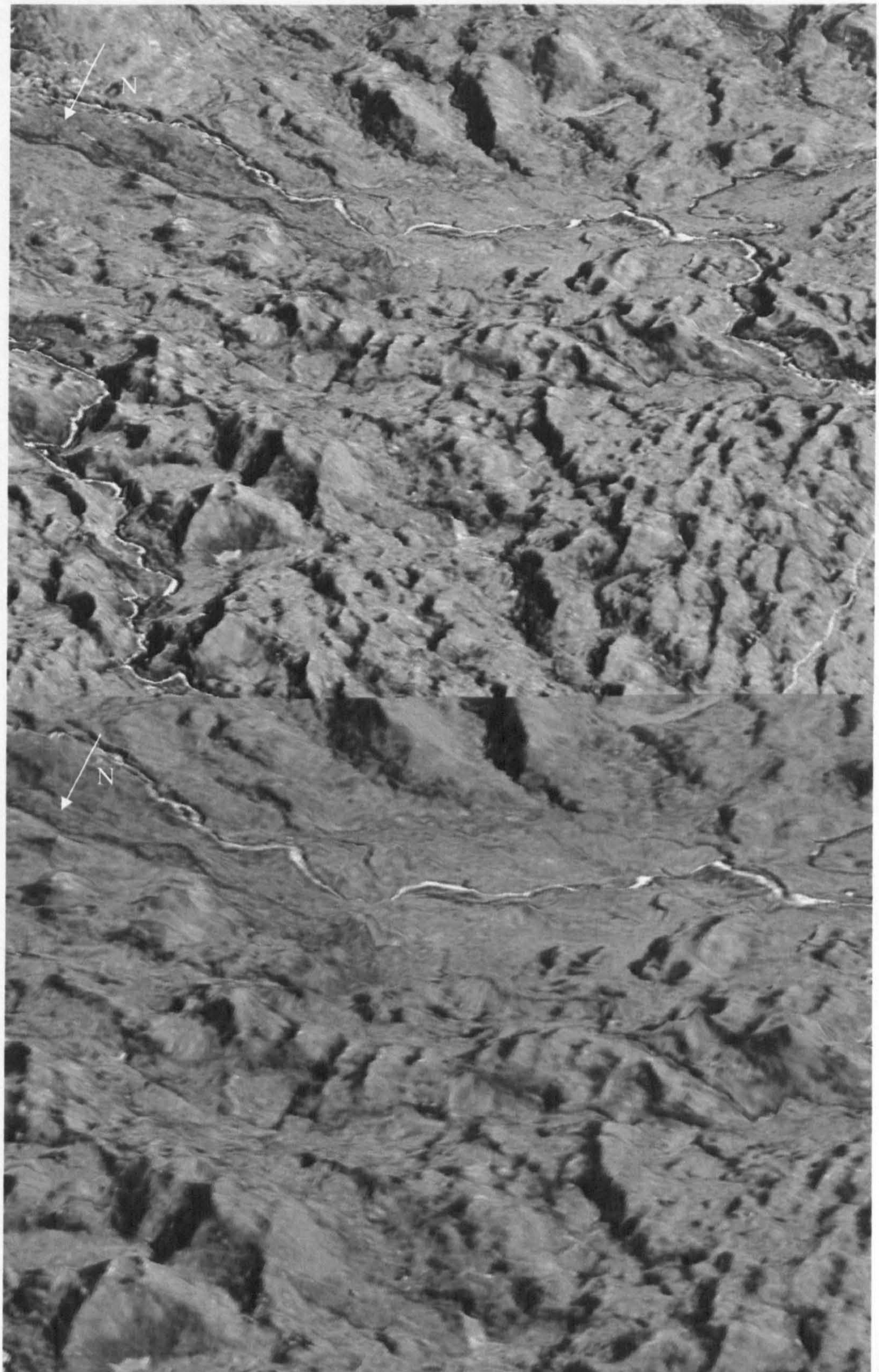


Figure 4.21 Map of Coire a'Cheud Chnoic cross-valley orientated moraines

Hodgson (1982, 1986, 1987) suggests that the sediments from which the flutings are constructed is at least in part older than the Loch Lomond Stadial. According to Hodgson the flutings consist of an upper and lower till, with the widespread occurrence of erratic clast lithologies in the lower till being interpreted as products of the Late Devensian ice sheet. Hodgson suggests that this was reworked into flutings. If the cross-valley moraines have been overridden, as the evidence suggests, it is possible that landforms deposited by the late Devensian ice sheet have survived in addition to the sediments of Devensian age.


N
N

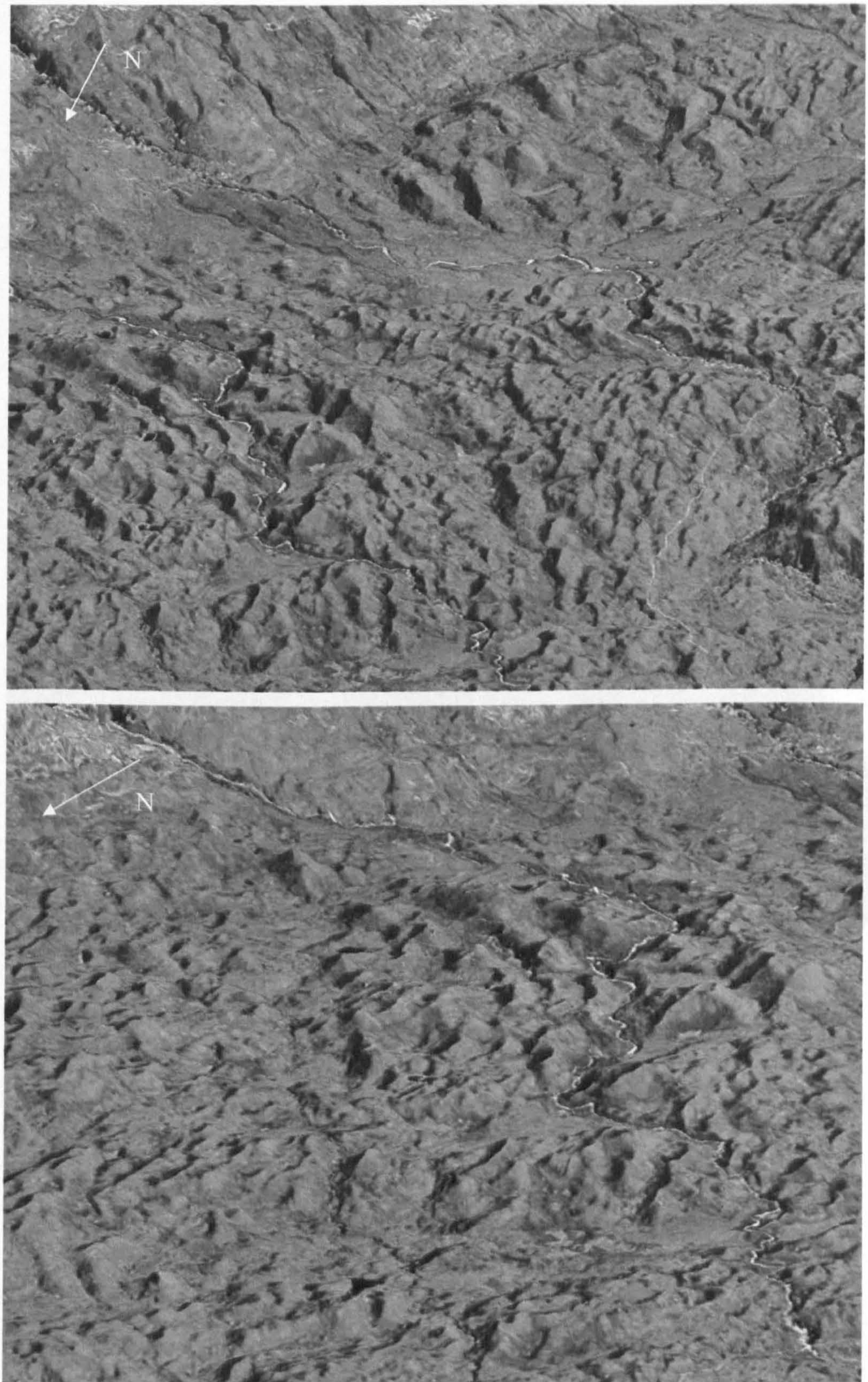


Figure 4.22 Overridden and fluted moraines Coire a'Cheud Chnoic, moraines orientated top left to bottom right, flutings orientated top right to bottom left.

Moraines overprinted with flutings have also been observed at contemporary glacier margins such as at Fjallsjökull and Breiðamerkurjökull (Evans and Twigg 2002, Evans 2003), Heinabergsjökull (Evans et al 1999) and Myrdalsjökull (Kruger 1987). An example of a large overridden moraine (Brenhola-Alda) occurs on the foreland of Breiðamerkurjökull (Evans & Twigg 2002). It is thought to have been overridden at the time of the Little Ice Age maximum, resulting in glacitectonised sedimentary units and a fluted surface on both its proximal and distal slopes (fig 4.23). The flutings have been accentuated by subaerial gullying since glacier recession.

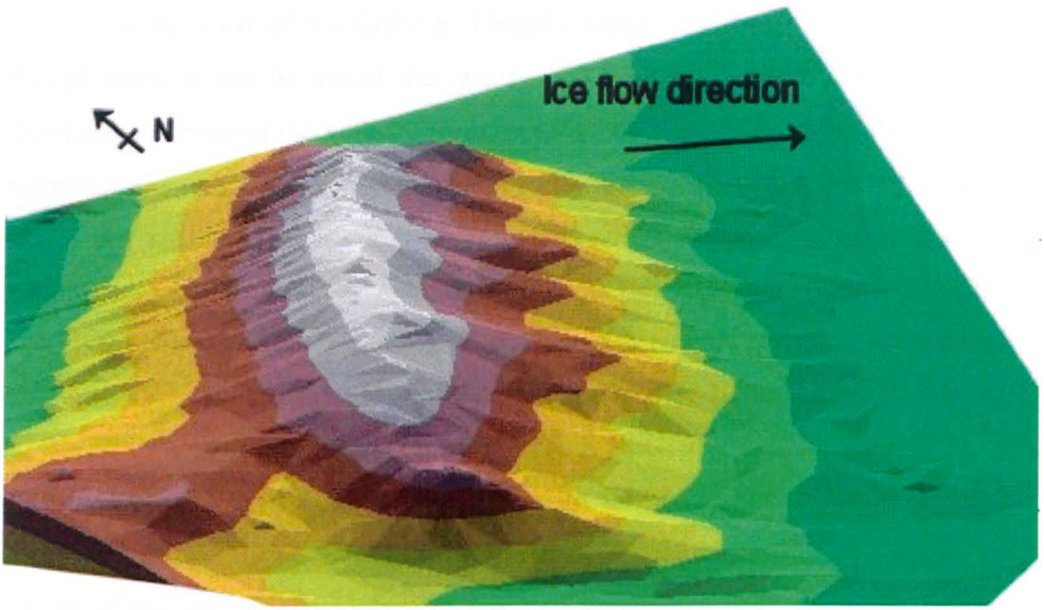


Figure 4.23 Brenhola Alda fluted moraine, produced using ArcView 3D analyst from 5m resolution D.E.M.. (D.E.M. produced by D. Twigg, Loughborough University)

The data presented above suggests that the cross-valley moraines of the Coire a' Cheud Chnoic pre-date the flutings in the valley and are likely to have been deposited as recessional moraines, marking temporary stand-still positions of a glacier receding back into the higher ground above Coire a' Cheud Chnoic. The moraines were later overridden by glacier ice during the Loch Lomond Stadial and superficially reworked by subglacial streamlining to produce down-valley orientated flutings. The reworking of the older moraines by subglacial streamlining and postglacial dissection has resulted in features with a chaotic appearance when viewed from the ground, leading to theories of aerial stagnation and incremental stagnation. It is proposed that the distribution of these features is not chaotic but represents the remnants of two separate spatial patterns of features, one cross-valley and one down-valley, which were deposited during two separate glacial events. The moraines and flutings of the Coire a'Cheud Chnoic therefore comprise a palimpsest landscape similar to those recently reported from a variety of glaciated terrains. An example of a palimpsest glaciated landscape in Sweden is discussed by Kleman (1992) who used the orientation of glacial landforms and the "morphological sharpness" of features to distinguish landforms of two glacial events.

To the west of the Coire a' Cheud Chnoic, in Glen Torridon, a latero-frontal moraine can be traced that gently descends the northern slopes of Glen Torridon and crosses the valley approximately 3km east of Torridon village. The moraine ridge is more prominent on the valley floor, although it is not visible on the south side of the River Torridon. The moraine has been quarried and sedimentological analysis was conducted in the available exposure (see section 4.3.2). It is thought that this moraine marks the westward extent of ice flowing from the Coire a' Cheud Chnoic and Beinn Eighe in Glen Torridon. Flutings observed in Srath Poll nam Dubh, to the south of Glen Torridon, suggest ice in this valley extended further to the west than in Glen Torridon. A large wide moraine located near the head of Upper Loch Torridon (fig 4.24) marks the extent of this glacier. This moraine was also interpreted as marking the western extent of ice in this area by Sissons (1967).

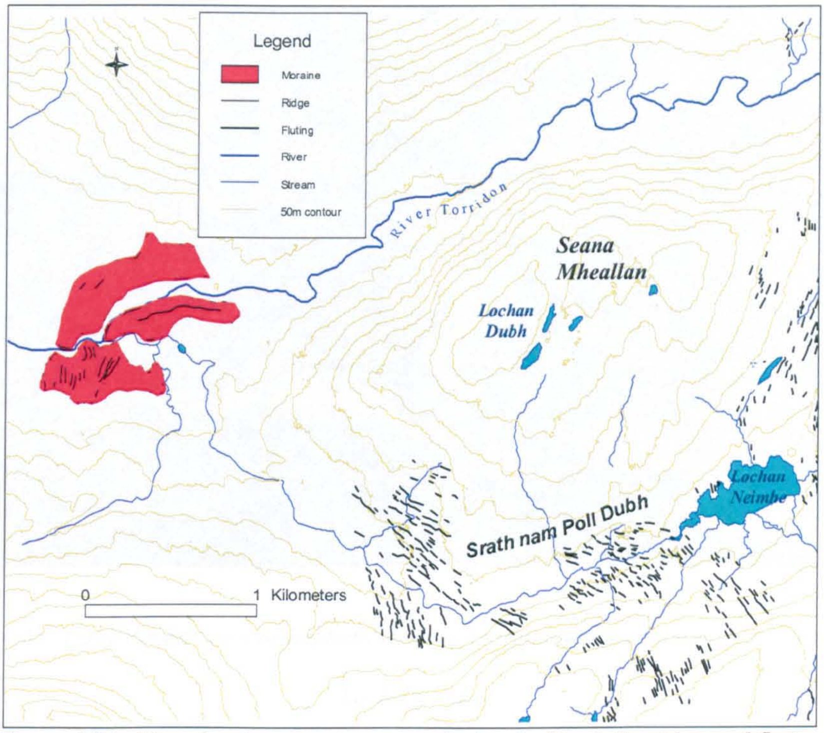


Figure 4.24 Map showing moraines near the head of Loch Torridon and flutings in Srath Poll nam Dubh

The surfaces of the moraines in which the section is exposed are near flat, with numerous small transverse ridges. A three dimensional image of this moraine showing the ridged surface, was produced (fig 4.25). A sediment exposure used in this study (see section 4.3.2) on the left of the image, was not exposed at the time the aerial photo was taken (1988).

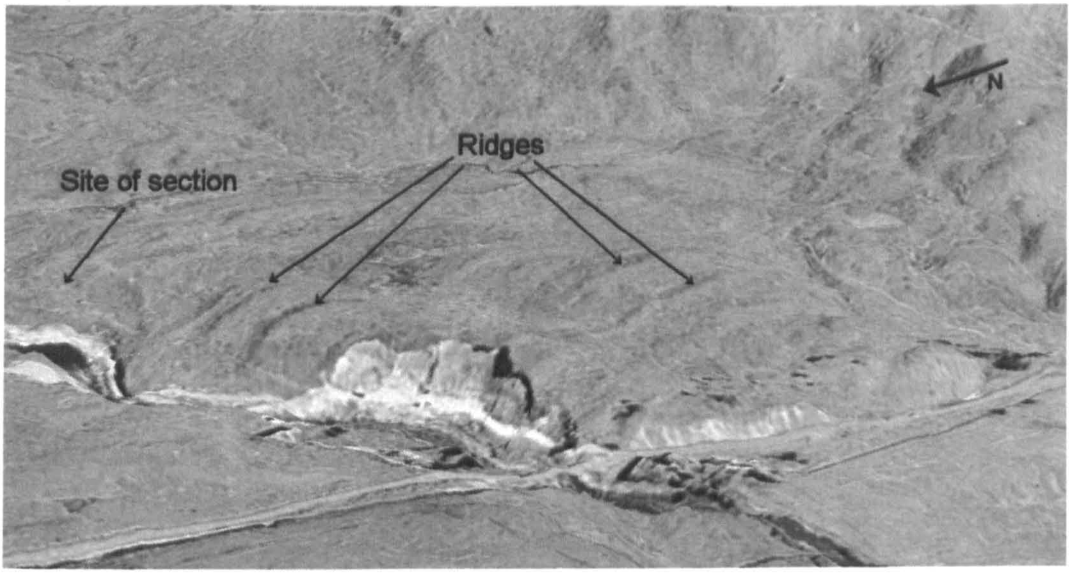


Figure 4.25 Three dimensional orthophoto showing moraine with surface ridges at the head of Loch Torridon

4.3.2 Sedimentology

Six clast samples (To1-To6) were taken on hummocks within the Coire a' Cheud Chnoic. Exposures in the hummocks were either cut by streams or exposed due to path erosion. Clast size in the exposures was varied and included boulders. Boulders were also common on the surface of the hummocks. All exposures, with the exception of sample To6 consisted of a clast rich massive diamict with a poorly consolidated matrix. Sample To6 had a similar matrix but with fewer clasts and more boulders than the other exposures.

Clasts measured are predominately sub-rounded or sub-angular with very few angular clasts. RA indexes are low for all the samples. (fig 4.26). Clast A, B and C axes were measured and plotted on ternary diagrams. (fig 4.27). All six ternary diagrams show similar clast shapes to samples published by Benn and Ballantyne (1994), interpreted as tills. Clast shape was also compared to samples from Glen Arroch, Isle of Skye published by Benn (1992). The samples from Benn (1992) were used as a comparison as the local bedrock of Glen Arroch (sandstone) is similar to that of the Torridon field area. The Coire a'Cheud Chnioc samples have similar clast shapes to samples from Glen Arroch interpreted as from moraines, lodgement till and raft sediments and are also similar to bedrock samples. Clast angularity of the Torridon samples is similar to Benn's moraine and lodgement samples. The clast samples taken in the Coire a'Cheud Chnioc are subrounded to sub-angular for all samples except To5 which is subangular to subrounded. Benn's raft and bedrock fragment samples are more angular and do not include any sub-angular or sub-rounded clasts.

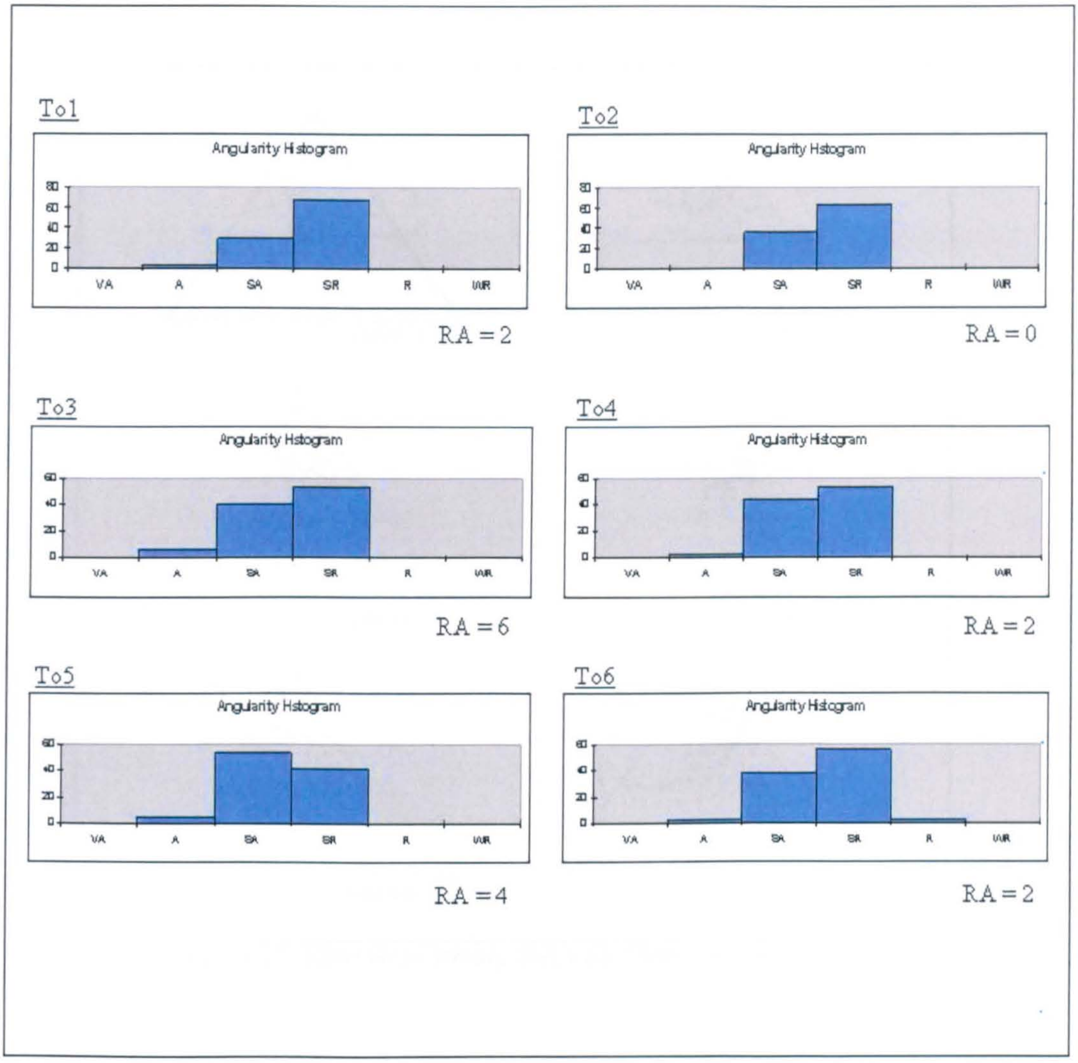


Figure 4.26 Clast angularity Coire a'Cheud Chnoic.

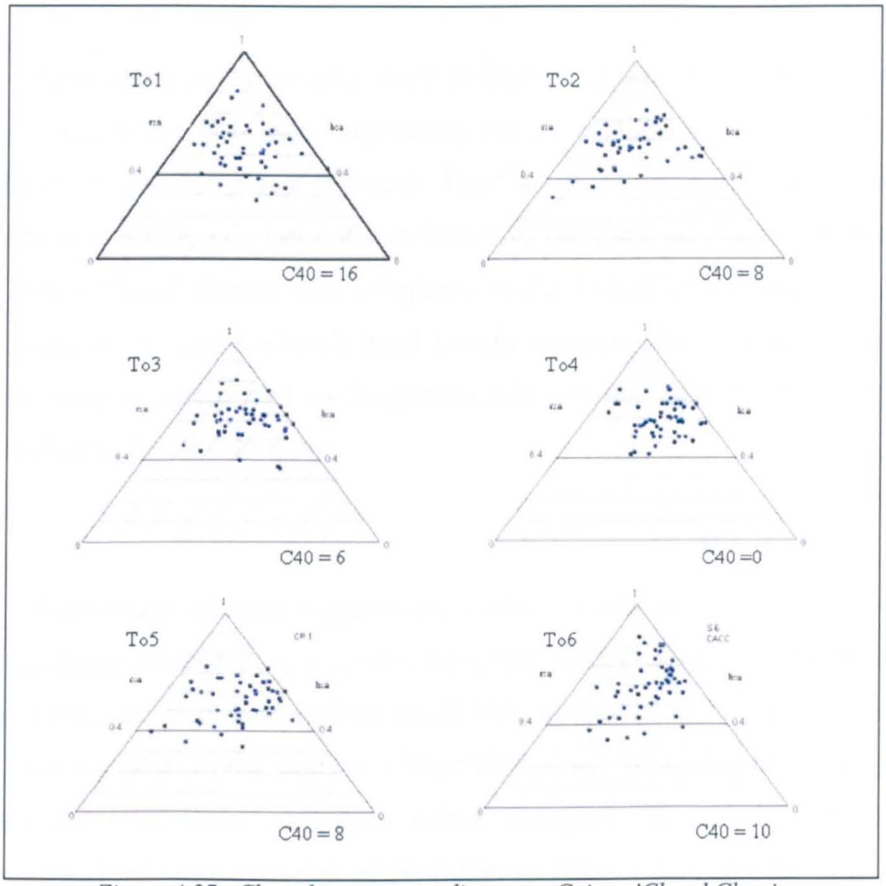


Figure 4.27 Clast shape ternary diagrams, Coire a'Cheud Chnoic

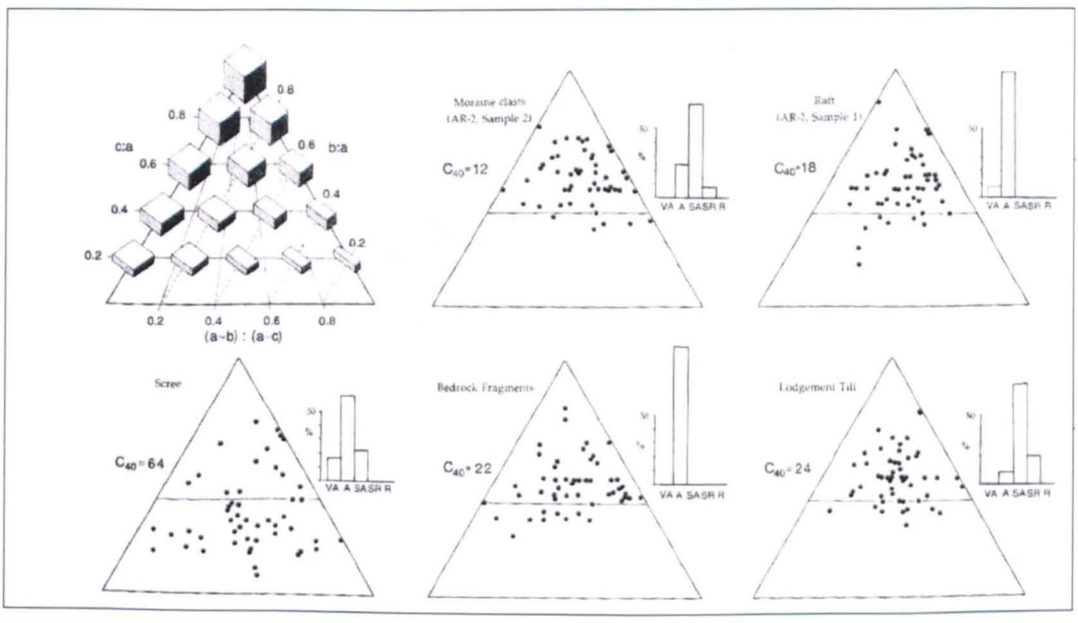


Figure 4.28 Clast samples Glen Arroch, Skye (Benn 1992)

Clast shape and angularity were plotted using the ratio of the C40 to RA indices, where the RA index represents the percentage of angular and very angular clasts in a sample of 50 clasts. The C40 index represents the percentage of clasts with a C:A axis ratio of less than 0.4. The clast sample data plotted for the Coire a'Cheud Chnioc was compared to clast samples published by Benn (1992) (fig 4.29). The Coire a'Cheud Chnoic samples plot in a similar area to Benn's samples interpreted as lodgement till, although the Torridon samples have a slightly lower C40 index.

Clast shape analysis suggests the clasts in the sediment exposures in the Coire a'Cheud Chnoic have a similar transport history to samples published by Benn (1992) and Benn and Ballantyne (1994) interpreted as lodgement till. The clast samples taken in the Coire a' Cheud Chnioc all show characteristics which suggest the clast have undergone active transport. This is consistent with Hodgson's (1986) interpretation of the ridges in Coire a' Cheud Chnioc as being formed subglacially, and with the morphological evidence for glacial over-riding presented in Section 4.3.1.

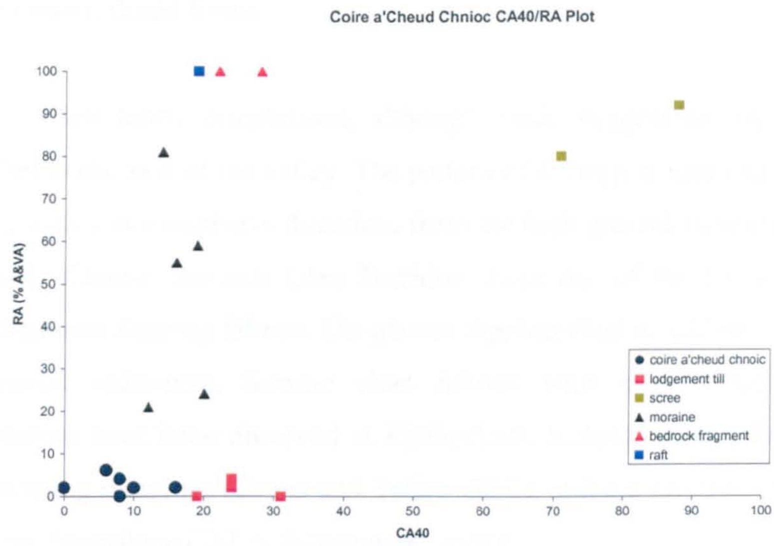


Figure 4.29 CA40/RA plot for Coire a'Cheud Chnoic.

Clast fabrics were also measured for the six samples taken in the Coire a'Cheud Chnoic. The samples generally have a weak orientation parallel to the valley axis. Clast orientation was compared to the orientation of the landforms they were taken from by overlaying a line representing the landform orientation on schmidt net diagrams depicting clast fabric shape (fig 4.30). The orientations of the features were measured in the field with a compass. It can be seen that there is a weak correlation between clast fabric and landform orientation for the six samples. Clast fabric eigenvalues were calculated and plotted on a ternary diagram representing clast fabric shape (fig 4.31). Only three of the six samples measured plotted within the envelope for deformation till. These three samples also plotted within the envelope for debris flow deposits. Clast shape however does suggest the samples are taken from sediments that have undergone an active transport history and are similar to Benn's (1992) till samples suggesting a sub-glacial origin. Fabrics however are not strong enough to define the sediments as sub-glacial in origin, as three of the samples plot outwith the till envelope and the three that plot within the envelope are close to the boundary. The overlapping nature of clast fabric characteristics from sub-glacial and other depositional environments, especially debris flow deposits is also a problem in identifying subglacial sediments. The weak fabrics could be due to some residual clast orientations from material deposited during an earlier period and reworked into their present fluted forms.

Clast fabric orientations, although weak, suggest an ice-flow direction parallel to the axis of the valley. The pattern of flutings would suggest ice flowed down-valley in a northerly direction, from the high ground surrounding the Coire a'Cheud Chnioc, towards Glen Torridon. Four out of the six samples display down-glacier dipping fabrics. Up-glacier dipping clast would be more typical of subglacial sediments. Similar clast fabrics with a preferred down-glacier orientation have been observed at Fjallsjökull, Iceland, where flutings override pre-existing moraines (Evans and Twigg 2002), and are interpreted as due to ice moving downslope (D.J.A. Evans pers. comm.).

Although the geomorphological evidence and clast shape analysis suggest a subglacial origin of the landforms and sediments of the Coire a'Cheud Chnoic clast fabrics are ambiguous, possibly due to sediment reworking. This suggests that caution should be exercised when using clast fabric shape to interpret sediments at locations where there is the possibility that the sediment has undergone a complex depositional history, such as where the sediment has been deposited and later reworked. It is possible for reworking to occur either by changing ice directions due to changing ice dynamics such as a migration of the ice divide of a large ice sheet, or by sediment deposited then reworked by subsequent glaciation. Weak fabrics could in some cases be due to some residual clast orientations from earlier events rather than being indicative of a single depositional event.

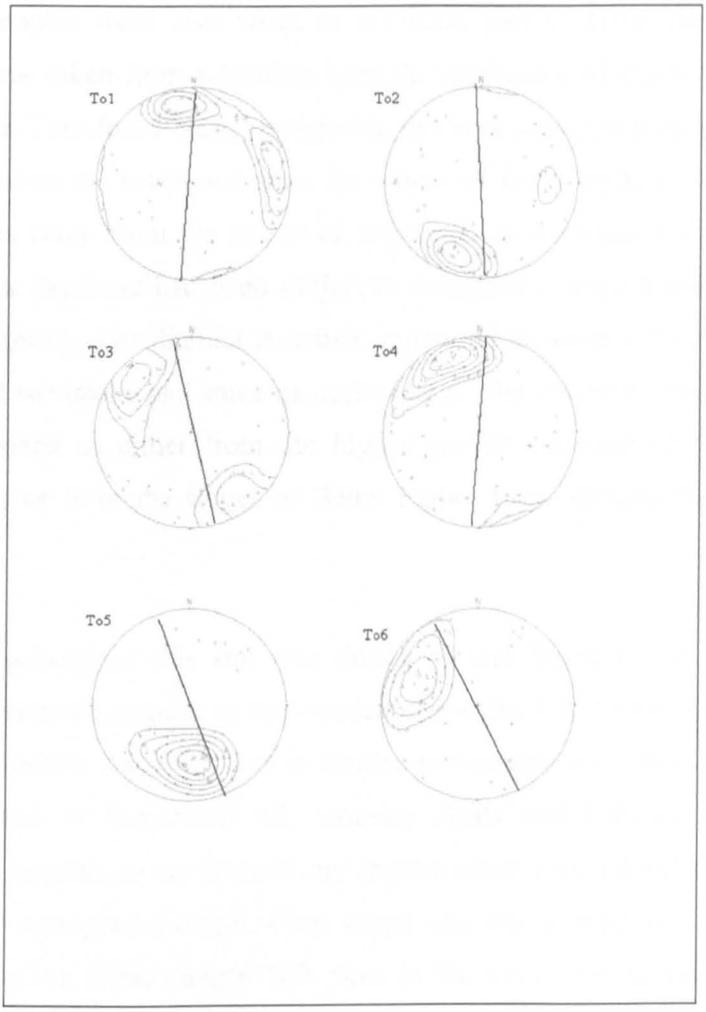


Figure 4.30 Clast fabric Stereonets with fluting orientations, Coire a' Cheud Chnoic

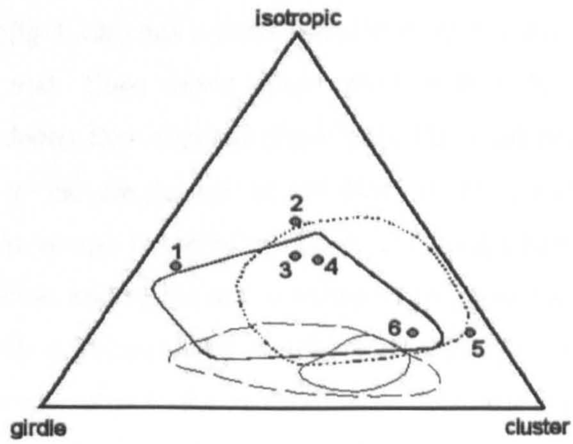


Figure 4.31 Clast Fabric Ternary diagram, Coire a'Cheud Chnoic

Clast samples were also taken in the main part of Glen Torridon. A sample (To7) was taken from a location near the confluence of Coire a' Cheud Chnoic and Glen Torridon. Flutings mapped in this area converge from the Coire a' Cheud Chnoic to the south and from the slopes of Benn Eighe to the north. The sample was taken from the top of an exposure, on a conical mound. The lower part of the exposure had been subject to extensive slumping and was not suitable for sampling. The diamict is matrix supported although clast rich, with clasts mainly of sandstone and some quartzite clasts. The source of the quartzite clasts is interpreted as either from the higher ground surrounding the Coire a'Cheud Chnoic or from the slopes of Beinn Eighe. Some striated clasts were observed.

Clast angularity at this site was similar to that found in the Coire a' Cheud Chnoic with sub-angular to subrounded clasts (fig 4.32). Clast shape (fig 4.32b) suggests active transport and is similar to samples published by Benn (1992) interpreted as lodgement till, moraine clasts and bedrock samples. However as the samples do not include any angular clasts they are unlikely to be of a bedrock or supraglacial origin. Clast shape was also plotted on a C40:RA index plot (fig 4.35). Clast sample To7 plots in the same area as the samples from Coire a' Cheud Chnoic suggesting a similar transport history (see fig 4.29).

Clast fabric (fig 4.32c) has a weak orientation with some dip orientation up glacier, to the east. Clast fabric shape plots within the envelopes for deformation till and debris flow deposits (fig 4.32d). The weak orientation of the clasts may be due to the confluence of ice flow at this location or due to reworking of material as was found in the Coire a' Cheud Chnoic. Clast shape suggests the material has undergone active transport and clast fabric shape plots within the envelope for deformation till which would suggest a subglacial origin of this material. However clast fabric orientation is weak and clast fabric shape also plots within the envelope for debris flow. The orientation of landforms in this area suggest they were formed as flutings, similar to the down valley orientated features in the Coire a' Cheud Chnoic. However it would be difficult to interpret this feature individually, based on its sediment characteristics and morphology.

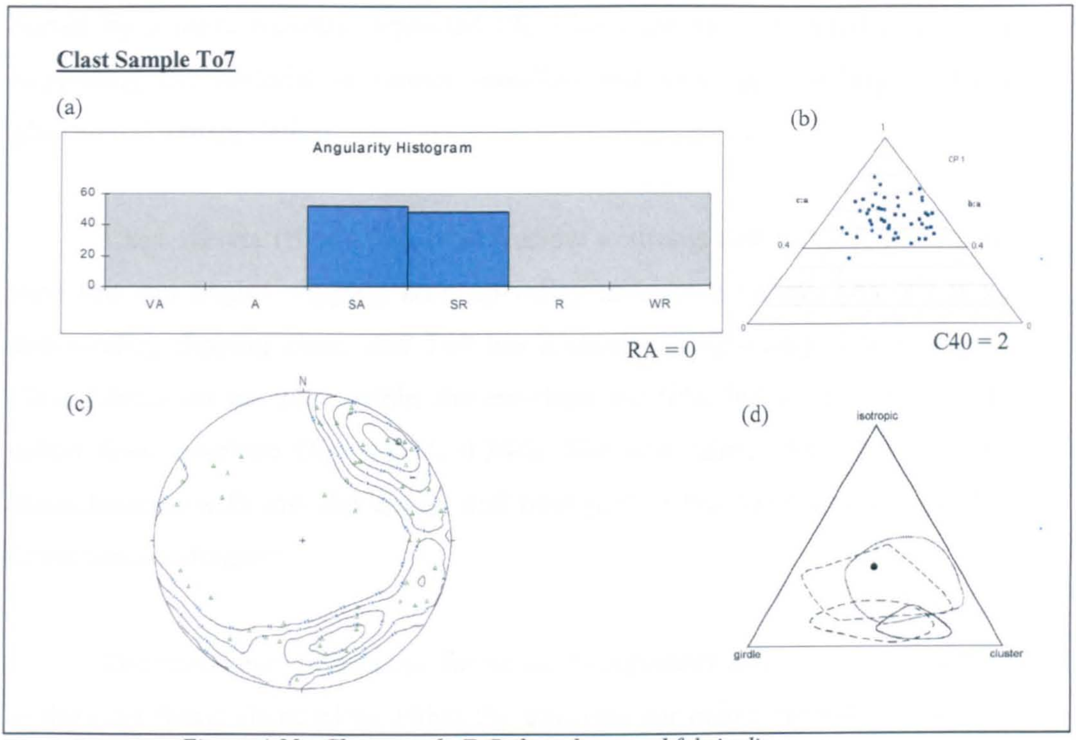


Figure 4.32 Clast sample To7 clast shape and fabric diagrams

Two clast samples (To8,To9) were taken in a disused quarry cut through a cross-valley orientated landform in Glen Torridon, approximately 2km east of Coire a' Cheud Chnoic. Both samples were taken from near the top of the feature as the lower slopes were affected by slumping. The diamict at this site includes gravel and is matrix supported. The matrix mostly consists of sand. A sample was measured on the east face of the quarry, To8 and on the west face, To9. Clast were predominantly sub-rounded, with few other clasts (figs 4.33a, 4.34a), and clast shape suggests an active transport history (figs 4.33b, 4.34b). Clasts plot in a C40:RA index plot in a similar area to Benn's lodgement till samples (fig 4.35). Clast lithologies include erratic clasts of schist and some granite, as well as local Torridonian sandstone. There is a higher proportion of erratic clasts at this site than in the Coire a' Cheud Chnoic. Clasts of schist and other non-local erratic lithologies were found in the Coire a'Cheud Chnoic by Hodgson (1982, 1986, 1987), although few were found in this study.

The erratic clasts found in the quarried landform may be due to the rafting or pushing of material belonging to an older till by the advancing glacier, whereas older sediments in the Coire a' Cheud Chnoic have been overridden and buried by a more recently deposited till. Clasts are more rounded at this site suggesting the material is further travelled and may have undergone some glacifluvial transportation.

Clast fabrics (figs 4.33c, 4.34c) show a strong east to west orientation with low dip angles, dipping both up-valley and down-valley. To8 has more down-valley dipping clasts and To9 has a cluster of up-valley dipping clasts. Clast fabrics do not plot within the envelope for tills, but do plot within the debris flow envelope (figs 4.33d, 4.34d). The two fabrics have very similar characteristics with low dip angles and both plot in the same area of the clast fabric ternary diagram.

The relatively strong clast fabric could represent down slope movement as the clast fabric shape plots within the envelope for debris flow deposits. This may be due to debris flow from the glacier snout or paraglacial debris flow. This is consistent with the interpretation of the landform as a marginal moraine. Clast samples with similar fabric shapes from Coire a'Cheud Chnoic were interpreted as subglacial in origin. However the geomorphological evidence and topographic locations of the sample sites in Coire a'Cheud Chnoic suggests a subglacial environment, whereas the morphology and location of the cross-valley moraine in Glen Torridon suggests ice marginal deposition. This again demonstrates the possibility of similar clast fabric shapes being due to different depositional processes, and emphasises the need to combine clast fabric and shape analysis with other information, such as the morphology and spatial organisation of the landforms they were taken from.

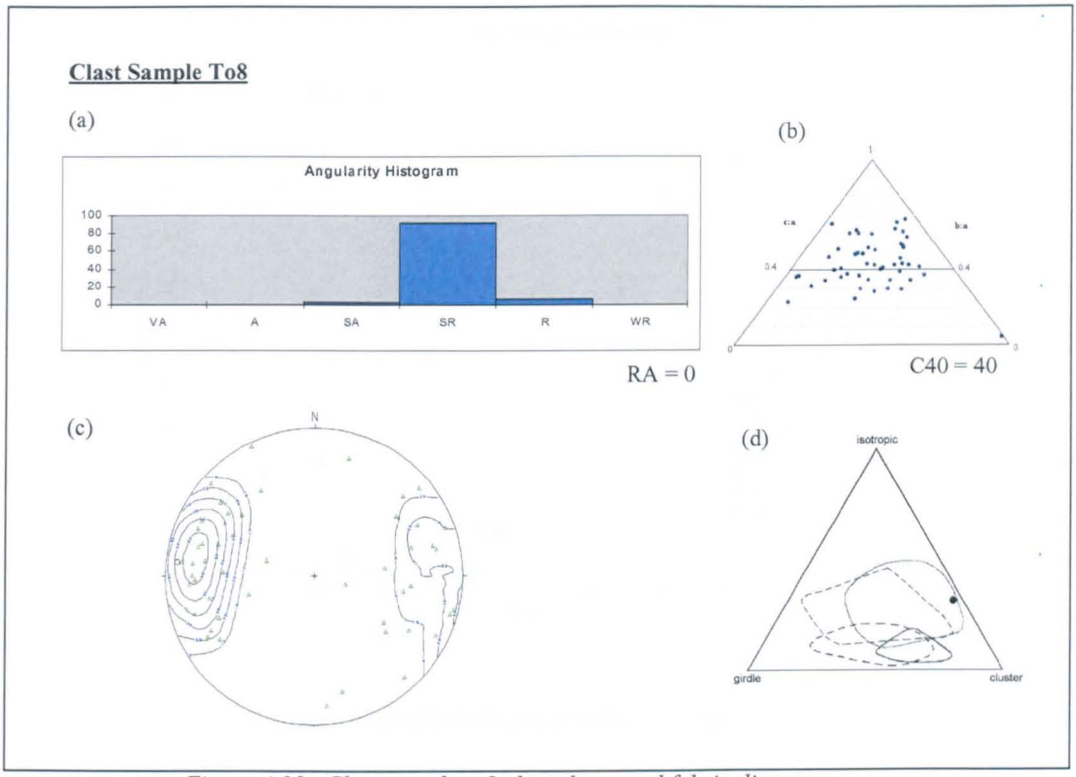


Figure 4.33 Clast sample to8 clast shape and fabric diagrams

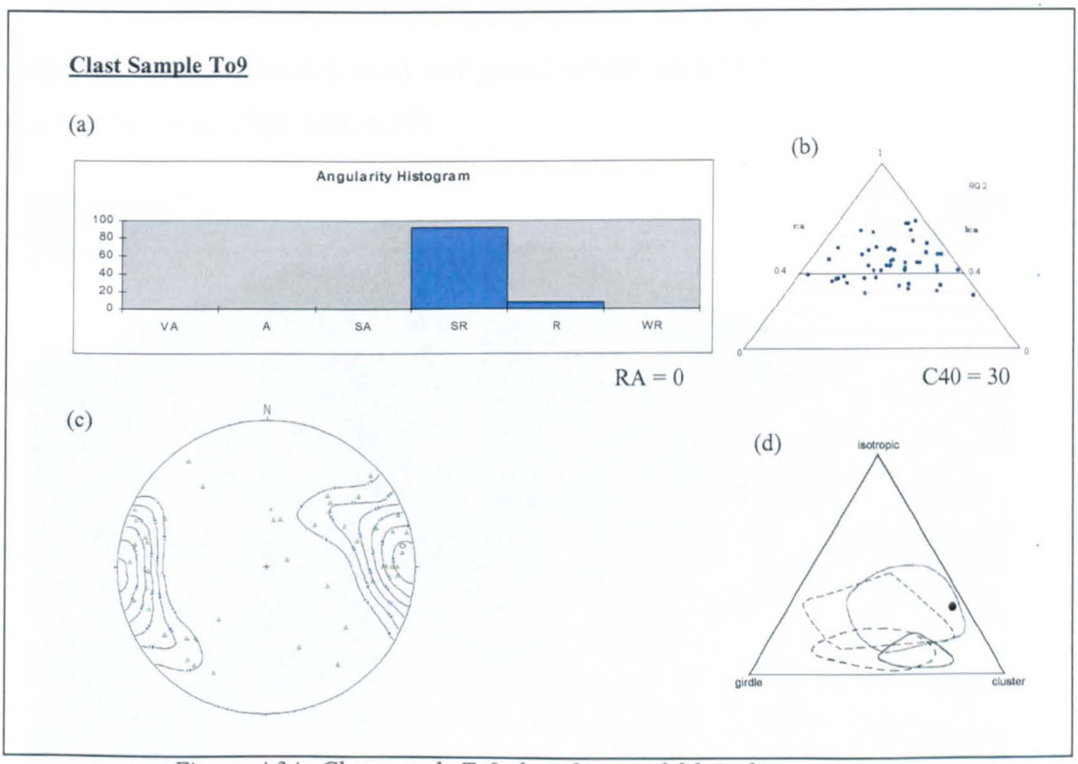


Figure 4.34 Clast sample To9 clast shape and fabric diagrams

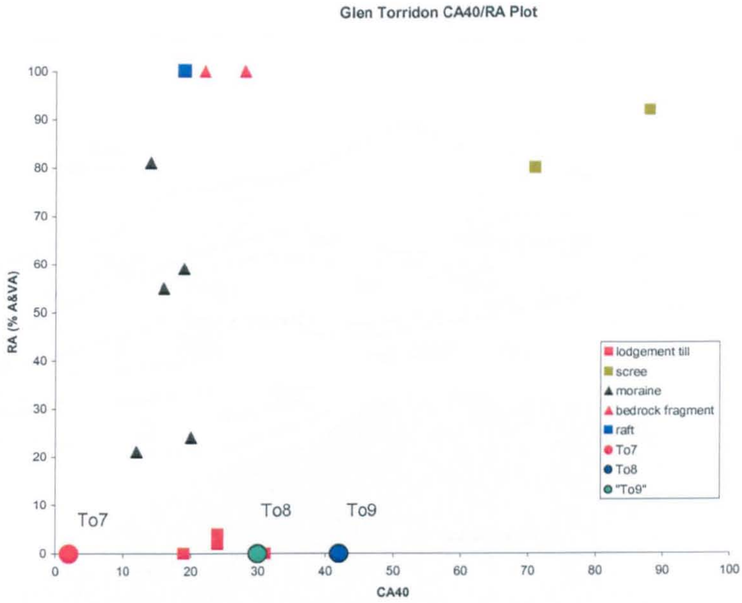


Figure 4.35 CA40/RA plot for Glen Torridon.

A quarried section in the moraine near the head of Loch Torridon displayed units of diamict, sand and gravel which have been contorted on their distal (west) side. (figs 4.36, 4.37)

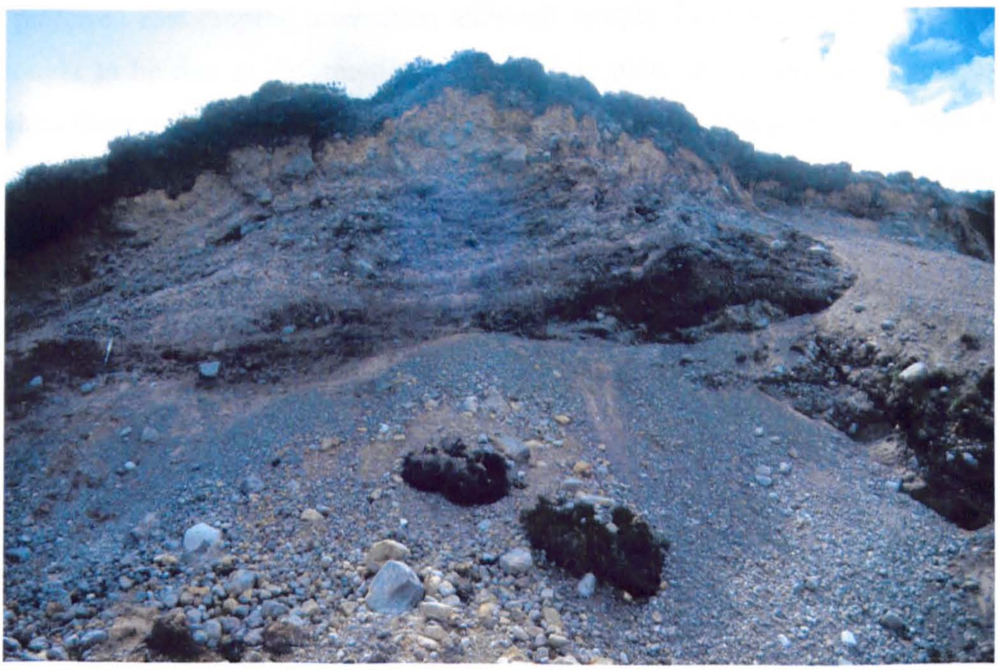


Figure 4.36 Section in moraine with contorted units

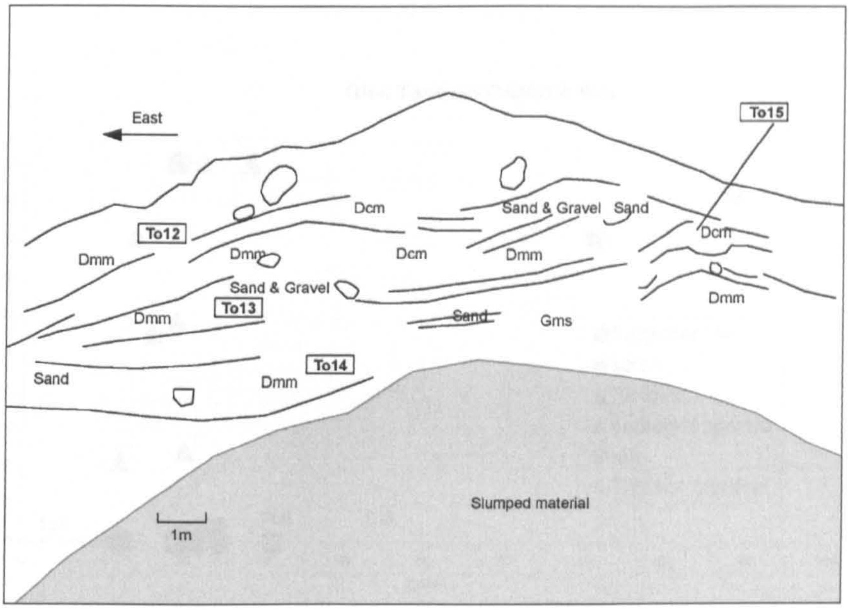


Figure 4.37 diagram of section of moraine with contorted units

Four clast samples (To12 to To15) were taken from the diamict units in this section. Clast angularity and shape suggests an active transport history (fig 4.39 a to h). Clast shape plots close to Benn's lodgement till samples, also suggesting active transport of this material. Clast fabrics (fig 4.39 I to L) display a preferred east dipping orientation although sample To15 has a weaker fabric thought to be due to deformation. Clast fabric plots within the envelopes for debris flow and deformation till, although two of the samples plot on the border of the till envelope. The diamicts are interbedded with units of gravel, sand and gravel, and sand. The location of this feature, with no evidence of overriding or glacial landforms beyond this location, to the west, suggests this is an ice marginal landform. The location and interbedded units suggest the sediment units were produced at the ice margin rather than subglacially. The sediments in this exposure are therefore interpreted as diamicts formed by debris flow from the glacier snout, which are interbedded with glacifluvial sands and gravels from meltwater flowing from the glacier margin. Deformation of the units on the distal side of the feature is interpreted as due to minor ice pushing and collapse of the poorly consolidated sands, gravels and debris flow deposits following withdrawal of the ice.

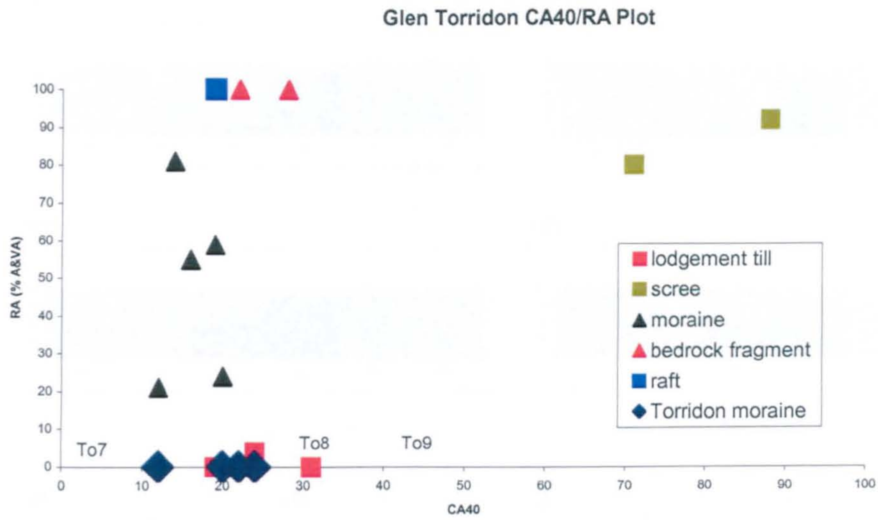


Figure 4.38 C40:RA index plot for Torridon moraine

Clast Sample from moraine at the head of Loch Torridon

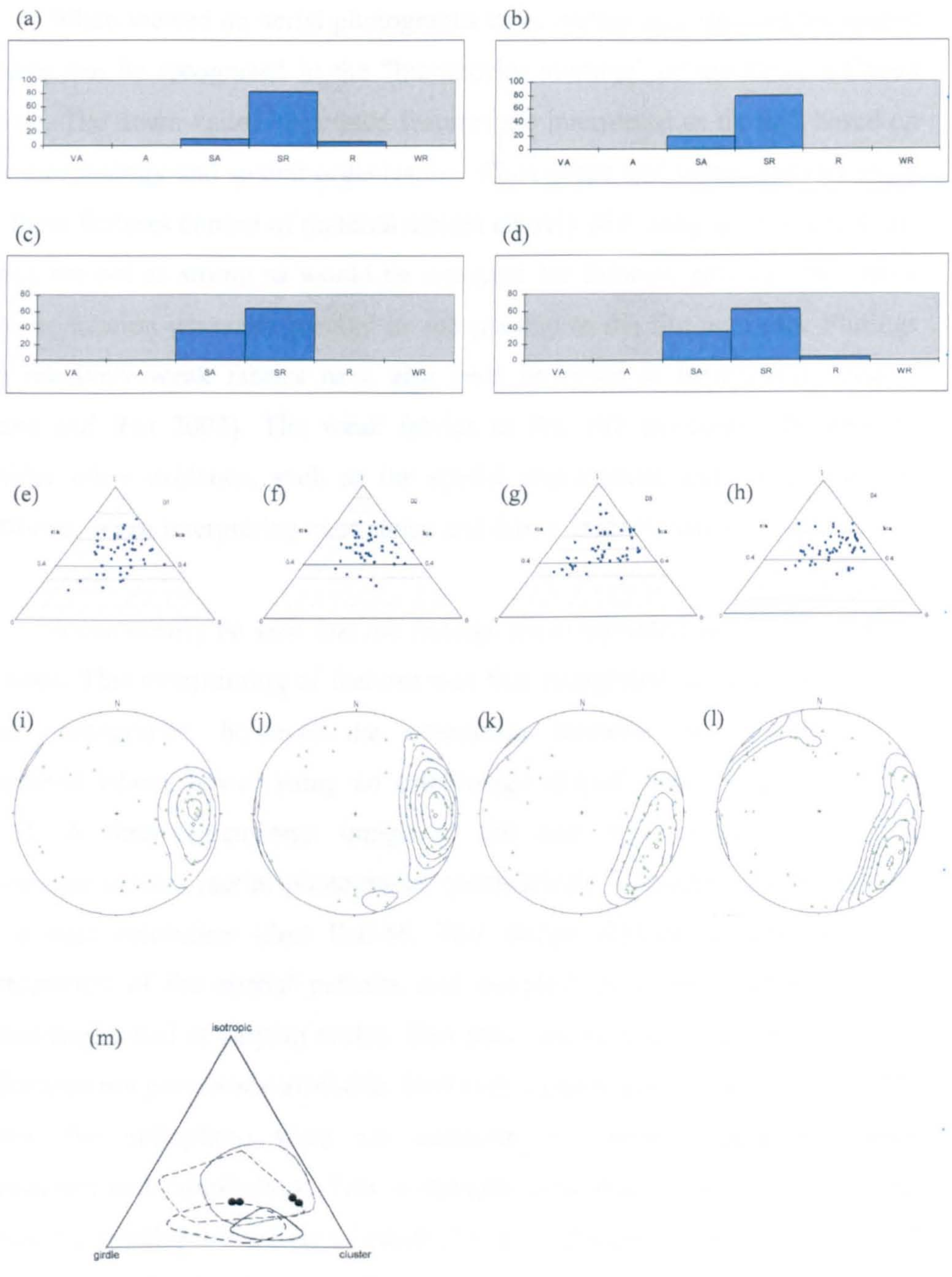


Figure 4.39 Clast diagrams for moraine at the head of Loch Torridon

4.3.3 Interpretation

When viewed on aerial photographs down-valley and cross-valley spatial patterns can be recognised in the "hummocky moraine" of the Coire a'Cheud Chnoic. The down-valley orientated features are interpreted as flutings based on their morphology and spatial organisation. Clast shape and fabric analysis show that these features consist of material almost entirely of a subglacial origin. Clast fabrics are not as strong as would be expected for flutings, although they have some orientation generally parallel or sub-parallel to the fluting crests. Flutings with relatively weak fabrics have also been observed at Bruarjökull, Iceland (Evans and Rea 2003). The weak fabrics at this site emphasise the need to consider other evidence, such as the spatial organisation and morphology of landforms, when interpreting clast shape and fabric characteristics.

It can clearly be seen that the flutings are overprinted on the cross-valley moraines. This overprinting of features was first recognised using stereo pairs of aerial photographs, however the overridden moraines were more easily recognised when viewed using an orthoimage draped over a high resolution D.E.M. A three-dimensional image of the area was produced using an orthoimage mosaic (aerial photographs geometrically corrected and mosaiced) and a high resolution (5m) D.E.M. This image allowed visualisation and interpretation of the spatial patterns and morphology of the landforms from various angles and at varying scales. This provided an insight into the nature of the features not previously available. However, images derived from the D.E.M. without the orthophoto were not adequate to interpret landform spatial organisation and morphology. This is thought to be due to these images using contouring, which joins points of equal elevation. As the outlines and crests of features on a steeply sloping hillside are not at a constant elevation, their morphology is not revealed by contouring.

The pattern of moraines can be explained by older marginal moraines being overridden and reworked to produce flutings and dissected moraines. This is consistent with Hodgson's theory (1982,1986,1987) that the down-valley orientated ridges, found mainly in Coire a'Cheud Chnoic and Srath nam Poll Dubh, are flutings. According to Hodgson some of the material in the flutings was brought into the area by ice pre-dating the Loch Lomond Stadial. The production of three dimensional images has allowed more detailed observations of the features to be made, and it is proposed here that not only did some sediments survive being overridden but also much of the moraines deposited previous to the flutings have survived, albeit in a much modified state.

Bennett (1998) interpreted the moraines and flutings in Coire a' Cheud Chnoic as controlled moraines produced by the meltout of debris bands at the glacier margin. The debris bands are thought to have been produced by sediment from the base of the glacier being entrained by thrusting within the ice. According to Bennett features similar to the landforms of Coire a' Cheud Chnoic were observed in Svalbard. This theory however does not explain the overriding flutings and is not consistent with a clast orientation parallel/ subparallel to the valley axis.

Also personal observations at the margin of Tungnafellsjökull, Iceland of moraines containing debris bands suggest there is limited preservation potential of these features. At Tungnafellsjökull moraines with debris bands were observed near the glacier margins. The moraines consisted of parallel upglacier dipping debris bands separated by bands of cleaner ice. The moraines have a high ice content and beyond the more recent ice margins, where ice bands in the moraines have melted out, the topography is more subdued, with only subtle topographic variability marking former ice limits. Figure 4.40 shows the debris and ice bands of a moraine in the proglacial areas of Tungnafellsjökull. The photograph (fig 4.42), taken from an outlet glacier of Tungnafellsjökull ice cap, illustrates the subdued topography beyond more recent ice margins. The large moraines in the foreground, near the present glacier margin, consist of alternate bands of debris and cleaner ice, and have a high ice content. Although these observations do not eliminate the possibility of the preservation of some features produced by the thrusting model, proposed by Bennett (1998), the use of modern analogues for features with significance ice content, such as those found at

Tungnafellsjökull, would have to consider the problem of poor preservation potential.

Figure 4.40 Debris and ice bands in moraine Tungnafellsjökull

Figure 4.41 Ice-cored moraines, Tungnafellsjökull

Figure 4.42 Ice-cored moraines in foreground with low-relief moraines with no ice-core in background

A south to north ice-flow direction is suggested by the direction of the flutings in Coire a'Cheud Chnoic. Fluting patterns on the north side of Glen Torridon suggest ice flowing in a south-westerly direction from the slopes of Beinn Eighe. It is proposed that the two glaciers, from Coire a'Cheud Chnoic and Beinn Eighe converged in Glen Torridon, flowing west for a short distance of approximately 3km. Glacier ice also flowed westward along Srath nam Poll Dubh, a valley to the south of Seana Mheallan. Glacier ice from the high ground to the south of the Coire a'Cheud Chnoic, diverged around Seana Mheallan, flowing northward into Coire a'Cheud Chnoic and westward along Srath nam Poll Dubh. This interpretation of these landforms as flutings, and the preservation of older moraines has significant implications for glacial conditions during Loch Lomond Stadial at this site. Sissons' model of aerial stagnation argues that the hummocky appearance of the landforms are indicative of stagnation due to climatic amelioration. However flutings are produced by active ice and do not require rapid climate amelioration. Bennett's model of thrusting would require cold based ice to freeze material to the glacier sole, whereas flutings are formed from saturated sediment below warm based ice.

A map of ice direction during the Loch Lomond Stadial was constructed based on the evidence of the flutings and clast fabrics (fig 4.43). The ice flowing along Srath nam Poll Dubh extended further westward than the ice in Glen Torridon, extending almost to the head of Upper Loch Torridon, Its extent is marked by a moraine consisting of contorted sands, gravels and diamict. It is suggested that this moraine was produced at the ice margin by a combination of debris flow from the glacier snout and glacifluvial deposition. The contorted units are due to minor pushing and collapse following ice withdrawal. A map showing the flutings, cross-valley moraine ridges, and marginal moraines can be seen in fig 4.44.

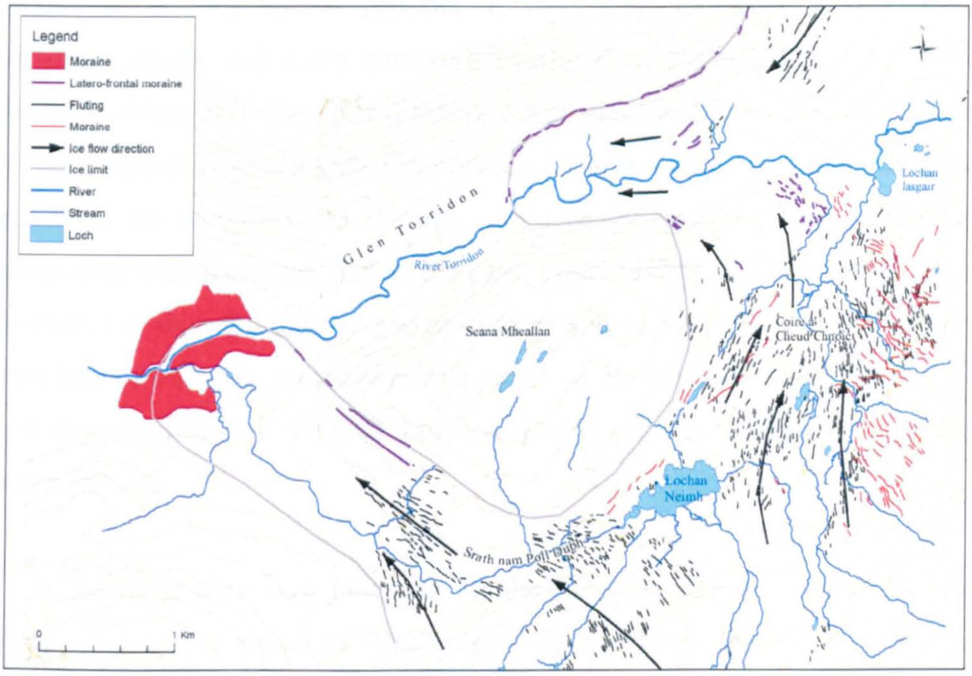


Figure 4.43 Map of Loch Lomond Stadial ice direction

4.4 Summary

Maps, digital elevation models and three dimensional orthophoto images were produced for Glen Torridon and the surrounding area including Coire a'Cheud Chnoic (corrie of a hundred hills) which has been the subject of numerous previous studies. The hummocky moraines of Coire a'Cheud Chnoic have previously been interpreted as chaotic hummocky moraine deposited by aerial stagnation, as the remnants of linear moraines deposited by incremental stagnation, as push and dump moraines, flutings and controlled moraines. Mapping and three dimensional visualisation of these features has allowed the recognition of two spatial patterns of landforms, including a cross-valley orientated pattern and more numerous down-valley orientated features. When viewed in stereo or on the three dimensional images the down-valley features can be recognised as overriding the cross-valley features. The down-valley orientated landforms are interpreted as flutings, produced by ice overriding older cross-valley orientated moraines, during the Loch Lomond Stadial. The older moraines therefore pre-date the flutings and are interpreted as being deposited before the Loch Lomond Stadial, probably during retreat of the Late Devensian ice sheet, or were deposited early in the Loch Lomond Stadial with the flutings representing a later readvance.

Flutings were also observed on the northern slopes of Glen Torridon where ice from the slopes of Beinn Eighe was confluent with ice flowing from Coire a'Cheud Chnoic. A latero-frontal moraine approximately 3km west of Coire a'Cheud Chnoic marks the extent of the glacier in Glen Torridon. Flutings were also mapped in Srath nam Poll Dubh, to the south of Seana Mheallan. The pattern of flutings in Srath nam Poll Dubh and the upper parts of Coire a'Cheud Chnoic suggest ice from the high ground above Coire a'Cheud Chnoic diverged around Seana Mheallan flowing north into Coire a' Cheud Chnoic and also west along Srath nam Poll Dubh to near the head of Upper Loch Torridon, where a moraine, consisting of deformed sands, gravel and diamict marks the westward extent of glacier ice in this area.

Digital terrain modelling allowed observations of the morphology and spatial organisation of landforms not previously seen. This allowed the recognition of two patterns of landforms, one down-valley and one cross-valley and allowed the relative dating of these features. The use of three-dimensional viewing using the photogrammetric software and stereoscope was found particularly useful as was the production of three-dimensional images produced by draping orthophotos over the D.E.M. Contouring and images derived from the D.E.M. did not provide adequate detail for the visualisation of landforms. This is due to contours joining points of equal elevation. As the landforms studied at this site were deposited on steep slopes the outlines and crests of the features are not at constant elevations. Contouring, therefore, does not follow the outlines of features and is therefore of limited use for studies of the morphology and spatial organisation of landforms on steeply sloping ground. This highlights a significant problem in the use of digital elevation models in geomorphological studies. However the orthophotos draped on the D.E.M. give information on the elevation and morphology of features and were found useful for mapping and three dimensional visualisation.

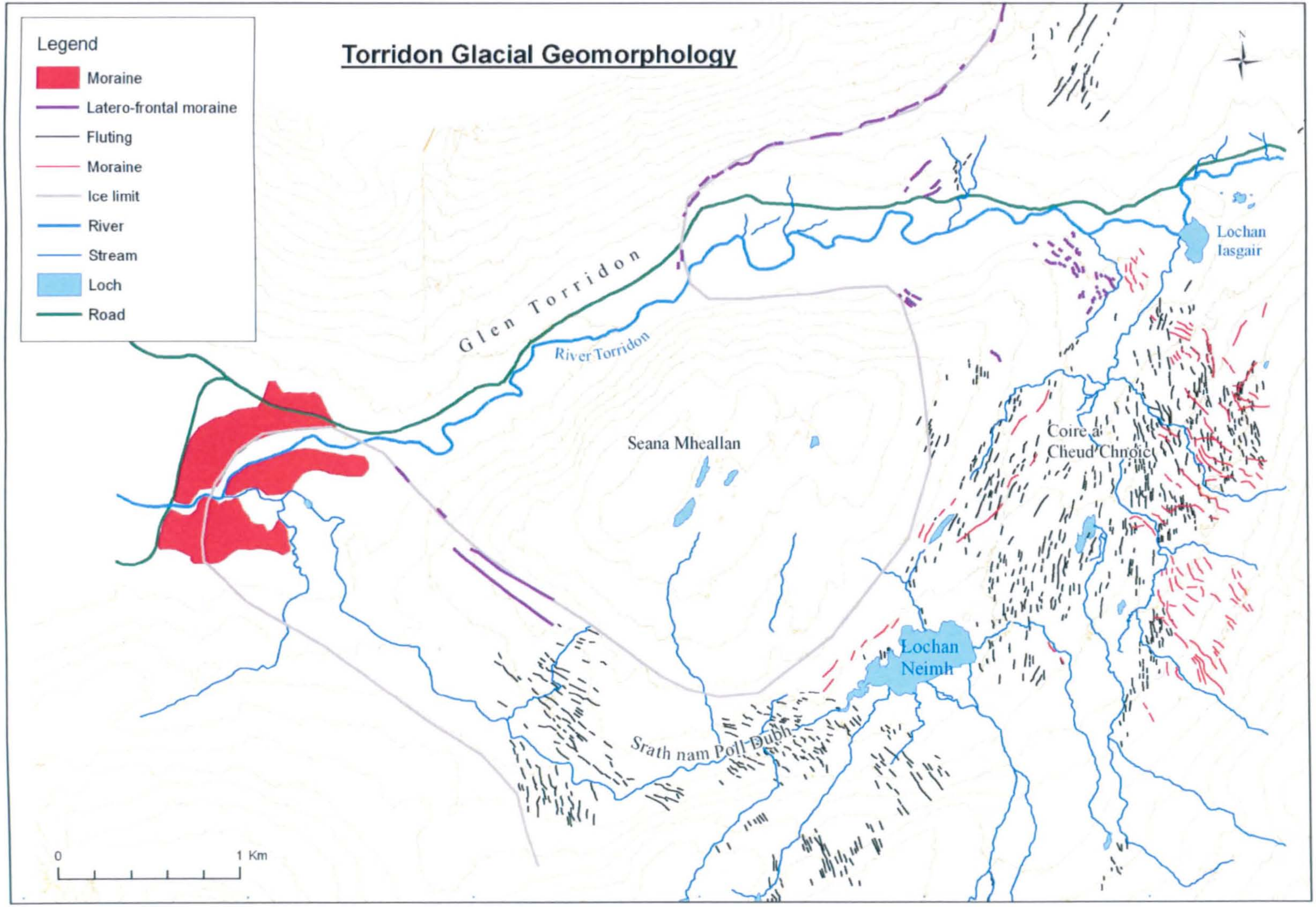


Figure 4.44 Torridon Glacial Geomorphology

5

Rannoch Moor

5.1 Introduction

5.1.1 Location

Rannoch Moor, situated in the south-west Grampian Highlands, has been regarded as the major centre of ice accumulation during previous glaciations and a centre of ice convergence during the Loch Lomond Stadial (Sissons 1967a). According to Sissons (1967a) the period of the Loch Lomond Stadial was too short to allow the development of an ice cap on Rannoch Moor, as had occurred during previous longer term glacial events, and ice accumulated in corries on the surrounding mountains and converged on Rannoch Moor. Prevailing weather systems from the south-west resulted in this region receiving some of the highest rates of precipitation in the British Isles (Sissons 1980). This resulted in high rates of ice accumulation in the west and a decrease in precipitation, and therefore in ice accumulation, towards the north and east. The combination of high precipitation and topography suitable for ice accumulation resulted in Rannoch Moor being the major centre of ice convergence. The moor has an altitude of approximately 300m above sea level, and is surrounded by higher mountains with heights ranging from approximately 650m to 1100m (fig 5.2).

Figure 5.1 Location of Rannoch Moor field site and extent of Loch Lomond Readvance (adapted from Sissons 1974)

Figure 5.2 Extract from Ordnance Survey 1:50 000 series map of Rannoch Moor (© Crown Copyright Ordnance Survey)

A radiating pattern of major rock basins surrounding Rannoch Moor was used by Sissons (1967a) as evidence that the moor was a major ice accumulation basin (fig 5.3). Sissons however points out that the radial pattern of ice dispersal from Rannoch Moor would only be possible when a sufficient volume of ice had accumulated in the Rannoch Moor basin to allow the outward flow of ice. At times of less ice accumulation on Rannoch Moor ice would have flowed into the basin from the surrounding mountains but would not have flowed out.

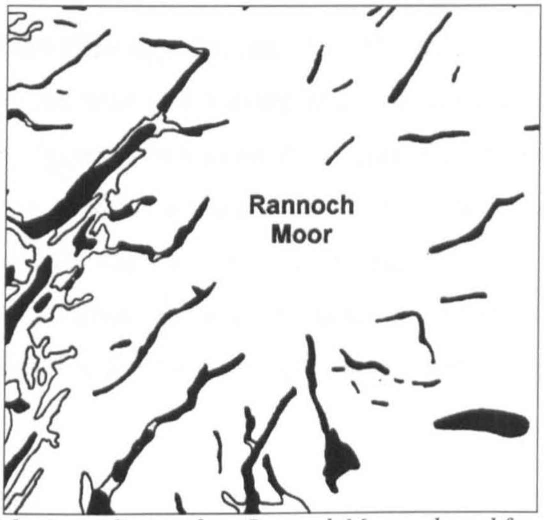


Figure 5.3 Rock basins radiating from Rannoch Moor, adapted from Sissons 1967a

Due to the short duration of the Loch Lomond Stadial, ice did not build up enough in the Rannoch basin to overflow into the adjoining valleys. However Sissons (1980) estimated the ice mass in the Rannoch Moor basin to have reached an altitude of 850-900m. Ice flow into Rannoch Moor from the surrounding mountains is inferred from the discovery of igneous erratics in the Rannoch Moor moraines. According to Sissons (1967a) erratics indicate that ice flowed eastward into the Rannoch Moor basin from Glen Coe and along the River Ba. This suggests an ice dispersal centre in the area of Aonach Mor to the south-west of Rannoch Moor.

5.1.2 Geology

The solid geology of the Rannoch Moor basin mainly consists of a large granite intrusion known as the Moor of Rannoch Granite, and is dated to around 400 million years (BGS 1:50000 Scotland series sheets 53, 54). Igneous intrusions, in the form of dykes, crop out on some of the surrounding mountains, especially to the south-west at the head of the Ba Valley such as at Coire a Ba, Aonach Mor and Stob Ghabhar. The summit of Meall a Bhuiridh, in the area of the White Corries to the west of the moor, has a summit consisting of schist with volcanic intrusions. Igneous intrusions also crop out on the mountains to the north-west of Rannoch Moor including Beinn Chrulaiste and Meall Bhalach. Volcanic lavas and tuffs can be found on Buachaille Etive Mor in Glen Coe, north west of Rannoch Moor. There are no igneous intrusions on Meall a' Phuill or on Stob Losgann and Stob Cruaiche, to the north of the field area.

5.1.3 Geomorphology

Hummocky moraine is abundant in the basin of Rannoch Moor. The moraines are generally steep sided and of varying size and morphology. From the ground the hummocky moraine has no obvious spatial patterns although it is more concentrated in some areas including the Ba Valley, in the south-west of the moor, around Lochan Gaineamhach, and to the north of Kingshouse on the north-west side of the moor. Sissons (1967a) proposed that these moraines were deposited during the Loch Lomond Stadial, when ice volume was not sufficient to flow out from the moor

According to Thorp (1991b) much of the hummocky moraine at other sites within the limits of the Loch Lomond Readvance can be related to sources of supraglacial rock debris. However, the hummocky moraines on Rannoch Moor are thought to be polygenetic (Thorp 1991b). Igneous erratics from Aonach Mor and the surrounding mountains at the western end of the Ba Valley were observed in moraines in the Ba Valley and on the eastern shores of Loch Ba. This is interpreted by Thorp as evidence that ice flowed from the Aonach Mor area along the Ba valley as far as the eastern shores of Loch Ba, transporting the erratics supraglacially. The moraines however contain more locally derived material that is thought to have been eroded and deposited subglacially. The higher ground to the west of the Ba Valley is thought to have been a major area of ice accumulation. Ice from this area flowed into the Rannoch Moor basin where ice accumulated to an altitude of 650 to 700 m producing an ice cap. Outlet glaciers flowed out of the moor in a radial pattern via Glen Orchy to the south, Glen Etive to the west, Glen Coe to the north and Glen Ossian to the east (Thorp 1986).

The moraines of Rannoch Moor are described by Boulton (1992) as including push moraines produced by minor readvances of active glaciers during retreat. Concentric patterns of features are described and interpreted by Boulton as ice marginal features, including push and dump moraines and ice-contact fans. These are used as evidence that glaciers retreated actively from the Rannoch Moor basin into ice-centres in the mountains to the west and south.

Charlesworth (1956) had also described a period of restricted glaciation, in the Rannoch area, termed substage O, which can be correlated to a late stage of the Loch Lomond Stadial. According to Charlesworth, during substage O the Rannoch ice receded leaving individual corrie glaciers in the corries of the surrounding mountains, while the Rannoch Moor basin was ice free.

If ice did not directly accumulate on Rannoch Moor, but accumulated in the surrounding mountains and flowed onto the moor, the pattern of ice flow and information on the sources of this ice should be reflected in the spatial pattern of landforms in the Rannoch Moor basin. This study will use digital photogrammetry and GIS to produce maps and three dimensional images to assess the spatial organisation and genesis of the glacial landforms of Rannoch Moor. Mapping and interpretation of landforms on Rannoch Moor will ascertain whether the moor was a centre of ice accumulation during the Loch Lomond Stadial, or if glacier ice developed in the surrounding mountains and converged on the Rannoch Moor basin. No maps of the glacial landforms of Rannoch Moor have previously been published.

5.2 Methods

5.2.1 Geomorphology

The hummocky moraines of Rannoch Moor were mapped and digital elevation models produced for the area using digital photogrammetry. Eight aerial photographs at a scale of approximately 1:24,000 were required to give stereo coverage of the field area. Aerial photographs beyond mapped areas were studied, but few moraines were recognisable and it was not thought to be cost effective to produce orthophotos for these areas. Twelve GPS control points were measured in the field, using differential GPS, which provided an adequate coverage for the photogrammetric process (fig 5.4). Some areas of Rannoch Moor were not accessible due to deep water channels in the thick peat, which covers large areas of the moor. Access was also restricted due to the foot and mouth disease outbreak at the time of the survey. Tie points were used during the photogrammetric process to compensate. Problems were also encountered in moorland areas when locating suitable control points visible on the aerial photographs.

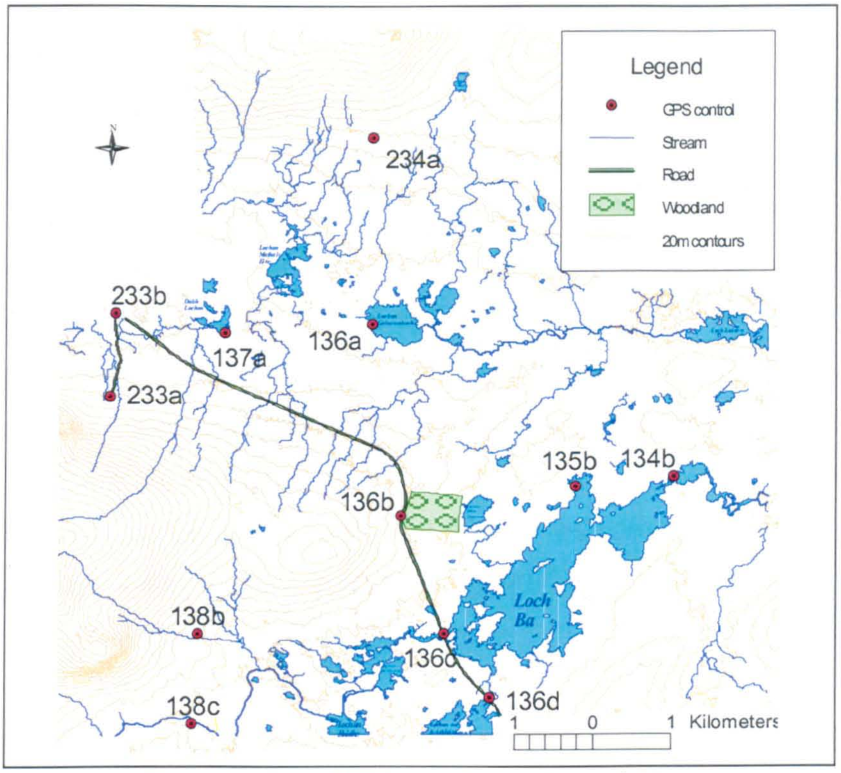
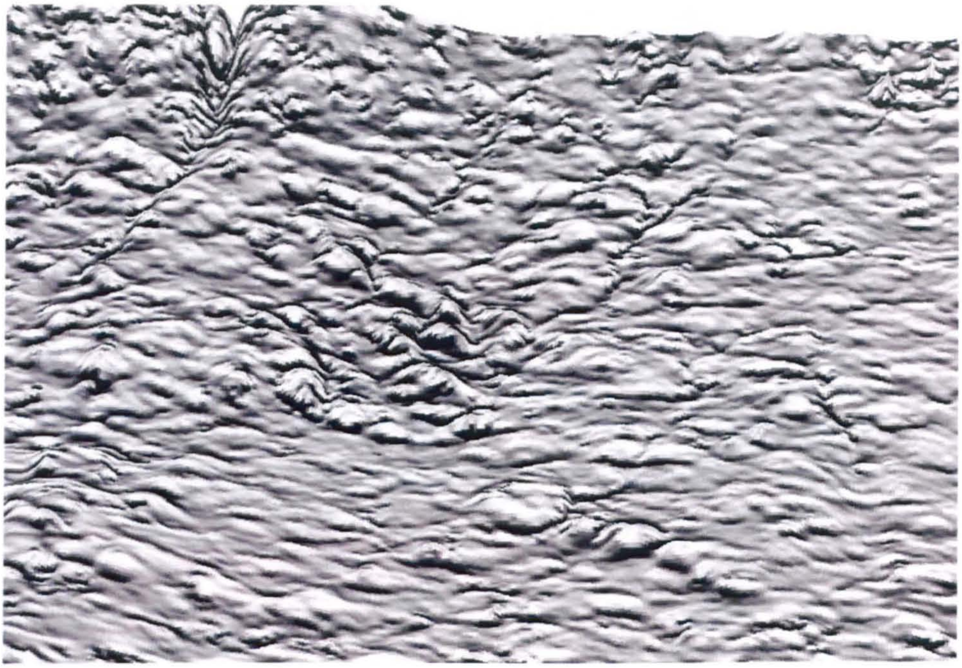


Figure 5.4 Map of GPS control points Rannoch Moor

The aerial photographs and GPS ground control were used to create an orthoimage mosaic and digital elevation model. Hummocky moraine on Rannoch Moor was mapped using three dimensional visualisation techniques in the photogrammetric software Helava Leica Socet Set. The mapped features were imported into the GIS for further processing and cartographic enhancement. Where glacigenic landforms were sufficiently large these were mapped as closed polygons. Smaller features and the crests of ridges were mapped as line features. To reconstruct iceflow directions it was necessary to include a wider area to determine the influence of the topography surrounding the Rannoch Moor basin. This was carried out using data downloaded from the Ordnance Survey Digimap web site, including raster map data at a scale of 1:50 000 and digital elevation models with a resolution of 50m. This was imported into ArcView and combined with the data and maps produced photogrammetrically. Although the Ordnance Survey data gave a wider coverage and was useful in the interpretation of moraines and for reconstructing palaeo-iceflow, it was not found to be suitable for mapping moraines or for three dimensional visualisation of landforms. Mapping and visualisation techniques employed the higher resolution D.E.M.s produced by digital photogrammetry.

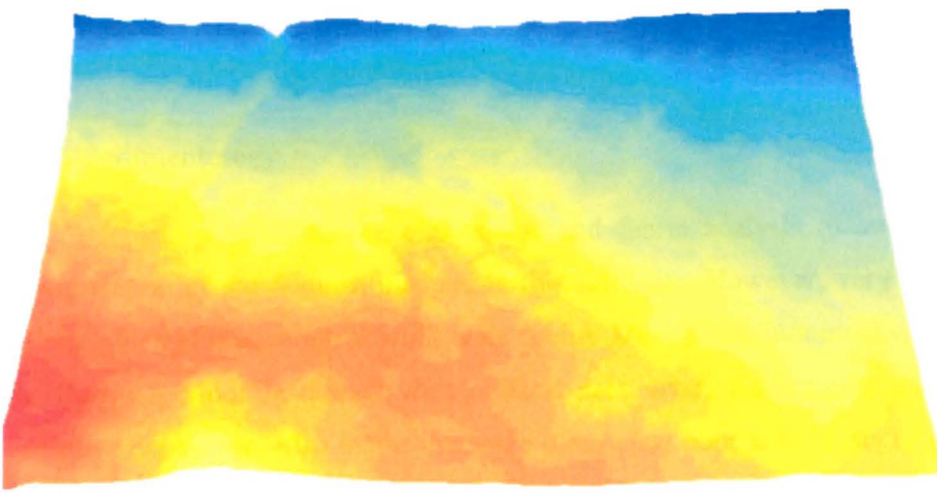
Visualisation techniques using the D.E.M. of Rannoch Moor, produced by photogrammetry were investigated. Techniques included coloured contouring, hillshading and aspect maps. Similar to the work carried out on the D.E.M. of Glen Torridon, the landforms appeared as a grain and recognition of individual features was problematic. Coloured contour maps again showed little of the geomorphology, probably for similar reasons to the Torridon D.E.M.s (see Chapter 4.2.1). Features could be recognised on the images depicting aspect, but it was difficult to recognise the boundaries of features in these images. Representations of the D.E.M. including hillshading, coloured contours and an aspect map for a sample area, on the north-west of Rannoch Moor, are shown if figures 5.5, 5.6 and 5.7.

Landforms were not as easily recognised on the orthoimages as they were on the images of the Torridon site. This may be due to the uniform nature of the peat covered surface of Rannoch Moor, or could be due to daylight conditions at the time of the aerial survey. The glacial landforms of Rannoch Moor were however clearly visible using the photogrammetric workstation with built in stereoscope. Using techniques including varying scale, contrast and brightness of the orthoimage combined with the D.E.M. it was possible to recognise and map the landforms present on Rannoch Moor. As landforms and their spatial organisation are not in all cases clearly visible on the orthoimages, maps of the landforms are presented with the orthoimages in this chapter.



Approx. Scale 500m

Figure 5.5 Hillshaded D.E.M., north-west Rannoch Moor



Approx. Scale 500m

Figure 5.6 Hysometric colour 3D image, north-west Rannoch Moor

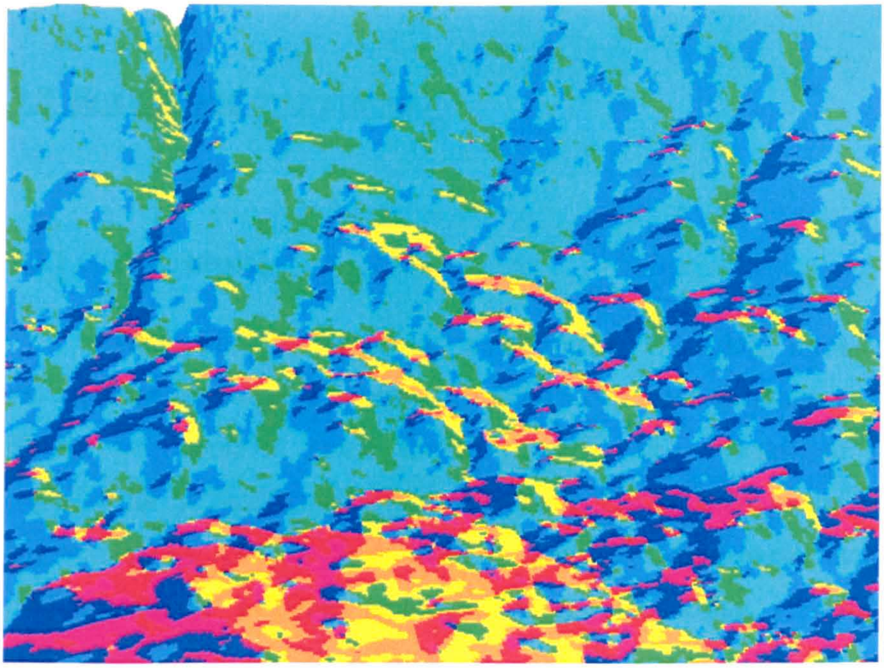


Figure 5.7 Aspect map (3D image), north-west Rannoch

See Fig 5.19 for location of images 5.5 to 5.7

5.2.2 Sedimentology

It was planned to use clast shape and fabric analysis to assist in the interpretation of the features mapped in this field site. However, very few sites suitable for sedimentological work were found. Most of the hummocky moraine on Rannoch Moor is draped with a thick peat layer, resulting in a lack of sediment exposures. Also exposures were often clast poor with clasts of granite that had degraded in situ and were therefore not suitable for clast shape and fabric analysis. Large areas of the central part of the moor were inaccessible due to waterlogged peat incised by deep channels. Only two suitable sites were found for clast analysis, in exposures cut through the peat and underlying diamict for track construction. These were located to the north-east of Kingshouse. Borehole records, obtained from the British Geological Survey were examined. Borehole records were only available for an area next to a road bridge near Kingshouse. These revealed little useful information for the glacial history of the area.

5.3 Results and Interpretation

5.3.1 Geomorphology

When viewed on aerial photographs or using three-dimensional visualisation techniques the glacial landforms deposited on Rannoch Moor show distinct but complex linear spatial patterns. An overview of the spatial organisation of landforms on Rannoch Moor can be seen in the orthomosaic below (fig5.8). Glacial landforms on Rannoch Moor were mapped using photogrammetric software employing three dimensional viewing using an orthoimage and digital elevation model. The pattern of landforms can be seen more clearly using the mapped features overlain on the orthophoto (fig5.9)

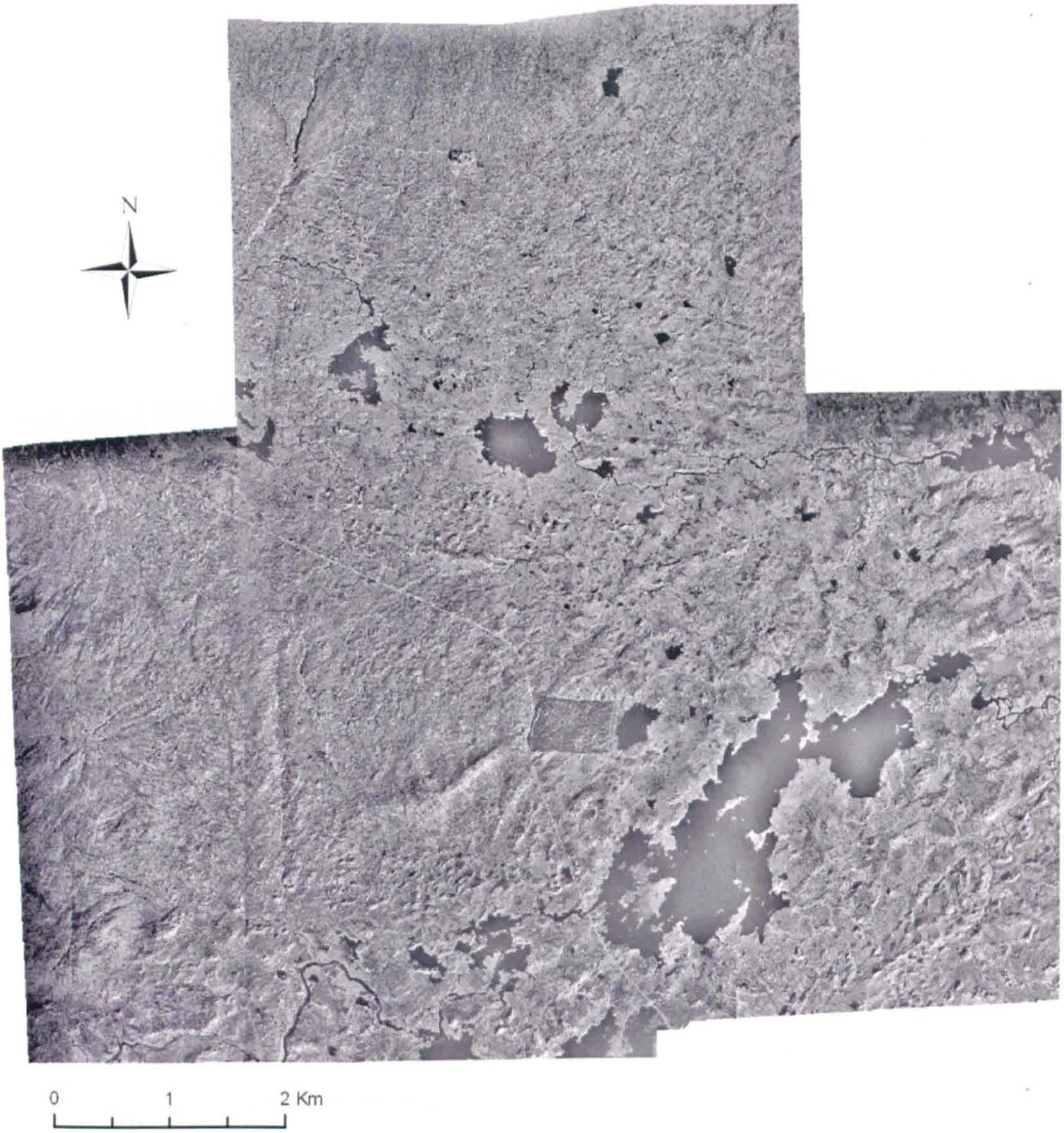


Figure 5.8 Orthomosaic, Rannoch Moor

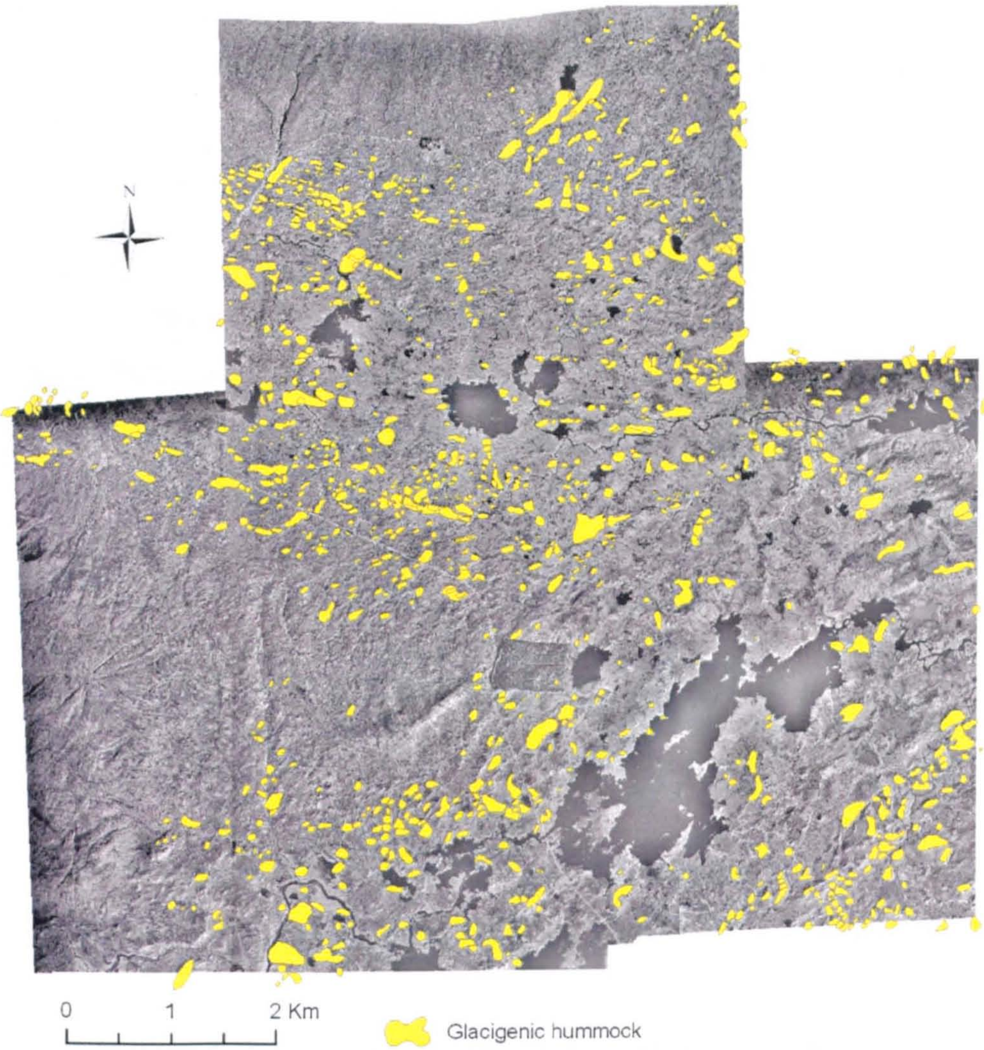


Figure 5.9 Orthomosaic with mapped glacial landforms

A west to east trending pattern of landforms can be seen in the valley of the River Ba, in the southern part of Rannoch Moor. These continue to the east side of Loch Ba. (figs 5.10, 5.11). Based on volcanic erratics Thorp (1986) suggested that ice from the mountains to the west of Loch Ba flowed down the valley of the River Ba as far as the north-eastern side of the loch. Thorp did not discuss the lithology or exact source of the erratics. Hummocky landforms are particularly abundant in the Ba valley especially on its north side (figs 5.11 and 5.12). The hummocks can be traced from the Ba Valley along the northern side of Loch Ba and on the slopes above the south shores of the loch on Glas Beinn and Leathad Beag. At the north-eastern side of Loch Ba, moraines with both cross-valley and down valley orientations occur. The moraines in the valley and on the hillsides and the cross-valley moraines suggest that the area was occupied by a glacier, possibly with its source in the mountains to the south-west of the Ba Valley.

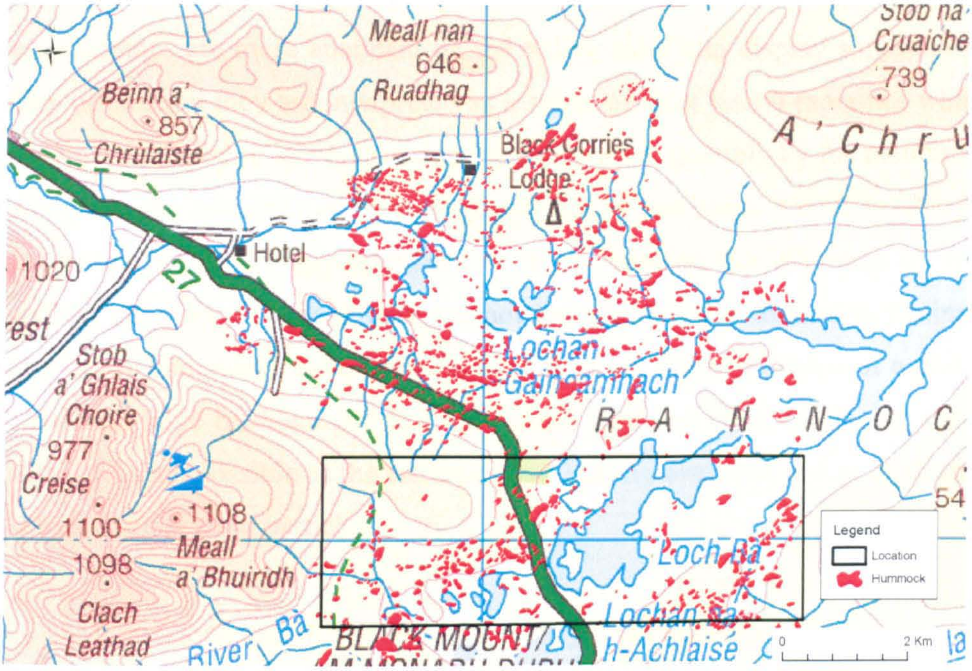


Fig 5.10 Location of moraines, Ba Valley

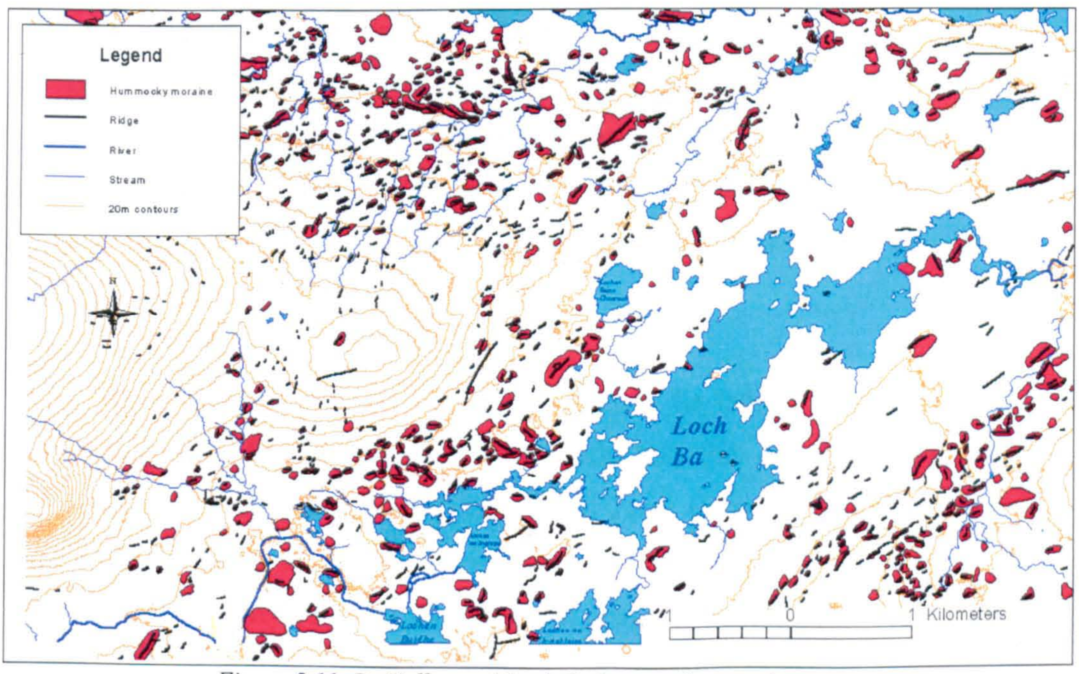


Figure 5.11 Ba Valley and Loch Ba hummocky moraine

Although some orientation of the moraines can be seen, especially on the north side of the Ba Valley and the slopes above Loch Ba, down-glacier orientation of these features is less pronounced than was found in Torridon. As these moraines are more abundant on the valley sides and display some down-valley orientation they are interpreted as a series of inset lateral moraines which have been degraded to leave a hummocky appearance, possibly by the meltout of ice-cores in the moraines or by post-glacial fluvial and slope processes. As the features are not as strongly orientated as those found in Torridon and are less abundant on the valley floor they are not thought to have formed as flutings. Some of the hummocks have been quarried showing them to consist of a gravel matrix with large boulders and few clast sized particles. Clast fabric and shape analysis was not possible as the exposures are heavily disturbed due to quarrying and lack of clast sized particles.

Moraines on the floor of the Ba Valley include down-valley and cross-valley orientated features but lack a consistent spatial pattern. Down-valley orientated features are thought to represent subglacially deposited and streamlined landforms, while the cross-valley features possibly mark standstill positions during active retreat of the glacier back into the corries to the east of the Ba Valley. No evidence of glacier readvances, such as fluted moraine surfaces, was found in this area. Any readvances of the glacier margin were not substantial enough to override previously deposited landforms, although it is possible that some of the cross-valley features could have been subject to pushing, as was suggested by Boulton (1992).

Elongate features to the north-west of Loch Ba indicate that ice flowed out of Rannoch Moor to the east. It is likely that this occurred before the deposition of the moraines around the area of Loch Ba and the Ba Valley, as there is no evidence of the Ba moraines being overridden. However, as these moraines are now covered by a thick layer of peat it is possible that evidence of readvancing, for example fluted moraine surfaces, may not be visible.

Moraines to the south of Loch Ba, on the slopes below Lochan Sidhean Duibh and Leathad Beag, display a linear spatial pattern, although they do not have a streamlined morphology (figs 5.13 and 5.14). These moraines are at a similar altitude (310m) to the moraines on the north side of the Ba Valley and are interpreted as the remnants of lateral moraines possibly deposited contemporaneously with the moraines on the north side. "Hummocky moraine" on the slopes below these lateral moraines displays a more linear, down-valley orientation and is therefore interpreted as an area of streamlining or flutings relating to the Ba Valley ice. It is also possible that some of these features relate to ice flowing out of the Rannoch Basin to the south towards the Glen Tulla area, however this area is beyond the limits of the aerial photography used in this study.

Figure 5.12 3D orthoimage showing lateral moraines north of Loch Ba

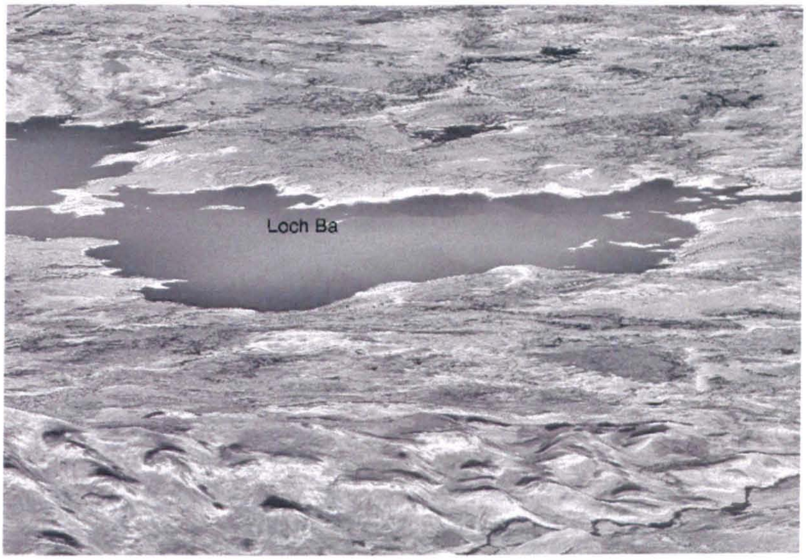


Figure 5.13 3D orthoimage showing lateral moraines south of Loch Ba

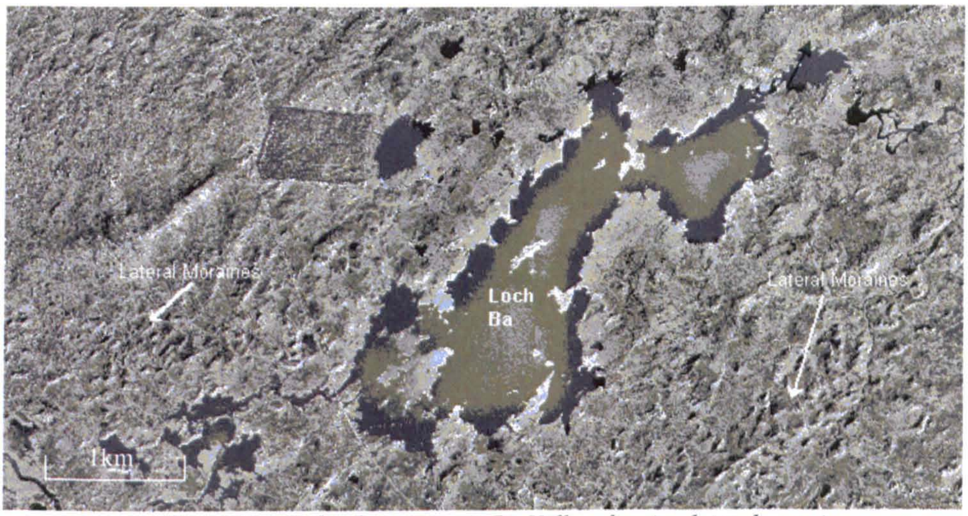


Figure 5.14 Orthophoto extract, Ba Valley showing lateral moraines

To the north of Beinn Chaorach streamlined ridges trend from the col to the south-west (figs 5.15, 5.16, 5.17) and from the slopes leading to Coire Pollach (white corries) on the eastern side of Meall a' Bhuiridh. The streamlined features, which can be traced west towards Coire Pollach, are less numerous than those emanating from the col west of Beinn Chaorach. It is likely that ice from the Ba Valley breached this col and flowed towards Rannoch Moor. The spatial pattern of streamlined landforms also suggest ice flowed onto the moor from Coire Pollach (fig 5.15).

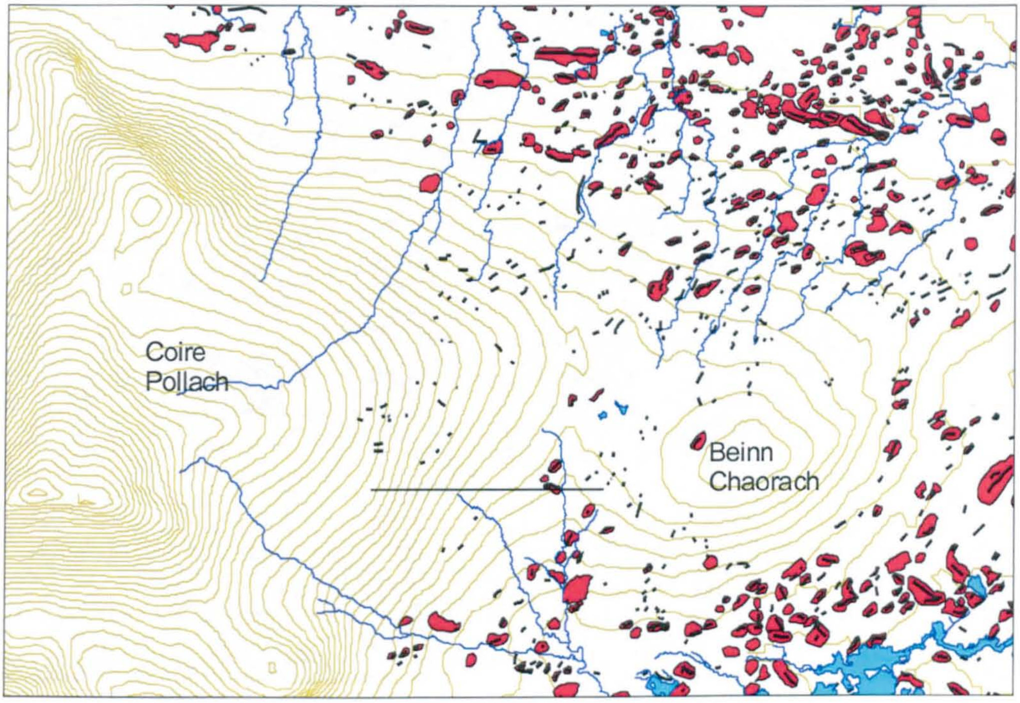


Figure 5.15. Glacial landforms west of Rannoch Moor

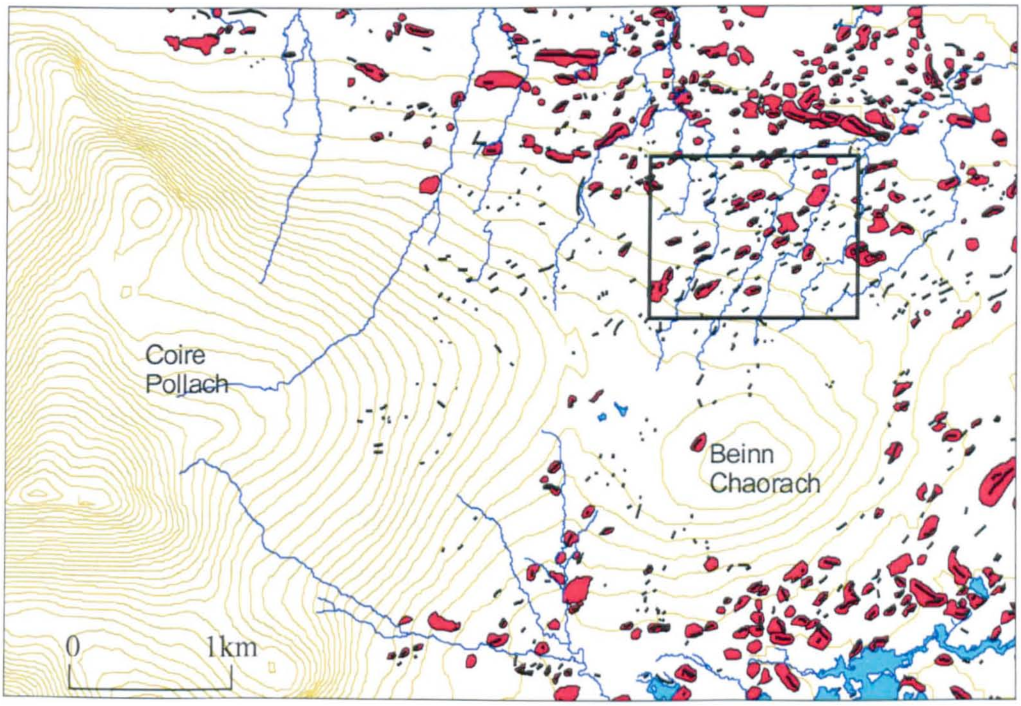


Figure 5.16 area of orthophoto extract fig 5.17

Figure 5.17 Orthophoto extract showing streamlined features suggesting ice flow from a col NW of Beinn Chaorach.

Below the white corries, on the floor of Rannoch Moor, some larger depositional features display an east-west orientation. These are interpreted as the products of ice flow out from the Rannoch basin towards Glen Etive. In the centre of the Rannoch Basin, moraine coverage is less dense, especially in the area north of Lochan Gaineamhach.

Glacial features in the north-west of Rannoch Moor have a streamlined morphology with a north-west to south-east orientation (figs 5.18 to 5.21). The spatial pattern and morphology of these features suggests they were deposited subglacially, possibly by ice moving out of the Rannoch Moor basin towards Glen Coe. Alternatively, the lineation in these features could represent ice moving on to Rannoch Moor in a south-easterly direction. These features are interpreted as flutings.

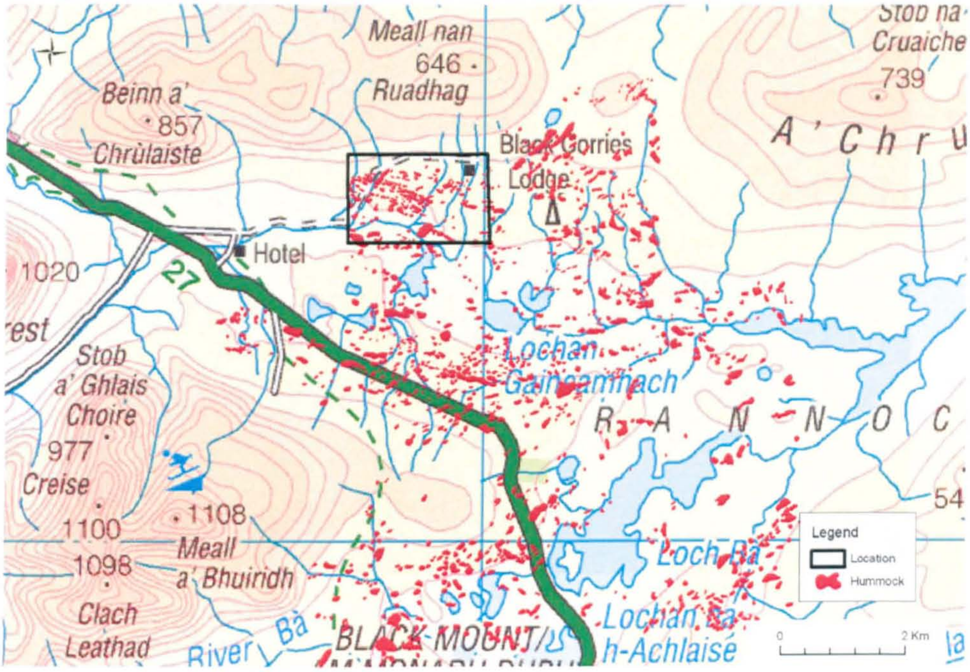


Figure 5.18 Location of streamlined landforms, north-west Rannoch Moor.

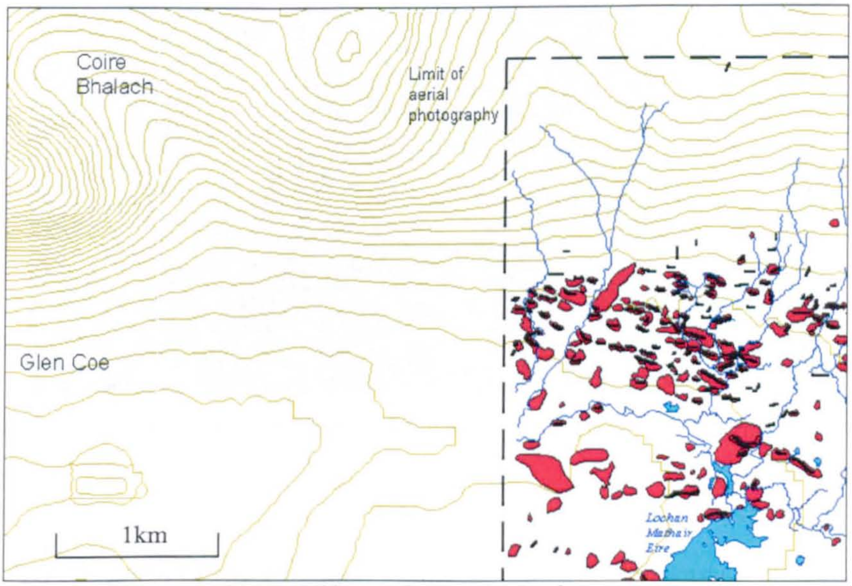


Figure 5.19 north-west Rannoch Moor

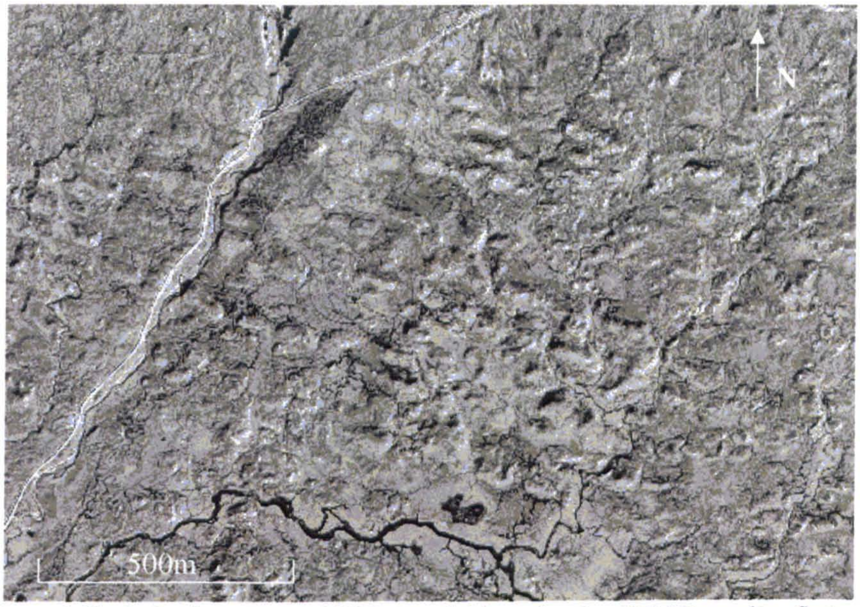


Figure 5.20 Orthophoto extract NW Rannoch Moor showing NW-SE trending flutings.

Figure 5.21 3d Orthoimage of north-west Rannoch Moor, showing NW-SE trending flutings.

To the north of the Rannoch Basin moraines were mapped crossing a col to the west of Stob na Cruaiche (figs 5.22, 5.23). The features can be traced from the col on to the summit of Meall a Phuill (448m), and trend towards lower ground to the north side of the col. The col and surrounding slopes however have no obvious areas of suitable topography for ice accumulation. It is therefore likely that these landforms were produced by ice flowing out of the Rannoch Moor basin. This would suggest that ice on Rannoch Moor reached an altitude of over 448m. Thorp (1986) suggested that ice on Rannoch Moor reached an altitude of 700m, based on trimline and periglacial evidence.

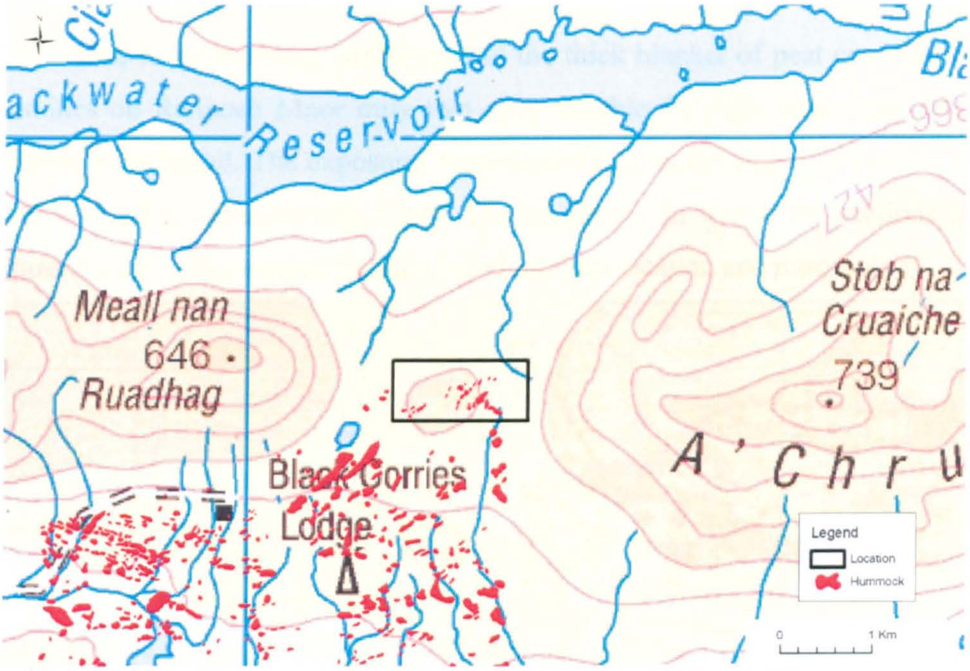


Figure 5.22 Location of streamlined landforms in col, north-west Rannoch

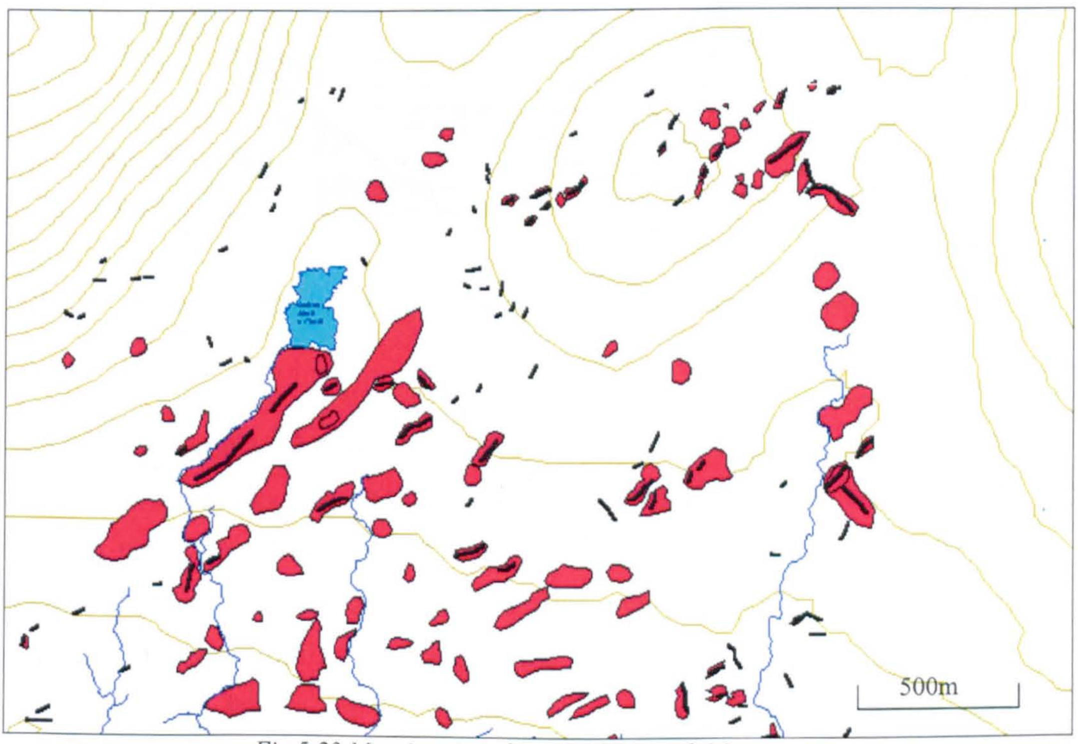


Fig 5.23 Moraines in col north of Rannoch Moor

5.3.2 Sedimentology

Due to accessibility problems and the thick blanket of peat covering the moraines on Rannoch Moor only two sites suitable for clast shape and fabric analysis were found. The exposures were in cuttings on the side of a track to the north-east of Kingshouse (fig 5.24). The landforms in which the sections are exposed were interpreted as flutings based on their location and morphology.

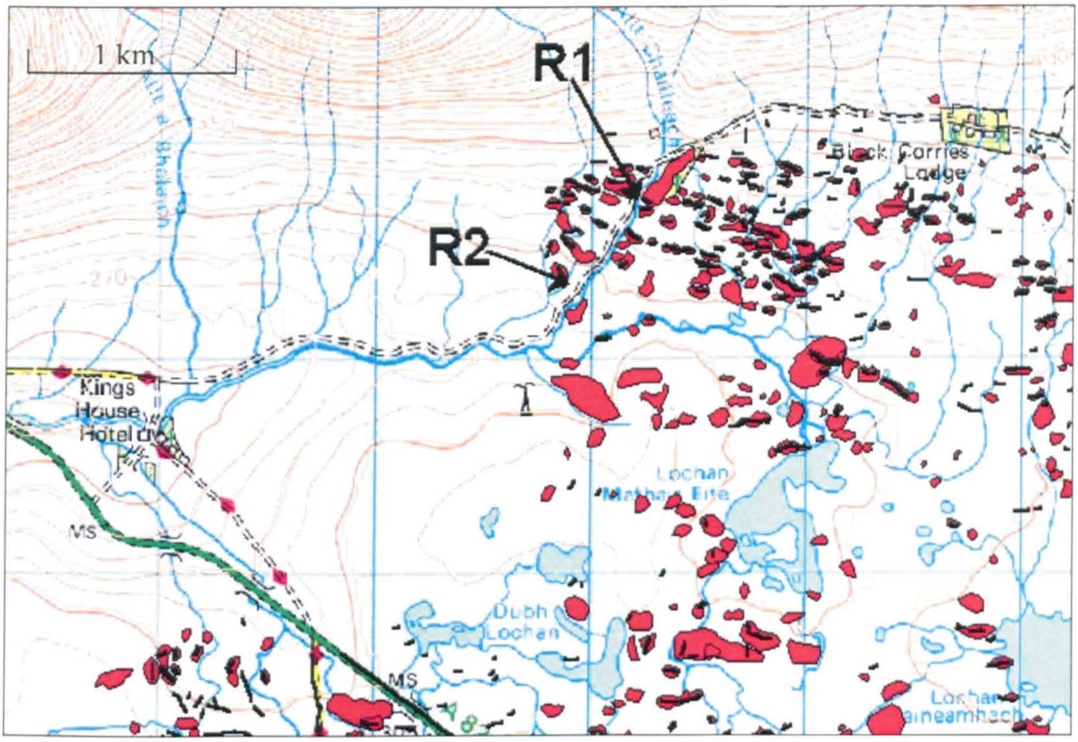


Figure 5.24 Map of NW Rannoch Moor showing location of clast samples

Clast sample R1 was taken from a narrow exposure, not large enough to reveal any structure. The section is cut in the south-east end of a SE-NW trending ridge. The diamict in the section is matrix supported with a matrix of sand and gravel with clasts of granite. Clast sample R2 was taken from an exposure in a hummock to the south of the location of sample R1. The sample was taken from the top of the section due to slumped material below. The diamict in the section was clast poor with a sandy matrix, and was poorly consolidated. Clast angularity for both samples was subrounded to subangular suggesting the clasts had been subject to active transport (fig5.26). Clast shape, plotted on ternary diagrams (fig 5.26), is comparable to published ternary diagrams of samples interpreted as tills (Benn & Ballantyne 1994). Clast shape and angularity were also plotted on a C40:RA index plot (fig 5.25. This allowed a comparison with data collected by D. Benn (unpublished thesis) for clasts of granite, including samples interpreted as scree, lodgement till and of a fluvial origin. The clast samples from Rannoch Moor plot in a similar area to Benn's lodgement till samples, suggesting a similar transport path.

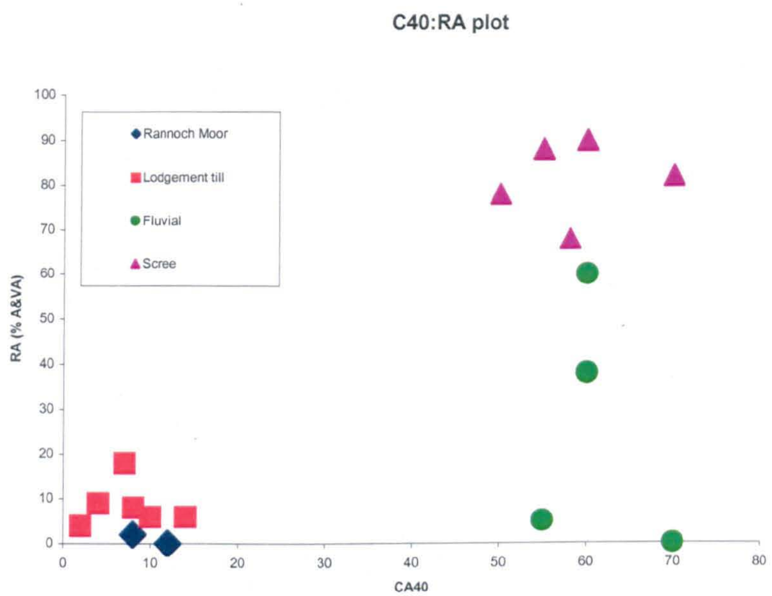


Figure 5.25 C40:RA plot, Rannoch Moor

Clast fabrics show weak preferred orientations dipping to the north-west (fig 5.26), indicating a south-easterly ice flow direction. Fabric shapes plot within the envelopes for deformation till and debris flow deposits (Benn 1994). Clast shape and fabric data are consistent with the interpretation of the landforms as being formed subglacially as flutings. The orientation of the fabric, although not strong, is near parallel to the crests of the flutings, which have an orientation of 288°. Fluting orientation is depicted on the Schmidt diagrams in Fig 5.26

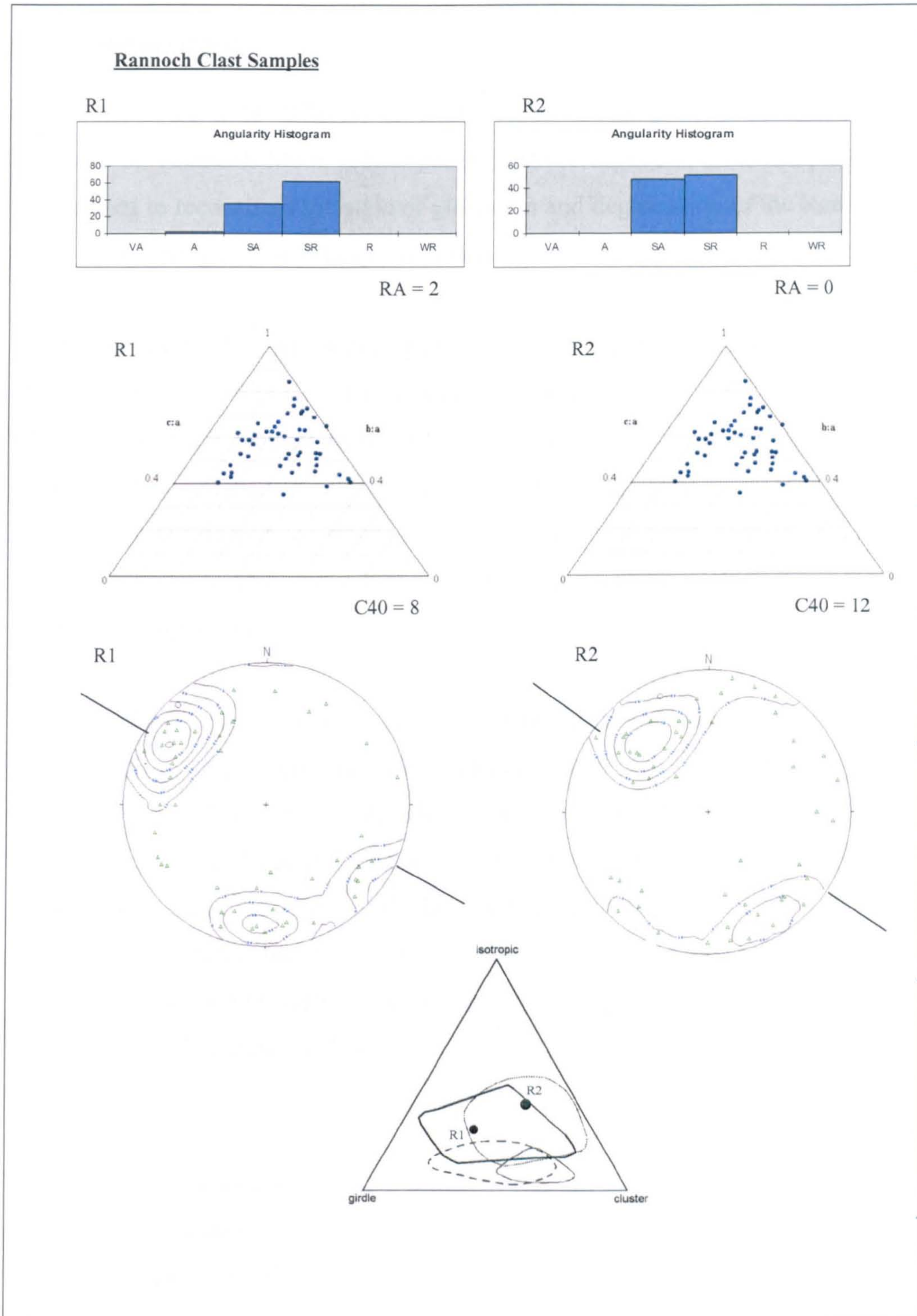


Figure 5.26 Clast sample clast shape and fabric diagrams

5.3.3 Interpretation

Although it is difficult to interpret the exact genesis of individual moraines on Rannoch Moor spatial patterns of moraines and their morphology can be used to reconstruct the style of glaciation and deglaciation of the Rannoch Moor basin during the Loch Lomond stadial.

Lineations in the spatial patterns of the "hummocky moraine" on Rannoch Moor can be used to reconstruct and map glacier ice flow directions. They are therefore thought to have been produced by glacial streamlining by advance from and active retreat into the surrounding corries. There is no evidence of widespread ice stagnation at the end of the Loch Lomond Stadial. Some features with no obvious spatial pattern may however relate to some local areas of ice stagnation.

Lineations in the patterns of the moraines suggest glacier ice moved onto Rannoch Moor, mainly from the west, especially from the mountains situated at the head of the Ba Valley. Possible sources of ice accumulation in these mountains are the large north-east facing corries on their eastern slopes, including Coireach a' Ba, Coire Dhomhnail, Coirein Lochain and Coire Creagach. This area is likely to have been a major accumulation centre. Ice also flowed from the white corries area towards the centre of the moor, probably coalescing with ice from the Ba Valley that breached a col to the west of Beinn Chaorach.

Landforms interpreted as flutings in the north-west of Rannoch Moor suggest ice either flowed out of the moor in a north-westerly direction or onto the moor in a south-easterly direction. Clast fabrics from the flutings show a preferred orientation parallel to the fluting crests also suggesting a north-westerly or south-easterly ice flow direction. However the suggested ice direction based on clast fabrics is tentative as it is based on only two relatively weak fabrics taken from poorly exposed sections. A large south-west facing corrie to the north-west of this site, Coire Bhalach on the eastern slopes of Beinn Chrulaiste is a possible source of ice that formed the flutings.

There is little evidence of Loch Lomond Readvance ice descending from the mountains to the north of the Rannoch Moor basin in a southward direction. The only possible exception to this was ice flowing in a south-easterly direction from Coire Bhalach. This suggests that the ice that accumulated on Rannoch Moor mainly had its source in the mountains to the west. There are no corries on the south-west facing slopes of Beinn Cruaiche and Stob nan Losgain to the north of the moor. The only corries on these mountains are The Black Corries, which are north-east facing and therefore do not face onto the moor.

The main ice accumulation centres for Rannoch Moor are were probably in the mountains to the west especially at the head of the Ba Valley, with only one corrie supplying ice to the moor from the north. There is no evidence that glacier ice accumulated in the Rannoch Moor basin, but was nourished in the mountains to the west of the moor and flowed onto the moor where it coalesced with ice from the less important accumulation areas of the White Corries and Coire Bhalach. Rannoch Moor is seen here as a centre for glacier ice convergence and not as a centre of glacier ice development. Although there are some areas of Rannoch Moor with less numerous landforms, on most areas of the moor "hummocky moraine" is abundant. If the Rannoch Moor basin had been a major centre of ice development, ice velocities in the vicinity of the ice divide would be low (Nye 1951) and the production of abundant "hummocky moraine" would have been unlikely. It is therefore more likely that these landforms were produced by ice flowing onto the moor from the surrounding mountains, producing subglacial landforms and marginal moraines.

Ice accumulation in the mountains to the west was also suggested by Thorp (1986). The dominance of ice from the western mountains can be explained by the larger and more numerous corries on the east facing slopes. This can be contrasted with the lack of large corries facing onto the moor on the mountains to the north and north-east. The north-east orientation of corries in the area can be explained by south-westerly precipitation bearing depressions which feed snow to the lee side of the mountains. Previous studies of corrie orientations in the British Isles have found a predominantly north-east orientation due to south-westerly low pressure weather systems (Seddon 1957, King & Gage 1961, Temple 1965, Sissons 1967a, Unwin 1973, Bennett 1990). Maps were produced of likely ice flow directions into the Rannoch Moor basin from the western corries and Coire Bhalach (fig 5.27). Ice directions are based on the glacial geomorphology mapped in this study correlated with previously published work including studies of erratics (Sissons 1967, Thorp 1991b)

Although some features transverse to ice flow, such as those around Loch Ba and in the Ba Valley, do not show any evidence of being overridden, suggesting they were produced during deglaciation, it is difficult to separate features produced during ice advance early in the stadial from those produced during deglaciation.

It is proposed that ice from the corries flowed into the Rannoch Moor basin during the early part of the Loch Lomond Stadial. Ice flowed out of the moor once a sufficient volume had accumulated to allow its dispersal into neighbouring valleys. Ice thickness suggested by Thorp (1986) would have been sufficient to force ice out of the Rannoch basin, and breach the col on the north side of the moor. A stage of corrie glaciation at the end of the Loch Lomond Readvance was suggested by Charlesworth (1956) for Rannoch Moor and other locations. Although a period of corrie glaciation following deglaciation of Rannoch Moor is speculative, the possibility of this occurring is consistent with the interpretation of the glacial geomorphology as indicative of active glacier retreat.

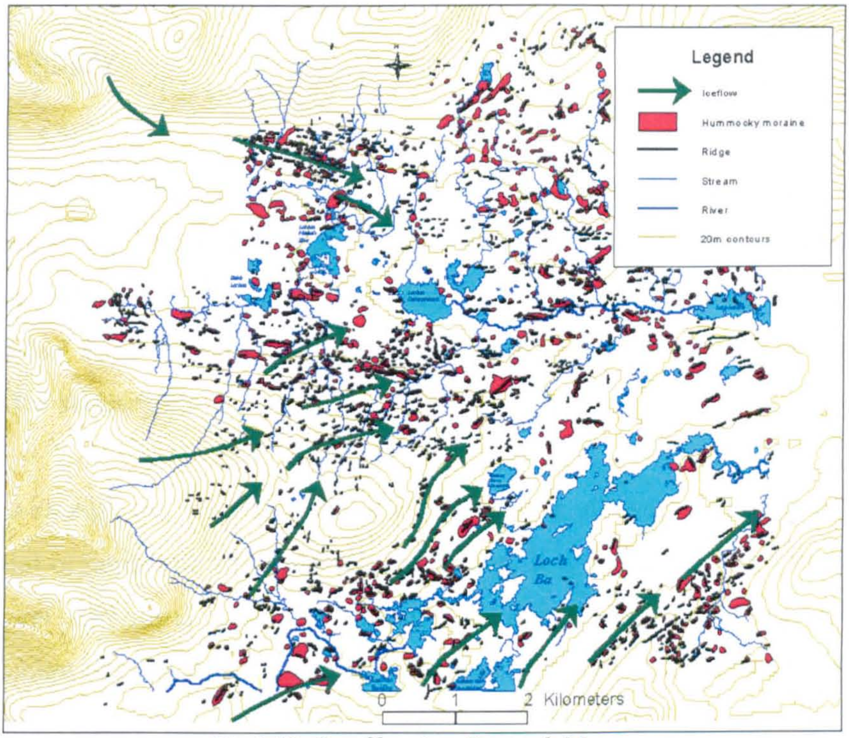


Fig 5.27 Ice flow into Rannoch Moor

5.4 Summary

Mapping the glacial landforms of Rannoch Moor, using digital photogrammetry and G.I.S. allowed the interpretation of spatial patterns of moraines, which exhibit linear patterns, thought to be indicative of active deglaciation. Some moraines with no linear spatial organisation may be evidence of local ice stagnation.

Although the work carried out at this site has allowed an interpretation of the spatial organisation of hummocky moraines, it was found to be problematic to interpret individual landforms due to their morphology being masked by a thick blanket of peat, and the lack of sediment exposures limiting the collection of sedimentological data.

Lineations in the spatial organisation of glacigenic landforms suggest ice flowed towards the Rannoch Moor basin from the large corries to the west and south-west of the moor. An area situated at the head of the Ba Valley with numerous large corries around the ridge of Aonach Mor, Stob Choire Odhar and Beinn Toaig appears to have been a major area of glacier ice accumulation. Ice from this area flowed towards Rannoch Moor along the valley of the river Ba. This ice converged in Rannoch Moor with ice flowing from less important accumulation areas of the white corries to the west the moor and Coire Bhalach to the north-west of the moor. Once a sufficient volume of ice had accumulated in the Rannoch Moor basin ice flowed out of the basin especially towards Glen Coe and Glen Etive to the west and towards Loch Laidon in the east. It is possible that a period of corrie glaciation followed the deglaciation of Rannoch Moor near the termination of the Loch Lomond Stadial, with ice flowing from the western corries with a similar ice flow pattern to that of the early Loch Lomond Stadial. A period of corrie glaciation has been inferred by previous workers at this site (e.g. Charlesworth 1956).

Similar to the Torridon site, the use of digital terrain models for visualisation and interpretation of glacial landforms was found to be problematic. A more detailed study of the morphology of the landforms of Rannoch Moor would have been interesting, but was not possible due to the lack of detail on images derived from the D.E.M. However, the D.E.M. combined with the orthomosaic, using the photogrammetric software and stereoscope, allowed the landforms to be mapped, producing the first accurate map of the glacial geomorphology of the Rannoch Moor basin, and interpretation of the spatial organisation of these features.

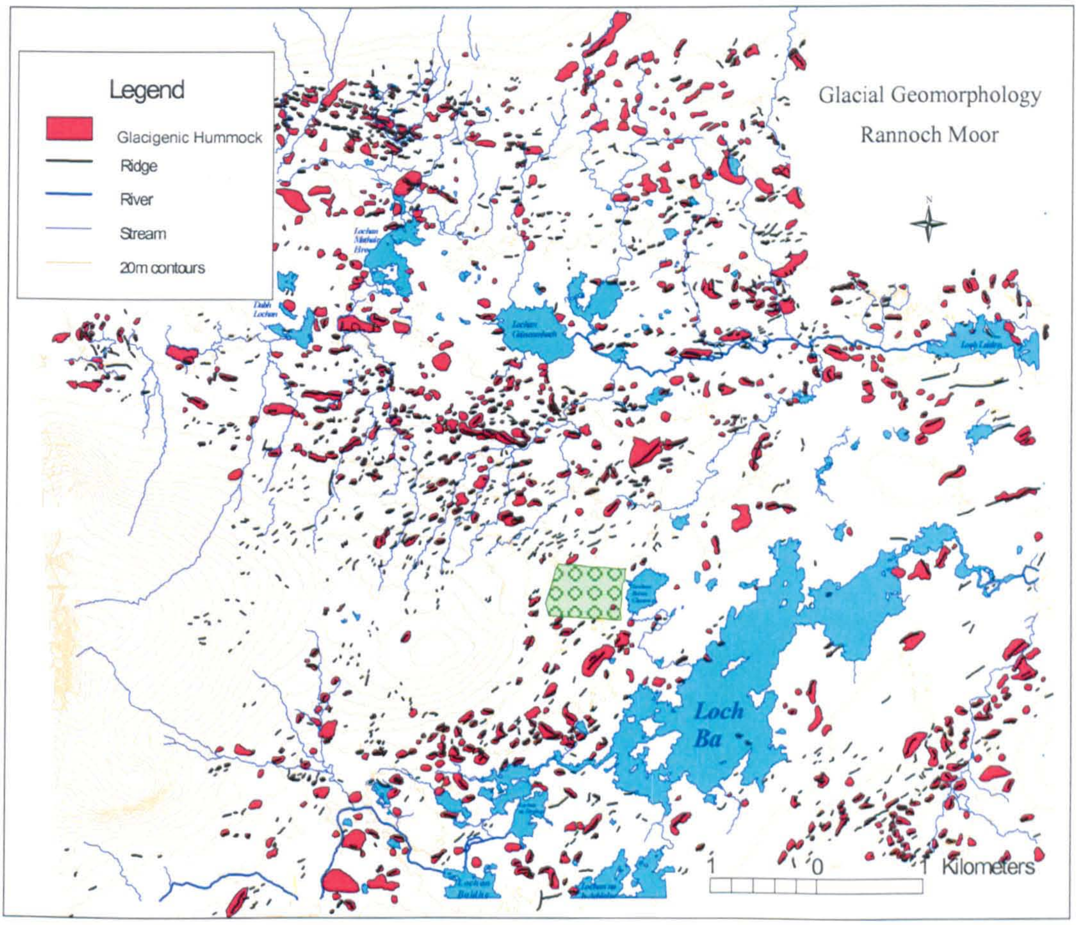


Fig 5.28 Rannoch Moor glacial geomorphology

6

Tyndrum and Strath Fillan

6.1 Introduction

6.1.1 Location

Tyndrum is situated in the south-west Highlands approximately 20km south of Rannoch Moor. The study area stretches from Tyndrum village in the north-west, along the north-west to south-east trending wide valley of Strath Fillan to the village of Crainlarich. The western part of Glen Dochart, to the east of Crainlarich is also included in this study area (figs 6.1, 6.2). The valleys of Strath Fillan and Glen Dochart are surrounded by mountains on all sides including Ben Challum (1025m) and Beinn Odhar (901m), Beinn Chaorach (818m) and Beinn nan Imirean (849m) to the north, Ben More and Stob Binnien (1174m, 1165m) to the south, and Ben Lui (1130m) Ben Os (1029m) and Beinn Dubhchraig (978m) to the south-west.

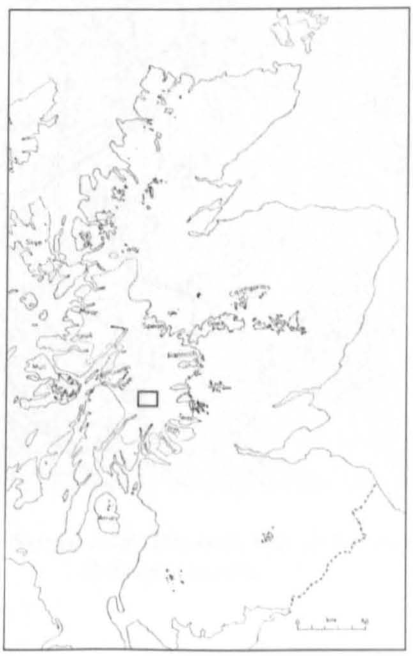


Figure 6.1 Location of Tyndrum field site and extent of Loch Lomond Readvance (adapted from Sissons 1974)

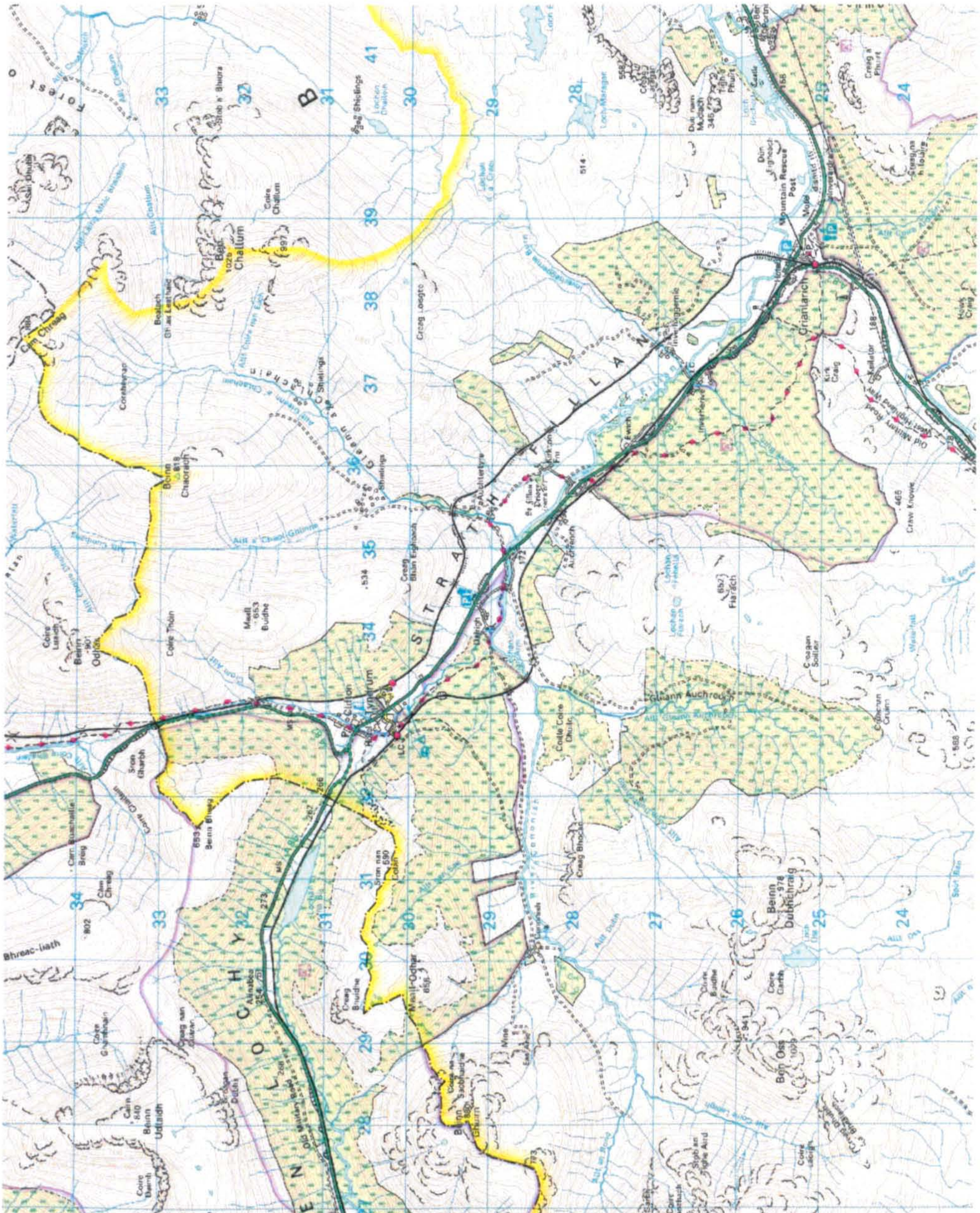


Figure 6.2 Extract from Ordnance Survey 1:50 000 series map of Rannoch Moor (© Crown Copyright Ordnance Survey)

6.1.2 Geomorphology

The geomorphology of the wide flat bottomed valley of Strath Fillan is dominated by large hummocks, some with a conical appearance but more commonly exhibiting flat topped surfaces. These are especially abundant in the vicinity of the River Cononish to the south-east of the village of Tyndrum, but also continue along Strath Fillan towards Crainlarich where they are particularly abundant on the south side of the valley. In Glen Dochart these features are less abundant though still numerous and extend beyond the area of the field site, as far as the village of Killin and the western shores of Loch Tay. Large hummocks with a more streamlined morphology can be seen in the western part of Glen Dochart especially to the west of Loch Iubhair. Tributary valleys on the north side of Strath Fillan lead to large corries especially Gleann a' Chlachain, between Beinn Odhar and Ben Challum, and an unnamed col below Coire Challum on the east side of Ben Challum. Smaller hummocks can be seen on the upper slopes on the north side of Strath Fillan. The south side of Strath Fillan has less tributary valleys except the large valley of the River Cononish at its north-western end.

This site includes hummocky features, on the valley floor, in close proximity to features with larger flat surfaced features. Hummocks are located in varying topographic settings including the flat valley floor and on the steeper valley sides. This study will determine the origins of the hummocks and flat topped features and their relationship to glacier activity at this site, by studying their morphology and spatial organisation using digital photogrammetry and G.I.S. It will determine if the hummocky landforms on the valley sides are of a similar origin to the valley floor hummocks. This site is also useful for assessing the application of digital terrain modelling to geomorphological studies. It was concluded in the Torridon chapter that digital terrain modelling is problematic when used to model landforms deposited on steep slopes. This site will allow a comparison between applying these methods to steep sloped areas such as Torridon and the valley sides of Strath Fillan and the flatter areas of Strath Fillan and the Cononish Valley.

6.2 Methods

6.2.1 Geomorphology

Maps, three dimensional images of the glacial geomorphology, a high resolution (5m) D.E.M. and orthoimages of the area, were produced. Nine aerial photographs at a scale of approximately 1:24 000 were required to provide stereo coverage of this field site. Ground control was measured using differential Global Positioning Systems (DGPS). Problems were encountered when measuring the ground control points due to restricted land access during the foot and mouth outbreak of 2001. To overcome this problem ground control was measured where public roads allowed access (fig 6.3) and tie points measured during photogrammetric processing where ground control was not possible. The accuracy of the resulting orthoimages and maps produced was assessed by visually comparing the maps and orthoimages to digital ordinance survey data and were found to be highly accurate.

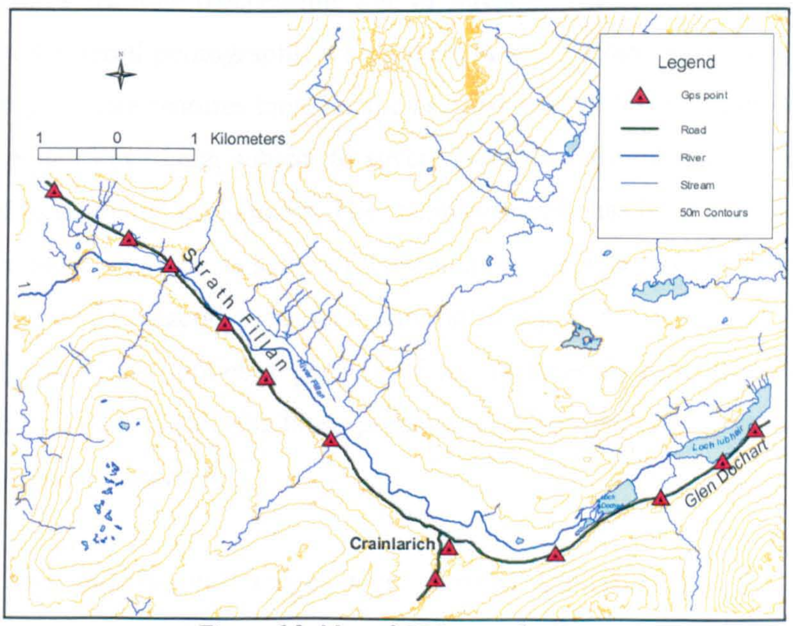


Figure 6.3 Map of GPS control points

A lower resolution (50m) D.E.M. covering a larger area was also used. This was obtained from Digimap, Ordnance Survey data archive. This was used to give an insight into the possible effects of the topography of the surrounding area. However the resolution of this D.E.M. was not high enough to allow studies of the glacial geomorphology of the area. Producing a 5m resolution D.E.M. with a greater coverage was considered too expensive and time consuming for this study. The D.E.M.s were used in ArcView G.I.S. to derive contours and produce hillshaded images to assist with interpretation of glacial landforms. The high resolution D.E.M. and orthophoto mosaic were used to create a 3D model of the site using ArcGIS ArcScene.

Mapping of the glacial landforms was carried out using three dimensional stereo viewing using the photogrammetric software, Helava Leica Socet Set. All the data produced were collated by importing into ArcView GIS. Provisional maps were produced and checked in the field and amended where necessary.

Features have been classified where possible for this site, and include glacifluvial features and moraines. Many of the hummocks mapped were difficult to interpret where they had no recognisable spatial pattern. Also many of these features are now inaccessible due to forestry. The features were however visible on the aerial photographs, which were taken in 1988 before the growth of the forestry. These features have been classified as undefined hummocks. Other features which have been subject to severe post-glacial modification have been classified as degraded hummocks. The term *hummocks* has been used here rather than hummocky moraine as some of these hummocks may have been formed by glacifluvial or subglacial processes and not formed as moraines. The term *hummocky moraine* implies a genesis of the features as moraines and in the absence of good evidence for these processes the non-genetic, descriptive term *hummock* has been used.

Three dimensional images were derived from the D.E.M., including hillshaded and coloured contour images (figs 6.5, 6.7, 6.8) and aspect maps (fig 6.6). Images produced for areas of the Tyndrum site with steep slopes gave similar results to the Torridon and Rannoch Moor sites, and were of little use to the recognition of individual glacial landforms. However individual landforms were visible in images produced for the Cononish valley area. Although the landforms were visible, their morphology was not clearly defined, and was more obvious on images of the orthophoto draped on the D.E.M. and on photographs taken in the field. This was especially the case for flat surfaced features, such as the terrace shaped features found on the east side of the Cononish valley. Unlike field based topographic survey, such as with a total station (combined electronic distance measurement and theodolite), D.E.M.s produced by photogrammetry consist of a regular grid of points. The points therefore do not necessarily fall on breaks of slope. This results in features appearing more rounded in the D.E.M. than on the ground.

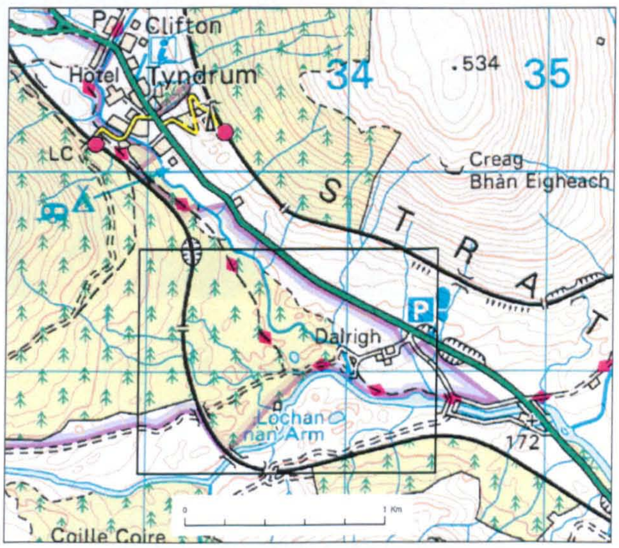


Figure 6.4 Location of 3d images, Cononish

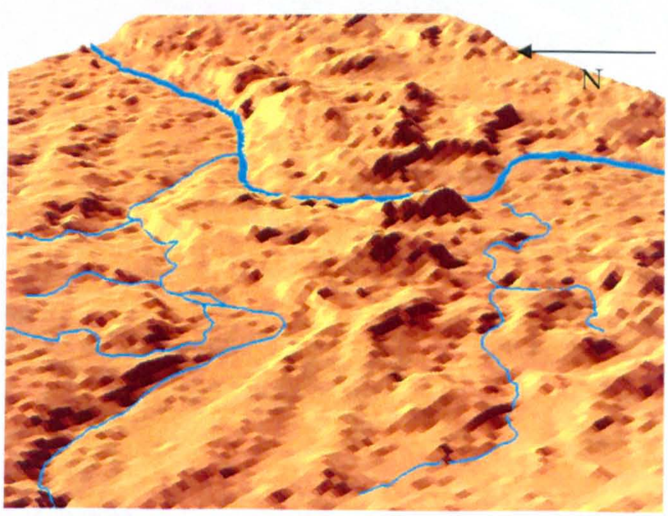


Figure 6.5 Shaded D.E.M., Cononish

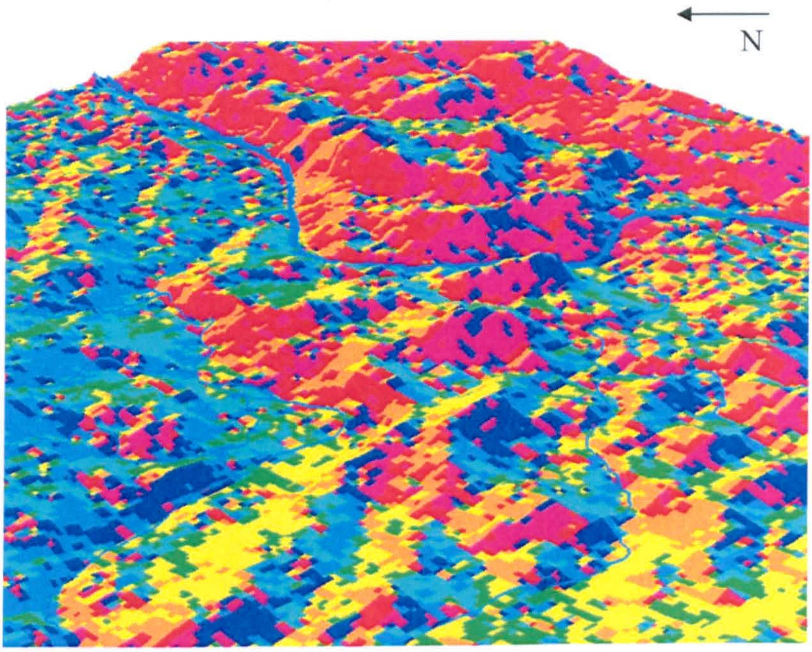


Figure 6.6 Aspect3D image, Cononish

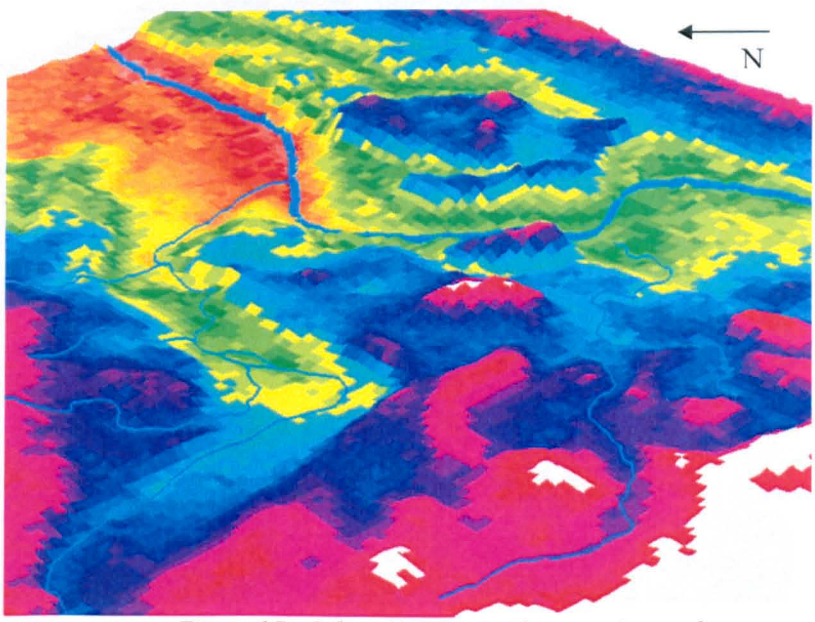


Figure 6.7 Colour 3D contoured image, Cononish

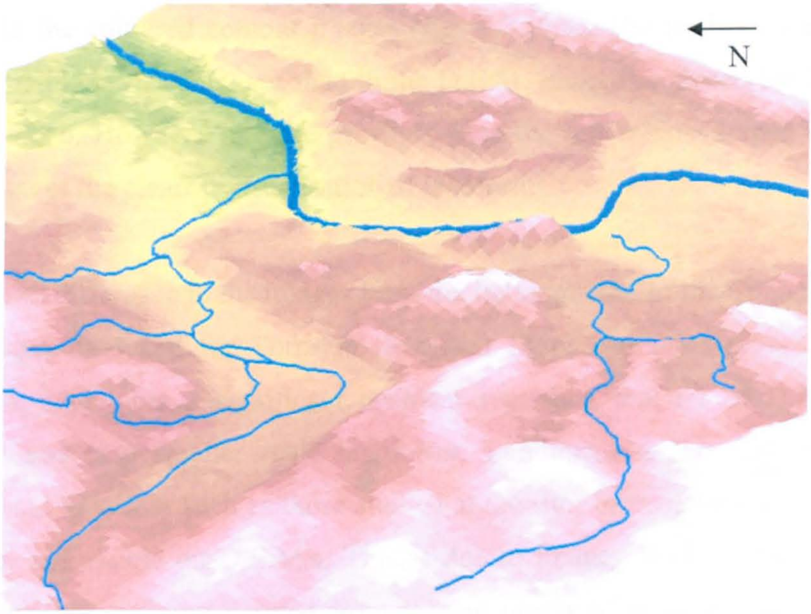


Figure 6.8 Colour contoured image, Cononish

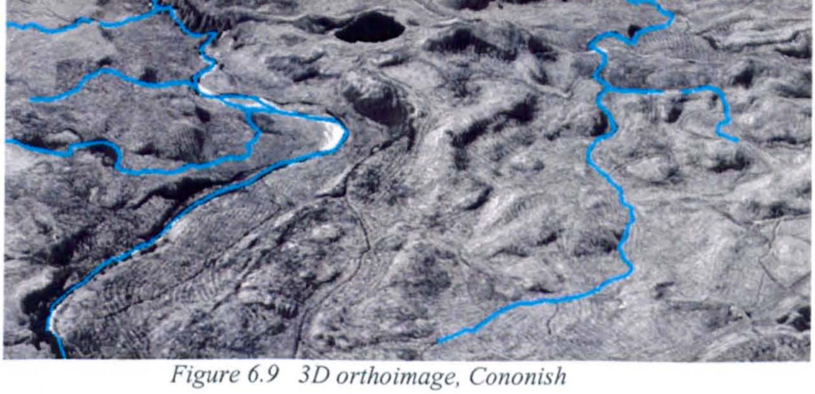


Figure 6.9 3D orthoimage, Cononish

Linear ridges and hummocks can be seen in the foreground of the shaded D.E.M. with a steep sided terrace in the background (fig 6.5). These features can also be seen in the aspect map, although not as clearly (fig 6.7). They are also visible in the coloured contour images (figs 6.7, 6.8). The landforms are more clearly visible in these images than in the D.E.M. images produced for Torridon and Rannoch. However like the previous sites the orthophoto draped over the D.E.M. gives the clearest visualisation of landforms.

The difference in the images from the flatter ground of the Cononish area, and images produced for Torridon, Rannoch Moor and the steeper areas of Tyndrum, highlights a significant problem regarding the use of D.E.M.s to interpret and map smaller scale landforms. Landforms at the scale of small flutings and moraines such as those studied at the sites investigated in this study, are often not visible on D.E.M.s. This is due to images, such as contoured or hillshaded images being derived from joining points of equal elevation. If the features are on steep ground the outline and crests of features may not be at the same elevation and are therefore are not joined by contours, or highlighted by hillshading. The nearest points at equal heights can be on an adjacent features. Any lineation in the image can therefore be due to joining points on different features and therefore give a false image of the geomorphology. The images of Cononish however do show some of the characteristics of the landforms as this is on less steep ground. The image presented in the methods chapter of a moraine in Iceland shows the feature clearly as it is situated on a flat surface (in this case a sandur). It is therefore concluded, from the images of Torridon, Rannoch Moor and Tyndrum that caution has to be exercised when using digital elevation models to interpret geomorphology in areas of steeply sloping ground.

Another problem found with steep ground was classifying coloured contour images. If small classes were chosen (e.g. 1 metre) a large number of classes would be required which is difficult for the viewer to understand, and difficult for the cartographer to choose enough distinctive colours. If larger elevation classes are used the heights are too generalised to reveal the nature of the geomorphology. In flatter areas this can be overcome by isolating small areas without great height difference. However this does not solve the problem where slopes are steep.

6.2.2 Sedimentology

Sedimentological data were collected at thirteen sample sites (fig 6.11) including clast fabric and shape analysis. Sediment exposures were not difficult to find at this field site and were reasonably accessible, except where features are located in forestry. Where sediments were thought to be too unconsolidated to preserve clast fabric or where the sediments had been disturbed only clast shape was measured.

Clast samples were compared to published clast shape and fabric data (Benn & Ballantyne 1994, 1993, Benn 1994, Benn & Evans 1996). Details of this data can be seen in the methods chapter (chapter 3). Clast samples were also compared to control samples from the field site. These samples included a sample of scree and a sample removed from a bedrock exposure by prising clasts from the bedrock with a crow bar (fig 6.10). This technique should produce clast characteristics similar to those produced by natural processes such as frost shattering or glacial plucking, as the rock will fail along fractures and other weaknesses in the rock.

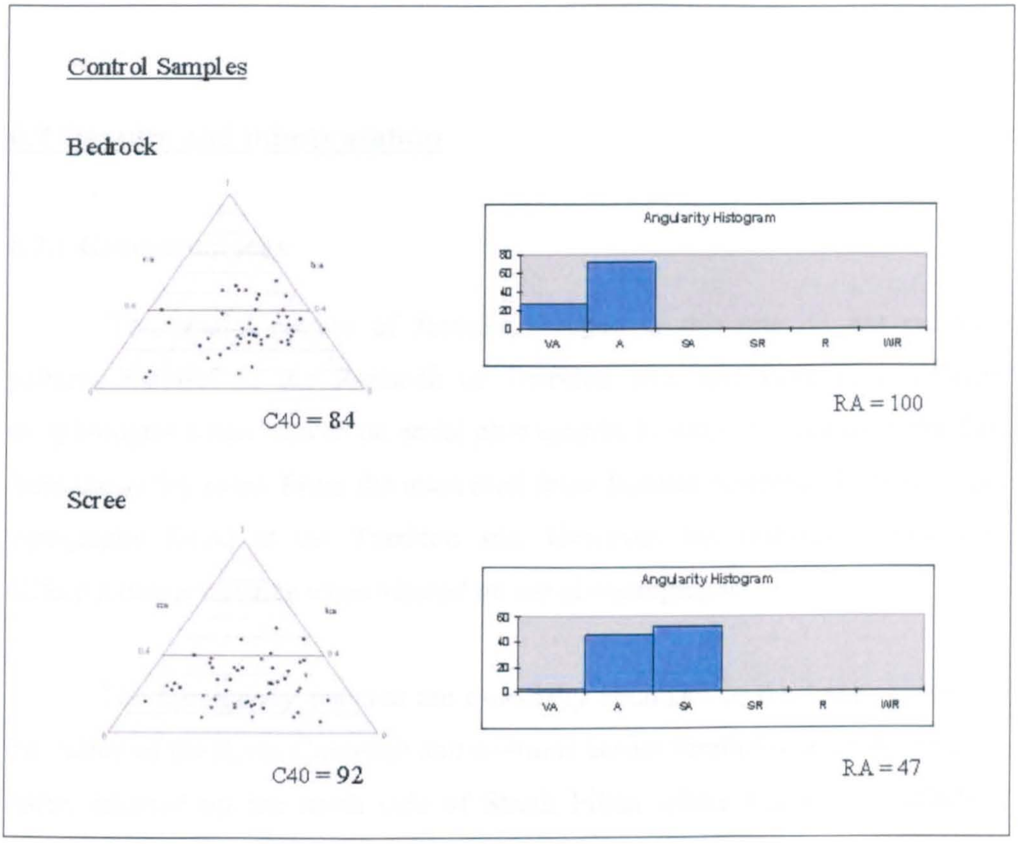


Figure 6.10 Clast bedrock and scree control samples

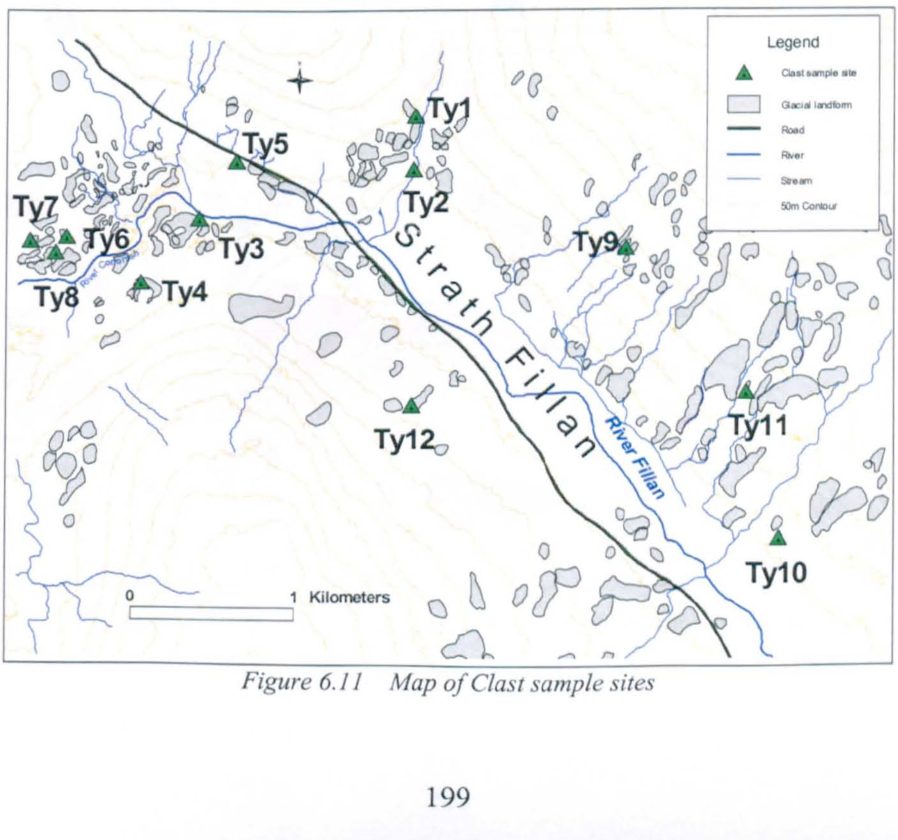


Figure 6.11 Map of Clast sample sites

6.3 Results and Interpretation

6.3.1 Geomorphology

The spatial pattern of features mapped at this site do not resemble patterns mapped at the Rannoch or Torridon site, and have very different morphologies when viewed on aerial photographs in stereo or viewed in the field from the valley sides. From the main road these features resemble the hummocky topography found at the Torridon site. However, the features exhibit very different characteristics when viewed on aerial photographs.

The hummocky features are especially abundant in the lower ground of the valley of the River Cononish and continue across Strath Fillan to Auchtertyre Farm, situated on the north side of Strath Fillan where Gleann a' Chlachain meets Strath Fillan (fig 6.5).

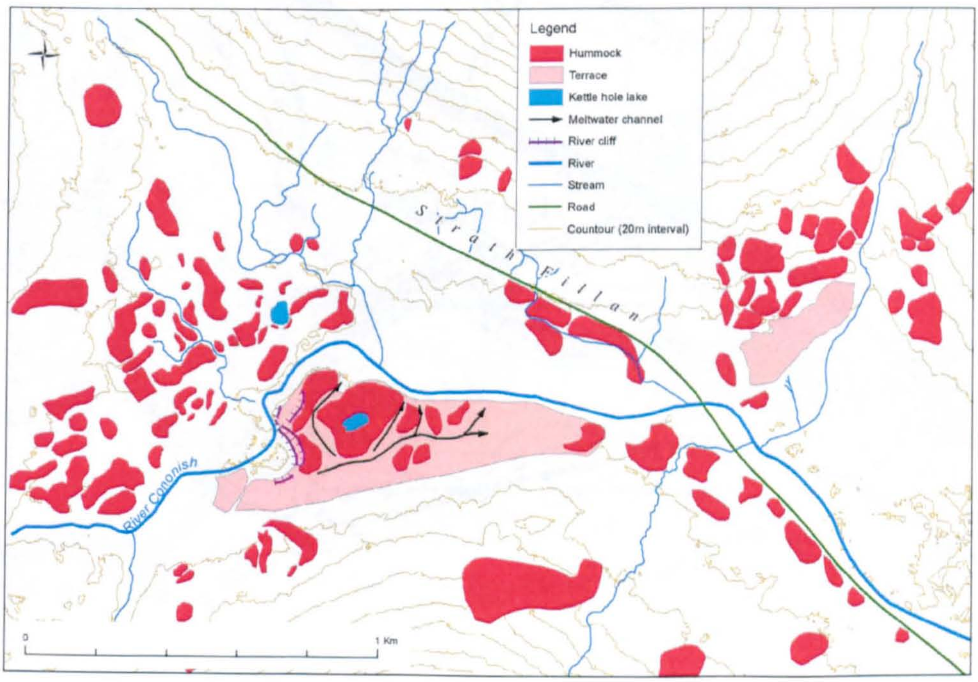


Figure 6.12 Map of hummocks and terraces, Cononish and Auchtertyre

The most prominent features in the valley of the River Cononish are large terrace like features on the south-east side of the river. These consist of steep sided, flat topped terraces with superimposed hummocks and small lakes (fig 6.14). A large steep sided terrace, with a small lake on its surface, can be seen on the south-east bank of the River Cononish (fig 6.14) Wide interconnected channels dissect the flat surface of the feature.

The terraces continue from the Cononish Valley around the northern slopes of the hill named Fiarach where the terrace has a flatter surface with no channels or lakes (fig 6.14). A line of hummocks follows the slopes of Fiarach beyond the terrace into Strath Fillan. The features shown in the photographs (figs 6.15, 6.16 and 6.17) can also be seen in the top middle of the 3D image (fig 6.14).

Figure 6.13 Location of 3D image, Figure 6.14

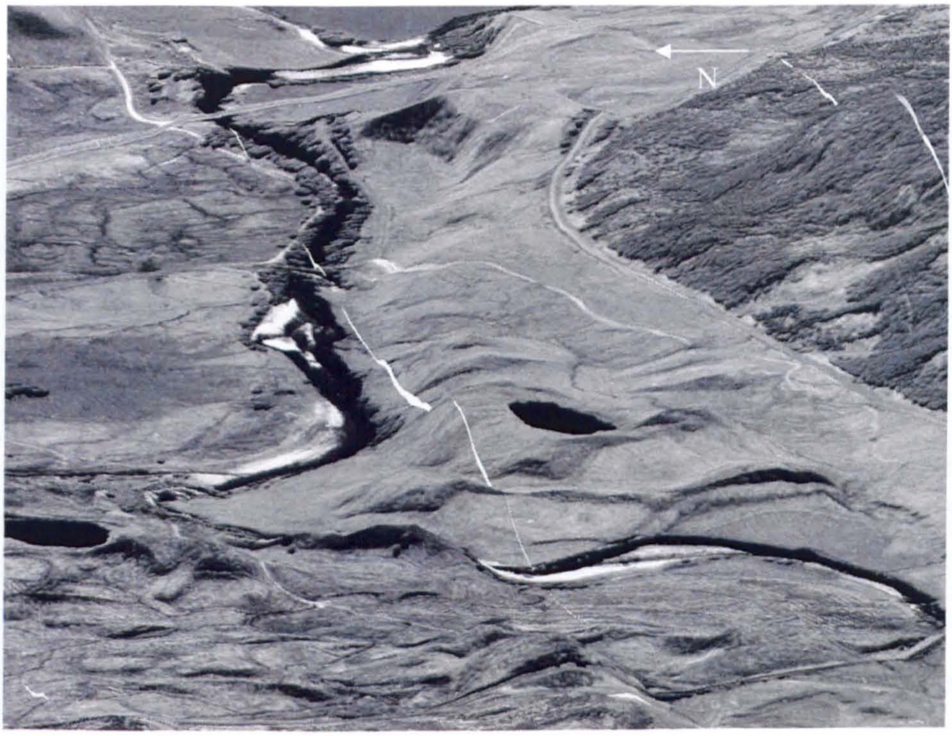


Figure 6.14 3D Orthoimage of terraces with superimposed hummocks and lakes, Cononish Valley viewed from sout-west Cononish Valley

Figure 6.15 Photograph of Cononish terraces viewed from the north-east

Figure 6.16 Photograph showing flat top of terrace viewed from the north-east

Figure 6.17 Photograph showing steep sides of Cononish terraces, east side of Cononish Valley

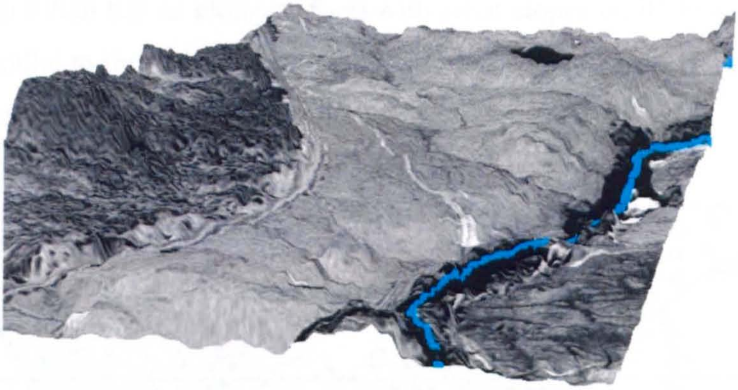


Figure 6.18 3D orthophoto extract showing steep sided terrace (looking south-west)

Figure 6.19 3D hillshaded image showing steep sided terrace (looking south-west)

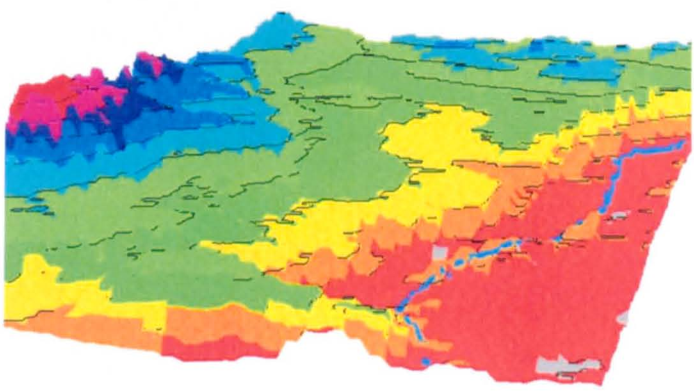


Figure 6.20 3D coloured contour image showing steep sided terrace (looking south-west)

Another terrace to the north of this site at Auchtertyre farm, on the north side of Strath Fillan has an elongate form with steep slopes on its east side. This terrace is parallel to the hillside with large hummocks on its surface. The surface of the feature is dissected by wide channels. (figs 6.22 and 6.23).

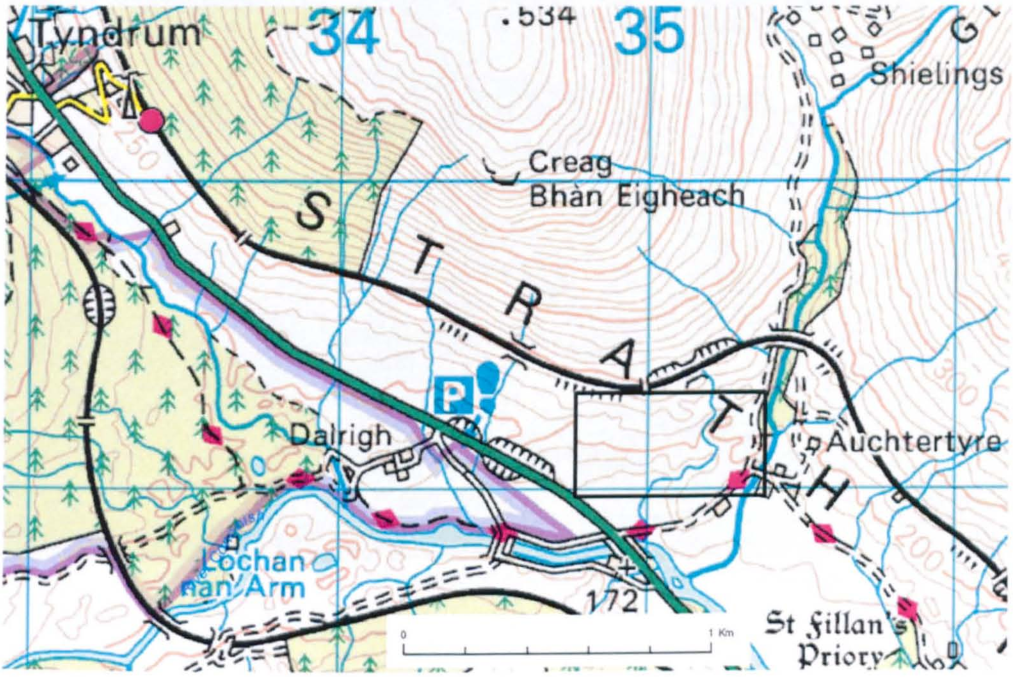


Figure 6.21 Location of terrace, Auchtertyre

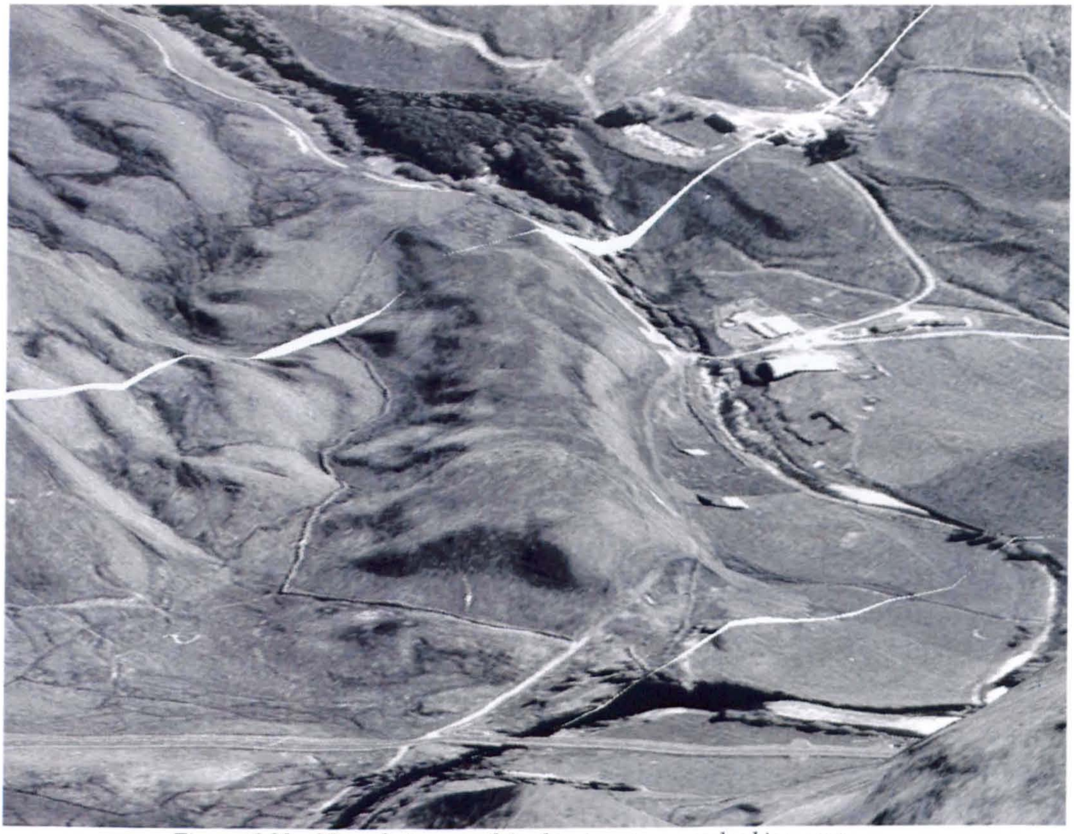


Figure 6.22 3D orthoimage of Auchtertyre terraces looking east

Figure 6.23 View of Auchtertyre terraces from the Cononish Valley

Figure 6.24 View of Auchtertyre terraces looking south

Figure 6.25 View of Auchtertyre terraces from the slopes of Ben Challum

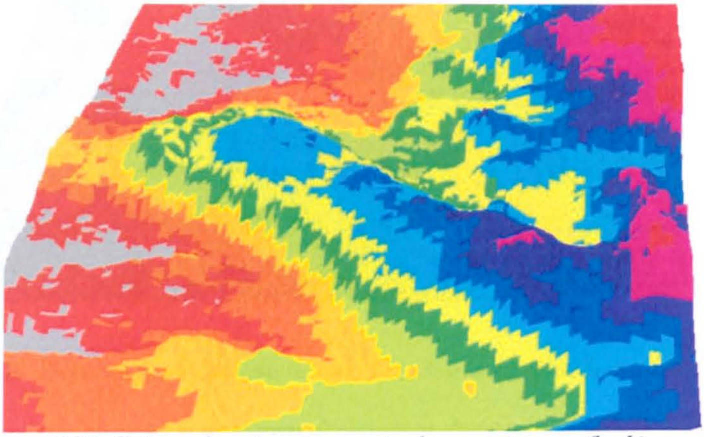


Figure 6.26 Coloured contour image, Auchtertyre terrace (looking west)

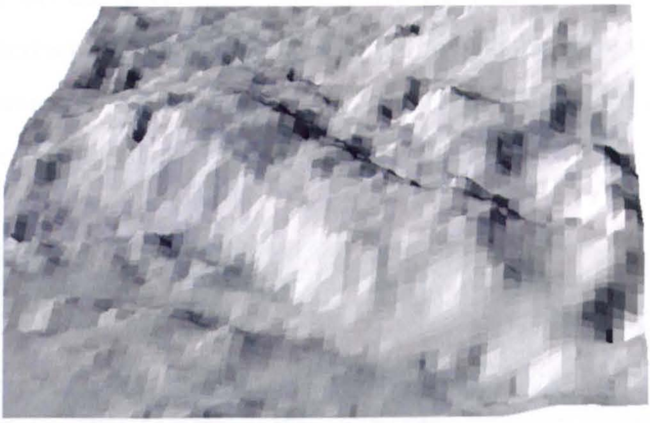


Figure 6.27 Hillshaded image, Auchtertyre terrace (looking west)

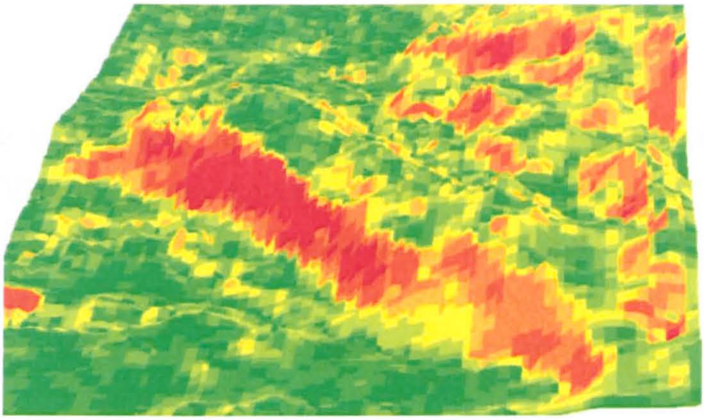


Figure 6.28 Slope map, Auchtertyre terrace, showing steep sided feature (looking west)

(red areas depict steep slopes)

Away from the lower hill slopes in the Cononish Valley the hummocks do not have a terrace-like morphology. The hummocks here are ridge shaped or have the appearance of chains of elongate hummocks. (fig 6.29). Many of these ridges have intervening channel shaped depressions.

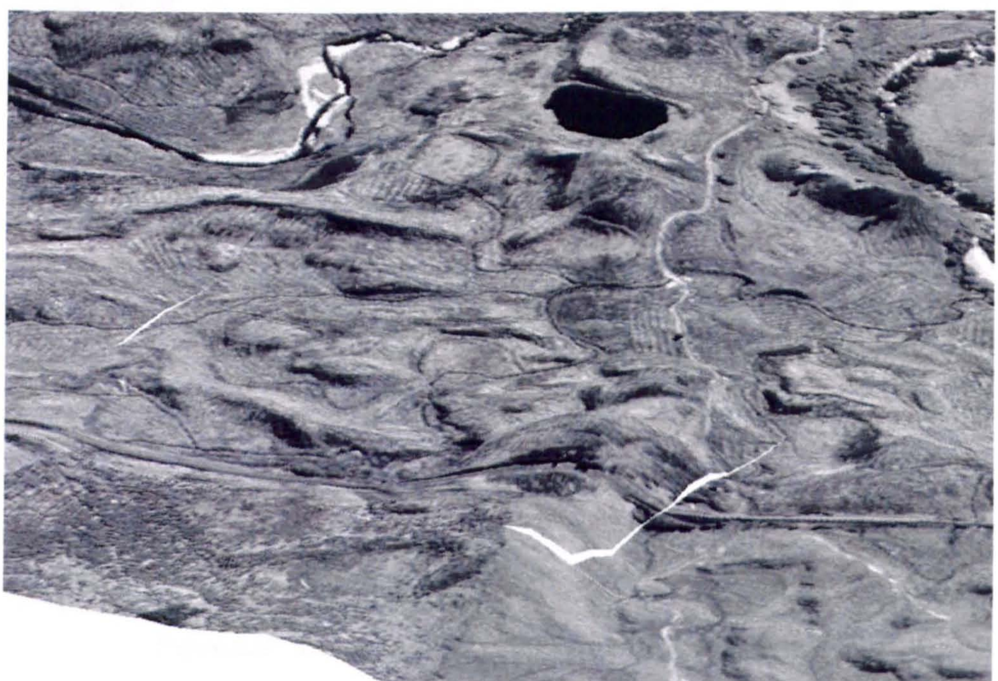


Figure 6.29 3D orthophoto of elongate hummocks in the Cononish Valley viewed from the south-west

The upper valley limit of the terraces and large hummocks in the Cononish Valley is abrupt. Up valley of this limit only smaller, less numerous hummocks exist. These have a similar morphology to the fluted hummocks of Torridon. These features however are beyond the aerial photograph coverage purchased for this field site so they have not been mapped.

Hummocky features on the northern slopes of Strath Fillan have less distinct morphologies than those in the Cononish and Auchtertyre areas. The landforms here consist of large elongate hummocks often with a downslope orientation (figs 6.30 and 6.31). Similar to the features found in the Cononish and Auchtertyre areas, these are composed of sandy material with clasts and boulders, and no obvious structures or stratigraphy. As discussed in the methods section of this chapter these features, located on steep slopes, are not clearly defined in images derived from the D.E.M.

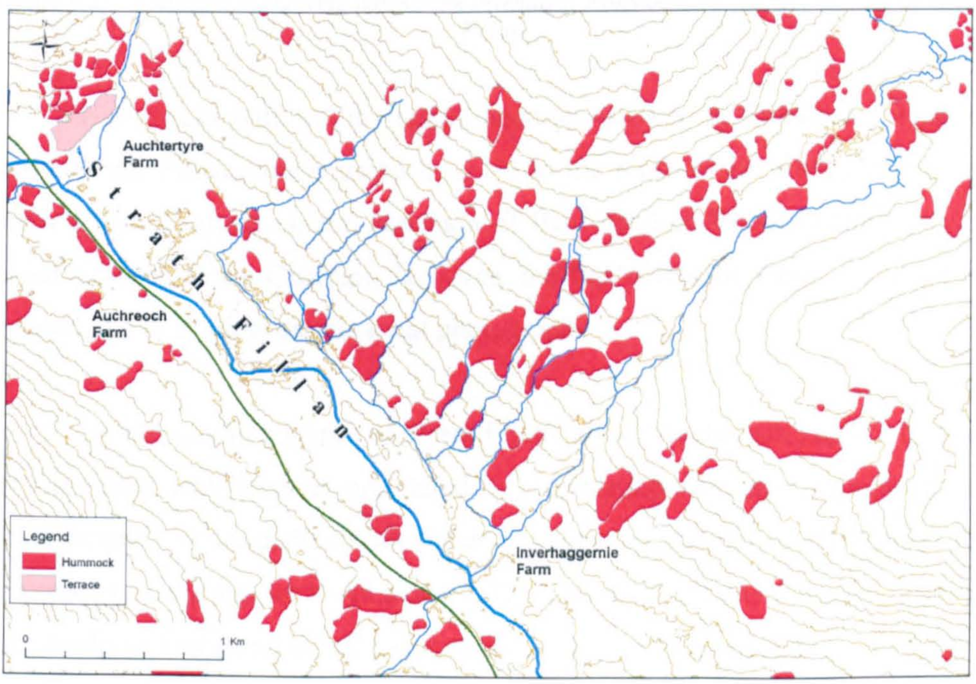


Figure 6.30 Map of Hummocks on the north slope of Strath Fillan

Figure 6.31 Photograph showing downslope orientated hummocks on the north slopes of Strath Fillan

Hummocks with no obvious orientation can also be found on the slopes above Strath Fillan, concentrated in a col to the north of Inverhaggernie farm, below Coire Challum on the east side of Ben Challum These features can be traced towards Coire Challum, however, the full extent of these could not be mapped due to shadow on the aerial photographs.

On the southern slopes of Strath Fillan, above Auchreoch Farm, a distinct area of hummocky features orientated in a downslope direction was observed. These hummocks are distinctively linear and concentrated in one area, unlike the hummocks on the steeper north slopes. To the east of this site a linear cluster of hummocks follow an unnamed valley with a north-south orientation.

Other hummocks with similar morphology and composition were found to the east of the Crainlarich in Glen Dochart, extending beyond the boundaries of the field site towards Killin. Large hummocks within the field area in Glen Dochart, near Loch Iubhair, differ from the landforms investigated in Strath Fillan as these mainly consist of bedrock with a thin covering of sandy diamict. In Glen Dochart, to the east of Loch Iubhair hummocks are composed of sandy diamict, similar to the features found in Strath Fillan, with no visible bedrock core.

6.3.2 Sedimentology

Six sites were sampled in the Cononish Valley. Samples Ty6, Ty7 and Ty8 were taken from elongate hummocks on the valley floor. The hummocks are arranged in chains suggesting they were formed as larger linear ridges. Ty3 was taken from the slope of a large terrace on the south-east side of the valley. Ty4 was taken from a large elongate ridge superimposed on the terrace and Ty5 from an elongate hummock where the Cononish Valley meets Strath Fillan. (fig 6.11)

Material in four of the samples Ty6, Ty7, Ty8 and Ty3 consists of poorly consolidated diamicts with clasts and some large boulders. Samples Ty4 and Ty5 were taken from exposures of unconsolidated clasts, gravel and sand. Clast fabrics were not measured for samples Ty4 and Ty5 due to poor preservation of fabric characteristics due to the unconsolidated nature of the material. Clasts in all samples are subrounded to subangular with a small number of rounded and angular clasts (fig 6.32). Clasts are considerably less angular than those sampled in the bedrock and scree samples and plot closer, on ternary clast shape diagrams, to Benn and Ballantyne's till samples than the control samples from Tyndrum. This suggests the material in the Cononish Valley has undergone some form of active transport. No evidence of sedimentary structures was observed in the sediment exposures.

Clast fabric shape for the Cononish valley samples plot within the envelopes for deformation till and debris flow deposits (fig 6.33). According to Benn and Evans (1998) debris flow deposits and deformation tills can display similar characteristics and are not easily distinguished. However deformation tills are likely to display spatially consistent fabric orientation in the direction of strain. Fabrics from the Cononish Valley are orientated parallel to the orientation of the slopes they were taken from. Fabrics are not orientated in a consistent direction and are not parallel to the valley axis, as can be seen on the map depicting clast orientation (fig6.34). The samples taken from elongate landforms are not orientated parallel to the long axis of the landforms. These characteristics suggest clast orientation does not reflect ice flow direction. Mean fabric dip angles range from 22 to 28 degrees with maximum dips of 60 to 78 degrees. Dip angles are therefore steeper than would be expected for tills.

Clast characteristics are similar for samples from the elongate ridges and samples taken from the slopes of the terrace (Ty3) and the ridge superimposed on the terrace (Ty4). It is therefore likely that the terrace and superimposed ridge were deposited in a similar depositional environment to the elongate ridges.

Clast shape and fabrics are consistent with a sub-glacial origin of the material. However clast orientation and dip are more typical of debris flow deposits rather than sub-glacially deposited material. The clasts in these samples are therefore interpreted as being deposited as debris flow deposits. Clasts have but subject to active transport mechanisms before final deposition by debris flow. A more consistent fabric orientation reflecting ice flow direction, and lower dip angles would be expected if the material was deposited directly from the ice in a subglacial environment.

Cononish Valley clast shape and angularity

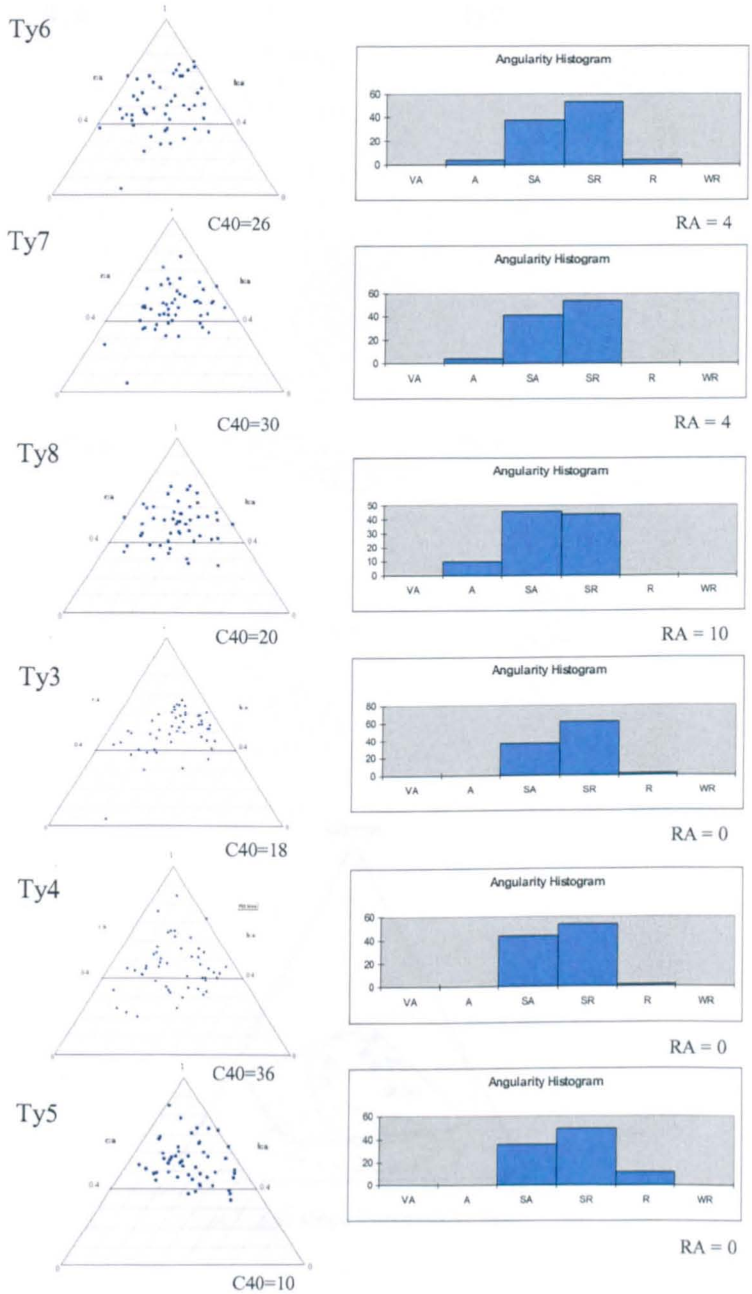


Figure 6.32 Clast shape and angularity, Cononish Valley.

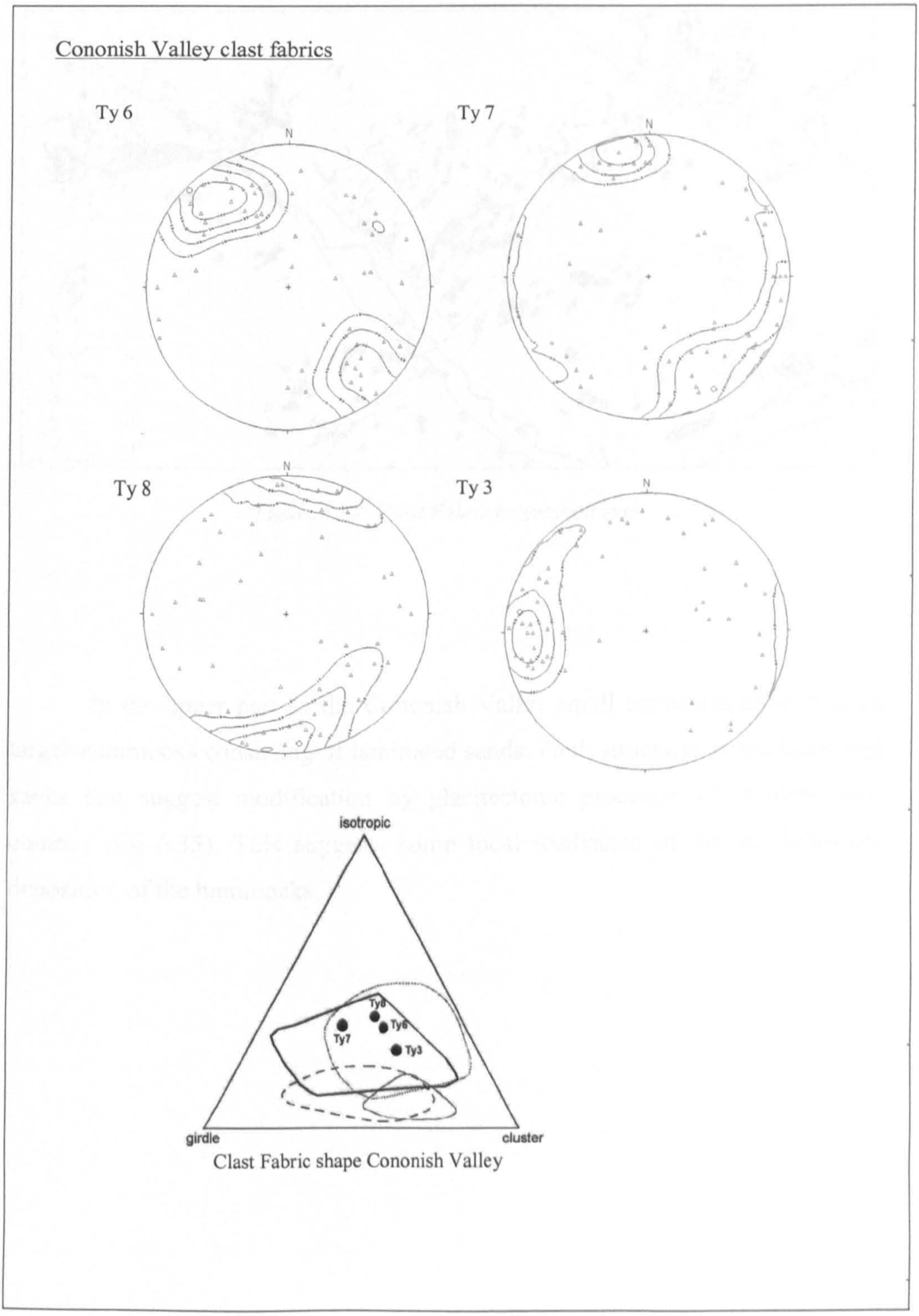


Figure 6.33 Clast Fabric shape and orientation, Cononish Valley

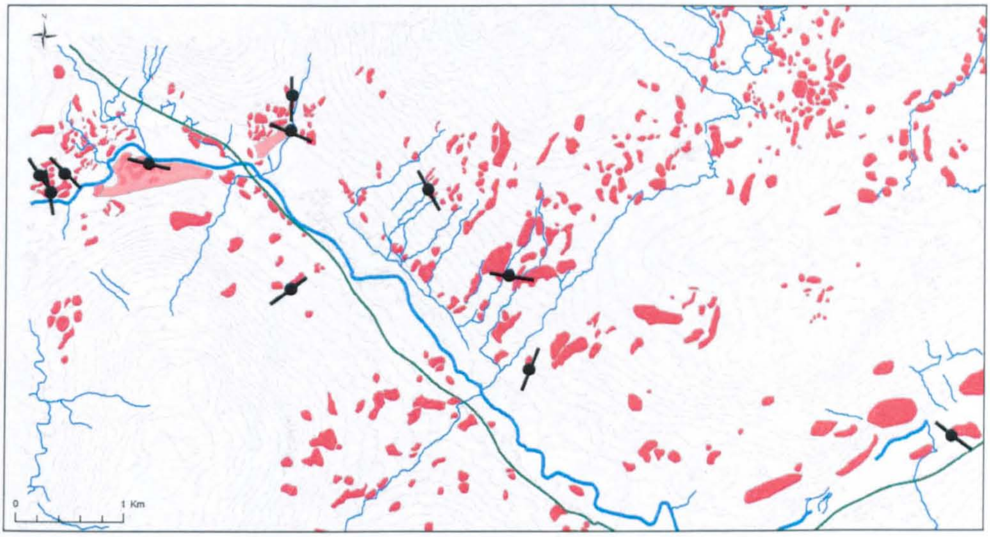


Figure 6.34 Clast Fabric orientation map.

In the upper part of the Cononish Valley small exposures exist through larger hummocks consisting of laminated sands. Fault structures in the laminated sands that suggest modification by glacitectonic processes (E. Philips pers. comm.) (fig 6.35). This suggests some local readvance of the ice following deposition of the hummocks.

Figure 6.35 fault structures Cononish Valley

Seven clast samples were taken in Strath Fillan (Ty1, Ty2, Ty9, Ty10, Ty11, Ty12, Ty13) (see fig 6.11). Samples Ty1 and Ty2 were taken from a steep sided feature, on the north side of Strath Fillan, similar to the terrace in the Cononish Valley. The morphology and location of this feature suggests a similar origin to the Cononish terrace. The diamict in the exposures consists of a poorly consolidated sand and gravel matrix with clasts and boulders. Clasts angularity for these sites is subangular to subrounded, with significantly more subangular clasts than found in the Cononish samples. However these samples contain significantly less angular clasts than found in the scree control sample. Clast shape plotted on ternary diagrams is similar to those published by Benn and Ballantyne (1994) interpreted as tills and are more block shaped than the scree and bedrock control samples. C40 indices are considerably lower than the control samples. Clast shape and angularity, compared to control samples, suggests the material has been subject to active transport. However clast angularity suggests they have undergone less modification by active transport than the Cononish clasts. The fabrics for both samples have a weak north to south orientation, and dips are variable with a range of 2° and 60° Clasts plot within the envelopes for deformation till and debris flow deposits. The unconsolidated nature of the sediment and wide range of dip angles, including steeply dipping clasts, suggest the material was not deposited in a subglacial environment. It is more likely that the sediment was deposited as debris flow.

Samples Ty9, Ty10 and Ty11 were taken from down-slope orientated features on the steep north slopes of Strath Fillan. Two samples were taken on the slopes above Inverhaggernie Farm and one to the west of these above Kirkton Farm. Clasts measured in samples Ty9 and Ty11 are mostly subangular with few subrounded clasts and some angular clasts. Clasts from sample Ty10 are subrounded to subangular. Clasts in these samples are more angular than those sampled in the Cononish Valley, although they contain less angular clasts than the scree control sample. Clast shape in sample Ty9 plotted on a ternary diagram show similar characteristics to Benn and Ballantyne's till samples. Samples Ty10 and Ty11 show characteristics closer to the scree and bedrock control samples and Benn and Ballantyne's scree samples (fig 6.36). Clast shape and angularity suggest some modification by active transport, however, with the exception of Ty10, they display less evidence of modification than the Cononish clasts. Clast fabrics for Ty 9 and Ty10 are weak and orientated downslope. Sample Ty11 has no preferred orientation. Clast fabrics for samples Ty10 and Ty9 again plot within the envelopes for debris flow and deformation till. Ty11 plots within the envelope for deformation till only (fig 6.37). Although the samples plot within the envelope for deformation till the varied dip angles, unconsolidated nature of the material and weak fabric orientations are not typical of tills. It is therefore more likely that the material was deposited as debris flow.

Another clast sample (Ty12) was taken on large hummocks on the south slopes of Strath Fillan. The clasts were taken from a small exposure on the south-east face of a downslope trending elongate hummock. The material in the section consists of a sandy matrix supported diamict with clasts. Large boulders were observed on the surface of the feature. Clast angularity is predominantly subangular with some subrounded clasts (34%). Clast shape is more blocky than the scree and bedrock control samples and is similar to tills sampled by Benn and Ballantyne (1992), although the C40 index of 36 is higher than Benn and Ballantyne's tills. The C40 index is significantly lower than the control samples. Comparison of this sample with the control samples suggests the material has been subject to active transport mechanisms. Clast fabric shows some orientation of clast dip to the north-east, however clast dips were varied (2°-62°) and included steeply dipping clasts. The clast fabric shape again plots within the envelopes for deformation till and debris flow deposits (fig 6.37). Similar to the other samples clast characteristics suggest the material was deposited by debris flow.

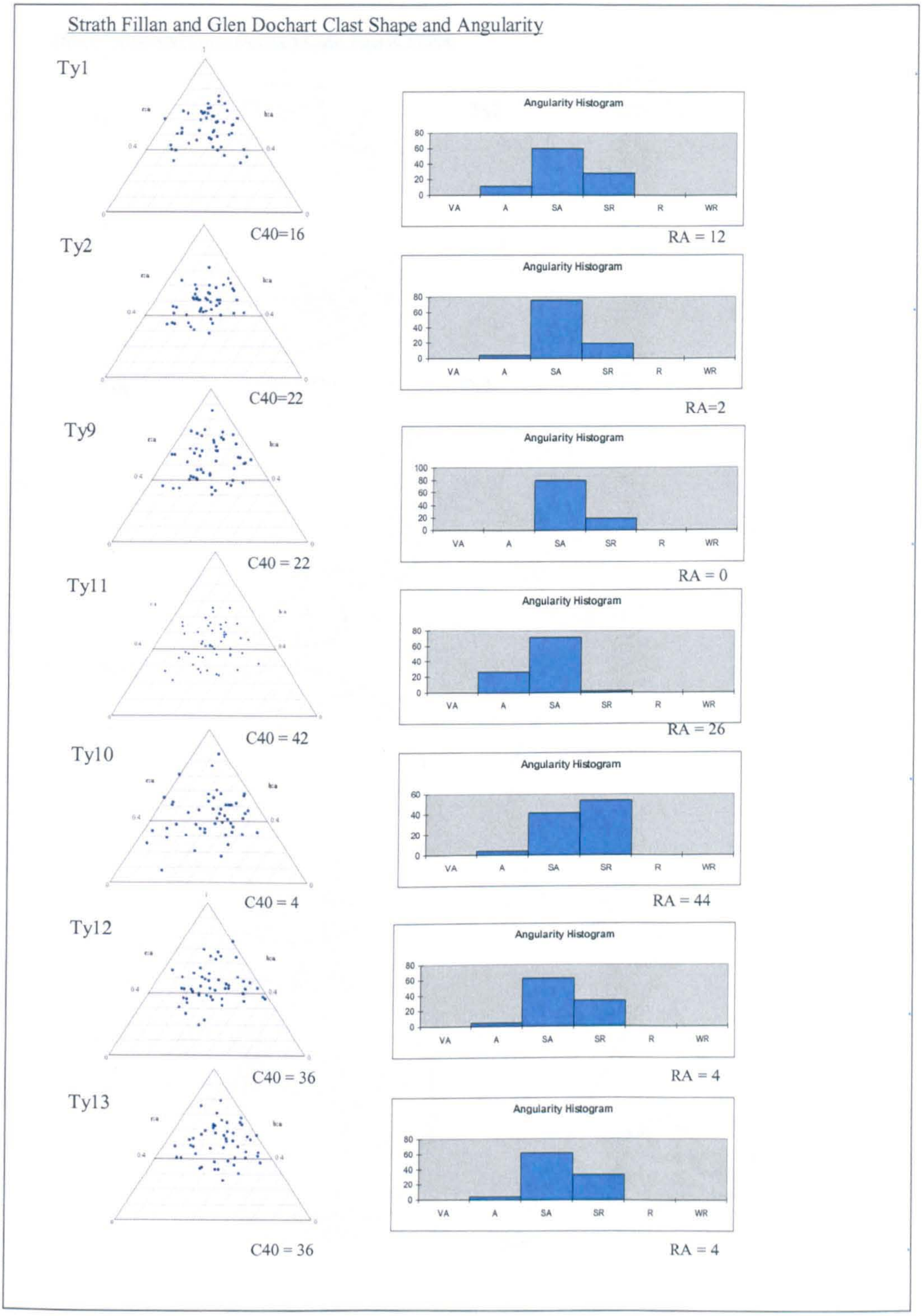


Figure 6.36 Clast shape and angularity, Strath Fillan

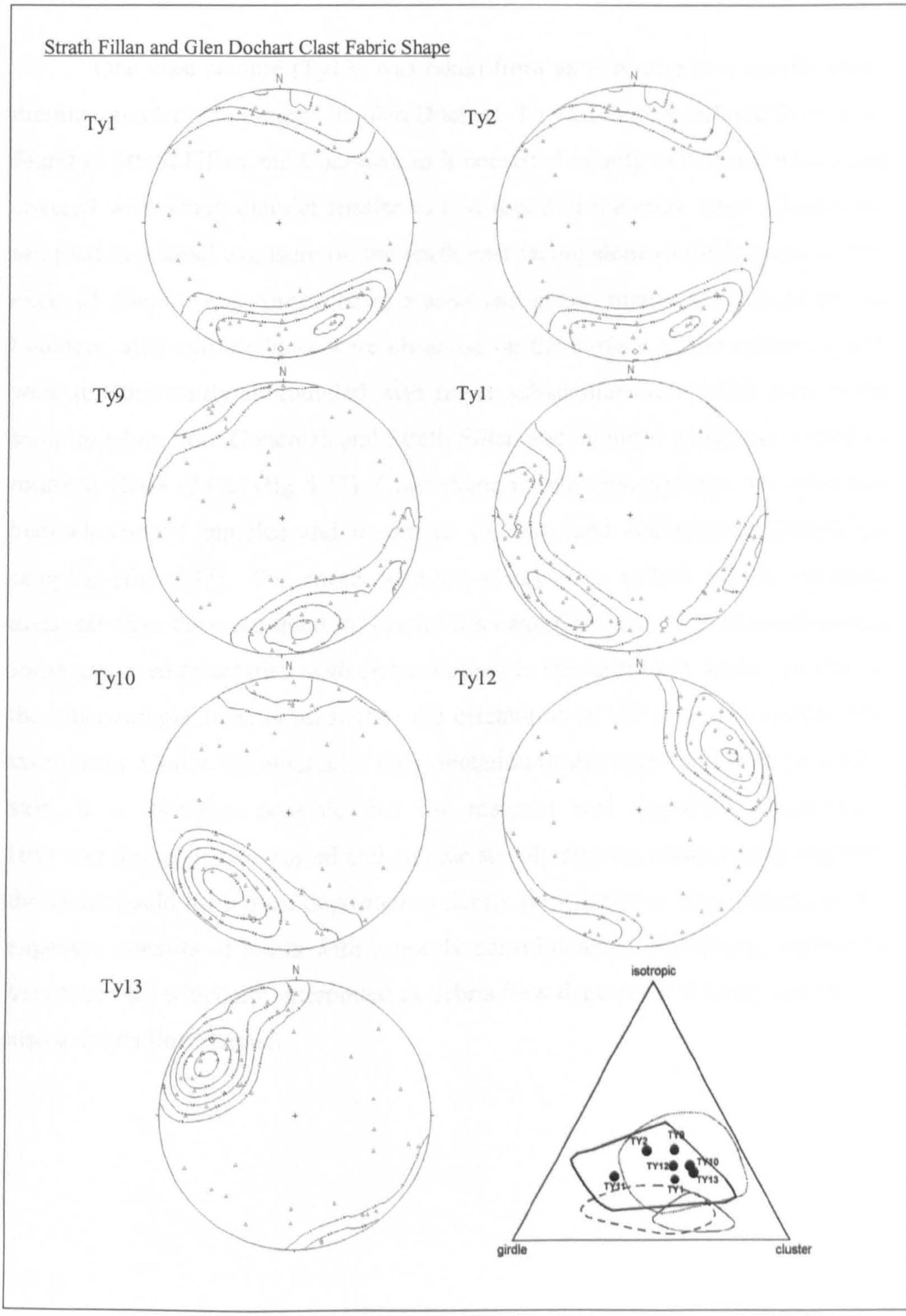


Figure 6.37 Clast Fabric Strath Fillan

One clast sample (Ty13) was taken from an exposure in a similar sandy diamict on a large hummock in Glen Dochart. This hummock differed from those found in Strath Fillan and Cononish as it consisted mainly of bedrock which was covered with sandy diamict similar to that found at the other sites. Clasts were sampled in a small exposure on the north-east facing slope of the hummock. The exposed diamict was composed of a sand and gravel matrix with clasts and no boulders, although boulders were observed on the surface of the feature. Clasts were predominantly subrounded with fewer subangular clasts (4%) than in the samples taken from Cononish and Strath Fillan and included a high proportion of rounded clasts (24%) (fig 6.37). Clast shape is more blocky than the scree and bedrock control samples and is similar to Benn and Ballantyne's (1994) till samples (fig 6.37). The more rounded clasts may reflect longer transport distances than those sampled in Strath Fillan and Cononish. The clast fabric has some preferred orientation with clasts dipping to the north-east, which, similar to the other sample sites, is parallel to the orientation of the slope the sample was taken from. Unlike the other sites the orientation is also near parallel to the valley axis. It is therefore possible that the material was deposited subglacially. However dip angles are varied and include steeply dipping clasts, which suggests the clasts could have been deposited as debris flow deposits. The material in his exposure consists of clasts with a poorly consolidated sandy matrix, similar to the other sites which are interpreted as debris flow deposits. It is likely that this is also a debris flow deposit.

6.3.3 Interpretation

The glacial geomorphology of the Tyndrum and Strath Fillan area consists of landforms with various morphologies including terraces, chains of hummocks, chaotic hummocks and elongate hummocks with a downslope orientation.

The terraces are found mainly in the Cononish Valley to the east of the River Cononish. These large terraces have steep sides and flat tops with small lakes and hummocks on their surface. The morphology and location of the terraces on the side of the valley suggest that they were deposited as kame terraces, deposited alongside ice that flowed out from the Cononish Valley, or as kames dissected by the River Cononish. The lake filled depressions on the surface of the terraces are likely to have formed as kettle holes, produced by meltout of buried glacier ice. The kame terrace in the Cononish Valley has an irregular surface with hummocks and channels that are interpreted as the products of melt-out of buried ice and erosion by glacial meltwater (fig 6.38). A similar landscape of pitted and channelled terraces can be seen at Kviarjökull, south-east Iceland (fig 6.39). The large volume of sediment deposited in the moraines, terraces and eskers at Kviarjökull are attributed to a high sediment load in the glacier and repeated glacier advance to a similar position (Evans Archer & Wilson 1999, Spedding & Evans 2001). It is likely that the glacier in the Cononish Valley that deposited the kame terrace, eskers and kames also had a high sediment content, although it is not suggested that debris entrainment conditions at Kviarjökull are necessarily analogous to the Cononish Valley during the Loch Lomond Stadial. A large volume of sediment would be required to produce the large terraces and eskers and to bury the ice that melted out to produce discontinuous eskers and kettle holes.

Figure 6.38 Cononish kame terrace with meltwater channels and kettle hole

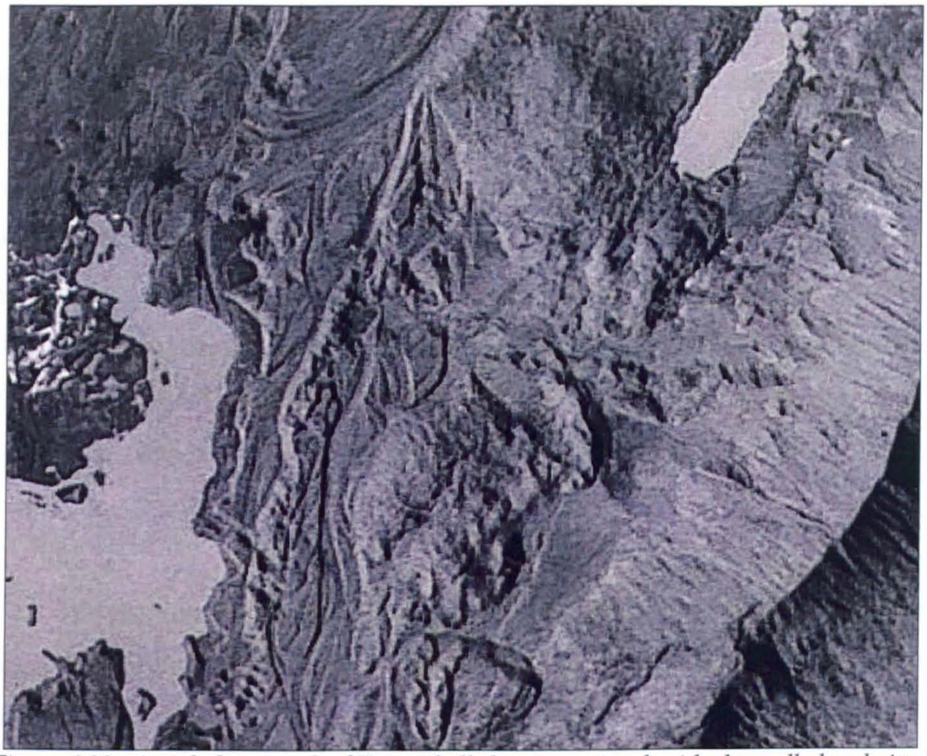


Figure 6.39 Aerial photograph of Kviarjökull showing outwash with channelled and pitted surface

Where the Cononish Valley meets Strath Fillan the terraces have a flatter surface, suggesting less buried ice in the kames at this location. Meltwater which affected the morphology of the terraces in the Cononish Valley may have flowed towards Strath Fillan taking a similar path to the present river and therefore not flowing over the flat terrace surfaces further down-valley. There is no evidence of meltwater channel erosion or glacifluvial deposition on the surface these terraces. Evidence of modification of the terrace surfaces is confined to the up-valley part of the terraces in the Cononish Valley. An elongate ridge consisting of sand, gravel and clasts, interpreted as an esker, is located on the hillside adjacent to the terrace suggesting local readvance of ice onto the surface of the terrace. There is also evidence of local readvance in sediments in the upper part of the Cononish Valley. The hummocks superimposed on the terrace in the Cononish Valley could have been deposited by ice over-riding the terrace. Alternatively these hummocks may represent the surface of the terrace prior to dissection by meltwater erosion and the meltout of buried ice.

A clast sample Ty3 was taken from the side of a kame terrace, near the River Cononish. The sediment is interpreted as a paraglacial debris flow deposit, due to the unconsolidated nature of the sediment, steep dip angles and the downslope orientation of the clast fabric. It is likely that the debris flow occurred after the ice retreated from the steep slopes of the kame terrace. Alternatively if this part of the terrace has been significantly modified by fluvial erosion the debris flow may have occurred during a later post-glacial period. Hummocks on the slopes of Fiarach to the east of the flat topped terraces are interpreted as the remnants of terraces which have possibly been subject to the meltout of buried ice and slope processes.

The terraces at Auchtertyre Farm on the north side of Strath Fillan have a steep eastern side suggesting this was in contact with glacier ice. It is proposed that this is also a kame terrace. The hummocks between the terrace and the slopes of Beinn Odhar are thought to have been incised by meltwater and degraded by meltout of buried ice. Large terraces, possibly outwash terraces and hummocky topography in Gleann a'Chlachain, to the north of Auchtertyre, are interpreted as deposited during the retreat of glacier ice with its source in the large corries at the head of Gleann a'Chlachain and on the western slope of Ben Challum. This is thought to have been confluent with the ice in Strath Fillan. The kame terraces at Auchtertyre are likely to have been formed at the confluence of these two glaciers. It is likely that the meltwater that incised the terrace flowed from the glacier in Gleann a'Chlachain.

Features with a more hummocky appearance were observed in the lower parts of the Cononish Valley, especially on the west side of the river. Like the terraces, these are steep sided and composed of sand with clasts and boulders. Clast fabric characteristics suggest these features have been subject to modification by debris flow. From three-dimensional orthophotos the hummocks can be seen to form chains (fig 6.40). The chains of hummocks are interpreted as the remnants of eskers.

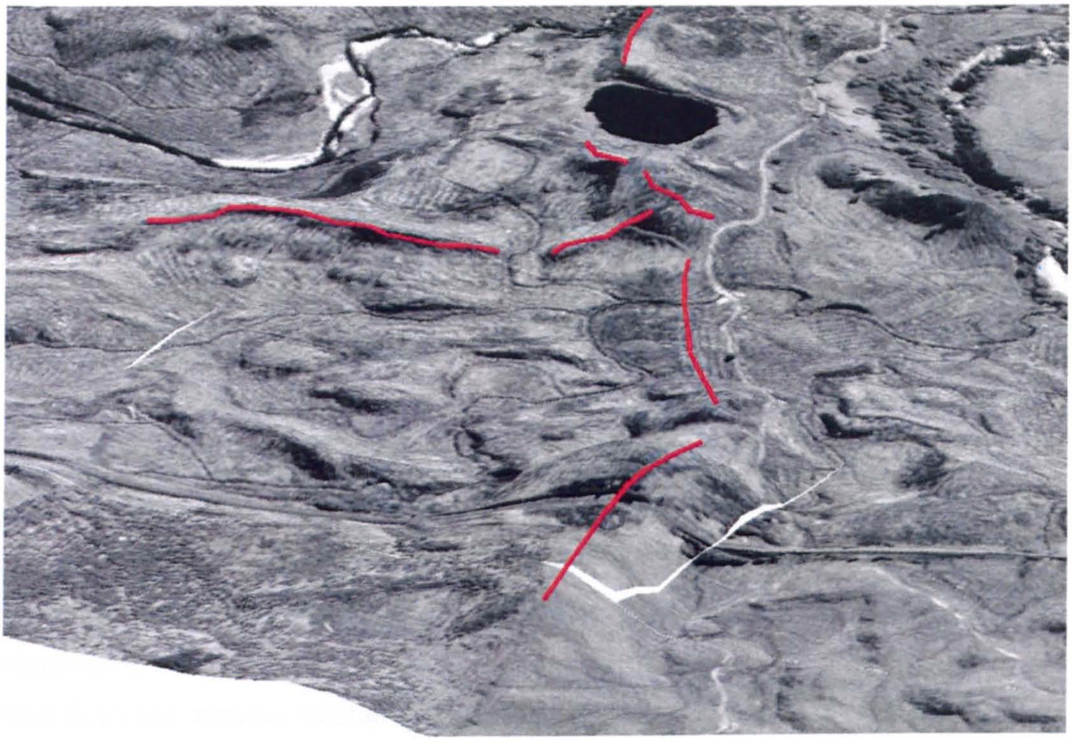


Fig 6.40 3D orthoimage showing remnants of eskers, Cononish Valley (esker ridges marked with red line)

Many of the ridges have intervening channels interpreted as meltwater channels. It is therefore difficult to determine whether the elongate ridge morphology represents the morphology of the features after deposition or have been modified by meltwater. An alternative explanation of the ridges is that they were formed as kames, with their elongate form being due to erosional rather than depositional processes. According to Benn and Evans (1998) it is difficult to categorise features as either eskers or kames, although the term kame generally refers to shorter discontinuous or terrace like features with the term esker reserved for more continuous ridges. This definition has been used to interpret the landforms in the Cononish Valley with more continuous ridges or the traceable remnants of continuous ridges interpreted as eskers.

Some of the hummocky landforms in the Cononish Valley do not form chains of hummocks and may either be the remnants of eskers which have been degraded more than the recognisable esker chains, kames, or moraines formed by localised in situ ice wastage, suggesting some ice stagnation at this location. Areas of chaotic hummocky moraine, interpreted as due to localised ice stagnation have been found on the Isle of Skye (Benn 1992). The hummocky moraine at this site probably has no climatic significance, such as that proposed by Sissons (1963,1967a, 1967b, 1973, 1979) for the widespread occurrence of chaotic hummocky moraine in northern Britain. The large terraces and hummocks of this site suggest that the glacier ice contained a high sediment load. The local stagnation of ice may have occurred due to the slow meltout of a snout that was locally debris covered and therefore at least partially decoupled from climatic change. A debris layer of 10 to 20cm on a glacier surface is thought to reduce ablation by approximately 40% due to the debris insulating the ice from insolation (Takeuchi 2000, Pelto 2000). However thinner layers of debris, of less than 5cm, can increase ablation due to reduced albedo (Nakawo & Young 1981). A decrease in ablation can result in periods of ice margin stability and sediment aggradation, producing ice marginal or proglacial landforms depending of the ability of meltwater to transport sediment from the ice margin (Benn et al 2003). Debris covered margins can also become decoupled and stagnate due to their decreased ablation, while cleaner ice up glacier with a higher ablation rate recedes (Pelto 2000). The large and numerous glacifluvial landforms in the Cononish Valley suggest a period of marginal stability with sediment transport and deposition mainly by meltwater.

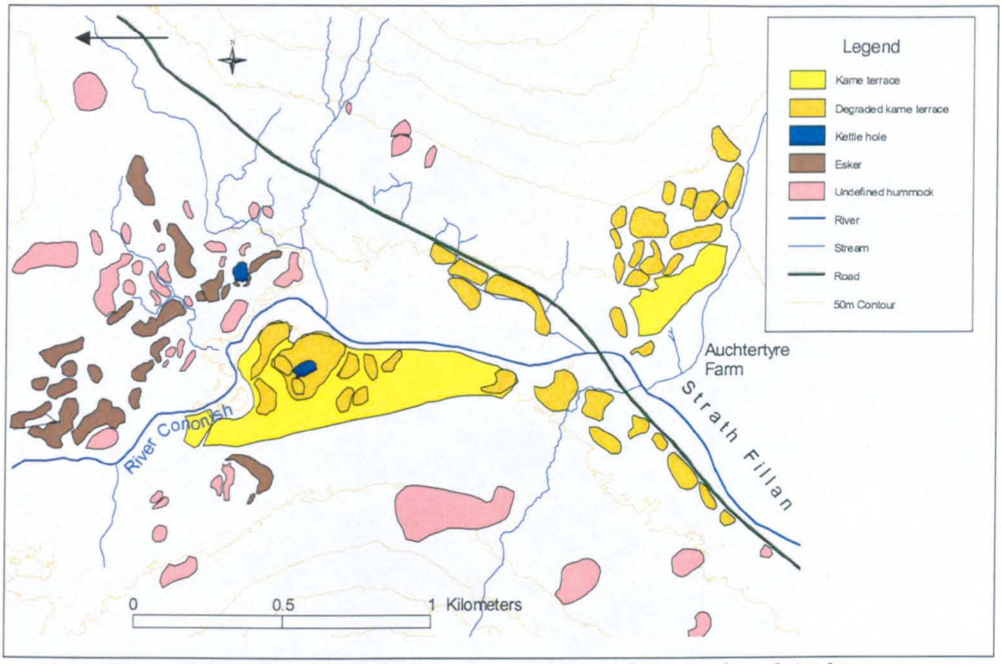


Figure 6.41 Map of the glacial geomorphology of Cononish and Auchtertyre

Hummocks on the south-side of Strath Fillan are concentrated in one area above Auchreoch Farm (fig 6.42). These have a linear spatial pattern with a cross-valley, downslope orientation. Clasts are more angular at this site than those sampled from the kame terraces and eskers to the south, suggesting a more passive transport history. The clast sample was not taken near any steep valley-side slopes and therefore is not thought to be likely to include a large amount of locally derived scree. Clast shape and angularity are dissimilar from the scree and bedrock samples, suggesting modification during transport. The spatial organisation of these features and the concentration of them in one area suggests they are ice marginal features. It is proposed that these were deposited as marginal moraines marking a standstill position of the ice as it receded back towards the Cononish and Auchtertyre area.

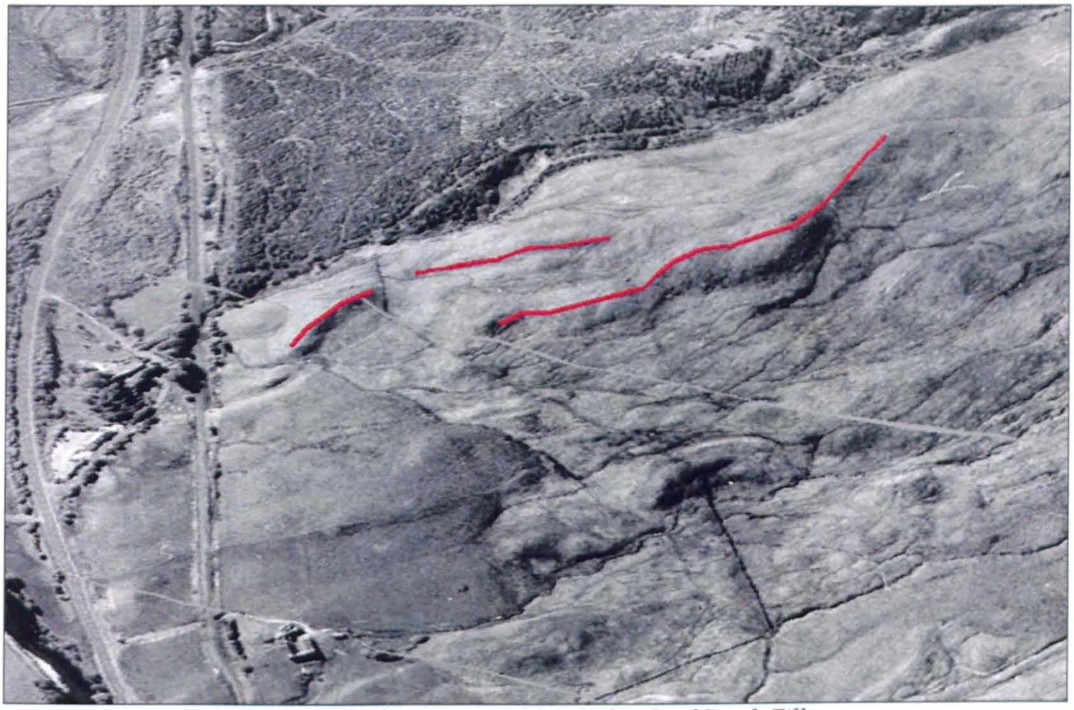


Fig 6.42 Marginal moraines on the south side of Strath Fillan

Elongate hummocks on the north side of Strath Fillan have a downslope orientation and are heavily gullied. Clast shape analysis suggests that material in these features has undergone less active transport than material in the Cononish Valley. However, the proportion angular clasts is lower than the scree and bedrock control sample, suggesting the material does not consist of scree or passively transported material alone. It is therefore likely that the material has undergone at least some active transport but has a different transport path from the material in the Cononish Valley.

The ratio of sub-angular to very-angular clasts to sub-rounded to well-rounded clasts was plotted against the C40 index to ascertain if clast shape is significantly different for the samples from the Cononish Valley and those from Strath Fillan. The plot also compared these samples to the scree and bedrock control samples.

Clasts from the two locations are not highly clustered. However it can be seen that the Cononish samples have similar C40 indices and that the C40 indices of the Strath Fillan samples are generally higher. The Strath Fillan samples plot slightly closer to the control samples. Clast fabrics either show no orientation or a weak fabric orientated to the south or downslope.

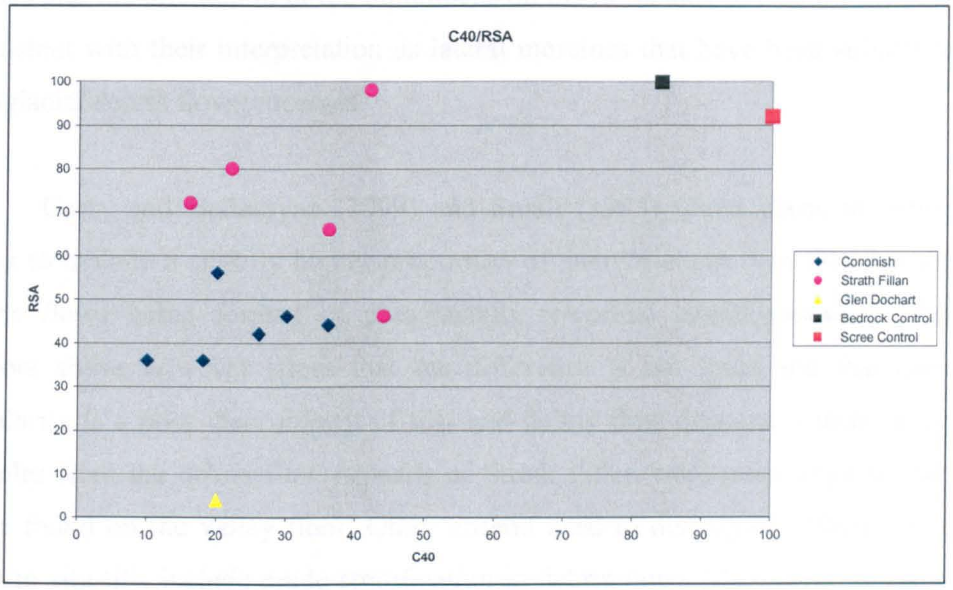


Figure 6.43 Clast shape plot

These characteristics and the downslope orientation of the features suggest they were deposited as lateral moraines. The lateral moraines have undergone severe paraglacial reworking by slope processes, re-orientating clasts to a downslope orientation and possibly gullying by streams. Work at contemporary glacier margins suggests debris flow is the main process responsible for paraglacial resedimentation of lateral moraines, although fluvial erosion has a secondary influence (Small 1983, Ballantyne & Benn 1994, 1996, Curry & Ballantyne 1999). Clast fabric and shape characteristics of debris flow deposits are similar to those of in situ tills (Small 1983, Ballantyne & Benn 1994, 1996, Curry & Ballantyne 1999), with similar clast fabric strength, clast shape and angularity. However in situ tills and debris flows can be distinguished by clast orientation, with tills displaying an orientation parallel to the valley axis, and debris flows displaying down-slope orientations. Neither the clast samples from Strath Fillan nor the sample from the Cononish Valley display a valley parallel orientation. Ballantyne and Benn (1994) also point out that others have commented on the difficulty in distinguishing debris flow deposits from in situ tills (Eyles et. al. 1988 Eyles & Kocsis 1988, Owen & Derbyshire 1989 Derbyshire & Owen 1990, Owen 1991). The downslope orientation of the clast fabrics and the orientation of the hummocks on the north side of Strath Fillan are consistent with their interpretation as lateral moraines that have been subject to paraglacial debris flow processes.

Curry and Ballantyne (1999) and Small (1983) found clasts in debris flows to include a slightly higher proportion of angular clasts than tills due the debris flows being formed of paraglacially reworked lateral moraines. The authors above however stress that the difference is not great and that clast angularity is a poor discriminant of tills and debris flow deposits. Clasts in the samples from the debris flow deposits of Strath Fillan were more angular than those found on the valley floor. Other criteria used to distinguish debris flows from in situ tills include crude stratification in debris flows (Ballantyne & Benn 1994, Curry & Ballantyne 1999) and a lower proportion of silt and clay and a higher proportion of coarse sand in the matrix of debris flow diamicts (Ballantyne & Benn 1994). No in situ tills were recognised in the Tyndrum area. However, grain size of the landforms on the north side of Strath Fillan, interpreted as debris flows, were compared to the grain size of features on the south side of the valley interpreted as marginal moraines (fig 6.44). The proportion of silt and clay (>4 phi units) is similar for the three debris flow deposits (Ty9, Ty10, Ty11), with a very slightly higher proportion of silt and clay found in the marginal moraine sample (Ty12). No stratification was found in the debris flow exposures.

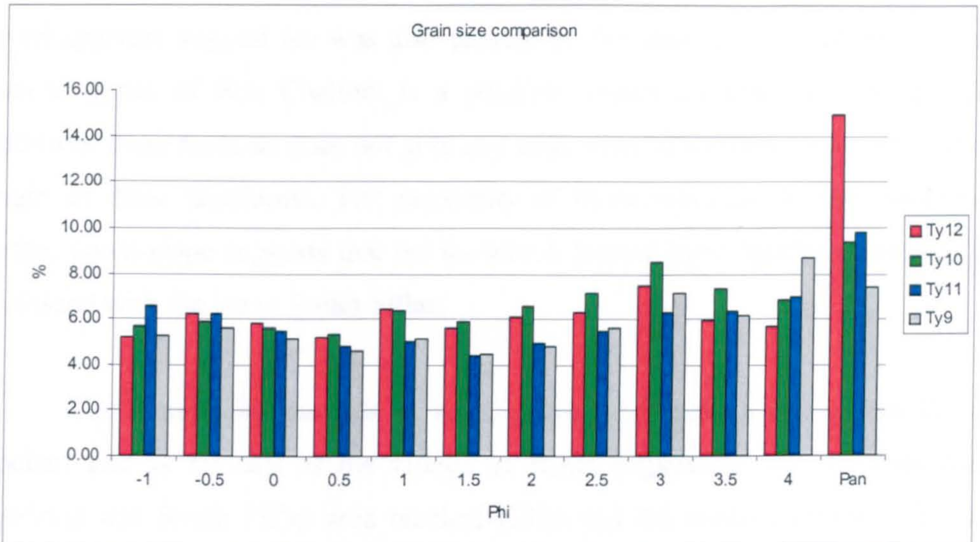


Figure 6.44 Grain size comparison of marginal moraine and debris flow deposits

The difference in clast angularity and shape between the features higher on the valley sides an the kames terraces, kames, eskers and hummocky moraine on the valley floor indicate that the material on the valley floor has been subject to a more modification by active transport than the material on the valley sides. This could be interpreted as due to subglacial transport of the valley floor clasts, with more supraglacial material in the landforms of the valley sides. However the morphology and spatial organisation of the valley floor landforms, unconsolidated material and inconsistent clast fabric orientations do not suggest these landforms were formed subglacially. The clasts in the valley side features are significantly more rounded than the scree and bedrock samples suggesting some modification during transport. The down-slope orientated landforms are therefore unlikely to consist of locally derived scree, and are interpreted as degraded lateral moraines consisting of material that has undergone some glacial transport. The large quantity of glacial debris both on the valley sides and valley floor are interpreted as having a supraglacial origin with the higher proportion of subrounded clasts in the mainly glacifluvial landforms of the valley floor being due to localised glacifluvial modification.

Hummocky features with no obvious spatial pattern on the slopes above Inverhaggernie suggest ice was also present in this area. Coire Challum on the eastern slopes of Ben Challum is a possible source for this ice. The spatial pattern of these features does not give any indication of ice-flow direction or the origin of these landforms. The proximity of these moraines to the moraines further down-slope suggests that the ice which formed these landforms probably coalesced with the ice in Strath Fillan.

The hummocky mounds of sand, gravel and clasts continue into Glen Dochart and as far east as the village of Killin suggesting that ice from the Tyndrum and Strath Fillan area reached Killin and the western shores of Loch Tay during the Loch Lomond Stadial. The glacial landforms of Tyndrum and Strath Fillan do not therefore mark the maximum limit of glaciation in this area during the Loch Lomond Stadial. Hummocks on the floor of Glen Dochart, in the vicinity of Loch Dochart, consist of bedrock with a thin covering of sandy diamict. The clasts in this diamict are more rounded than those found to the west. Clasts are mostly subrounded with a high proportion of rounded clasts. The high proportion of rounded clasts suggests some glacifluvial modification. As bedrock exposures can be seen along the length of these features they are interpreted as glacially streamlined knolls with glacial and glacifluvial drapes.

6.4 Summary

The glacial landforms of Tyndrum and Strath Fillan are dissimilar in morphology to those found at the Torridon and Rannoch Moor field sites. Large terrace like features on the eastern side of the Cononish Valley and at Auchtertyre on the north side of Strath Fillan are interpreted as kame terraces. Two spatial patterns of hummocky features were recognised in the Cononish Valley including chains of hummocks interpreted as eskers, and hummocks with no obvious spatial pattern which could either be the remnants of eskers, kames, or chaotic hummocky moraine formed by the meltout of buried ice due to glacier ice with a high sediment content and therefore are not thought to have any climatic significance. Faults in the sediments of sandy hummocks to the south west of the eskers in the Cononish Valley, and an esker superimposed on a kame terrace, suggest some minor readvance as the glacier receded to the upper part of the Cononish Valley.

Glacigenic landforms on the higher slopes on the north side of Strath Fillan have a down-slope orientation, are heavily gullied and include more material of a supraglacial origin. These are interpreted as lateral moraines, which have been subject to slope processes and some fluvial modification. Above Inverhaggernie hummocks with less spatial organisation suggest ice was also present in Coire Challum, on the eastern slopes of Ben Challum. Linear hummocks concentrated in one area above Auchreoch Farm, on the south side of Strath Fillan have a cross-valley orientation and are interpreted as marginal moraines. These features are thought to represent a standstill position of the glacier as it receded back to the area of Auchtertyre and Cononish.

The "hummocky moraine" of the Strath Fillan and Tyndrum area therefore includes glacial landforms of varying genesis including landforms of glacifluvial and supraglacial origins, some of which have been subject to paraglacial resedimentation. These landforms are thought to have been formed during active retreat of the glaciers back towards the corries of the surrounding mountains, although some periods of marginal stability may have occurred due to the effects of debris cover at the glacier margins in the Cononish Valley.

Digital elevation models were found to be more useful for landform visualisation in area of less varying relief such as the Cononish Valley. Landform morphology and spatial organisation was difficult to recognise on images derived from the D.E.M.s for steeper relief areas such as Strath Fillan. This is due to contouring methods based on joining points of equal elevation. If landforms are located on steeply sloping ground there outlines are not at an equal elevation and therefore contours join points of equal elevation on adjacent landforms, resulting in images that poorly depict the landforms. This has important implications for the use of digital elevation models in the study the geomorphology at this scale, in steeply sloping terrain.

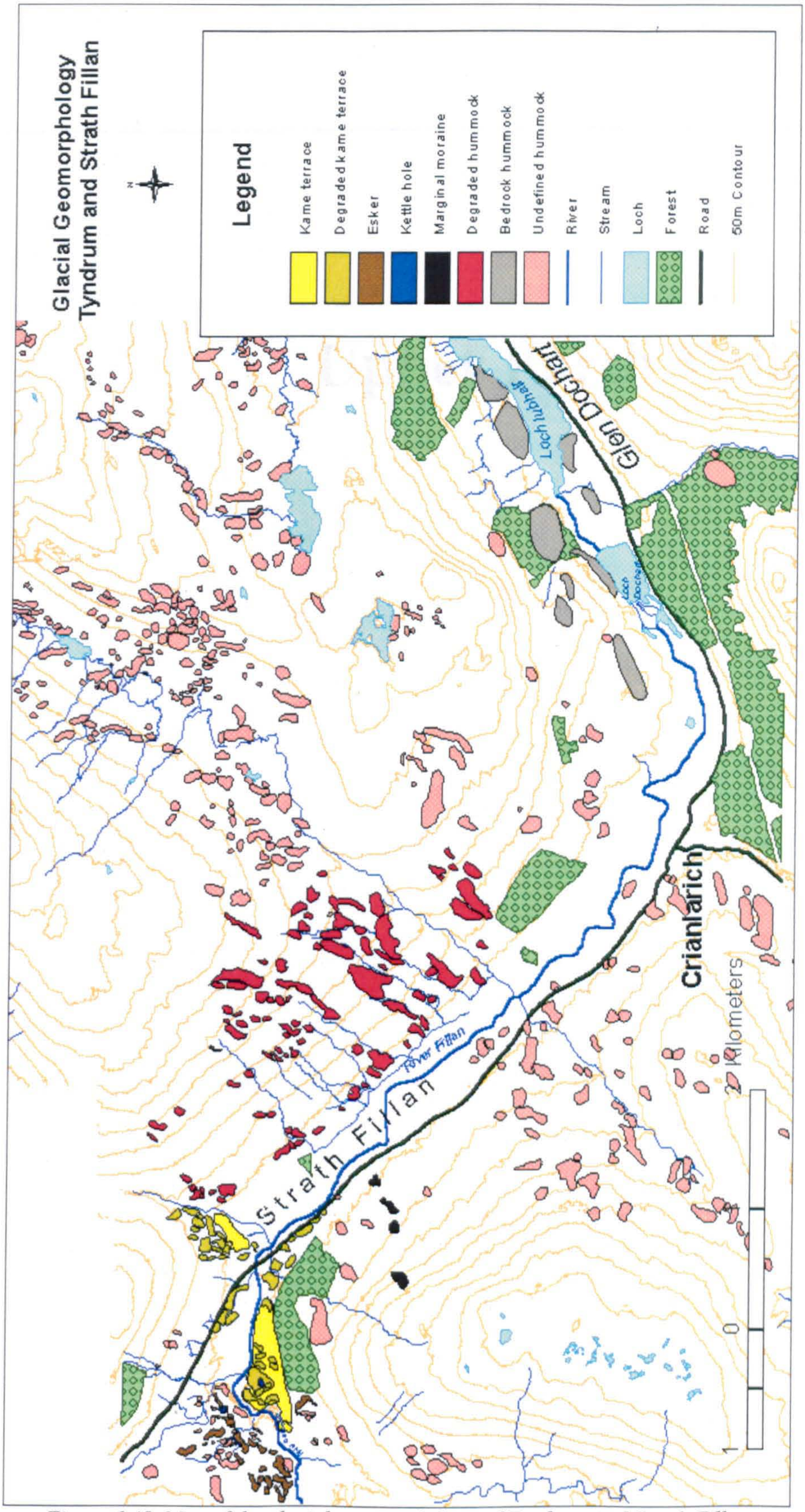


Figure 6.45 Map of the glacial geomorphology of Tyndrum and Strath Fillan

7

Upper Forth Valley

7.1 Introduction

7.1.1 Location

The upper Forth Valley is situated in central Scotland on the south-east boundary of the Highlands, approximately 12km from the shores of Loch Lomond (fig 7.1). The field-site is located around the floodplain of the western part of the River Forth and the low-lying topography of the Carse of Stirling. Prominent moraines can be traced along the southern and western parts of the field site. The field site is roughly bounded by the Glasgow to Aberfoyle road (A81) and the villages of Buchlyvie and Arnprior to the south. The eastern extent of the field site is approximately 3km east of the Lake of Menteith on the low lying carseland of the Forth Valley.

Figure 7.1 Location of upper Forth Valley field site and extent of Loch Lomond Readvance (adapted from Sissons 1974)

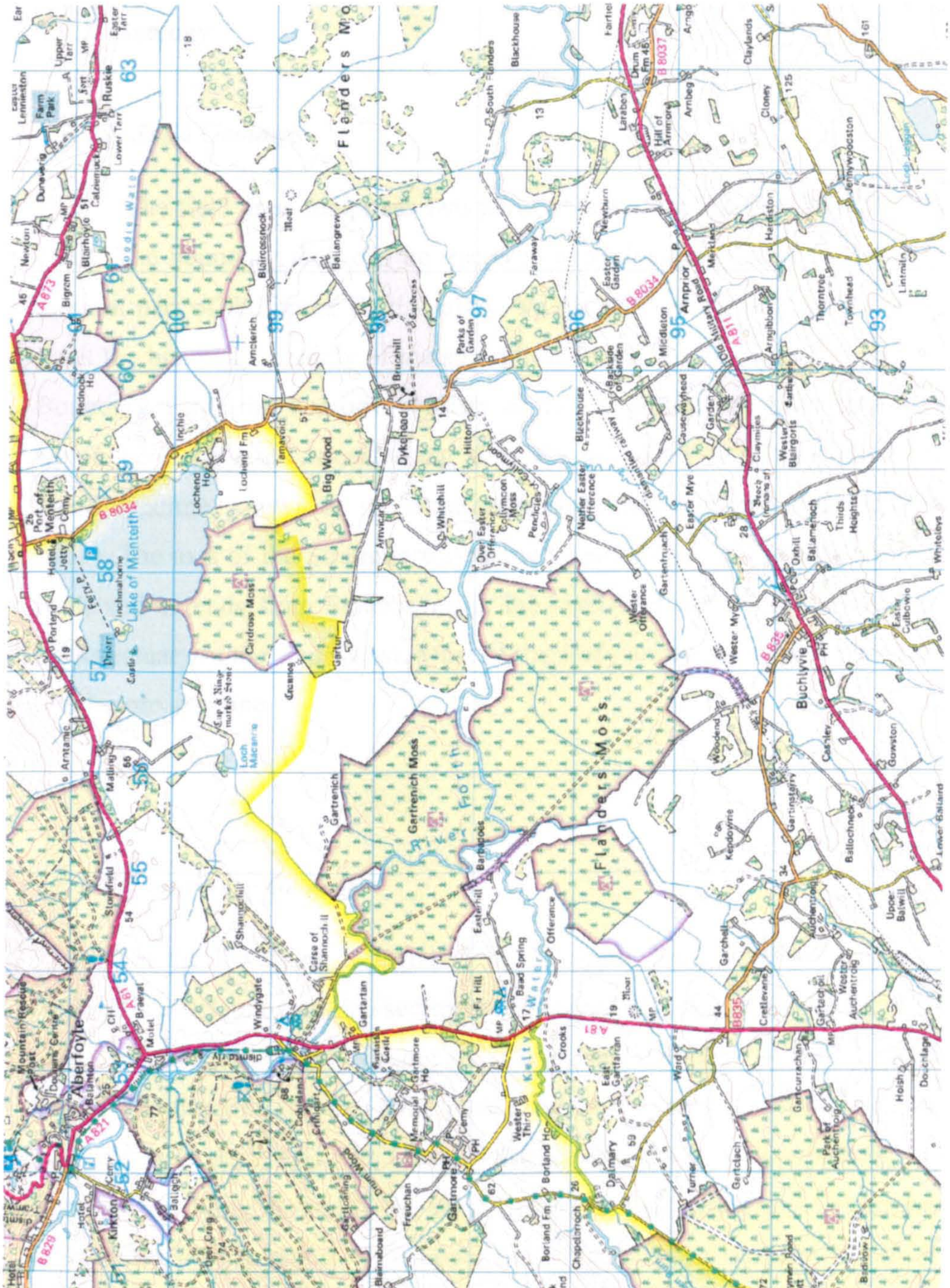


Figure 7.2 Extract from Ordance Survey 1:50 000 series map of upper Forth Valley (crown copyright Ordnance Survey)

7.1.2 Geology

7.1.2.1 Solid Geology

The field area comprises two parts separated by the Highland Boundary Fault. The boundary fault can be traced in a north-easterly direction across the western part of the upper Forth Valley. To the west of the Highland Boundary Fault the bedrock is mainly of metamorphosed rock. To the east of the Highland Boundary Fault the bedrock consists of Lower Devonian sedimentary rocks which were deposited as coalescing alluvial fans, which were later folded into a broad syncline, known as the Strathmore Syncline (Cameron and Stephenson 1985). The axis of the Strathmore syncline is parallel to the Highland Boundary Fault and extends from Stonehaven in the north-east to Loch Lomond and the Clyde estuary in the south-west. Most of the study area lies within the area of the Strathmore syncline.

7.1.2.2 Quaternary Geology

On the low lying topography of the upper Forth Valley the Devonian bedrock is overlain by marine sediments deposited during marine incursion in the Late Devensian and again during the Flandrian. The term "carse" is used in Scotland to describe flat low lying plains, especially those surrounding estuaries (Hansom & Evans 2000). The Carse of Stirling extends for approximately 50 km from the low lying ground to the west of the Lake of Menteith to Grangemouth in the east. Sedimentation in the upper Forth Valley has a complex history with evidence of two periods of glaciation and changing sea levels, although evidence of glaciation prior to the Loch Lomond Stadial is sparse within the Loch Lomond Readvance limit. The area of the upper Forth Valley has been inundated by marine water on several occasions (Simpson 1933, Sissons 1966, Sissons & Brooks 1971, Smith 1993, Hansom & Evans 2000). There is however little evidence of the environmental history of the area pre-dating the Dimlington Stadial. Tills dating to the Dimlington Stadial are overlain by a unit of marine clays and silts. These are the Forth Valley equivalent of the Clyde Beds, which are found to the west in the Clyde estuary and in the Loch Lomond Basin. The Clyde Beds have been described as grey to greyish brown clayey silts and sands with some gravel and some more angular material, and some cobbles and boulders, thought to be due to ice rafting during winter (Peacock 1981). The lower beds of the Clyde Beds at some sites are coarser with more angular material than the overlying material. This is attributed to meltwater influx from the retreating glaciers at the end of the Dimlington Stadial. The Clyde Beds have been dated to around 13,500 to 10,000 ^{14}C years BP (Peacock 1981)

According to Simpson (1933), sea level was still high during the Loch Lomond Stadial. Shells found in the Menteith Moraine, at Inchie Farm on the east shore of the Lake of Menteith were interpreted as evidence of sea level being at least 19.8 m O.D. The occurrence of shells at this site has however been reinterpreted as due to the glacial reworking of the Clyde beds (Smith 1993). According to Sissons (1966) sea level in the upper Forth Valley was lower during the Loch Lomond Stadial than Simpson proposed. Meltwater channels and outwash terraces descending to 8.8m O.D. are used as evidence that sea level was lower than that altitude. The Lake of Menteith is thought not to have been affected by marine incursion following the Loch Lomond Stadial as no postglacial carse clays have been found in the floors of meltwater channels on the north-east shores of the Lake. Carse clays deposited since the Loch Lomond Stadial however can be found on the lower ground of the flood plain of the River Forth

In the early Flandrian, around 10,000 to 8,500 ^{14}C years B.P., relative sea level fell due glacioisostatic recovery, allowing peat to develop. Around 8,000 ^{14}C years B.P. relative sea level rose again, mainly due to the disintegration of the Laurentide Ice Sheet. Relative sea level at Stirling rose by 7 metres in 1000 years, resulting in a return to marine estuarine conditions in the upper Forth Valley (Fig 7.3).

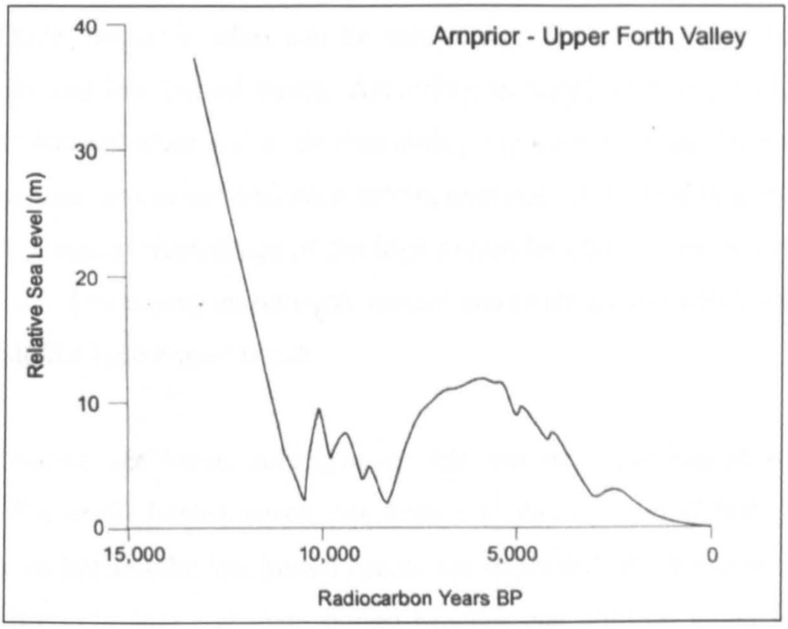


Figure 7.3 Relative sea level curve for the Upper Forth Valley (Sissons & Brooks 1971)

To deposit the carse clay the environment would have to be one with a strong enough tide to transport sediment into the area and of low enough wave energy to allow the clay particles to settle out of the water column (Hansom & Evans 2000). The settling out of clays and silts in a low energy environment would create estuarine mudflats. The distribution of Flandrian carse clays can be seen on the map below (fig 7.4)

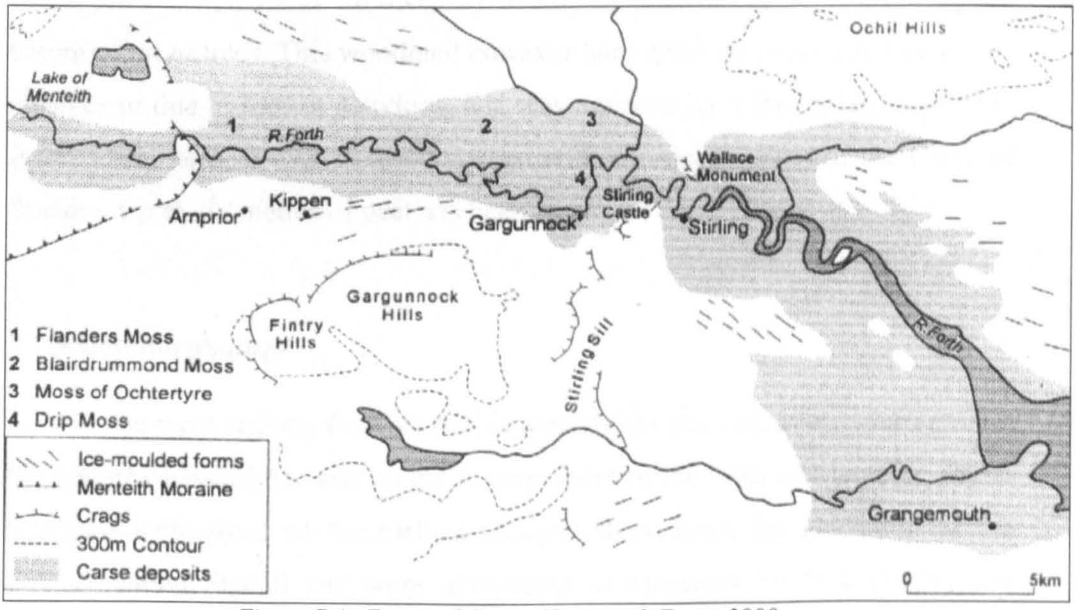


Figure 7.4 Extent of Carse: Hansom & Evans 2000

Three former beaches can be recognised. These have been termed the high, main and low buried beach. According to Smith (1993) the high buried beach was formed when sea levels rose during the Loch Lomond Stadial. Glacier ice, at this time was at its maximum extent, terminating at the Menteith Moraine. The Loch Lomond Stadial age of the high buried beach is based on evidence of beach material overlying an outwash surface and evidence of meltwater channels cutting into the high buried beach.

Relative sea levels subsequently fell and the main buried beach was formed. The main buried beach has been ^{14}C dated to 9600 B.P. Sea level continued to fall and the low buried beach was deposited, and has been ^{14}C dated to 8700 B.P. The low and main buried beaches can both be found within the limits of the moraine loop according to Smith (1993), however the high buried beach, interpreted as being formed while glacier ice occupied the upper Forth Valley, is not found west of the Menteith Moraine. This suggests that marine incursion into the area to the west of the moraines has occurred during the Flandrian, but did not occur during the Loch Lomond Stadial.

The carse clays which cover the low lying areas of the upper Forth Valley were deposited during high Flandrian sea levels, which persisted until around 8,000 yrs B.P. This was followed by a drop in relative sea level allowing the colonisation of trees. This woodland however later declined either due to climatic changes or due to human activities, and was replaced by a thick blanket of peat. From 1767 the peat was removed for agricultural improvement of the Carse of Stirling. Up to six metres of peat has been removed.

7.1.3 Geomorphology

The most striking features of this area are the prominent moraines around the village of Buchlyvie and on the eastern shore of the Lake of Menteith. These moraines were some of the earliest recognised evidence for glaciation of the Loch Lomond Stadial and were interpreted as moraines by Jack (1874) and

Renwick and Gregory (1907). Prominent moraines can be observed around the village of Buchlyvie, in the south-west of the field site and can be traced eastward to Arnprior and from there north along the eastern shores of the Lake of Menteith to Port of Menteith. Some moraines can be identified to the north of the Lake of Menteith. However on the north-west of the field area moraines are difficult to distinguish from the bedrock features related to the Highland Boundary Fault.

To the south of the moraines on the south side of the upper Forth Valley drumlins can be seen, which have a generally south-west to north-east orientation. As these are outside the limit of the moraines they are not thought to relate to glaciation during the Loch Lomond Stadial. and were interpreted by Rose (1981) as being formed by the Late Devensian Ice Sheet. Also the likely direction of ice during the Loch Lomond Stadial is to the south-east, as ice flowed along valleys connecting the upper Forth Valley with the high ground around Ben Lomond, to the north-west (Renwick and Gregory 1909, Simpson 1933).

Numerous large meltwater channels punctuate the moraines on the south of the Forth Valley and the Menteith Moraine, to the east of the Lake of Menteith. Small lakes can also be found on the low-lying area of the valley, within the limit of the moraines. It is possible that these were produced as kettleholes, following the meltout of buried glacier ice. Smith (1965) mapped numerous kettleholes on the carse, west of the moraine limit, however much of the area mapped by Smith is now covered with commercial forestry and the geomorphology is no longer visible. This study used aerial photographs from 1988, when much of the area to the west of the Lake of Menteith was forested.

Smaller scale landforms, common within the limits of terminal moraines of receding glaciers, such as hummocky moraine, crevasse squeeze ridges and flutings, were not found anywhere in the low-lying area west of the Menteith marginal moraines. Recognising landforms at this scale was found to be problematic, especially on the carse. This is due to natural and anthropogenic modification of this area. This may be due to burial by the carse clays and the thick blanket of peat. Removal of the peat and improvement of the land for agricultural purposes could also have removed evidence of past glacial deposition. Also much of the surface of the carse is obscured by commercial forestry and other intensive agricultural uses. The centre of the upper Forth Valley has also been subject to fluvial modification by the meandering River Forth and its tributaries.

The moraines of the Upper Forth Valley have been interpreted as ice marginal, frontal and lateral moraines (Renwick and Gregory 1907), as push moraines (Sissons 1976, Smith 1993) and as formed by glacitectonic processes due to ice moving rapidly over unconsolidated marine sediments with low shear strength due to high porewater pressures. According to Thorp the moraines in the upper Forth Valley were produced either by surging or continual rapid basal sliding. If these landforms were produced by the mechanisms proposed by Thorp (1991a) the moraine building processes may reflect the local topography and the nature of the underlying sediments and are not necessarily indicative of the climatic events of the Late Loch Lomond Stadial. As observed at the other field sites investigated in this study the spatial pattern and morphology of glacial landforms may be influenced more by local glaciological and topographic conditions rather than regional climatic changes as proposed by Sissons (1963, 1967a, 1967b, 1973, 1979).

This study will employ mapping, using GIS, and digital elevation models to ascertain if there is any evidence for the processes proposed by Thorp (1991a), as this non-climatic model of the glacial history of this area has important implications for climatic reconstructions based on the glacial geomorphology of the Loch Lomond Stadial. Sediments of the Forth Valley will be investigated to verify the conclusions of the geomorphological studies. Comparisons with glacitectonic landforms found at contemporary glacier margins in Iceland will also be used to interpret the landforms of this site.

7.2 Methods

7.2.1 Digital Photogrammetry and mapping

The glacial geomorphology of the upper Forth Valley was mapped and digital elevation models with a resolution of five metres were produced. This study area was covered in stereo by fourteen aerial photographs, in three strips with five photographs in the top and centre strips and four photographs in the lower strip. The photographs were fully orthorectified to remove all distortions.

Ground control used for the photogrammetric work was obtained using differential Global Positioning System (GPS) to measure the coordinates and heights of a network of control points covering the area. For each photograph a control point was measured as near to the fiducial centre of the photograph as possible and two other points per photograph were taken, one near the top centre and one close to the bottom centre of the photograph. This gave a coverage of six control points for each overlapping pair of stereo images. This is in accordance with practices for digital and analogue photogrammetry and allows an extensive coverage of control points enabling decisions on which points to include in the orientation and rectification of the images during the photogrammetric process. The reference GPS station was situated near Drymen for security reasons. This resulted in base lines of between 6.44 km and 19.11 km. Figure 7.5 shows the network of control points measured.

It was decided not to use all the control points but to use an adequate number of control points combined with tie points allowing the best positioning of points to tie together stereo models and strips of aerial photograph images. The GPS control points used in the final rectification are also shown on figure 7.5. Points chosen were based on their position, the accuracy of the GPS measurement and how they affected the rectification solution. Some points were difficult to recognise in the images due to various factors, including the nature of the terrain and feature chosen, the quality of the photographs and changes on the ground occurring between the date of the aerial photography and the GPS survey, which was approximately twelve years. Problems were found especially in the lower strip of photography due to this being an area of moorland where control points identifiable on the ground and in the photographs were found to be problematic. The low quality of the photographs covering this area was also a problem. This area however was not thought to be critical as no glacial landforms were visible. The control points used gave a good spread of coverage for the main area being mapped. Where less ground control was used this was substituted by using more tie points. Accuracy of the GPS control points and RMS values for the points used for rectification can be found in the appendix.

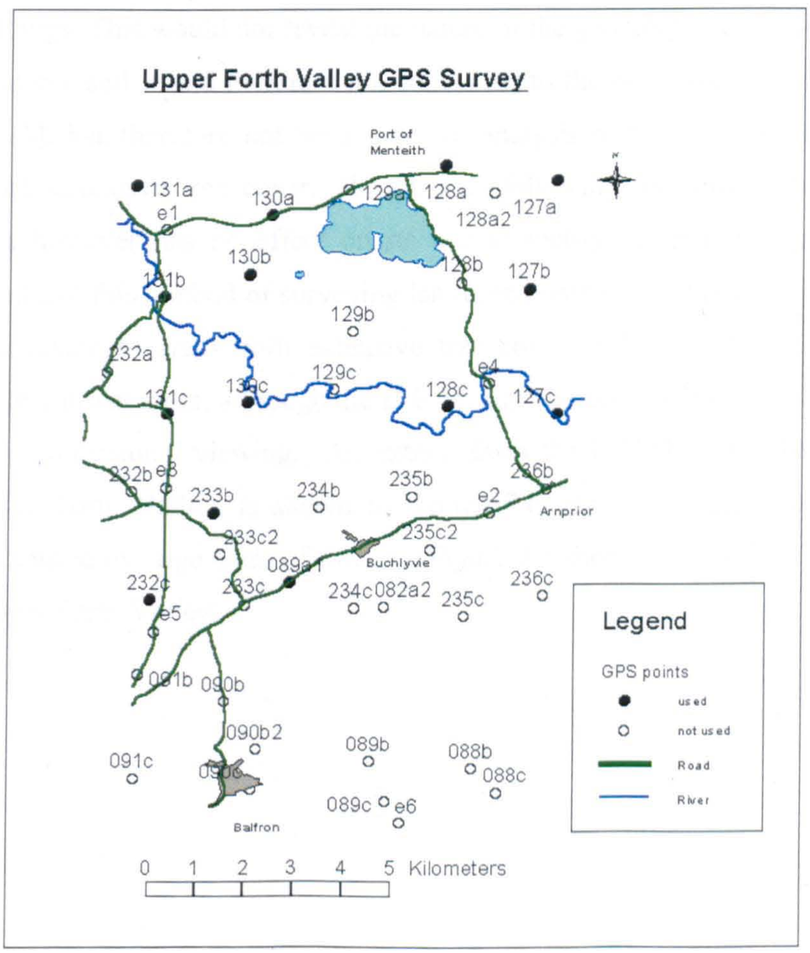


Figure 7.5 Upper Forth Valley GPS survey

After rectification a digital elevation model was produced for each stereo pair and the images corrected to produce orthoimages, which were then used to produce an orthomosaic. The D.E.M.s for each stereo pair were merged to create one D.E.M. of the study area. Using the D.E.M. was problematic however, as the D.E.M. heights are measured as the top of any feature in the aerial photoimage. This includes trees, buildings, fencing etc. and does not necessarily reflect the natural topography.

Although it is possible to correct the heights of the D.E.M. for the heights of trees and buildings this was not carried out as this would be very time consuming and only result in smoothing the D.E.M. for areas covered by forestry and buildings. This would not reveal the nature of the geomorphology underlying other features and would therefore not contribute to the objectives of this study. The D.E.M. has therefore not been used for analysis of the geomorphology in areas with extensive tree cover. The D.E.M. following the tops of trees and buildings however has no effect on its use to rectify the photoimages. It is concluded that this method of surveying landforms using digital photogrammetry is not adequate in areas with extensive tree cover and/or areas of intensive farming and urban areas, although the D.E.M. can be used for photo rectification and three dimensional viewing. An extract from the D.E.M., from the central part of the Forth Valley, is shown in figures 7.6 and 7.7 to demonstrate the problem caused by large areas of forestry. Figure 7.8 shows the extent of forestry in the upper Forth Valley.

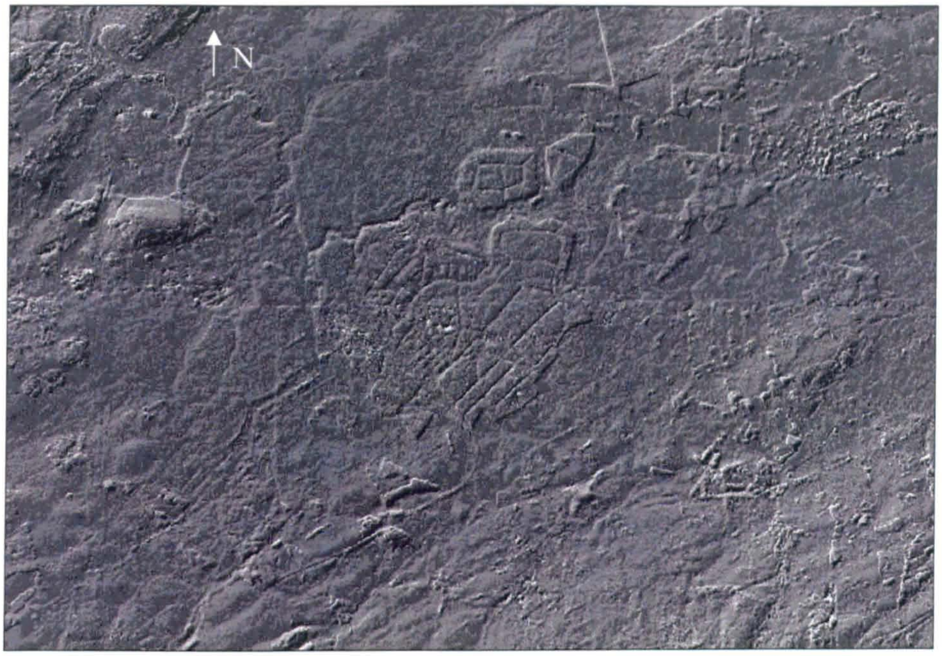


Figure 7.6 Extract from hillshaded D.E.M. upper Forth Valley

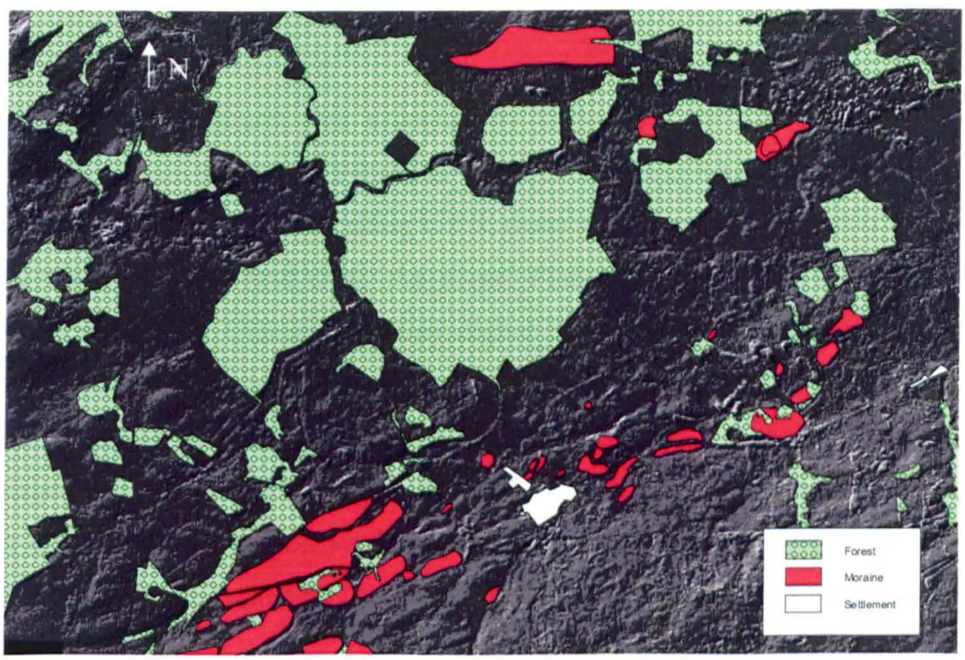


Figure 7.7 Extract from shaded D.E.M. showing location of forestry and moraines

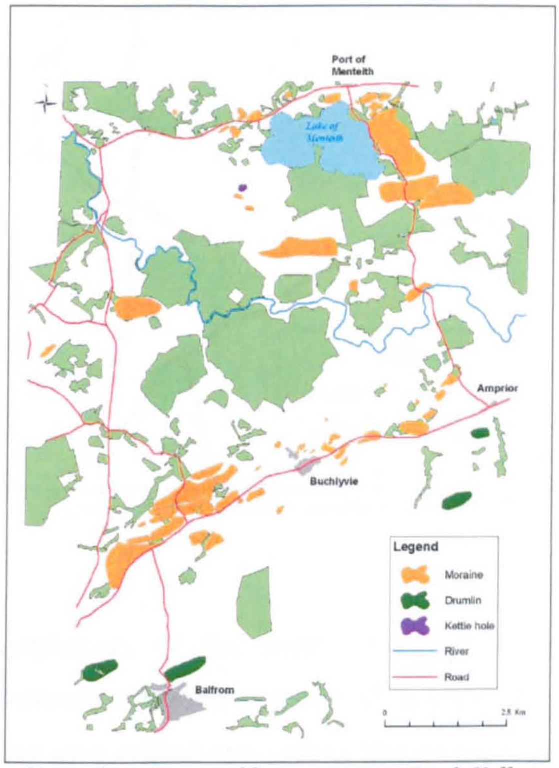


Figure 7.8 Extent of forestry, upper Forth Valley

Planimetric accuracy was assessed by comparing the coordinates of features on Ordnance Survey 1:25 000 and 1:50 000 scale maps to coordinates of features measured on the D.E.M. using G.I.S. these were found to be within the accuracy which can be read from the maps. Planimetric accuracy was also assessed by comparing Ordnance Survey digital data to data derived from the orthoimage. Digital map data of roads for the area were obtained from Ordnance Survey Digimap (in meridian format) and compared to roads digitised from the orthoimages. Roads were chosen for this rather than natural features as the position of roads is less subjective than the boundaries of natural features. The map below shows a section of this comparison, overlaying Ordnance Survey and digitised data (fig 7.9).

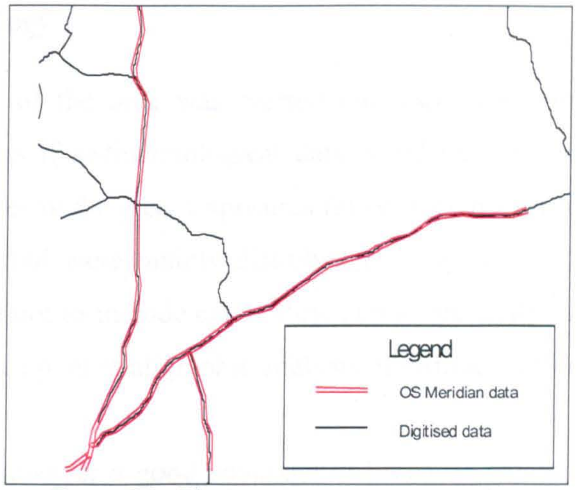


Figure 7.9 Planimetric accuracy comparison

The geomorphology of the study area was mapped using digital photogrammetric software, allowing mapping while viewing in three dimensions. Some problems were encountered in mapping this area, partly due to the quality of the D.E.M., due to trees and buildings, as discussed above and also due to land improvement for farming and large areas of forestry which either obscure, or have removed the geomorphological evidence. This area has also undergone peat development with most of the low-lying topography of the central part of the upper Forth Valley being covered. Much of this peat was removed for agricultural improvement from the late eighteenth century onwards. It is therefore difficult to interpret the origin of small scale features in the area. Larger scale features such as the larger marginal moraines found on the south of the valley and to the east of the Lake of Menteith are easily recognisable, and mappable from the orthoimages (corrected photo images).

Although it was possible to map landforms on the ground away from the carse, and where there is less tree cover, a combination of tree cover and poor quality aerial photographs prevented more detailed studies of the landforms at these locations. It is therefore concluded that the use of digital photogrammetry for the interpretation of glacial geomorphology is highly dependent on the amount of vegetation cover, the nature of the topography and aerial photograph quality. The technique was therefore not found to be satisfactory at this location.

7.2.2 Sedimentology

A survey of the area was carried out, especially around areas of the moraines to assess *if* sedimentological data could be collected. There are few sediment exposures in the area. Exposures found were not large enough to reveal any stratigraphy and were mainly disturbed by slumping or tree roots. It was therefore decided not to include clast fabric and shape analysis for this site or to undertake any attempt at stratigraphic analysis of sediments from field evidence.

There is however a good coverage of borehole records available for the upper Forth Valley, with the exception of the western part of the carse, held by the British Geological Survey. Borehole diagrams were drawn and the locations of the boreholes mapped in the G.I.S. This allowed visual spatial analysis of the borehole records and allowed the correlation of the borehole records with other data including the mapped glacial geomorphology and its topographic position, based on the D.E.M. It was found useful to use ArcView's facility to "hotlink" images to maps. This allows the user to click on a feature to display an image of that feature. This tool was found to be useful to spatially analyse the data visually in the borehole records. Digital photographs of landforms were also stored and mapped in the G.I.S. using the hotlink facility.

The borehole records are of varying age and quality. Some give detailed descriptions and interpretations, however others, especially the older records, have less information on the sediment units. Some of the older records were hand written and faded, with unrecognisable abbreviations. Correlating the sediment units in the boreholes to produce a three-dimensional fence diagram was attempted, however, due to the varied descriptions of materials, and lack of boreholes for the central part of the Forth Valley, to the west of the moraine limit, this was found to be problematic. It was found more appropriate to correlate selected boreholes to produce cross section diagrams. Four cross sections were produced, one west to east, parallel to the valley axis, one north to south in the area of moraines to the east of the Lake of Menteith and in the vicinity of Arnprior, and two on the carse beyond the moraine limit. This allowed comparison of sediments within the moraine limits to those to the east of the

Lake of Menteith and Arnprior, outside the limit of the moraines. Cross sections were not produced for the Ballat area as the boreholes were clustered, with little spatial variation. The borehole sediments were generalised for the purpose of producing cross profile diagrams but are discussed in more detail in the text. The full description of sediments as recorded in the BGS borehole records are given in appendix 4.

7.3 Results and Interpretation

7.3.1 Geomorphology

The glacial geomorphology of the upper Forth Valley lacks detail, due to the absence of recognisable small scale features within the limit of the marginal moraines, for reasons previously discussed. The more prominent features such as the marginal moraines and meltwater channels can be mapped and inferences made about their genesis (fig 7.10). The digital elevation models were, however, not of a high enough quality to allow a more detailed study of these landforms. This was due to the influence of tree cover and buildings, in this intensely forested and farmed landscape, and the poor quality of the aerial photographs.

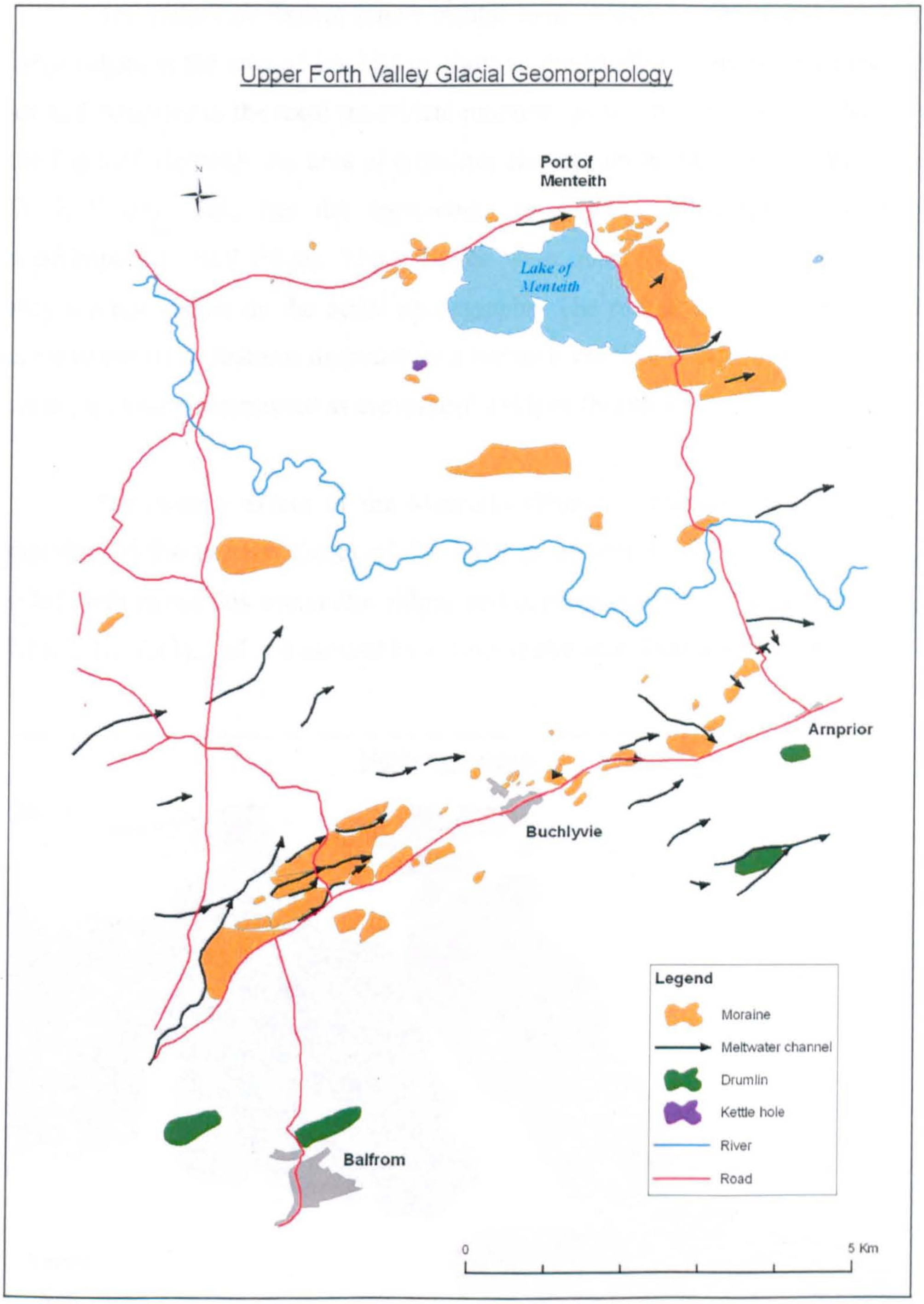


Figure 7.10 Upper Forth Valley geomorphology

The moraines form a latero-frontal loop, which can be traced from the large ridges in the area of Buchlyvie, through the smaller ridges towards the east around Arnprior to the most prominent moraines in the area on the east shores of the Lake of Menteith. An area of moraines also occurs in the central of the upper Forth Valley. This has the appearance of a large topographic high with superimposed small ridges. These ridges were observed in the field, however they are not visible on the aerial photographs. The moraines of the central area are interpreted as features draped over a bedrock knoll. The ridges on this feature were previously interpreted as crevasse-fill ridges (Smith 1993)

The eastern extent of the Menteith Glacier is marked by a prominent moraine on the eastern shores of the Lake of Menteith. The moraine is steep-sided with numerous transverse ridges and depressions on its distal slope (figs 7.11, 7.12, 7.13), and is dissected by a large meltwater channel (fig 7.14).

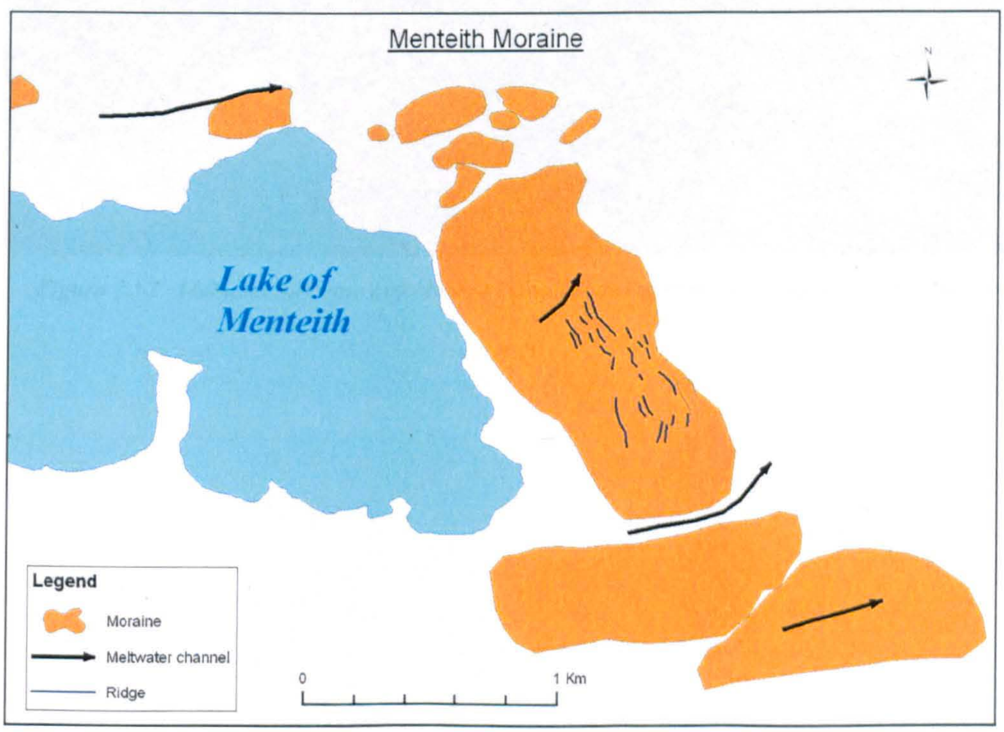


Figure 7.11 Menteith Moraine

Figure 7.12 Menteith Moraine orthoimage extract showing transverse ridges on the distal slopes

Figure 7.13 Menteith Moraine distal slope with ridges and depressions

Figure 7.14 Menteith Moraine meltwater channel

The exact shape of this feature and its slope angles are difficult to determine from aerial photographs and the D.E.M due to a dense tree cover of varying height and the poor quality of available aerial photographs. The ridges have been mapped on the southern part of the moraine, but could not be identified on the northern part due to the tree cover. Little of the morphology of this landform was visible on the D.E.M (fig 7.15). However the extent of the moraine and morphology of it's southern, non-tree covered, part was visible on the orthophoto and three-dimensional model based on the D.EM. draped with the orthophoto (Fig 7.16). The effects of tree cover can also be seen by comparing these images. Features were mapped digitally using the digital orthophoto displayed with the D.E.M. using Helava Leica Socet Set's stereo viewing tools. Similar problems were found with the D.E.M. for other moraines in the upper Forth Valley.

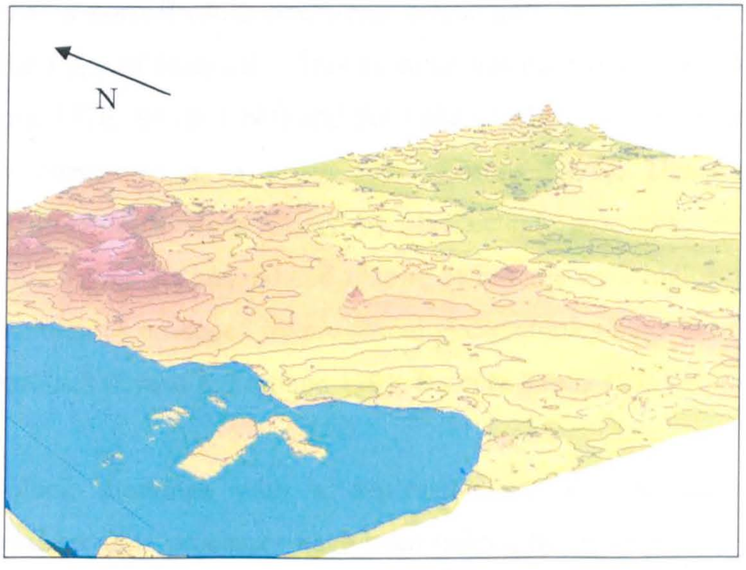


Figure 7.15 3d contoured image , Menteith Moraine

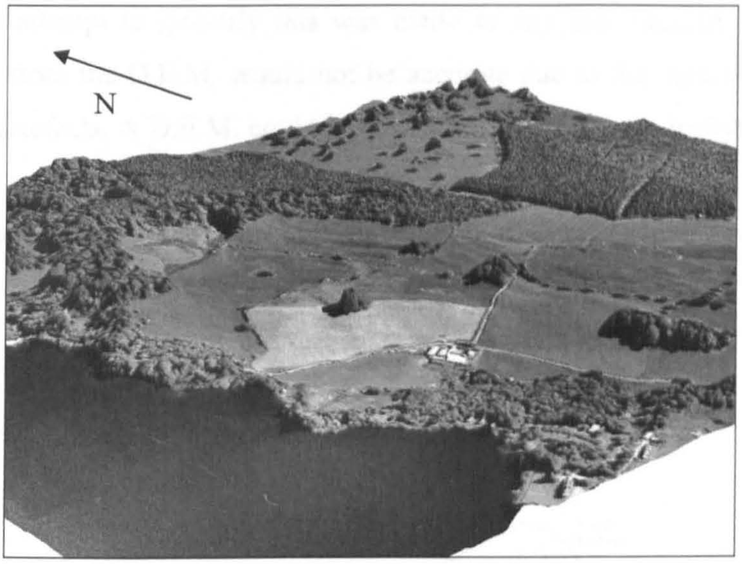


Figure 7.16 3d orthoimage, Menteith Moraine

The main part of the Menteith Moraine is approximately 1.5km long and 0.7 km wide, has a north-west to south-east orientation, and is situated on the east shore of the Lake of Menteith. This moraine has been described as a push moraine (Sissons 1976, Smith 1993) and the Lake of Menteith, on its upglacier side has been interpreted as a kettle hole (Sissons 1976). Thorp (1991a) interpreted this moraine as being formed by glacitectonic processes, by glacier ice flowing rapidly over unconsolidated marine sediments with high porewater pressure. Such moraines produced by proglacial glacitectonics have been termed thrust-block moraines (Evans & England 1991, Benn & Evans 1999).

Thrust-block moraines with a depression on their upglacier side, excavated by glacitectonic processes have been termed hill-hole pairs (Bluemle & Clayton 1984). The depression of a hill-hole pair should be of similar size to the moraine. It can be seen from the map that the moraines on the eastern shore of the Lake of Menteith are smaller in area than the Lake. However it can be seen from the bathymetry shown in the map in figure 7.17 that the lake is shallow, mostly less than 15m deep. The volume of material in the moraines may therefore be similar to that of the lake, which would suggest the Lake of Menteith and the moraine on its east shore constitute a hill-hole pair.

No attempt to quantify this was made as any measurement of volume calculated from the D.E.M. would not be accurate due to the inclusion of trees and other artefacts. A D.E.M. could have been created from the bathymetric data for the lake. Comparing the volume of the lake calculated from such a D.EM., which would have an irregular point distribution to a D.EM. with a regular grid of points derived from photogrammetry would not be reliable as any difference in volume may be due to the differing methods of terrain modelling.

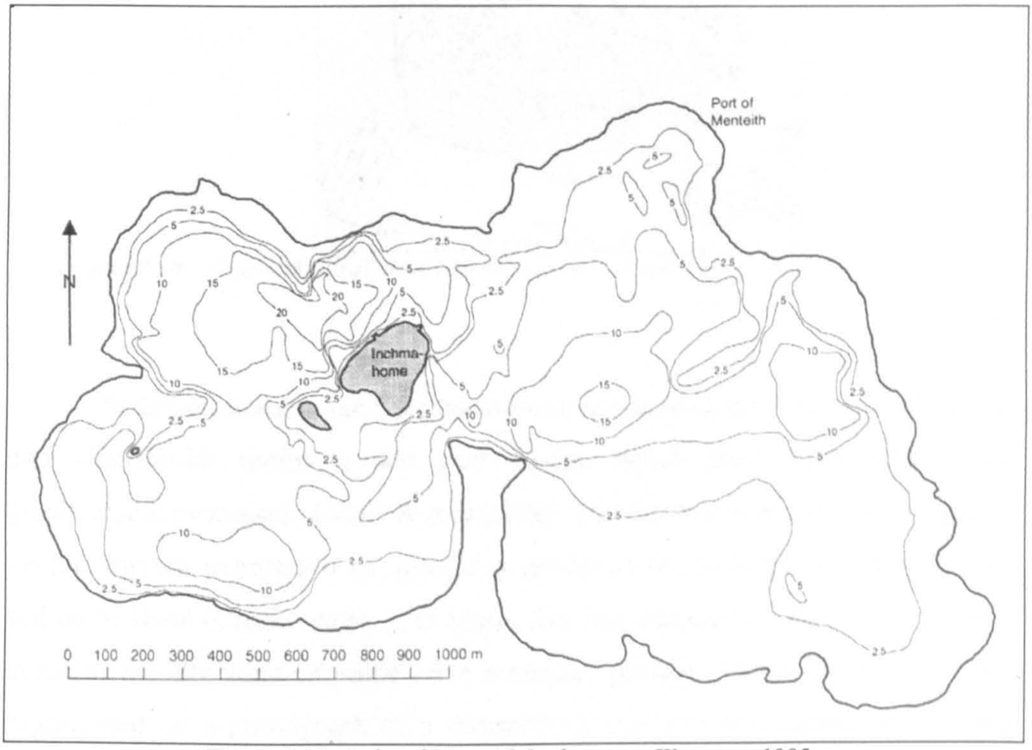


Figure 7.17 Lake of Menteith bathymetry, Wewetzer 1995

Similarities in the morphology of the moraine of the east shore of the Lake of Menteith and proglacial moraines at Eyjabakkajokull, on the north-east side of Vatnajokull ice cap, Iceland, suggest this feature could have been produced by similar processes. Eyjabakkajokull is known to have surged, producing large thrust-block moraines with transverse surface ridges, similar to those found on the Menteith Moraine. The moraines at Eyjabakkajokull have depressions on their upglacier side, now filled with water, and can be compared to the depression of the Lake of Menteith on the upglacier side of the Menteith Moraine. The map (fig 7.11) of the Menteith Moraine can be compared to the map of a thrust-block moraine at the margin of Eyjabakkajökull (fig 7.18). A full version of this map, as published by Evans and Rea (2003), can be seen in the Literature Review Chapter (Chapter 2, fig 2.7)

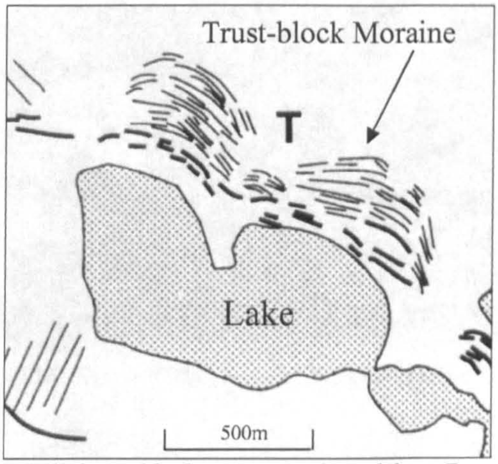


Figure 7.18 Eyjabakkajökull thrust-block morain,e adapted from Evans & Rea (2003)

Sediment units in the Eyjabakkajökull moraines consist of slabs of glacial and glacifluvial sediment and peat layers, which have been stacked by glacitectonic processes (Evans & Rea 2003). The transverse ridges are thought to be the surface expression of anticlines produced by thrusting and stacking of sediment slabs (Croot 1988). It is likely that the transverse ridges on the distal slope of the Menteith Moraine have a similar genesis. The sediment slabs are highlighted on a photograph of a thrust-block moraine at Eyjabakkajökull (fig 7.19). As sediment exposures on the Menteith Moraine are not extensive enough to show the internal structure of the feature, the structure cannot be compared to similar features at contemporary glacier margins, and interpretation of the moraine can therefore only be based on morphology and juxtaposition with other features alone. An attempt was made to investigate the structure of the Menteith Moraine using ground penetrating radar (GPR). However this was not successful due to the structure of the moraine being obscured by groundwater. It was not possible to differentiate between GPR signals due to sedimentary properties and ground water.

Figure 7.19 Thrust-block moraine, Eyjabakkajokull

According to Evans and Rea (2003) the thrust-block moraines at Eyjabakkajökull were produced by proglacial glacitectonic thrusting of unfrozen sediments. It has been suggested (Aber et al. 1989, Evans & Rea 2003) that thrust-blocks can be produced either by glacier surging or by steady state flow at sub-polar glacier margins with discontinuous permafrost. Failure and stacking of large blocks can also occur where high pore-water pressures develop, such as in proglacial glacimarine, marine and glacifluvial sediments.

Two cross profiles were measured, using the D.E.M. and ArcView G.I.S. on the southern part of the Menteith Moraine. It was not possible to measure cross profiles on the northern part of the moraine due to tree cover. The dense tree cover would also prevent the use of land survey techniques, such as levelling, total station survey or G.P.S. to measure a cross profile, so this was not attempted. The two cross profiles measured are shown in fig 7.20

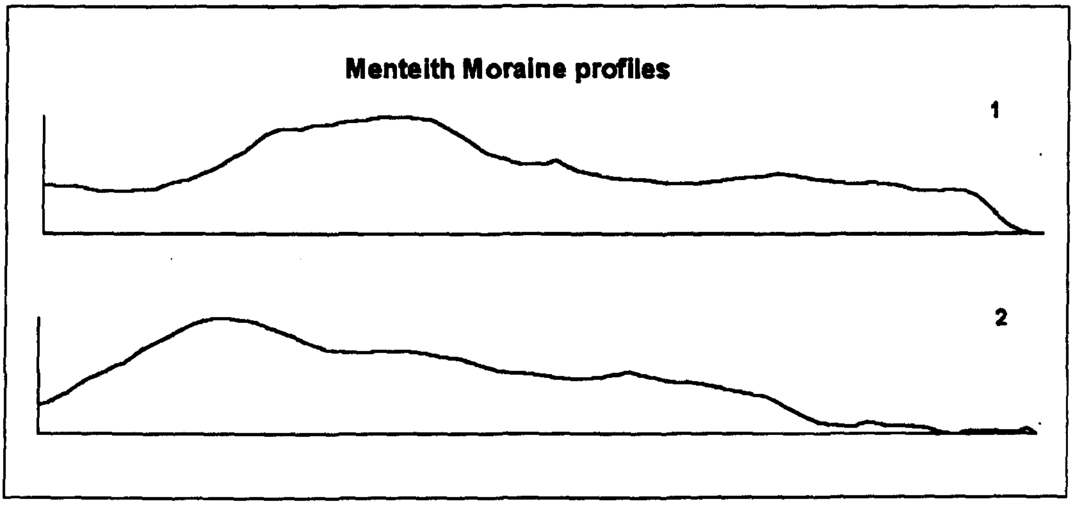


Figure 7.20 Menteith Moraine cross profiles

The cross profiles show a steeper proximal slope and more gently sloping distal slope. A model of the sequential development of a thrust-block moraine at Eyjabakkajökull was proposed by Croot (1988) (fig 7.21). The final profile of the model exhibits a low angle slope on the upglacier side of the moraine, which has been overridden by the glacier snout and a steep slope where the moraine was compressed by the glacier snout. The low angle distal slope shows thickening due to compressional shortening. This profile is similar to the profiles for the Menteith Moraine, especially profile 1. The morphology of the ridge including its profile and the transverse ridges on the distal slope are similar to the characteristics of the thrust-block moraines at Eyjabakkajökull, suggesting the Menteith Moraine could have been produced by similar glacitectonic processes.

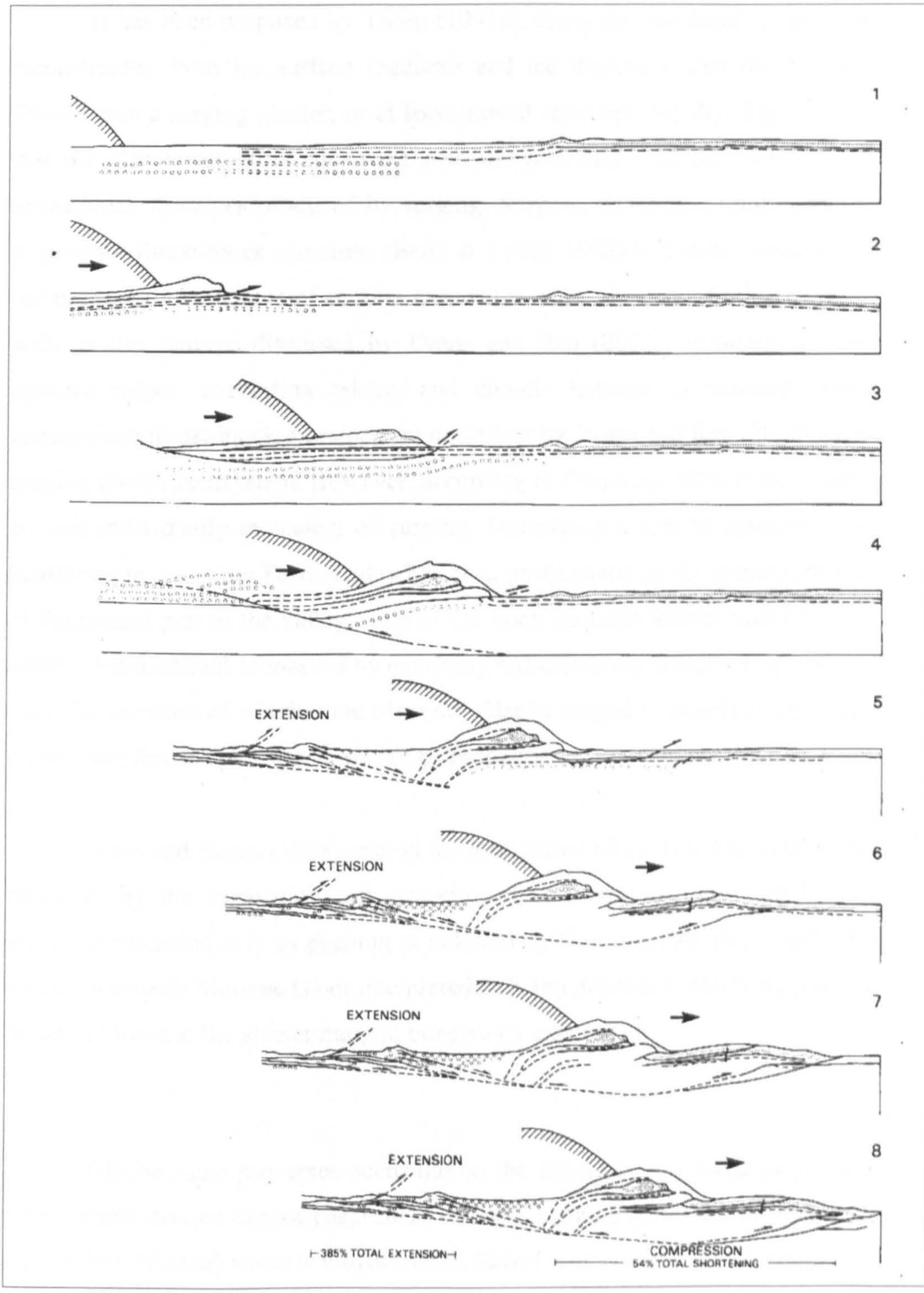


Figure 7.21 Model of the development of a thrust-block moraine Eyjabakkajökull: Croot 1988

It has been proposed by Thorp (1991a), based on low basal shear stress, reconstructed from ice surface gradients and ice thickness, that the Menteith Glacier was a surging glacier, or at least moved relatively rapidly. The proposal that the glacier surged is consistent with the comparison of the moraine with thrust-block moraines produced by surging. Surging, however, is not necessary to produce thrust-block moraines (Benn & Evans 1998) and such moraines are not necessarily indicative of surging especially in the absence of other evidence such as the features discussed by Evans and Rea (2003) including crevasse squeeze ridges, concertina eskers, and chaotic hummocky moraine. These features and thrust-block moraines are described by Evans and Rea (2003) as the surging glacial landsystem. However, according to Evans and Rea, these features are not individually indicators of surging. Identifying a similar assemblage of landforms in the upper Forth Valley has been problematic as the geomorphology of the central part of the valley, west of the Loch Lomond Stadial moraines, has either been modified or masked by overlying sediments and intensive agricultural use. The question of whether the Menteith Glacier surged is therefore dependent on whether thrust-block moraines can be produced by non-surging glaciers.

Benn and Evans (1998) restrict the term thrust-block moraine to moraines produced by the excavation and elevation of sediment and does not include moraines produced only by pushing or bulldozing. This terminology is used here, and the Menteith Moraine is not interpreted as being produced merely by pushing by lateral force at the glacier margin, but also by excavating.

Glacitectonic processes occur due to the failure of proglacial sediments, when lateral stresses exceed basal shear strength, pushing material away from the glacier bed. Normal stress is transferred to lateral stress as glacial materials tend to bulge out away from the normal stress produced by the weight of the overlying ice. Ice does not have to be very thick to produce normal stress great enough for this to occur (Benn & Evans 1998). The amount of normal stress transferred to lateral stress is related to sediment cohesion, which is affected by porewater pressure.

High pore water pressure in the underlying poorly drained marine silts and clays in the upper Forth Valley could have resulted in low sediment cohesion, and therefore conditions suitable for glacitectonic processes. High porewater pressure has also been thought to occur during glacier surging, which would increase the likelihood of glacitectonic processes at the glacier margin. High porewater pressure in the underlying marine sediments has been proposed as a mechanism for surging of the Menteith Glacier (Thorp 1991a). Although glacitectonic processes and the production of thrust-block moraines and hill-hole pairs have been linked to surging behaviour, surging is not thought to be necessary for the production of thrust-block moraines. Recently however thrust-block moraines in the Canadian high Arctic, previously thought to have been produced by non-surging glaciers have been reinterpreted as products of surges after the identification of former surge activity on the glacier surfaces (Copland et al 2003).

Large meltwater channels can be seen at locations within the limit of the moraines in the Upper Forth Valley, and also dissecting the moraines, especially at the eastern margin of the moraine loop. The meltwater channels are mainly associated with the Menteith Glacier, but also with water from the Lomond Glacier. Channels issuing from Ballat Gap show water from Lake Blane, fed by meltwater from the Lomond Glacier, drained via the Forth Valley through Ballat Gap (Rose 1981). The absence of evidence for continuous drainage along the southern margin of the Menteith Glacier suggests that the meltwater/lake overflow water drained through the bed of the glacier. The large amount of meltwater on the poorly drained gently sloping marine sediments of the upper Forth Valley may have contributed to fast flow, and glacitectonic sediment failure at the glacier margin, due to sediments with high porewater pressure and low basal shear stresses.

The area that the Menteith Moraine has been deposited on is at a slightly higher altitude than the central part of the Forth Valley, and therefore the glacier would have been advancing onto a reverse slope at this location increasing the likelihood of glacitectonic processes at a glacier margin (Bluemle & Clayton 1984)

Two large east-west orientated moraines dissected by meltwater channels, are situated to the south-east of the Lake of Menteith (figs 7.11 and 7.22). Again there are no sediment exposures in these moraines and they do not show any distinguishable morphological characteristics of thrust-block moraines. Only the proximity of these moraines to the lake depression and the thrust-block moraine to the north suggests that they have a similar origin to the thrust-block moraine.

Figure 7.22 South Menteith Moraines viewed from the south

Moraines with a similar morphology to the Menteith Moraine occur on the south side of the upper Forth Valley, especially around the village of Buchlyvie. Two areas of moraines, one to the east of the village and one to the west are termed the East Buchlyvie Moraines and the West Buchlyvie Moraines respectively. The West Buchlyvie Moraines consist of at least two moraine ridges (fig 7.24). The morphology and number of the ridges are difficult to map due to their dissection by large meltwater channels (figs 7.23 and 7.24).

Figure 7.23 Meltwater Channels, West Buchlyvie Moraines

The origin of these moraines is difficult to determine from the maps and aerial photographs. However, they are similar in appearance to the Menteith thrust-block moraine. Again there are no adequate sediment exposures to help confirm this interpretation, however given that the moraines have a similar morphology as the Menteith Moraine and are likely to have been produced contemporaneously with the Menteith Moraine by the same glacier, it is possible that they were produced by similar processes.

Meltwater channels, dissecting the West Buchlyvie Moraines can be traced back into Ballat Gap suggesting that much of the meltwater which eroded the channels issued from proglacial Lake Blane. The channels are therefore related to meltwater from the Lomond catchment and not the Menteith Glacier. As these meltwater channels are above the floor of the Forth Valley, they must have been produced while the valley was ice filled. The meltwater channels dissect the West Buchlyvie Moraines and therefore must have been produced post moraine deposition. The meltwater channels dissecting the moraines were, therefore, produced after the moraines were deposited, but while ice was still present in the lower in the Forth Valley. Water from the spillway flowed along the margin of the Menteith Glacier creating meltwater channels and eroding the moraines before disappearing under the ice in the vicinity of Buchlyvie. Some meltwater channels continue from the Ballat Gap towards the valley floor suggesting water continued to flow from the Ballat Gap after the ice had receded from this area. Similar to the Menteith Moraine, the D.E.M. was not of a high enough quality to allow a more detailed study of the moraines at this location (fig 7.25). This again highlights some of the problems of interpreting landforms using photogrammetrically produced D.E.M.s, which require high quality aerial photographs.

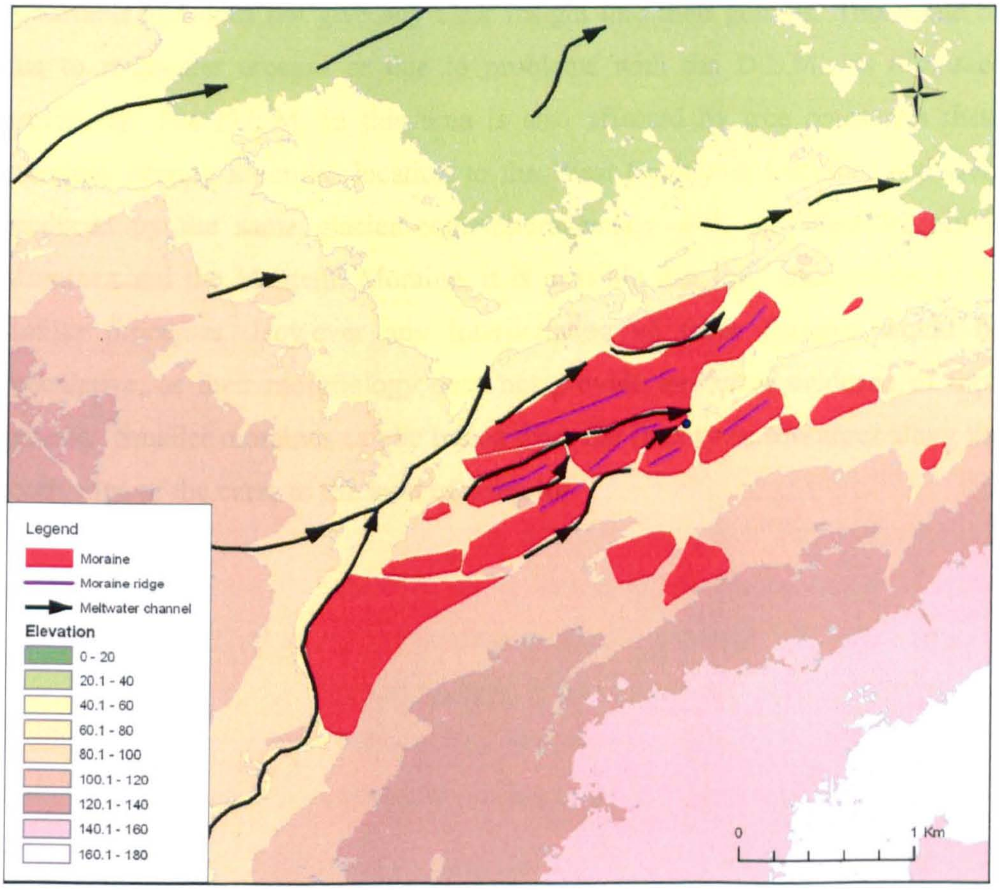


Figure 7.24 West Buchlyvie Moraines

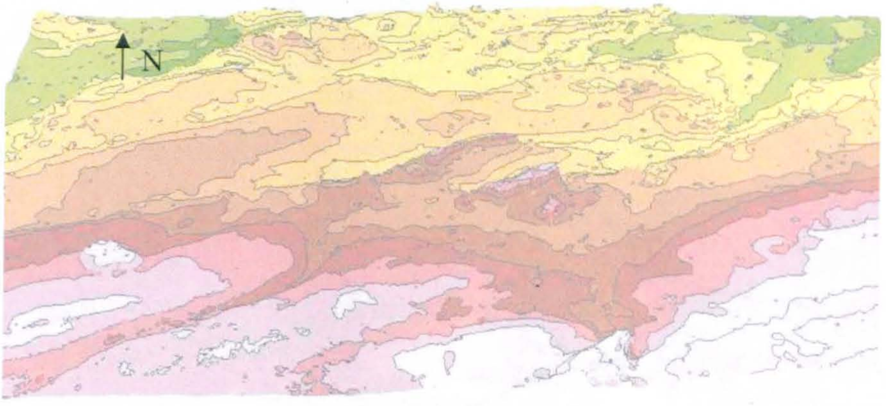


Figure 7.25 Contoured 3d image, West Buchlyvie Moraines

The East Buchlyvie Moraines (fig 7.26) again consist of at least two sets of ridges. As at the West Buchlyvie site this suggests at least one readvance of the Menteith Glacier. These large moraines are steep sided, but the morphology is variable and does not give any clear insight into their genesis. This could be due to meltwater erosion or due to problems with the D.E.M., as discussed previously. The D.E.M. in this area is also affected by tree cover. As these moraines occupy a similar location to the West Buchlyvie moraines and were produced by the same glacier contemporaneously with the West Buchlyvie Moraines and the Menteith Moraine, it is possible that they were produced by similar processes. However any interpretation of these features would be speculative, as their morphology does not provide any clear evidence of their genesis. Smaller moraines can be traced from the Buchlyvie Moraines along the south edge of the carse to the west of Arnprior.

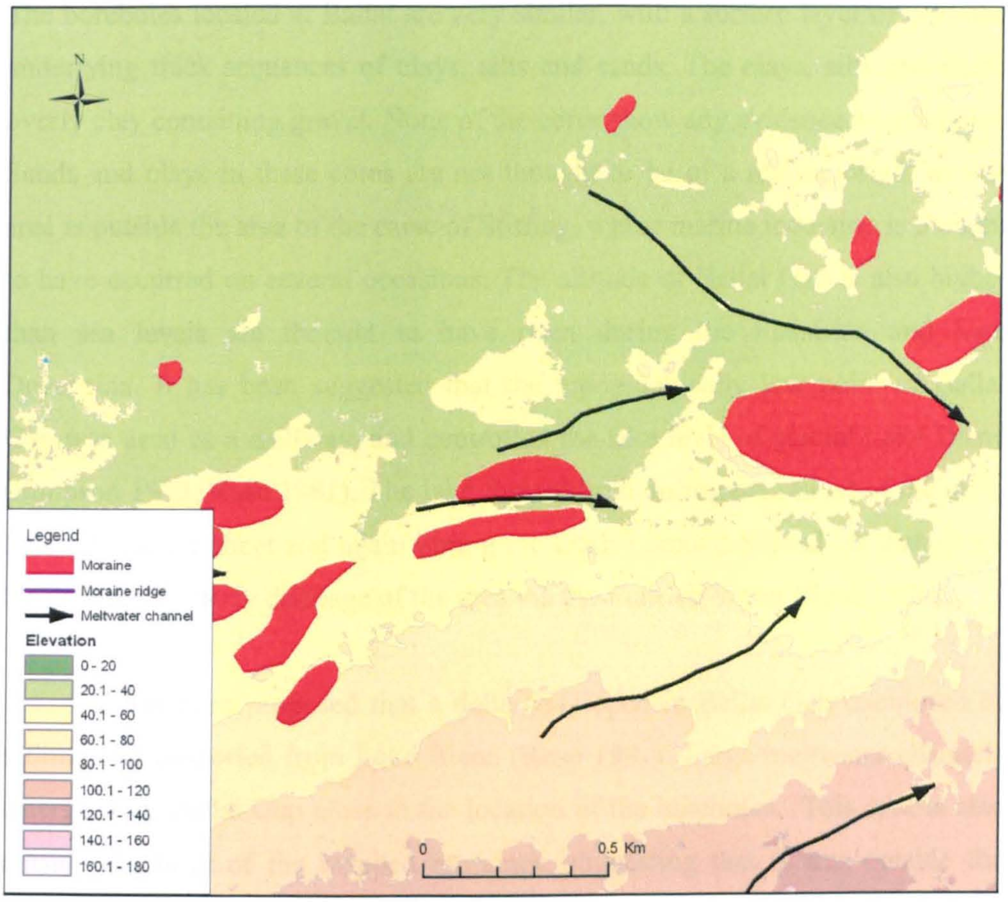


Figure 7.26 East Buchlyvie Moraines

7.3.2 Sedimentology

Due to the lack of sedimentary exposures in the moraines of the upper Forth Valley, no clast fabric or clast shape analyses were carried out. However, 29 borehole records for the area were obtained from the British Geological Survey. These were located in areas to the south of the Menteith Moraine, beyond the moraine limit in the low lying carse east and south east of the Lake of Menteith, in the vicinity of the Buchlyvie Moraines, on the carse within the moraine limit and in Ballat Gap to the south-west of Buchlyvie. The boreholes were used to produce four cross-section diagrams.

Nine boreholes were available for the Ballat Gap area, at around 80m O.D., to the south-west of the moraine limit in the upper Forth Valley. As these boreholes were clustered cross profile diagrams were not produced for this area.

The boreholes located at Ballat are very similar, with a surface layer of peat and underlying thick sequences of clays, silts and sands. The clays, silts and sands overly clay containing gravel. None of the cores show any evidence of a diamict. Sands and clays in these cores are not thought to be of a marine origin as this area is outside the area of the carse of Stirling, where marine incursion is thought to have occurred on several occasions. The altitude of Ballat Gap is also higher than sea levels are thought to have risen during the Flandrian and Late Devensian. It has been suggested that the topographically low point of Ballat Gap was used as a spillway, and controlled the lake level of glacial Lake Blane (Simpson 1933, Rose 1981). The lake formed both during the retreat of the main Late Glacial ice sheet and again during the Loch Lomond Stadial, as glacier ice blocked the westerly drainage of the area via the Endrick Water (Rose 1981).

It has been proposed that a delta developed in Ballat Gap composed of sediments transported from Lake Blane (Rose 1981). Large meltwater channels emerge from Ballat Gap close to the location of the boreholes. This area is also outside the limit of the mapped moraines, suggesting that it was outside the margins of the Menteith Glacier. The lack of diamict in these sediments is consistent with the interpretation of the Buchlyvie moraine as marking the southern limit of the Forth Valley glacier. Cores m20, m21, m23, m24 and m25 (see Appendix 4) have units of sandy clay containing gravel in their lower parts. These cores are located to the south-west of Ballat Gap. The inclusion of silts and clays suggest deposition in a low energy environment. This may be due to ponding of water from the Ballat Gap due to ice in the Forth Valley blocking the flow of water towards the valley floor.

Cores m26, m27, and m28 (see Appendix 4) are clustered and located about 240m north-east of the other Ballat cores and are similar to the other cores with thick sequences of clay, silt and sand but have no gravel in their lower units. The sediment in these cores is also interpreted as relating to water from the Ballat Gap. The boreholes are located outside the moraine limit and at too high an elevation to be deposited as carse sediments.

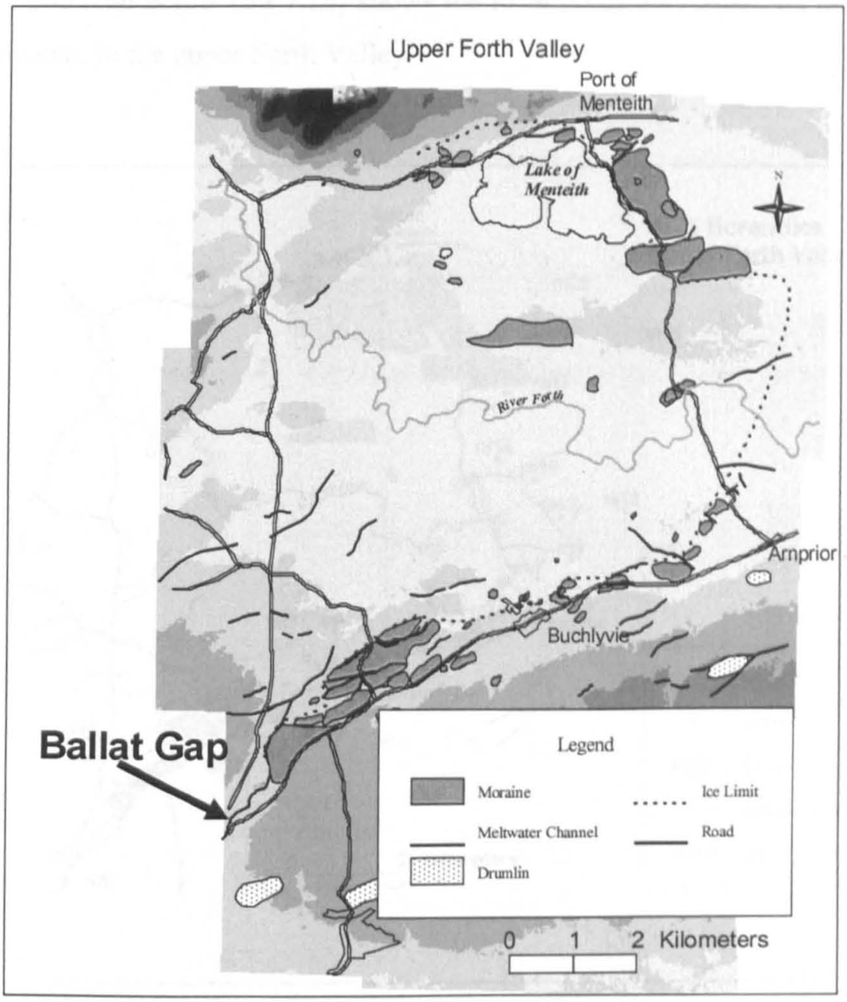


Figure 7.27 Location of Ballat Gap

The map below (fig 7.28) shows the location of the remaining boreholes investigated, in the upper Forth Valley.

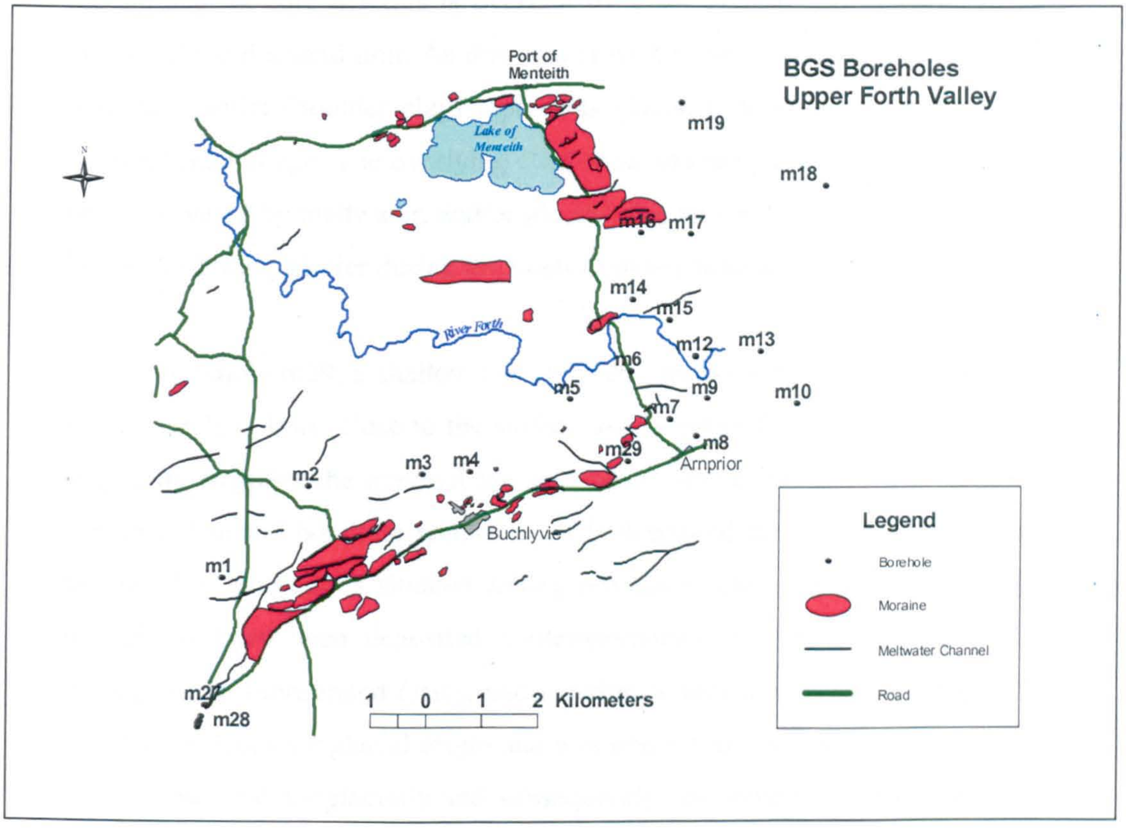


Figure 7.28 Location of boreholes

Boreholes m1 and m2 both contain diamicts close to the surface. In borehole m2 the diamict is overlain with 2.3m of clay. They are both located within the Menteith Moraine loop. This suggests that the diamict is of a glacial origin and dates to the Loch Lomond Stadial. The clay overlying the diamict in m2 could either have been produced by ponding of meltwater from the Menteith Glacier or from the outflow of Lake Blane via the Ballat Gap. Alternatively the clay unit could be due to the reworking of Late Glacial carse clays by the advancing glacier during the Loch Lomond Stadial. The clay is not thought to have been deposited at this location as carse clay as the elevation of this site is higher than the maximum relative sea levels of the Loch Lomond Stadial and Flandrian.

Boreholes m3 and m4 both contain what is described as boulder clay near the surface. In core m3 this is overlain by 2.3m of clay and in core m4 by a gravel unit and a sand unit. As this area is within the moraine limit it is thought that the diamict (boulder clay) represents glacially deposited diamict of Loch Lomond Stadial age. The overlying clay, sand and gravel units could either have been deposited by meltwater, and/or glacimarine and marine sediments reworked by the advancing glacier during the Loch Lomond Stadial.

Borehole m29, a shallow core of 5.2m, shows a diamict with subangular to subrounded clasts, close to the surface and overlain by a thin clay unit. Clast angularity suggests the material has undergone active transport. The diamict is interpreted in the borehole record as a till deposited during the Loch Lomond Stadial. The core site is situated among prominent moraines and the diamict is thought to have been deposited contemporaneously with the moraines. The subangular to subrounded clasts, and location within the moraines, suggest that this diamict has a subglacial origin and was either deposited directly from glacier ice, or deposited subglacially and subsequently reworked by glacier pushing or glacitectonic processes. Alternatively the subangular to subrounded material could represent material that has been transported passively by the glacier followed by a short period of glacifluvial transport, as was found for similar material sampled at the Tyndrum site (see Chapter 6 for details).

Core m6 is situated at the eastern margin of the ice, as suggested by the location of moraines, and is a shallow core of diamict with a laminated clay matrix. The clay matrix is described as consisting of highly contorted laminae, and contains shells. The laminated clay is interpreted as the Forth Valley equivalent of the Clyde Beds, deposited during the Late Glacial Interstadial. The highly contorted nature of the sediments could be due to glacitectonic processes, or ice pushing at the glacier margin. There is no evidence in the cores in the area of the cross valley moraines of intact Late Glacial Interstadial marine sediments although clay and silt is present in the diamict, which is recorded in the borehole records as of Loch Lomond Stadial age. This is consistent with the interpretation of the moraines marking the eastern ice limit as being produced by glacitectonic processes or by pushing of the marine sediments at the glacier margin.

One core (m5) within the moraine limit does not include the diamict described above. This core consists of clay, interpreted as carse clay of Flandrian age, overlying a unit of sand 14.75m thick. No details of the nature of the sand unit were recorded. As the borehole records suggest and has been discussed in the literature on the site, the marine carse sediments mainly consist of clays and silts. The sand is therefore not interpreted as marine in origin but glacifluvial. As there is no information on the nature of this thick sand unit and no visible surface expression of any landform it is difficult to speculate on its exact origin.

Four boreholes (m14, m15, m16, m17) were available for area of the eastern limit of the former Menteith Glacier. Cores m14 and m15 are shallow cores both with a depth of 1.9m. Both cores show diamict close to the surface. The diamict has a mixed clast lithology and mixed clast roundness (angular to subrounded for core m14 and angular to subangular for m 16). The angular clasts in both cores suggest that some of the material has been transported passively as supraglacial or englacial debris, or has been transported actively for a very short distance.

Borehole m17 includes a diamict overlain by 0.4 m of clay. The diamict is described as a sandy gravel with some coarse cobbles, and was interpreted in the borehole record as a till. Clasts found in the diamict are subangular to subrounded suggesting an active transport path, which is consistent with the interpretation as a till. The overlying clay could be due to marine deposition during the Flandrian, or could have been deposited as ponded outwash during the Loch Lomond Stadial. The altitude of the post-glacial carse clays at this site are thought to be no higher than 15m (Smith 1965, Hansom and Evans 2000), the clay is therefore more likely to have been deposited as ponded outwash during the Loch Lomond Stadial.

Borehole m15 is located at a lower altitude towards the centre of the valley. Here the diamict is thinner, again with a mixed clast lithology and mixed clast angularity (angular to rounded). This is thought to be the same diamict as found in cores m14, m15 and m17. The diamict is overlain by laminated clays, which were interpreted in the borehole record as postglacial in age. The surface elevation of this core is 12.4m, which is consistent with the altitude of deposition of postglacial carse clays. These four borehole records show a diamict which is found at a higher altitude on and around the moraines. It is also found on the lower ground of the centre of the valley, where it has been buried by marine clay during periods of higher sea level in the mid Flandrian.

Cores from the carse, to the east of the Menteith Moraines are distinctly different from those inside the moraine, with no evidence of a diamict near the surface and thick silt and clay units. Two of the cores from outside the moraines (m8 and m19) included sand and pebbles, which are interpreted as glacial outwash, deposited during the Loch Lomond Stadial.

Cores from the centre of the carse area, to the east of the moraines, generally consist of laminated silts and clays. Cores m10 and m9 have a peat layer overlain by clay, which can be attributed to the development of peat in the terrestrial environment of the carse in the early Flandrian, before the later Flandrian marine incursion as represented by the overlying clay unit.

Cores m18 and m19 are situated on the north side of the Forth Valley to the east of the Menteith Moraine. Core m19, situated approximately 2km east of the moraine, mainly consists of clay with stones to a depth of 4.97m with sandy clay in the lower 2.3m. Below 4.97m there is a unit of sand with pebbles underlain by bedrock at a depth of 5.89m. As the surface elevation of this borehole is 42.6m all the units in the core are above the upper limits of sea levels during the Late Glacial and the Flandrian. The clay with stones and underlying sand with pebbles are therefore interpreted as being deposited in a non-marine environment. Given the proximity of the location to the Menteith Moraine, which is punctuated by large meltwater channels it is likely that the units of clay and sand represent the distal component of glacial outwash deposited during the Loch Lomond Stadial

Borehole m18 is located on lower ground (15m O.D.) approximately 4km east of the Menteith Moraine. Below 0.3m of soil lies a unit of stiff clay to a depth of 1.8m. This was described in the borehole record as being of postglacial age, and is underlain by a peat layer from a depth of 1.8 to 3.0m. The peat overlies a layer of sandy silt, again recorded as postglacial in age. As the surface elevation of this core is 15m the sediments below the soil horizon are below the elevation of the higher sea levels of the early and mid Flandrian. The clay units and intervening peat unit are interpreted as Flandrian in age. Below 3.6m there is a unit described as clayey sand with gravel and angular to subangular rock fragments and rare clasts up to 15cm in diameter. This is underlain by a unit of laminated clay described in the borehole record as Lateglacial marine. If the laminated clay is a Lateglacial marine sediment, equivalent to the Clyde Beds, the overlying clayey sand can be attributed to deposition during the Loch Lomond Stadial, and is likely to have been deposited as distal outwash from the Menteith glacier. The clay content of this unit is either due to ponding of outwash or is derived from the underlying marine sediments. A unit of clay with subangular clasts underlying the laminated Lateglacial marine clays is described in the borehole record as a till. There is no evidence to suggest whether or not this is indeed a till deposited directly from glacial ice. However the stratigraphic position occupied by the diamict suggests it was deposited before the marine incursion of the Lateglacial (Windermere) interstadial, and therefore is likely to be of Dimlington Stadial age. No other BGS borehole from either inside or outside the moraine limit of the upper Forth Valley includes this diamict.

Borehole m8 is a shallow borehole located on the south-east margin of the Menteith moraine limit. It consists of two units. The upper unit consists of sandy gravel with fine and coarse platy pebbles. This overlies a lower unit of finer sand with silty laminae. This is interpreted as outwash from the Menteith glacier, with the upward coarsening possibly representing more proximal deposition during glacier advance. The elevation of this location (29.8m) and the coarseness of the sediment are incompatible with deposition in an estuarine environment. Sediments in a low energy estuarine environment are more likely to be finer, such as clays and silts, due to the lack of energy to transport coarser marine sediment far up the estuary.

The remaining boreholes m7, m9, m10, m12 and m13 do not include any diamict and are beyond the limit of the moraines. All have surface elevations below 15m. These cores mainly consist of clays and silts, with some units including laminations. According to the BGS borehole records abundant shell fragments were found in core m7, and cold water fauna were observed in m7 and m12 in units, interpreted in the borehole records as indicative of deposition during the Lateglacial. A peat layer was observed in cores m10 and m9 between the two highest units of silts and clays. This is likely to have formed during the early Flandrian, when sea level fell due to glacioisostasy, and was followed by a subsequent sea level rise in the mid Flandrian. The clay and silt in these cores are interpreted as low-energy estuarine deposits, deposited both in the Lateglacial and the Flandrian. The lack of glacigenic sediment indicates that the locations of these cores are outside the limits of the Loch Lomond Readvance.

Four cross sections were produced to analyse the spatial distribution of the sediment units recorded in the boreholes. The location of the cross sections can be seen in figure 7.29. Cross section 1 (fig 7.31) shows the change in sediments from east to west and includes boreholes from inside the moraine loop (m4 and m29) and from the carse beyond the moraine limit (m7, m9, m13). A clear distinction in sediments to the east and west of borehole m29 can be seen, with sediments mainly consisting of diamict to the east and clays to the west of m29. Borehole m29 is located in an area of moraines close to the village of Arnprior. This is consistent with the interpretation of the moraines as marking the eastern extent of ice during the Loch Lomond Stadial.

Cross section 2 (fig 7.32) includes boreholes along the eastern ice moraine limit, from Arnprior in the south to near the Menteith Moraine in the north. No boreholes were available for the Menteith Moraine. Sediments in this cross section consist almost entirely of diamict with some clay in borehole 29, which is on lower ground.

Cross sections 3 and 4 (figs 7.33 and 7.34) are located to the east of the moraine limit on the carse. These cross sections do not include any diamict near the surface, although a diamict was found lower in the stratigraphic sequence in borehole m18. Two marine clays in the cross sections are separated by a peat layer, which is likely to have been deposited during the early Flandrian, before the relative sea level rise and deposition of the overlying clay in the mid Flandrian. The cross section were created using RockWare geological software. The sedimentary sequences joining the boreholes are interpolated by the software, and therefore may be inaccurate at some locations.

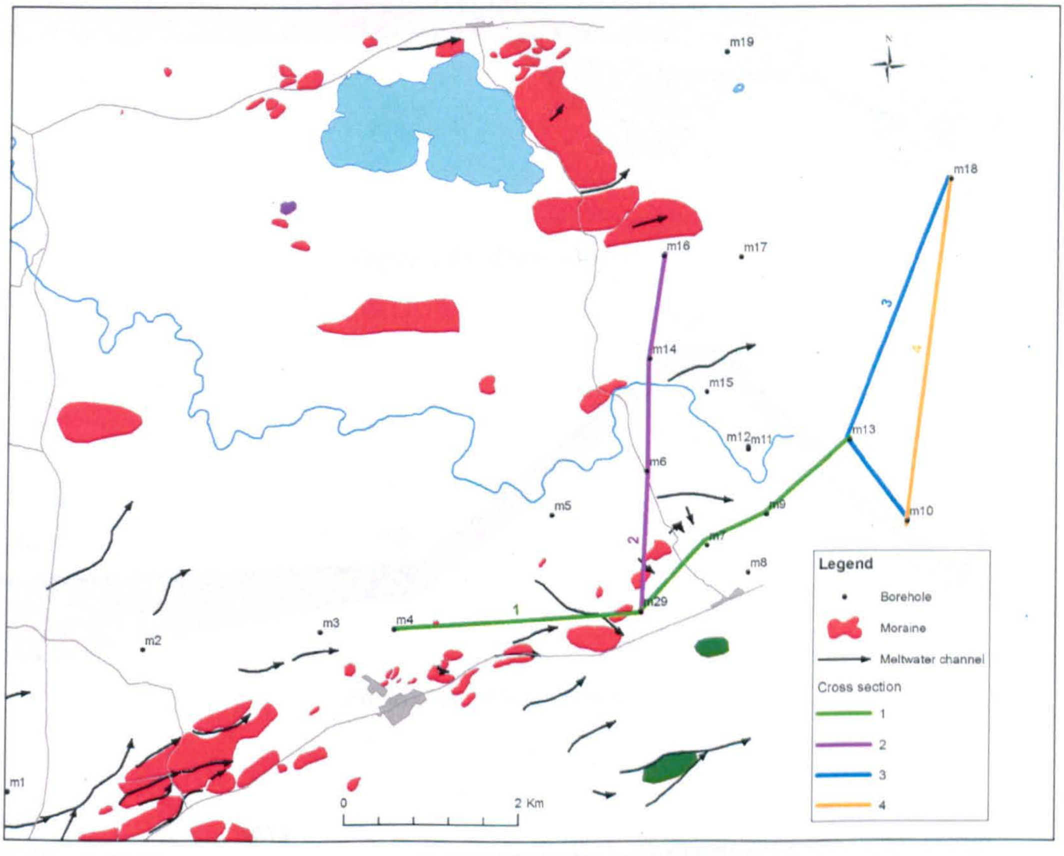


Figure 7.29 Location of Cross-section

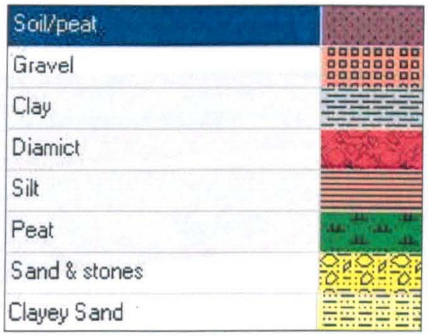


Figure 7.30 Cross section legend

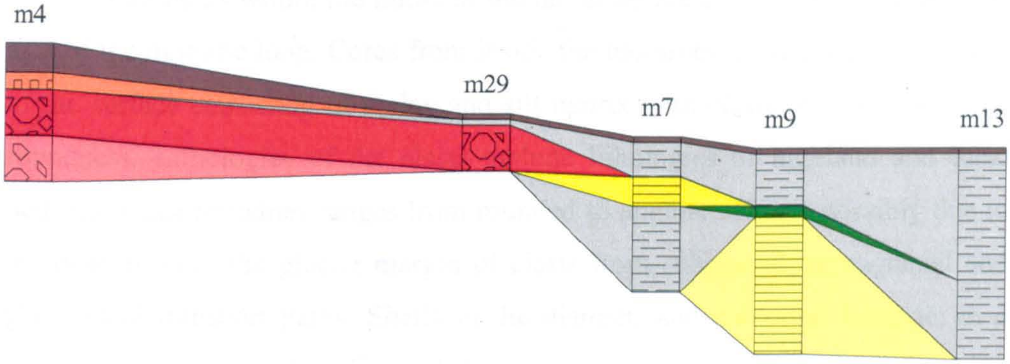


Figure 7.31 Cross section 1

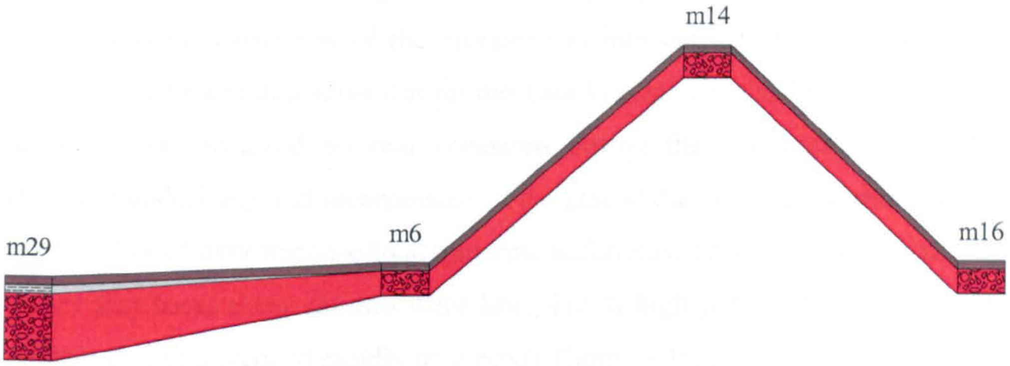


Figure 7.32 Cross section 2

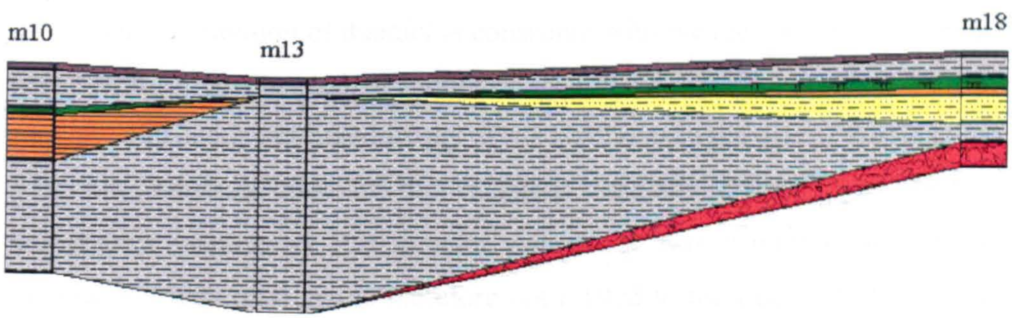


Figure 7.33 Cross section 3

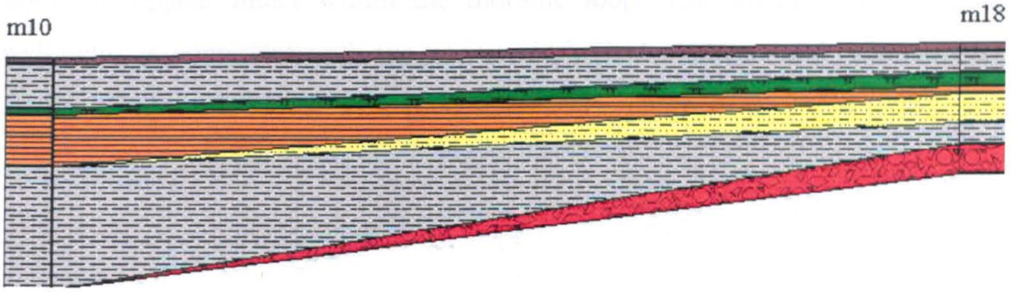


Figure 7.34 Cross section 4

Sediments within the limits of the moraines are distinct from those to the east of the moraine loop. Cores from inside the moraines include a diamict close to the surface consisting of a clay and silt matrix with clasts of mixed size and roundness. Lithologies of the clasts include lithologies of highland and local bedrock. Clast roundnes ranges from rounded to angular. This is possibly due to the deposition at the glacier margin of clasts from subglacial, supraglacial and glacifluvial transport paths. Shells in the diamict, and contorted laminae, in a core located at the eastern limit of the moraines, suggests reworking of marine sediments of Late Glacial age (Forth Estuary equivalent of the Clyde Beds). Cores from the carse east of the moraines mainly consist of marine sediment, including sediment deposited during the Late Glacial and the Flandrian. Marine incursion has occurred on two occasions during the Flandrian. The marine sediment underlying and incorporated in the glacial diamict suggest the Menteith Glacier flowed over unconsolidated marine sediments. This is consistent with the theory that basal shear stresses were low, due to high pore-water pressure, and that the glacier advanced rapidly or surged (Thorp 1991a).

The distribution of diamict is consistent with the reconstruction of the ice limit based on the location of moraines. The diamict is found only within the moraine loop and is not found in any of the boreholes to the east of the moraines. Only one borehole east of the moraines contains diamict, however, the stratigraphic position of this diamict suggests it was deposited prior to the Lateglacial Interstadial and is therefore not related to the Loch Lomond Stadial ice. The carse clay is dominant in the sediments to the east of the moraines and does not appear intact within the moraine loop. The spatial distribution of sediments is consistent with the geomorphological evidence and published ice limits. (Simpson 1933, Sissons 1966, Rose 1981, Thorp 1991, Smith 1993).

7.4 Summary

The geomorphology of the upper Forth Valley consists of a latero-frontal moraine loop dissected by meltwater channels. Within the area of the latero-frontal moraine loop there is little geomorphological evidence of glaciation except for some large meltwater channels and a bedrock knoll near the valley centre with morainic deposits on its surface. The paucity of evidence is thought to be due both to natural and anthropogenic alteration of the landscape of the central part of the upper Forth Valley.

Evidence presented in this study is consistent with the theory that the moraines of the upper Forth Valley were produced by glacitectonic processes due to surging or continual rapid basal sliding as the glacier advanced onto the unconsolidated marine sediments of the Forth Valley (Thorp 1991a). The Menteith Moraine and Buchlyvie Moraines are interpreted as thrust-block moraines based on their morphology, topographic location and similarity to contemporary moraines observed at Icelandic glacier margins. Adequate evidence for the interpretation of the genesis of the Menteith Moraine was found in this study, but there is less information that can be utilised in interpreting the genesis of the Buchlyvie Moraines.

It is suggested that the Menteith thrust-block moraines were produced by surging or at least relatively rapid glacier advance. Sediments within the moraine limit include a diamict near the surface. Outside the moraine limit the sediments mainly consist of estuarine silts and clays and some outwash. Silts and clays either underlie or are incorporated in the diamict found inside the moraine limit suggesting the Menteith Glacier flowed over, and incorporated, fine grained marine sediments. This would have resulted in high porewater pressure in these sediments facilitating either surging or at least rapid ice flow. This is consistent with the theory that the Menteith and Buchlyvie Moraines were produced by glacitectonic processes. The production of the moraines of the upper Forth Valley is therefore related to the topography and pre-existing Quaternary geology of this site. The morphology, location and spatial pattern of glacial landforms of the upper Forth Valley has therefore little significance for the reconstruction of climatic conditions at the termination of the Loch Lomond Stadial.

The interpretation of the genesis and spatial pattern of the moraines and evidence from boreholes have allowed an estimation of the maximum ice extent during the Loch Lomond Stadial for the upper Forth Valley (fig 7.35). This is consistent with previously published ice limits (Simpson 1933, Sissons 1966, Rose 1981, Thorp 1991, Smith 1993).

A more detailed study of the moraines could have produced more evidence for their genesis, and possibly gave new insights into the formation of the glacial landforms at this site. However the quality of available aerial photographs for this area was poor. This combined with extensive tree cover resulted in poor quality digital elevation models. Although the D.E.M.s were found useful to map landforms, using photogrammetric software, and are necessary to produce orthophotos, images derived from the D.E.M. gave little insight into the morphology of the glacial landforms of this site. It is therefore concluded that the use of digital elevation models is highly dependent on the quality of available aerial photographs and is not suitable in areas with extensive tree cover or buildings. A more detailed study of the geomorphology of the upper Forth Valley would require better quality aerial photographs and/or digital elevation models produced by other methods such as lidar. These were not available at the time of this study.

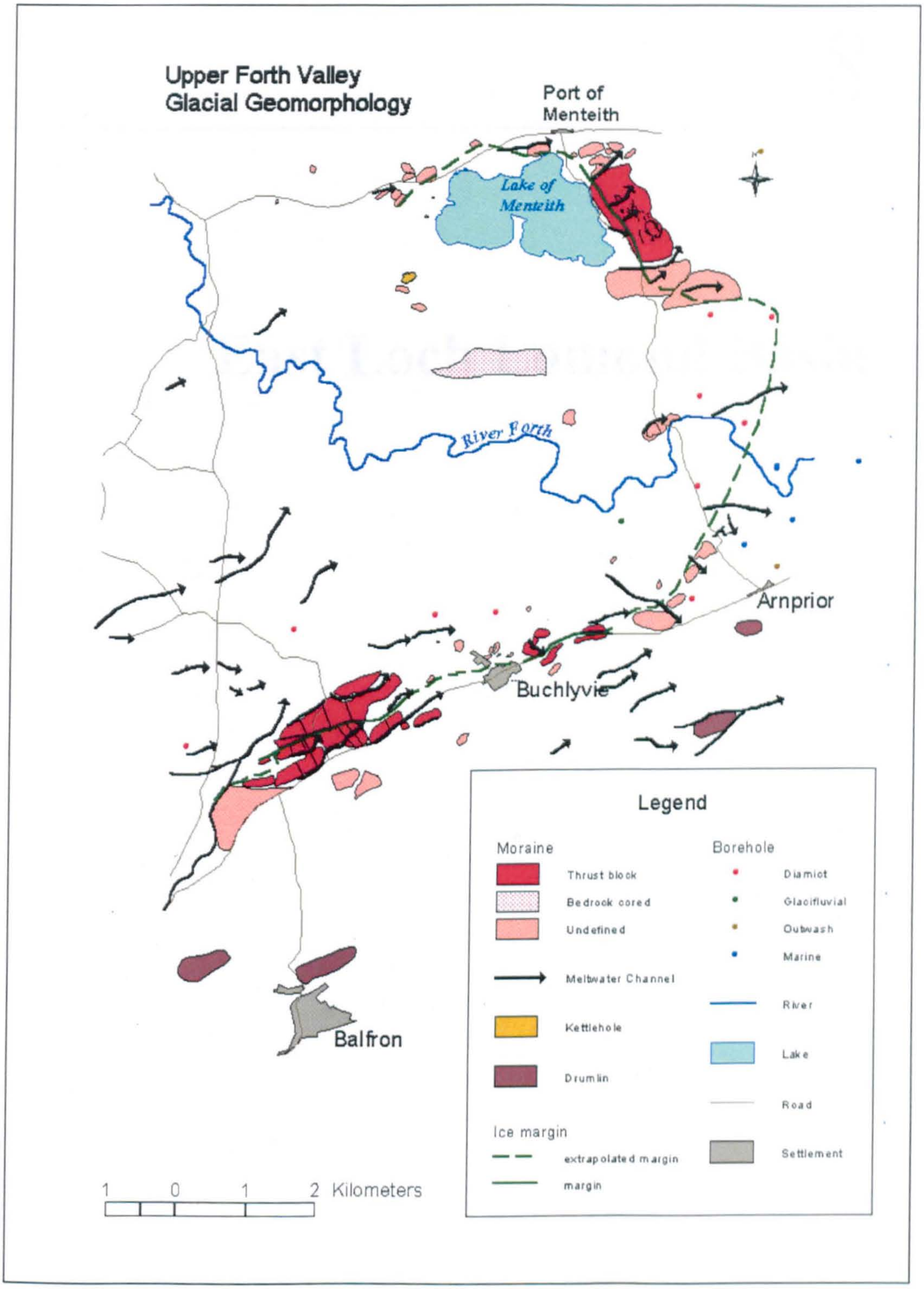


Figure 7.35 Map of upper Forth Valley glacial geomorphology

8

East Loch Lomond Basin

8.1 Introduction

8.1.1 Location

The area of the east Loch Lomond basin investigated in this study is the south-eastern limit of the Loch Lomond Readvance and is situated approximately 25 km north-west of the city of Glasgow. The area studied extends from the village of Drymen and Loch Lomond in the west to Killearn and the Campsie Fells to the east. To the north the study area extends to Ballat, the southern limit of the upper Forth Valley study area, and in the south to the lower slopes of the Kilpatrick Hills (figs 8.1, 8.2)

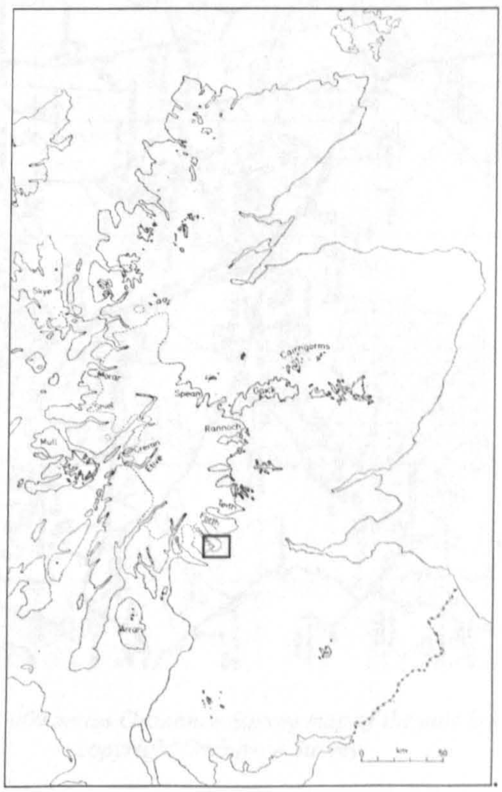


Figure 8.1 Location of east Loch Lomond basin field site and extent of Loch Lomond Readvance (adapted from Sissons 1974)

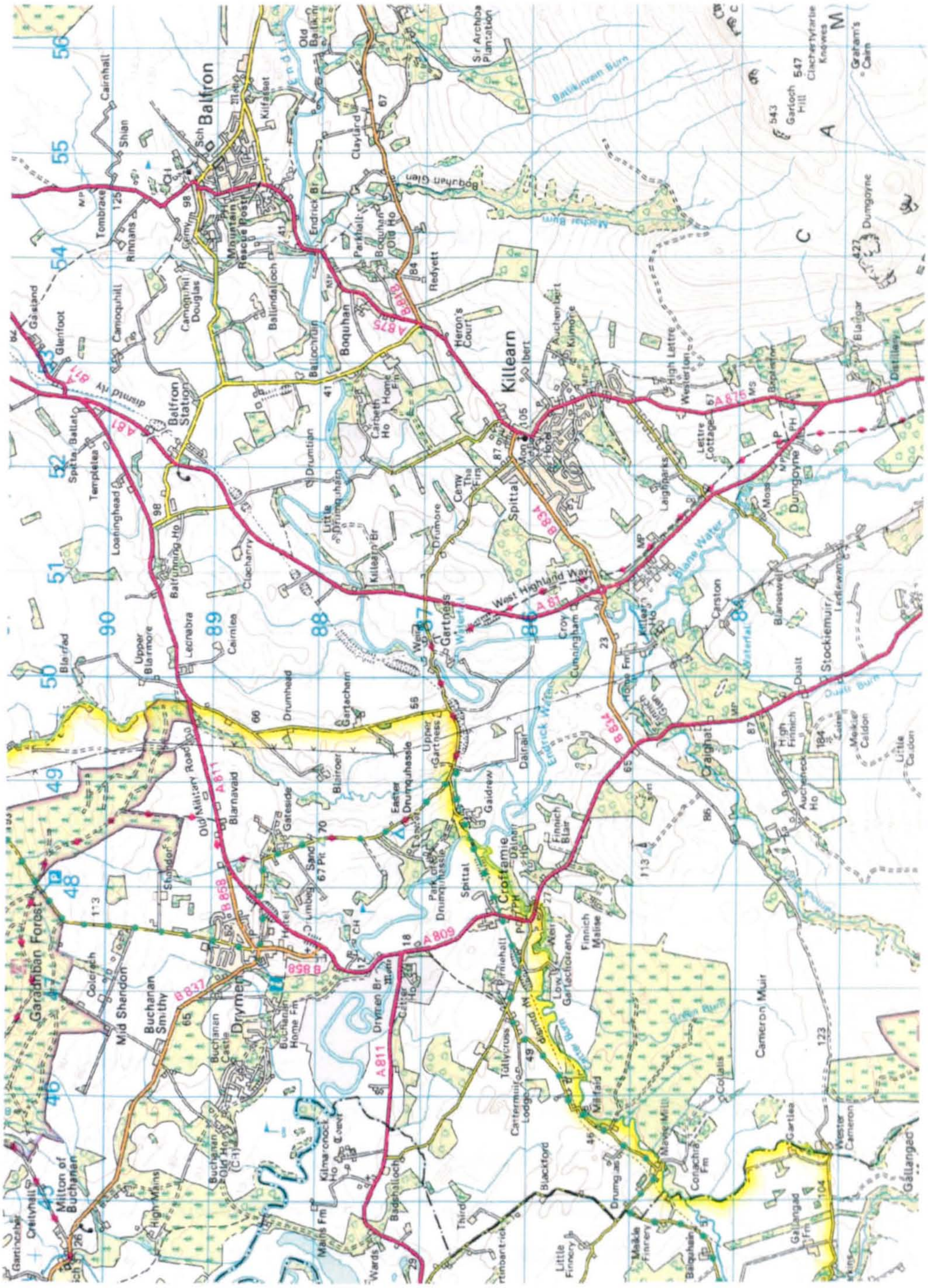


Figure 8.2 Extract from 1:50 000 series Ordnance Survey map of the east Loch Lomond basin (crown copyright Ordnance Survey)

8.1.2 Geology

Solid Geology

The solid geology of the east Loch Lomond basin is dominated by sandstones of the Teith Formation, the Stockiemuir Formation and the Kinneswood Formation. The oldest of these, the Teith Formation, underlies Quaternary sediments in the northern part of the field area around Drymen and Gartness, and consists of grey and purple-brown sandstone deposited by west flowing rivers during the Lower Devonian. Drainage was reversed during the Middle Devonian due to uplift and erosion. This was followed by the deposition, by easterly flowing rivers, of the Upper Devonian Stockiemuir Formation. The upper part of this formation includes aeolian sediments deposited in an arid climate in the late Upper Devonian. The Stockiemuir formation forms the bedrock of the middle and southern part of the study area. The bedrock of the southern part of the field area consists of the red and white sandstones of the Kinneswood Formation deposited in the Lower Carboniferous. This was followed by a volcanic episode which formed the rocks underlying the Kilpatrick Hills to the south and the Campsie Fells to the east. These once formed a continuous plateau that was eroded during the Cainozoic forming the Blane Valley.

Quaternary Geology

The Quaternary sediments of the east Loch Lomond basin include two tills dating from the Late Devensian: the Wilderness Till, deposited by the Late Devensian ice sheet (Dimlington Stadial) and the Gartocharn Till deposited during the Loch Lomond Readvance (Rose 1981). These are separated by the Gartness Silts, the Clyde Beds and the Blane Valley Silts. The marine sediments of the Clyde Beds were deposited during the Late Glacial (Windermere) Interstadial when relative sea levels were higher than present and Loch Lomond was a fjord. The Gartness Silts, found in the Blane and Endrick valleys, are freshwater deposits and have been interpreted as proglacial lake sediments, deposited in glacial Lake Blane which was formed by ice damming the Endrick and Blane waters (Rose 1981). According to Rose (1981) the Gartness Silts were deposited during recession of the Late Glacial ice sheet. However they have also been interpreted as part of the later Killearn Formation (Hall et al. 1998) or Killearn Member (Sutherland 1999). The Blane Valley Silts were deposited as proglacial lake sediments during advance and retreat of ice during the Loch Lomond Stadial and can be found immediately above and below the Gartocharn Till. The Gartocharn Till deposited during the Loch Lomond Stadial can be distinguished from the earlier Wilderness Till by the presence of shell fragments derived from the Clyde Beds. The table below shows the stratigraphy and comparison of the nomenclature for these stratigraphic units used by Rose (1981), Hall et al. (1998) and Sutherland (1999), adapted from Evans and Rose (2003).

Rose (1980)	**Hall et al. (1998)**	**Sutherland (1999)**
Blane Valley Silts	Blane Water Formation	Blane Member
Rhu Sands & Gravels	Drumbeg Formation	Drumbeg Member
Gartocharn Till	Gartocharn Till Formation	Gartocharn Member
Blane Valley Silts	Blane Water Formation	Blane Member
Organic detritus and palaeosol		Croftamie Member
Clyde Beds	Linwood & Paisley Formations	Linwood & Paisley Members
Gartness Silts	Killearn Formation (part)	Killearn Member (part)
Wilderness Till	Wilderness Till Formation	Wilderness Member

8.1.3 Geomorphology

Some of the earliest evidence for the Loch Lomond Readvance was found in the east Loch Lomond basin (Jack 1874, Bell 1892, Renwick & Gregory 1909). Moraines marking the extent of the Loch Lomond glacier can be traced, to the south-east of Loch Lomond, along the northern slopes of the Kilpatrick Hills and in the Blane Valley to the east of Drymen. The southern part of this moraine, on the lower slopes of the Kilpatrick hills, consists of ridges 5 to 7m high and 40m wide, and has been interpreted as a subaerially deposited push moraine (Rose 1981). Smaller ridges parallel to the moraine and hummocky moraine occur on Cameron Muir on the north side of the main moraine ridge. The moraine is more prominent to the east of Drymen where it was deposited as coalescing Gilbert-type deltas (Rose 1981, Benn & Evans 1996, Phillips et al.

2001). At least three ridges can be seen to the east of Drymen between Drymen and Gartness, with a large outer and inner moraine and a smaller less obvious ridge between these (figs 8.3, 8.4 and 8.5). The moraines can be traced north-west of the Blane Valley where, similar to its southern parts, it was deposited subaerially.

Another large ridge to the south of these three ridges has a south-west to north-east orientation. This is mainly deposited on higher ground than the three ridges to the east of Drymen. However the north-eastern part of the ridge is deposited on lower ground and displays two distinct flat surfaces.

Detailed studies of exposed sediments in the inner moraine, at Drumbeg Quarry, east of Drymen, have revealed a complex history of deposition, and local oscillation of the ice margin (Benn & Evans 1996, Phillips et al. 2001). Maps and interpretation of the glacial geomorphology in this area have been published by Rose (1981). This study will investigate the nature of ice margin advance and retreat by reviewing published evidence and employing digital elevation models and orthoimages, derived from digital photogrammetry, to accurately map and model the glacial geomorphology of the area and to assess the possibility of these methods revealing additional information to previously published interpretations by allowing a more accurate and detailed study of these landforms.

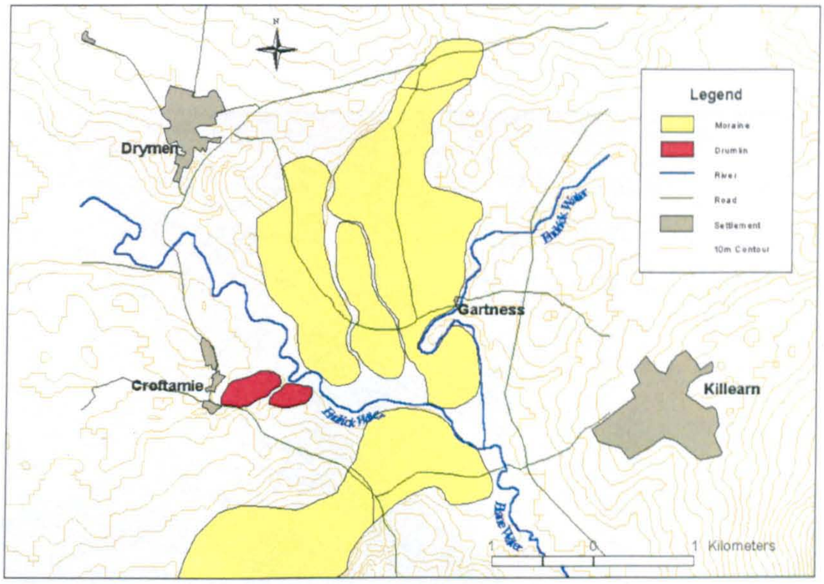


Figure 8.3 Map of moraines in the east Loch Lomond Basin

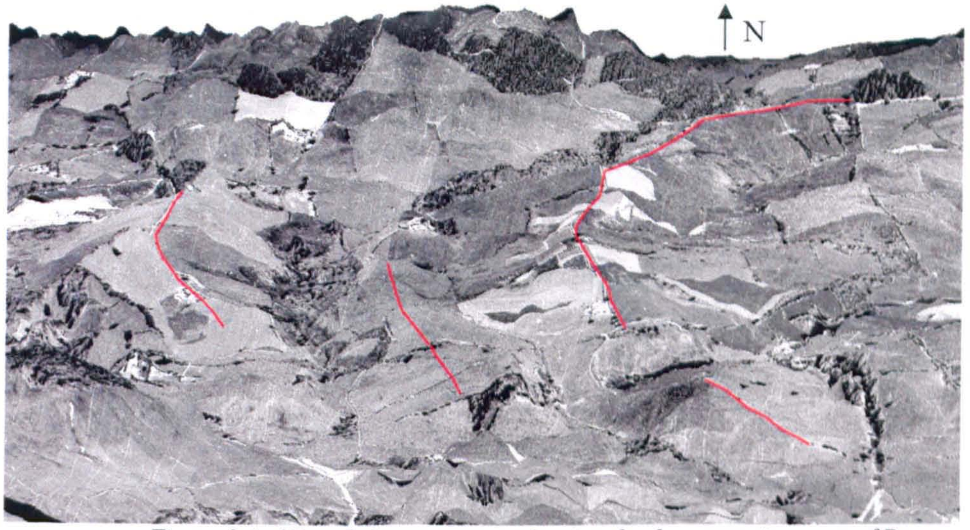


Figure 8.4 3D orthoimage mosaic showing the three moraines east of Drymen (moraine ridges highlighted in red)

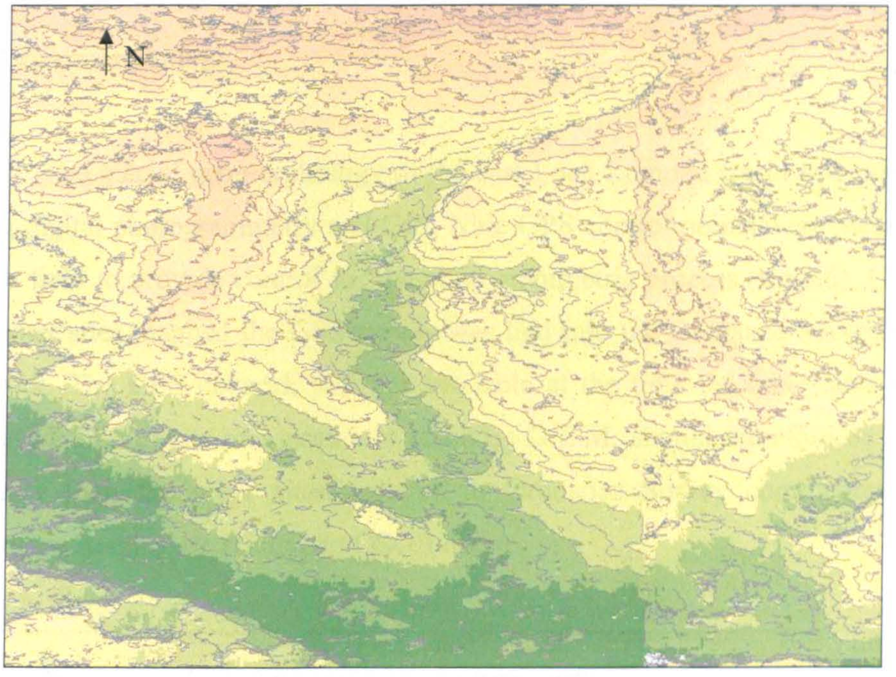


Figure 8.5 3D D.E.M. derived image of moraines

8.2 Methods

8.2.1 Geomorphology

The glacial geomorphology of the east Loch Lomond Basin was mapped using digital photogrammetry and GIS. Nine GPS control points were measured in the field to provide control for the photogrammetric process (fig 8.6). Unlike the other sites mapped the GPS survey was tied into the Ordnance Survey GPS network. The GPS network was not available at the time the other sites were surveyed. The points measured and resulting D.E.M. should therefore be more accurate than the other sites, relative to Ordnance Survey coordinates and elevation. Heights are relative to OSGB datum.

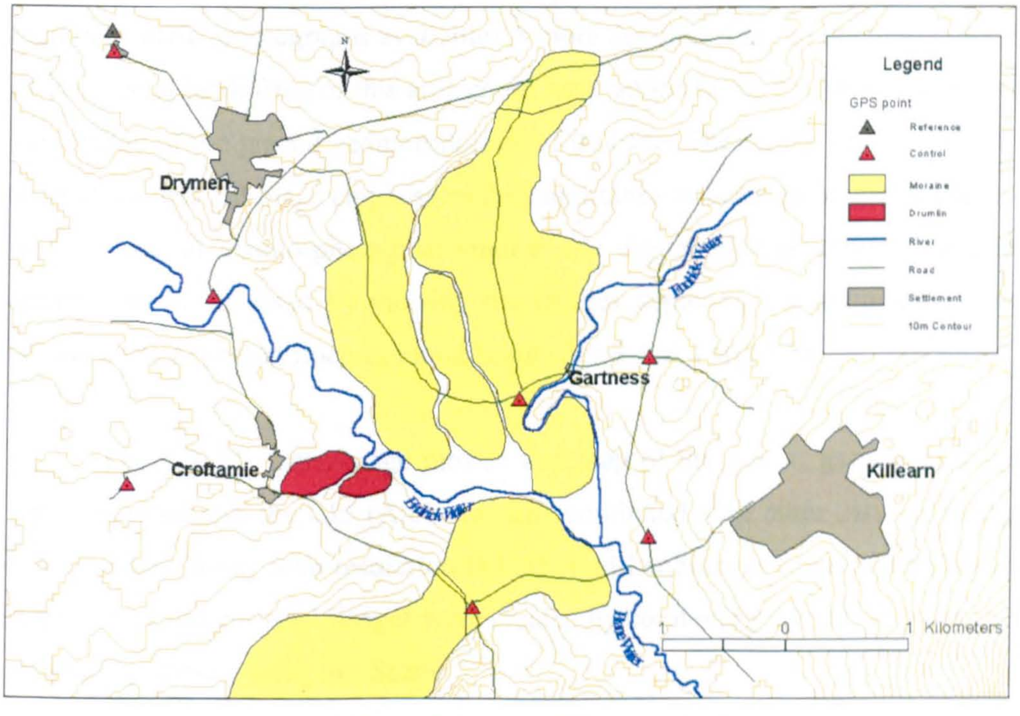


Figure 8.6 Map of GPS control points

Six aerial photographs, in two strips of three, at an approximate scale of 1:24,000 were required to give stereo coverage for this study area. However problems were encountered due to the poor quality of the scanned images, especially photos in the southern strip. It is thought that the original images were not of sufficiently good quality for photogrammetric processing, possibly due to poor storage and handling. The image quality may also have been affected by photographic reproduction and scanning. Due to the poor quality of the images aerial triangulation of the block of images failed. As the northern strip of photography covered most of the field area it was decided to create maps, D.E.M.s and orthophotos of the area covered by the northern strip of aerial photography only.

The quality of the northern strip of photographs was sufficient to give good results for the aerial triangulation of the photo images. The resulting digital elevation model and orthophoto were sufficient to map the major landforms of this area, but did not allow detailed mapping due to poor aerial photograph quality. The recognition and mapping of glacial landforms is therefore less detailed than other sites, as the techniques used are highly dependent on the quality of aerial photographs available. A more detailed study of the morphology of the glacial landforms of this area could have added to the extensive published knowledge of the glacial geomorphology of this site. The failure of the methods to produce detailed maps emphasises the importance or aerial photograph quality of their use in geomorphological studies and digital photogrammetry. Image quality can be assessed by viewing the images depicting the moraines of the central part of the east Loch Lomond basin (figs 8.3, 8.4 and 8.5)

The D.E.M., orthoimage mosaic and map of the glacial geomorphology were imported into the GIS (ArcView) and combined with other data including an Ordnance Survey 50m resolution D.E.M., and Landranger series raster format maps. Three dimensional images were created by combining the D.E.M. with the orthoimage mosaic using ArcScene.

Hillshaded images derived from the D.E.M. were also produced. These were of limited use for detailed analysis of the morphology of the landforms due to the poor quality of the D.E.M.

8.2.2 Sedimentology

As previously collected, highly detailed sedimentological data were available for this study area no new data were collected. Sedimentological data from a large quarry in a moraine, at Drumbeg, interpreted as a glacitectonised Gilbert-type delta with a complex polyphase deformation history, were found particularly useful (Benn & Evans 1996, Phillips et al. 2002). Sedimentological data have also been collected from exposures in the outer moraine, near the village of Gartness. (Rose 1981, Evans pers. comm.). The location of these study sites and Drumbeg Quarry can be seen on the map below (fig 8.7).

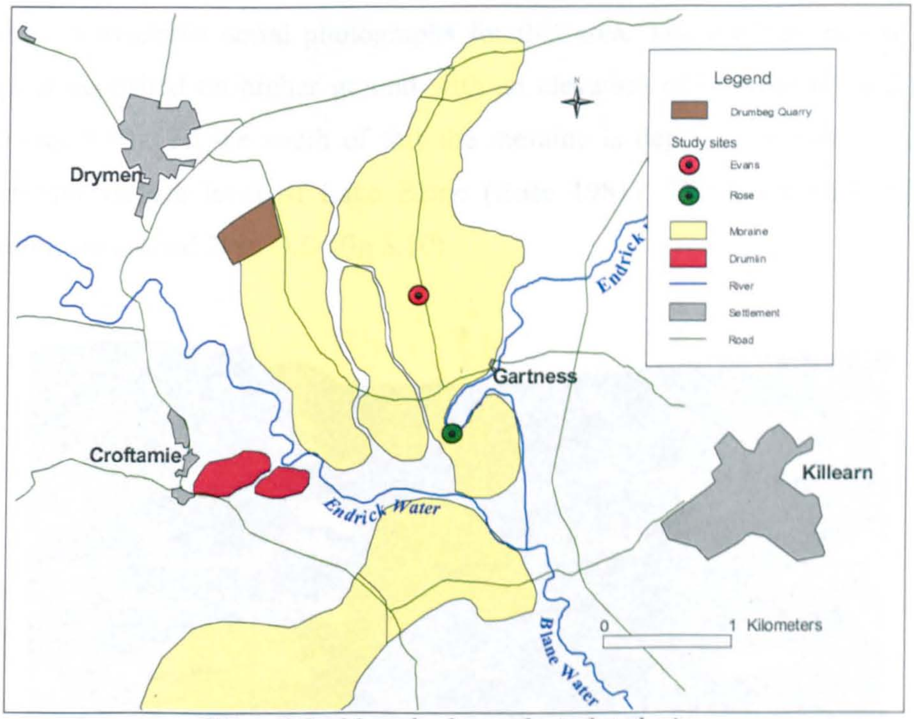


Figure 8.7 Map of sedimentological study sites

8.3 Results and Interpretation

8.3.1 Geomorphology

Three north to south trending moraine ridges were recognised in the east Loch Lomond basin between the villages of Gartness and Drymen consisting of large outer and inner moraines with a smaller moraine between. The inner and outer moraines have an arcuate planform and are convex on their ice proximal sides. The outer moraine is approximately 4 km long and 1.5 km wide at its widest part. It is wider in its central part and has been eroded by the Blane Water in its southern part (figs 8.8, to 8.12). Figures 8.8 and 8.9 also highlight the poor quality of available aerial photographs for this area. The northern part of this ridge is deposited on higher ground with an elevation of between 65 and 85m O.D (fig 8.10). To the south of this the moraine is deposited below 65m, the maximum surface level of Lake Blane (Rose 1981). The lower parts of the moraine are around 20m O.D (fig 8.10).

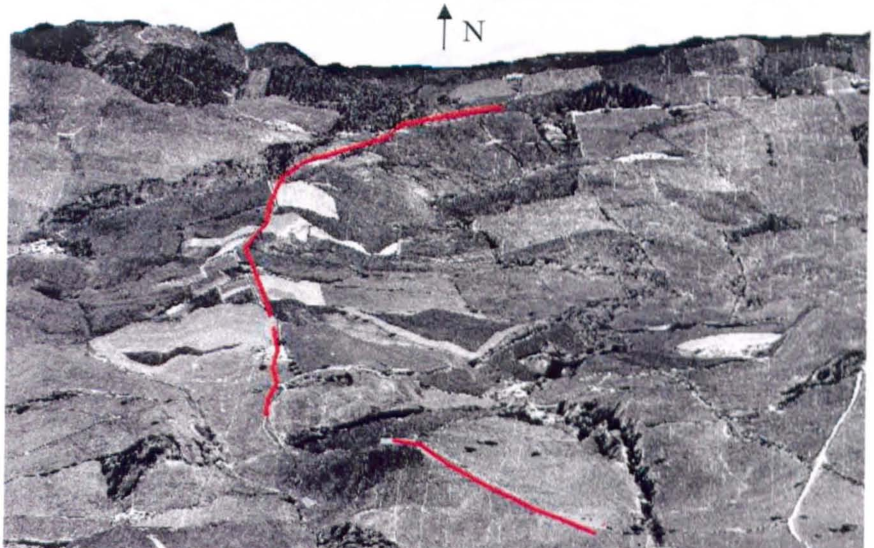


Figure 8.8 3D orthoimage mosaic showing outer moraine (red line)

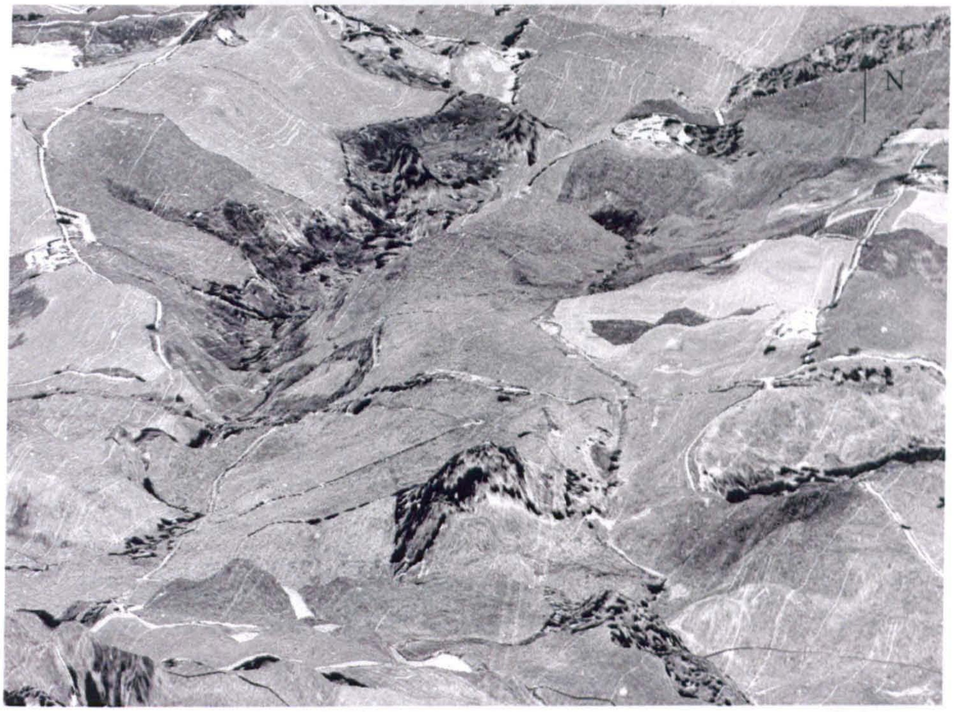


Figure 8.9 3D orthoimage mosaic showing middle moraine

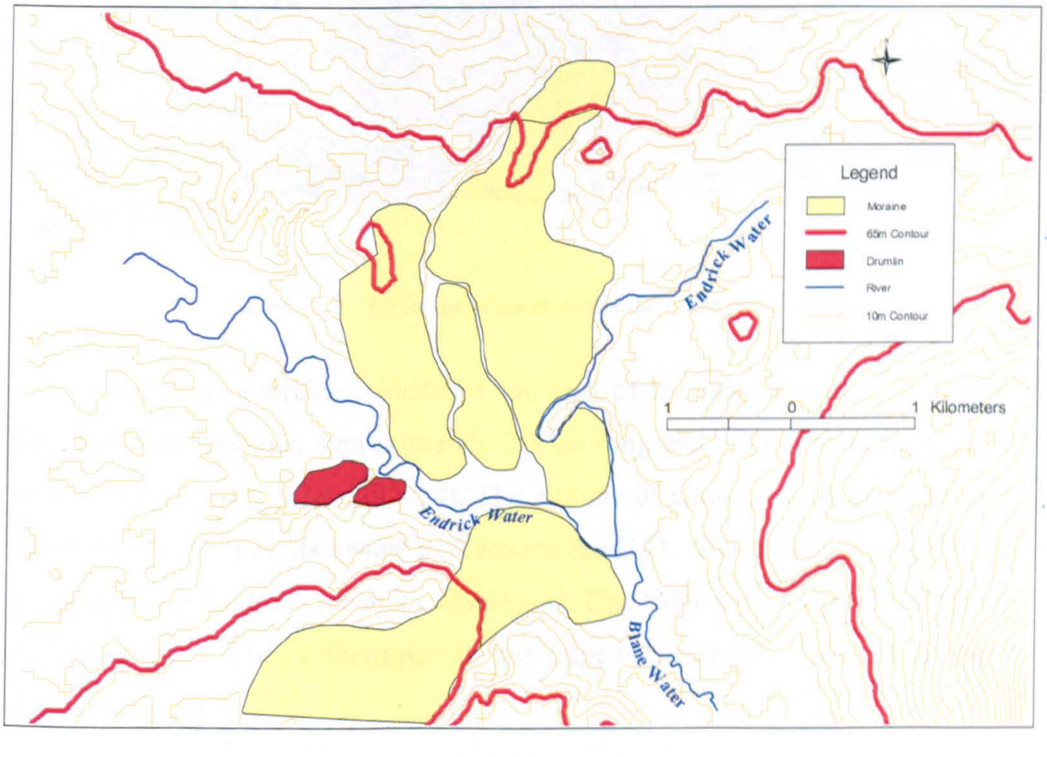


Figure 8.10 Map showing moraines and 65m contour

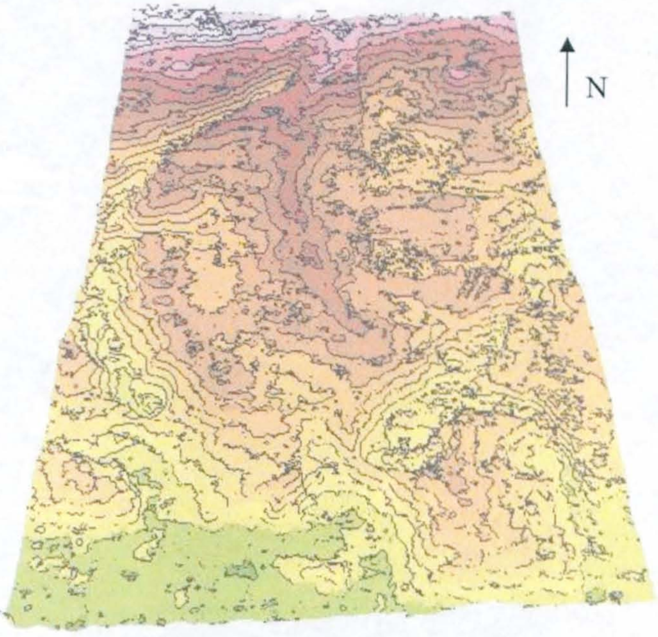


Figure 8.11 3D image of outer and inner moraines, looking north

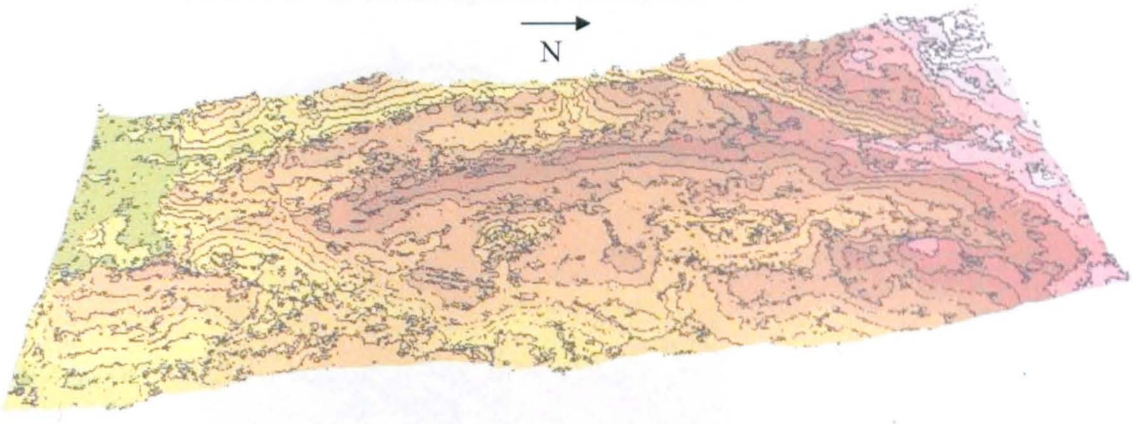


Figure 8.12 3D image of outer and middle moraine, looking west

The inner moraine, situated 1 km east of the outer moraine, is smaller than the outer moraine, approximately 2.3 km long and 0.6 km wide for most of its extent (figs 8.13, 8.14 and 8.15). The altitude of almost the entire moraine is below 65m O.D. with its lowest part around 8m O.D. The middle moraine is 1.5 km long and is 0.4 km wide at its widest part. This ridge has an altitude of 45m at its highest point. The northern part of this ridge is flanked by a lobe of the outer moraine (fig 8.10).

Figure 8.13 3D orthoimage mosaic showing inner moraine

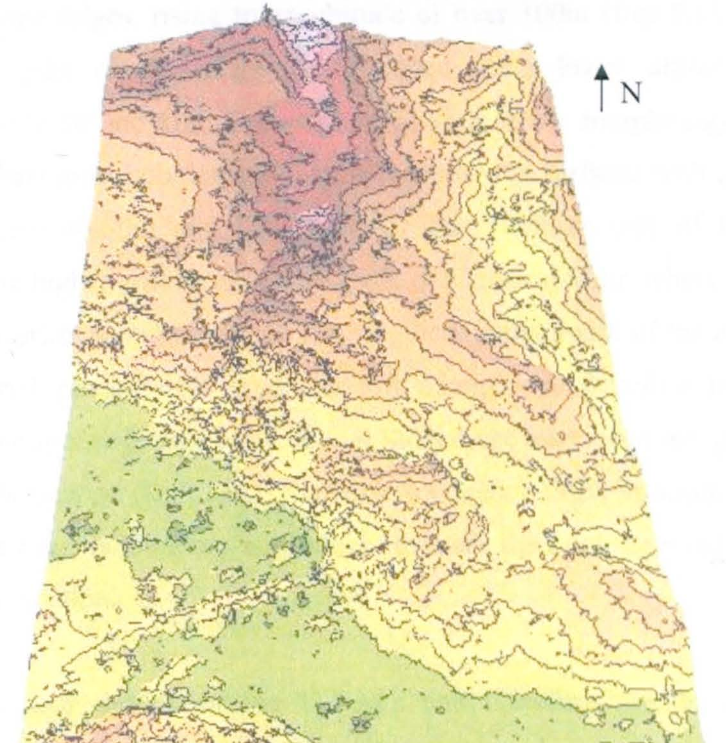


Figure 8.14 3D image of inner moraine, looking north

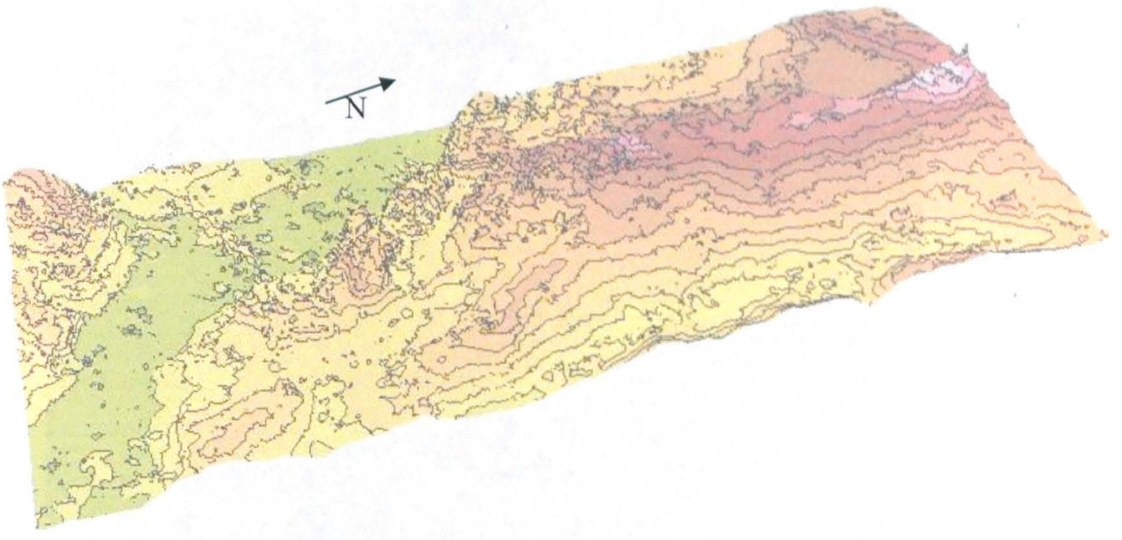


Figure 8.15 3D image of inner moraine, looking west

Another ridge to the south of these three moraines has a south-west to north-east orientation and is for most part deposited at a higher elevation than the other moraine ridges, rising to an altitude of over 100m (figs 8.16, 8.17). The north-west part of the ridge is deposited at a lower altitude, between approximately 50 and 10m O.D. and displays a lobate morphology (fig 8.16). The north-east lobe includes two distinctive, near flat surfaces with elevations of approximately 40-50m and 20-30m O.D. The southern part of the ridge is deposited on higher ground on the east side of Cameron Muir, where the moraine probably overlies a bedrock high. The ridge continues south of the area covered by the aerial photographs used. Its full extent was therefore not mapped. Moraines thought to be of Loch Lomond Stadial age have been recognised to the south of this location (Bell 1982, Renwick & Gregory 1909, Simpson 1933, Rose 1981). This ridge is therefore not thought to mark the Loch Lomond Readvance limit at this location.

The poor quality of the D.E.M.s and therefore the derived images prevented a more detailed description of the moraines.

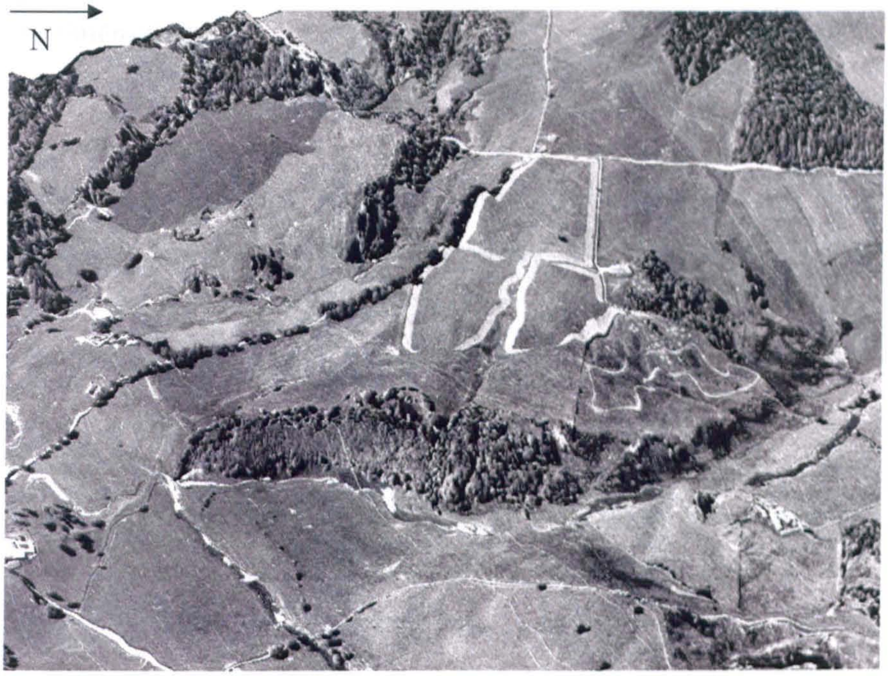


Figure 8.16 Orthoimage showing lobate form of the southern moraine

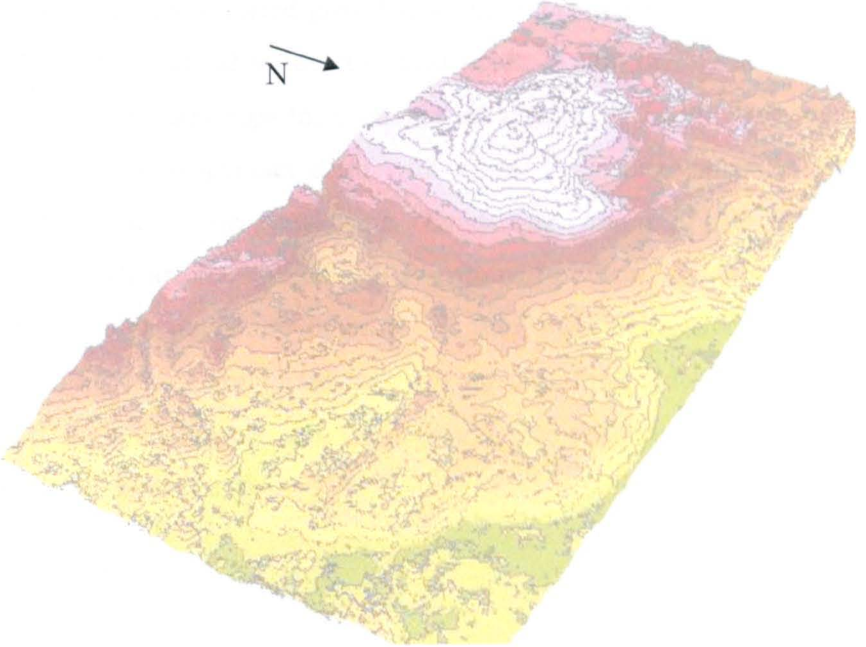


Figure 8.17 3D image of southern moraine

8.3.2 Sedimentology

A river cut sedimentary exposure, near the village of Gartness, on the lower slopes of the outer moraine consists of pre-Loch Lomond Stadial sediments including the Lateglacial interstadial marine sediments of the Clyde Beds. These are overlain by the Loch Lomond Stadial proglacial lake sediments known as the Blane Valley Silts (Rose 1980, 1981). These are undisturbed on the distal slope of the moraine but contorted on the proximal slope due to glacitectonic processes (Rose 1981). An exposure in the flat top of the moraine close to Gartacharn Farm, north of Gartness, consists of approximately 3m of undisturbed cross-bedded fine sand overlain by heavily contorted cross-bedded laminated sands and contorted muds (Evans pers. comm.) (figs 8.19, 8.20 and 8.21). Faults and reverse faults were observed in the upper 50cm of the sands (figs 8.20, 8.21) suggesting the sediment has been subjected to glacitectonic deformation. A poorly sorted gravel lens (fig 8.21) and water escape structures (fig 8.19) were observed in the contorted sands. A thin muddy deformation till, derived from the muds, caps the sequence at this site (fig 8.19). This sequence is interpreted as an ice-contact delta with a unit of glacitectonically thrust and folded muds on its proximal side (Evans per. comm.). Structures in the underlying sands are interpreted as being formed by water escaping through the sands due to high porewater pressures as they were being overridden. As the glacitectonised muds are found only on the proximal side of the ridge it is suggested that ice advanced into the proximal face of the ice-contact fan but did not completely override it.

Figure 8.18 Section in flat topped outer moraine

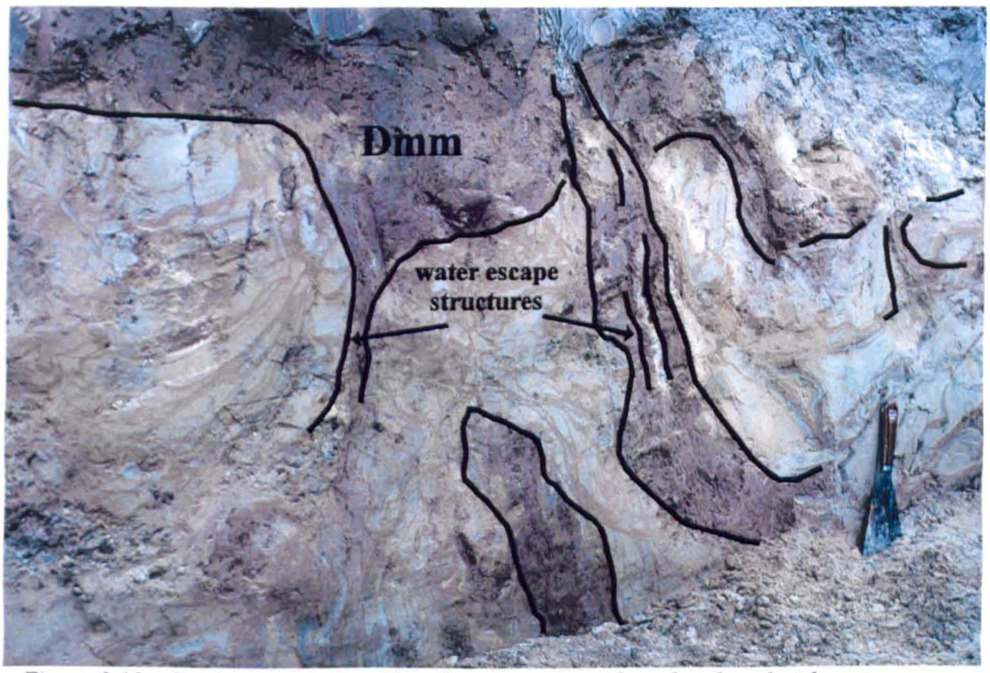


Figure 8.19 Section in outer moraine showing contorted sand and mud with water escape structures and overlying diamicton

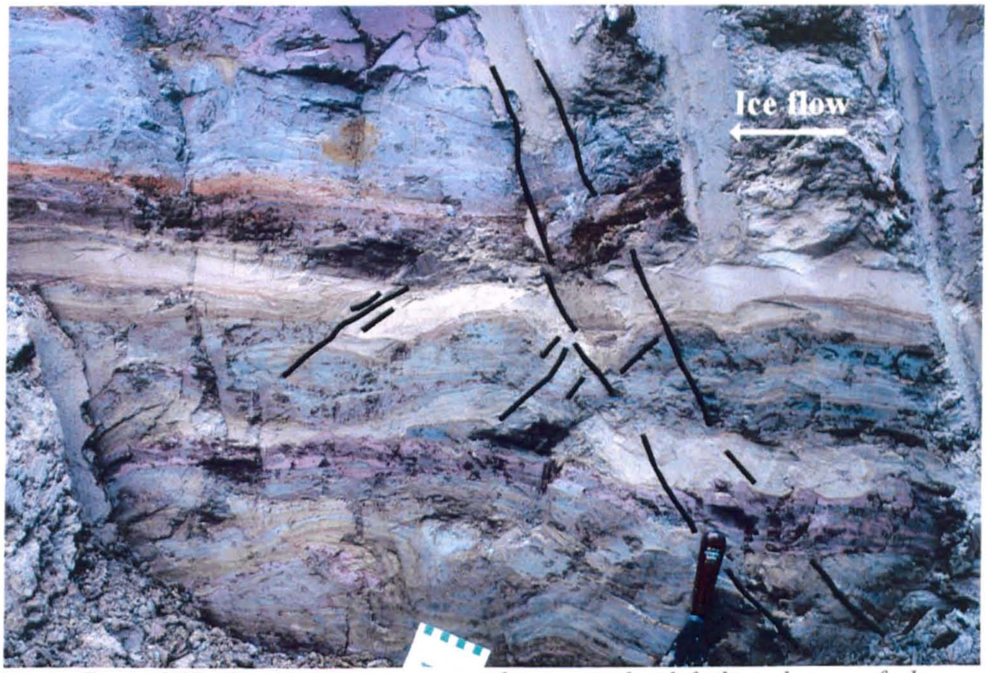


Figure 8.20 Section in outer moraine showing sand with faults and reverse faults

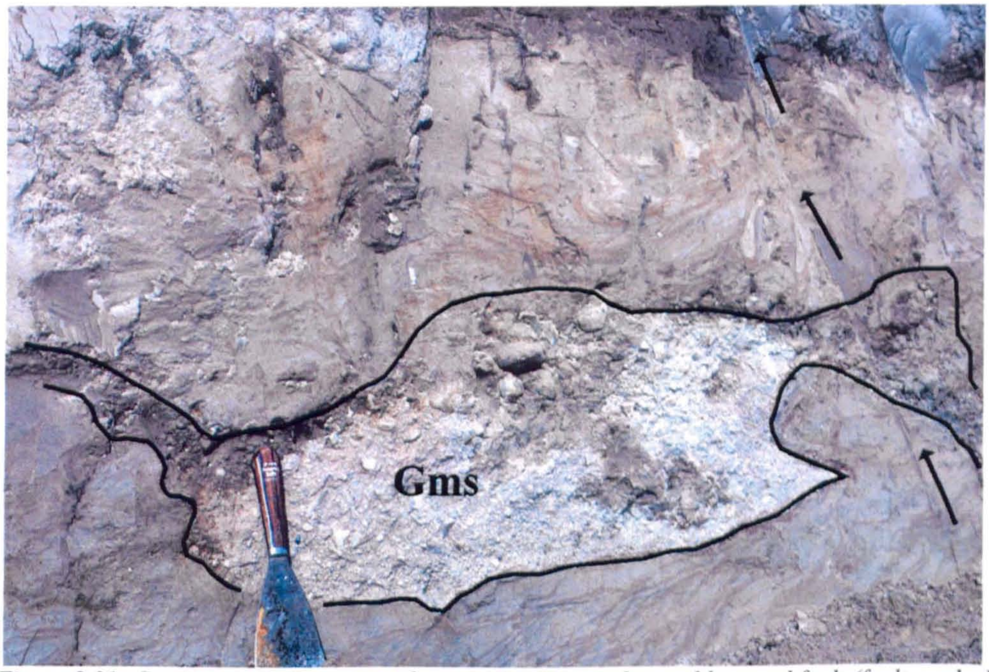


Figure 8.21 Section in outer moraine showing poorly sorted gravel lens and fault (fault marked with arrows)

Based on extensive sediment exposures in a quarry at Drumbeg on the proximal slopes of the inner moraine, the moraine has been interpreted as a glacitectonised Gilbert-type delta displaying a polyphase deformation history (Benn & Evans 1996, Phillips et al. 2002). The delta is thought to have formed during temporary stabilisation of the Loch Lomond Glacier during recession. Sedimentary structures in the deltaic sediments, indicative of glacitectonic deformation, suggest that after a minor recession of the glacier it readvanced into the proximal slope of the delta. This was followed by retreat and erosion of the glacitectonised delta by meltwater from the receding glacier. This was then followed by a second readvance, which overrode the delta superimposing a diamict over the deltaic sediments. This suggests an oscillating margin at this location and active retreat of the ice interrupted by two minor readvances (see section 2.3.3 for details).

8.3.3 Interpretation

As the Blane Valley was occupied by glacial Lake Blane to an elevation of 65m O.D. during the Loch Lomond Stadial, where the moraines are below this elevation they were deposited in a glacilacustrine environment. The outer moraine, in the vicinity of Gartness, is mostly below this elevation, except for a small section of the north of the moraine. Sediments in the moraine observed by Rose (1981) and Evans (pers. comm.) are indicative of deposition in a lacustrine environment. Sediment exposures in the outer moraine reveal undisturbed cross-bedded fine sands on its distal slopes, which is compatible with the interpretation of the moraine ridge as being deposited in a proglacial lake. The ridge is interpreted an ice contact delta, deposited in ice dammed Lake Blane. Contorted units of sand and mud on the proximal slope and ridge top, glacitectonic faults and water escape structures suggests that there has been at least one readvance onto the proximal slope of the delta.

If the moraine was deposited at a time when the Blane Valley was occupied by Lake Blane, the ice margin must have extended to the south of the moraine and onto the higher ground on the east side of Cameron Muir. If the ice did not extend this far Lake Blane would have been able to drain along the present path of the Endrick Water.

The elevation of the inner moraine is almost entirely below 65m. Excellent sediment exposures in Drumbeg Quarry on the north-west of this moraine have allowed detailed sedimentological studies of this feature (Benn & Evans 1996, Phillips et al. 2002). The characteristics of sediment exposures in the quarry suggest the ridge was formed as a Gilbert-type delta formed during recession of the Lomond Glacier from the Blane Valley towards Loch Lomond. The delta has been modified by glacitectonic processes, during two separate readvances punctuated by ice retreat and erosion and deposition by meltwater (Phillips et al. 2002). Based on its similar location, morphology and sedimentology the outer moraine is thought to have been constructed by similar means to the inner moraine, although the fine grain sizes suggest discharges were lower.

The middle moraine is significantly smaller than the inner and outer moraine. No sedimentary exposures were found on this moraine, however as its elevation is below the surface level of Lake Blane and it is located between the two larger moraines, both of which were initially deposited as ice contact deltas, it is likely that the middle moraine was also deposited as coalescing glacilacustrine deltas. As this moraine is smaller than the others it is possible that the ice margin occupied this location for a shorter period of time than at the inner and outer moraines. There is no evidence to determine whether or not this moraine has been overridden. If it has not been overridden it is likely that it was deposited as the Lomond Glacier receded between the location of the outer and inner moraines. If the middle moraine has been overridden it could have been deposited during the oscillation of the ice between the period of deposition of the outer delta and the later readvance into its proximal slopes.

The outer, middle and southern moraines all possess areas that display the morphology of debris fans. As the fans are below the elevation of the former water surface of Lake Blane it is possible that these fans were deposited subaqueously. Alternatively they could have been deposited subaerially following the drainage of Lake Blane. The fans were visible on the orthoimages when viewed in 3D. However the poor quality of the D.E.M.s prevented a more detailed study of the morphology of the fans, which could have revealed evidence of their origin. Elevations of the fans range from 14m to 40m. O.D. However given the poor quality of the D.E.M.s it would be difficult to use the elevation of the fans to interpret their origin. However all fans are at a significantly lower altitude than the 65m maximum lake elevation.

Above the elevation of Lake Blane, where the moraine was deposited subaerially, there is only evidence of one ridge. This may be due to the central part of the ice margin, which was in contact with lake water, receding while its northern and southern margins remained anchored to the higher ground. It is therefore possible that recession between the outer and inner moraine was due to calving and draw-down rather than being climatically driven (Phillips et al. 2002).

The interpretation of the inner and outer moraines as glacitectonised ice-contact deltas suggests oscillation of the ice margin in the vicinity of Gartness, producing the large outer moraine and subsequent advance into its proximal slope, followed by retreat with a possible short term stabilising of the margin at the location of the middle moraine. This was followed by retreat eastward to the location of the inner moraine, at Drumbeg, with the ice margin oscillating for some time before receding eastwards allowing the drainage of Lake Blane.

The extent of the former Lake Blane is reconstructed here using the locations and genetic interpretations of the moraine ridges and using the GIS software to produce a 65m contour for the Blane and Endrick Valleys (figs 8.22, 8.23 and 8.24). It is thought that the lake surface remained at an elevation 65m at the time the inner moraine was being deposited, based on the interpretation of sediment units in the inner moraine (Philips et al. 2002). The ice margin has been extrapolated across the present course of the Endrick water to the 65m contour on the higher ground to the south. The ice margin to the west of the moraines has not been included in the reconstructions of the lake as the ice margin was beyond extent of aerial photographs purchased and processed for this project. The D.E.M used for these images was acquired from the Ordnance Survey and has a resolution of 50m.

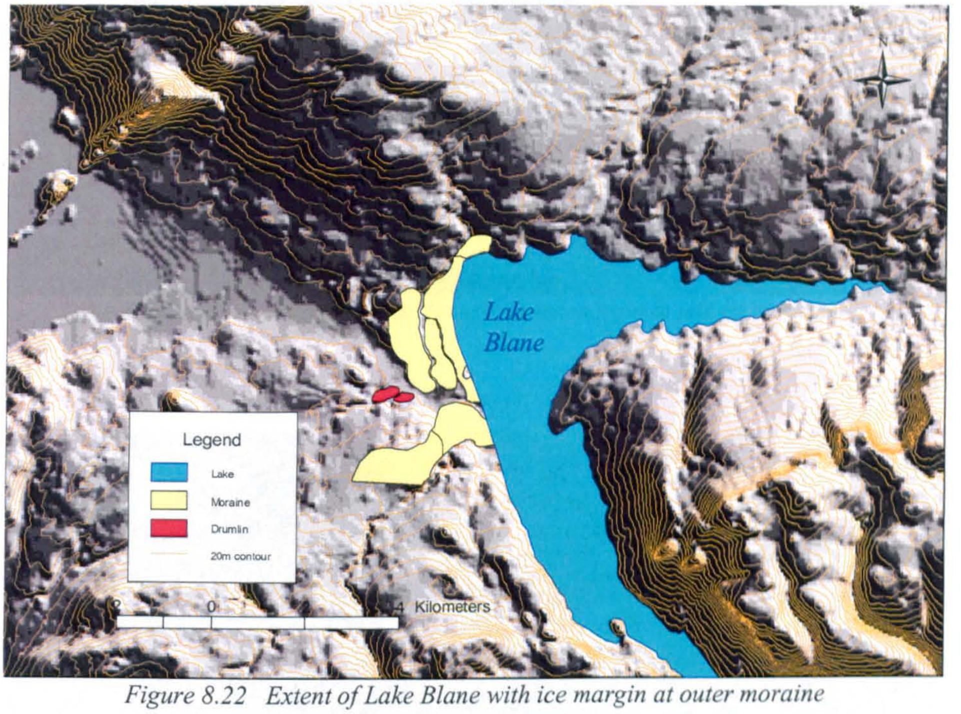


Figure 8.22 Extent of Lake Blane with ice margin at outer moraine

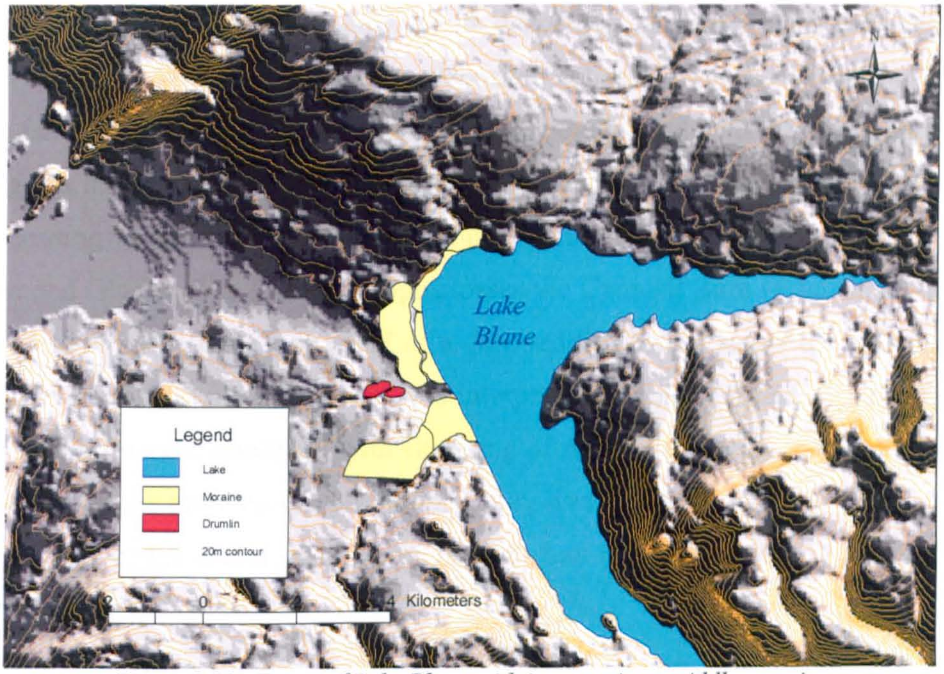


Figure 8.23 Extent of Lake Blane with ice margin at middle moraine

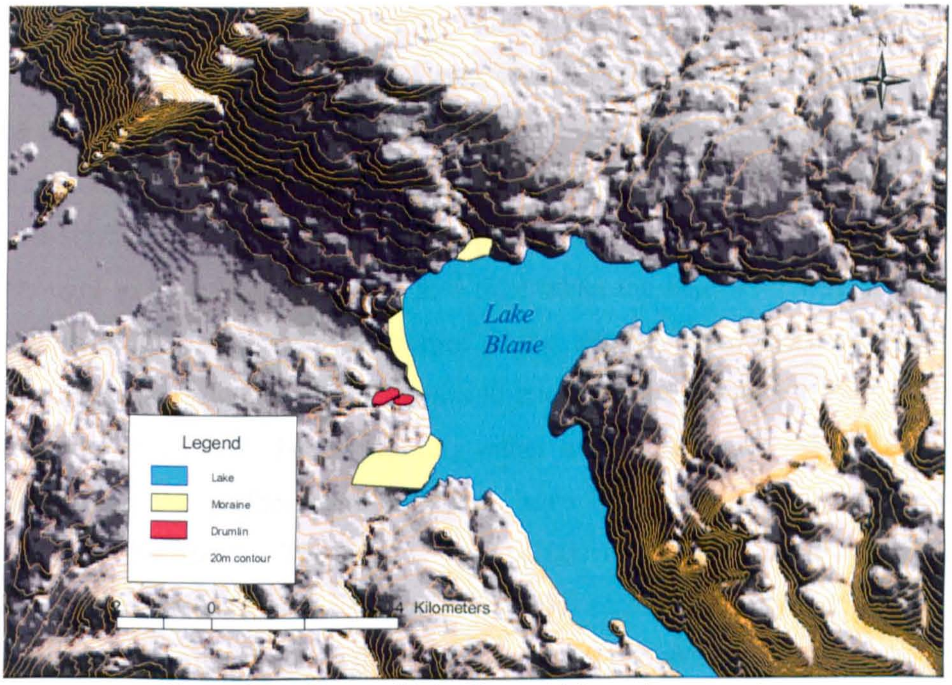


Figure 8.24 Extent of Lake Blane with ice at inner moraine

The moraine to the south of the study area, on the east side of Cameron Muir is thought to overlie a bedrock high (Rose 1981). As no exposures were found in this feature and its full extent cannot be mapped, it is not possible to suggest the processes responsible for its deposition, although as its elevation is above 65m O.D. it must have been deposited subaerially, with the exception of the fan on the east side of the ridge, which is below 65m. This ridge and another ridge to the south, have however been interpreted and mapped by Rose (1981). According to Rose the ridge to the south marks the south-eastern limit of the Lomond Glacier. The southern ridge crosses the Carnock Burn (Finnich Glen) in its western part, and is composed of a dark reddish brown sandy till with clasts aligned parallel to the ridge crest. It is interpreted as being formed by pushing at the glacier margin combined with slumping of material from the glacier surface. The area of the moraine mapped in this study was described by Rose (1981) as a thick body of till with a surface comprising of an irregular scatter of hummocky moraine (fig 8.25).

The flat surfaces of the north-eastern lobe of this feature are likely to have been subject to erosion by the lake waters and are interpreted as two shorelines. As the elevation of the two surfaces (40-50m and 20-30m) of this lobe are significantly below the 65m surface level of the lake it is probable that the surfaces were eroded at a times when the lake level was below its maximum. These surfaces are therefore not contemporaneous with the inner moraine, which is thought to have been deposited at a time when the lake level was 65m O.D. (Phillips et al. 2002). It is therefore likely that the shorelines were either deposited as the Lomond glacier advanced into the area, or when it was receding with water from Lake Blane draining either around or under the ice margin. Channels on the surface of this feature have been interpreted as meltwater channels (Rose 1981). The lobate shape of this feature suggests it could have initially been deposited as a delta or subaqueous mass flow, however its genesis cannot be substantiated due to the lack of sediment exposures.

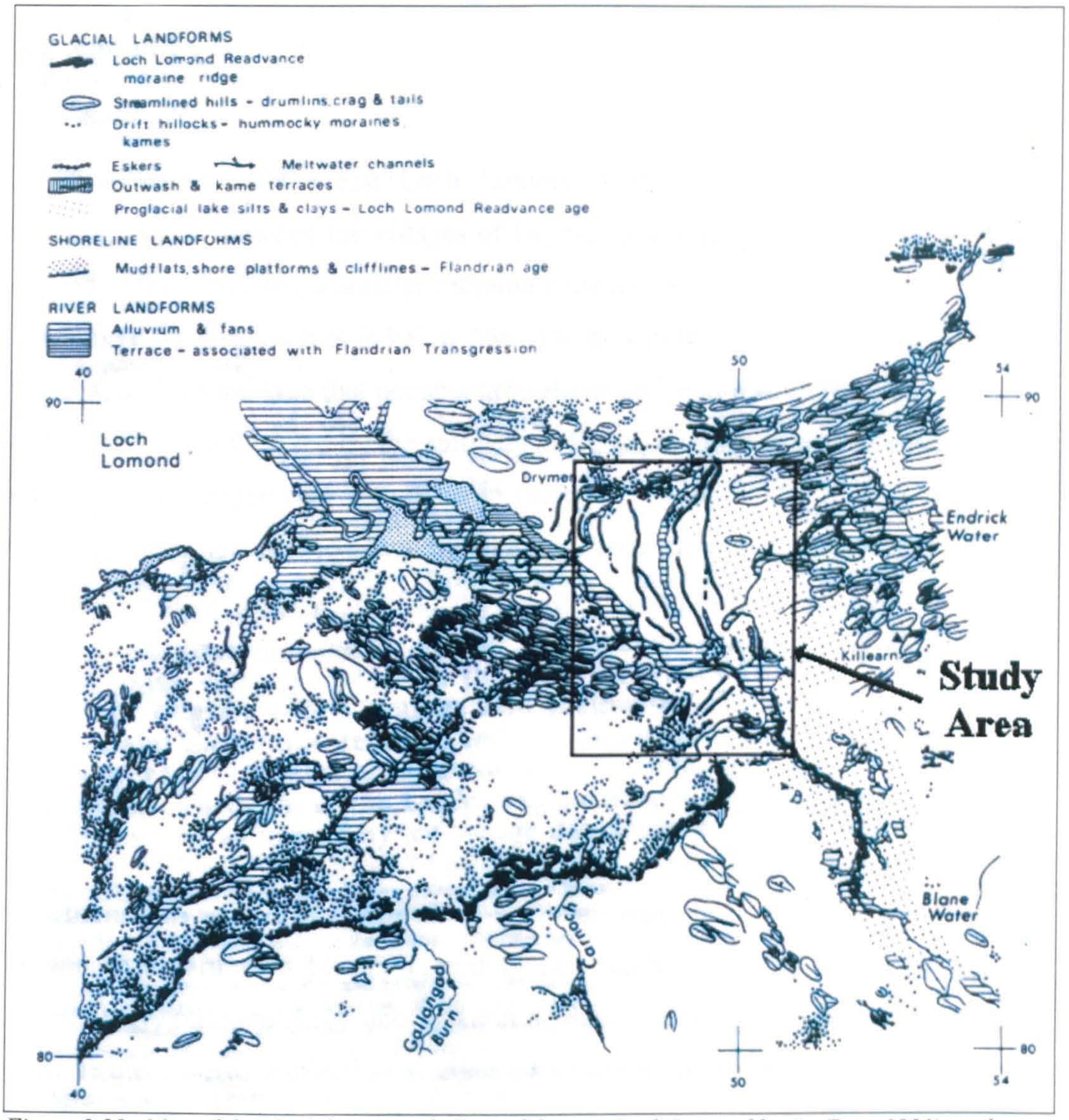


Figure 8.25 Map of the glacial geomorphology of the east Loch Lomond basin (Rose 1981), and study area used for this research

The retreat of the ice margin to the west, punctuated by minor readvances, especially while in the location of the inner and outer moraine, may have been driven by climatic oscillations near the end of Loch Lomond Stadial. Alternatively the retreat and readvances may be due to changes in the rate of calving and draw-down due to the glacier being in contact with deep water. Recession of the glacier is thought to have been interrupted by stabilisation of the glacier margin at the inner moraine, due to development of the moraine ridge allowing the glacier to retreat from the lake margin (Phillips et al 2002).

8.4 Summary

Moraines of the east Loch Lomond basin include three north-south trending ridges, between the villages of Drymen and Gartness, with larger outer and inner moraines and a smaller moraine between. For most of their extent the elevation of these moraines is below 65m, the maximum surface elevation of the former ice dammed lake that occupied the Blane and Endrick Valleys. The level of the lake was controlled by the spillway at Ballat, on the north side of the lake (Rose 1981). Sedimentary exposures in the outer moraine indicate the moraine was produced as an ice-contact delta and later modified by glacitectonic processes, due to a minor readvance onto its proximal side (Rose 1981, Evans pers. comm.). The north part of this moraine has an elevation of greater than 65m O.D. and is thought to have been deposited subaerially.

Sedimentary exposures in the inner moraine have been intensively studied by Benn and Evans (1996) and Phillips et al. (2002) who concluded that this moraine was initially formed as a Gilbert-type delta, with a subsequent polyphase deformation history recording two readvances onto the delta. The morphology, sedimentology and location of the three moraines east of Drymen indicate these were produced as glacilacustrine deltas and subsequently deformed by minor readvances of an oscillating ice margin.

In the south of the study area a moraine with a south-west to north-east orientation was deposited above the surface level of Lake Blane and was therefore probably deposited subaerially. This moraine is thought to overlie a bedrock high. The north-east part of this moraine, however, is below the lake level and displays two distinct near flat surfaces interpreted as lake shorelines. The outer and middle moraine and the north-east part of the southern moraine have been subject to debris flow possibly occurring subaqueously as they are below the surface level of the former Lake Blane. The debris flow could however have occurred subaerially following the drainage of Lake Blane.

The retreat of the ice margin punctuated by short readvances could have been climate driven or due to changes in calving and draw-down rates, as the glacier margin was in contact with the deep water of the former Lake Blane.

The poor quality of aerial photographs available for this location resulted in poor quality digital terrain models and orthoimages. Although this study allowed a review and correlation of previously published interpretations of the glacial geomorphology and sediments at this location, and mapping of the main landforms, the poor quality of the aerial photographs prevented a more detailed study of the morphology of landforms, which could have provided new insights into the genesis of these features. This emphasises the need for good quality aerial photographs to employ digital methods of mapping and morphological studies. There is potential for future research on the morphology of the glacial landforms of the East Loch Lomond basin if new aerial photographs are available and/or accurate, high resolution digital elevation models produced by methods other than photogrammetry, which is highly dependent on aerial photograph quality.

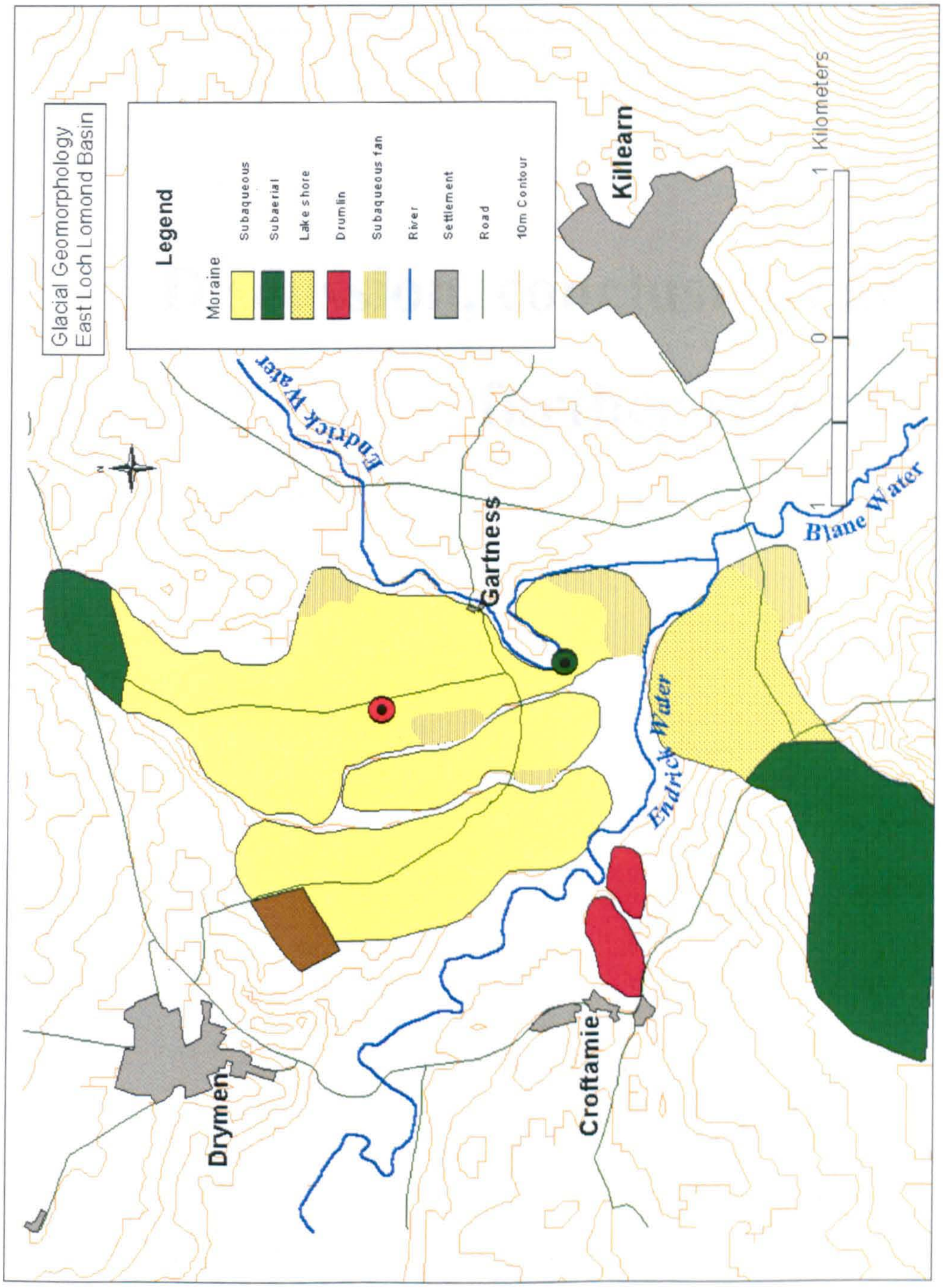


Figure 8.26 Map of the glacial geomorphology of the east Loch Lomond basin

9

Discussion, conclusions and further research

9.1 Introduction

The morphology and spatial organisation of glacial landforms have been studied at five sites in the Scottish west Highlands. Digital photogrammetry and GIS were employed to create maps of glacial landforms and three dimensional visualisation techniques used to provide insights into the morphology and spatial organisation of glacial landforms. This chapter will discuss the genesis of glacigenic landforms at the five field sites investigated and also critically assess the use of the methods of digital terrain modelling and mapping of glacial landforms using digital photogrammetry and GIS, based on the findings of this study.

9.2 The Genesis and Climatic Significance of Loch Lomond Stadial Moraines

Landforms at three of the five field sites included features with the appearance of 'Hummocky Moraine', including Torridon, Rannoch Moor and Tyndrum. The Torridon site, especially the Coire a.' Cheud Chnoic, has been the subject of various studies of hummocky moraine deposited during the Loch Lomond Stadial. Landforms traditionally interpreted as hummocky moraine, deposited by aerial stagnation have been reinterpreted as moraines deposited by incremental stagnation (Eyles 1983), by active recession (Bennett and Boulton 1993, Bennett 1994), as controlled moraines, produced by thrusting (Bennett et al 1998), and as flutings, formed by ice overriding and subglacially remoulding older glacial sediments (Hodgson 1986, 1987). By mapping these features and employing three dimensional visualisation techniques it can be seen that the landforms of Coire a' Cheud Chnoic have two spatial patterns, one cross-valley and one down-valley. The more numerous down-valley orientated features have a consistent orientation and can be traced from the higher ground to the south of

Coire a' Cheud Chnoic, in a northerly direction towards Glen Torridon and also in a westerly direction, along Srath nam Poll Dubh, towards the head of Upper Loch Torridon. The spatial pattern of these landforms is consistent with Hodgson's theory that they were formed subglacially as flutings. Three dimensional visualisation using digital elevation models and orthophotos provided interesting insights into the relationship between the flutings and the cross-valley moraines. It can clearly be seen on these images that the flutings override the cross-valley moraines. Deposition of the moraines can therefore be relatively dated to before the production of the flutings. The moraines must therefore either pre-date the Loch Lomond Stadial or have been deposited early in the stadial and overridden by a later readvance.

Based on erratic lithologies, Hodgson concluded that the material the flutings are constructed of was transported into the area during a previous glaciation. This study finds that not only was sediment from a previous glaciation preserved but that moraines have also survived, albeit in a much modified form. This has implications for the interpretation of the spatial organisation of landforms deposited during the Loch Lomond Stadial. Landform patterns with a chaotic appearance may be due to the preservation of glacial landforms deposited before the Loch Lomond Stadial that have been overridden to produce a palimpsest landscape. The use of three dimensional digital techniques or traditional stereoscope viewing may in other cases allow the relative dating of landforms from more than one glacial event. The existence of flutings that continue to the glacier margin, as marked by moraines in Glen Torridon and close to the head of Upper Loch Torridon suggests ice was warm based and not cold based near the margin as suggested by Bennett et al (1998). Cold based ice would be required to allow freezing on of sediment to the base of the ice and subsequent thrusting as suggested by Bennett et al.

Hummocky moraine on Rannoch Moor was also mapped. Three-dimensional images derived from the D.E.M. did not reveal much detail of the landforms but did allow a map of the landforms to be produced. No maps of the glacial landforms of Rannoch Moor have previously been published. The D.E.M. and orthophoto allowed mapping using digital three dimensional techniques, which were found useful for landform recognition. Much of the detail of the morphology of landforms on Rannoch Moor may be hidden due to features being covered by thick peat, or may not have been revealed in the aerial photographs due to lighting conditions. This prevented the interpretation of individual landforms based on their morphology. However, the spatial organisation of landforms could be mapped and interpreted. The pattern of hummocky moraine on Rannoch Moor is not chaotic, with most features showing linear patterns in their spatial organisation. The pattern of these landforms is indicative of active ice flowing onto the moor, mainly from the mountains to the south-west. Glacial landforms deposited on Rannoch Moor include flutings, marginal moraines and lateral moraines. Some small areas of moraines with no obvious lineation may have been deposited by local ice stagnation but there is no evidence of widespread ice stagnation at this location. As suggested by Thorp (1991a, 1986) Rannoch Moor was not a centre of ice accumulation during the Loch Lomond Stadial but a centre of ice convergence as ice advanced onto the moor from the surrounding mountains, especially the mountains to the south-west. A period of corrie glaciation following ice retreat from Rannoch Moor was suggested by Charlesworth (1956). The spatial pattern of landforms, suggesting deposition by active ice, is consistent with this possibility.

Glacigenic landforms in the Tyndrum and Strath Fillan area include features with the appearance of 'hummocky moraine' in close proximity to larger terrace shaped features, and hummocky landforms on the steeper slopes of Strath Fillan. The terrace shaped features are interpreted as kame terraces. Hummocks in the Cononish Valley, in close proximity to the kame terraces, can be seen to form chains of hummocks, interpreted as the remnants of eskers. Hummocks on the north slopes of Strath Fillan have a down slope orientation and are interpreted as lateral moraines that have been heavily modified by paraglacial debris flow. Clast shape and fabric analysis revealed different sediment characteristics for the hummocks in the Cononish Valley and those on the slopes of Strath Fillan. Clasts from the Strath Fillan landforms were more angular and therefore indicative of a less active transport path, suggesting a supraglacial origin. Clasts in the Cononish Valley are more rounded, which was interpreted as due to glacifluvial transport over a short distance. Clast fabric strength suggested the clast samples from the Cononish Valley and Strath Fillan could be of a subglacial or debris flow origin. However, clast fabric orientation was variable and not parallel to the valley axis as would be expected if the fabric reflected the former direction of ice flow. Clast fabrics were varied and parallel to the slopes they were taken from, which is more typical of debris flow deposits (Benn & Evans 1998). Some hummocks with no obvious lineation were observed in the Cononish Valley. These could be the remnants of eskers that have been less well preserved than the chains of hummocks interpreted as eskers, or these could have been deposited as hummocky moraine due to local ice stagnation. Based on the abundant glacial and glacifluvial landforms at this site it is thought that the glacier had a high sediment content. The effect of surface debris cover insulating the underlying ice from insolation could have resulted in localised ice stagnation.

'Hummocky moraine' found at these sites has been interpreted as flutings, overridden moraines, lateral and marginal moraines, lateral moraines modified by paraglacial debris flow, moraines deposited by localised ice stagnation and as the remnants of glacifluvial landforms. As these features are clearly polygenetic the term 'hummocky moraine' is misleading as it infers genesis of the features as being deposited as moraines, whereas this study has found these landforms also include features of a glacifluvial and subglacial origin. It would therefore be more appropriate to use a descriptive term such as 'hummocky topography' or 'hummocky glacial topography' that does not infer the genesis of these polygenetic landforms. As these features are polygenetic it would be problematic to associate these with any climatic conditions, such as inferred by Sissons theory of aerial stagnation.

Mapping and analysis of larger moraines at the southern limits of the Loch Lomond Stadial ice was also included in this study. The methods used of mapping and three dimensional visualisation techniques were found to be less successful for the field sites in the upper Forth Valley and East Loch Lomond Basin. The methods therefore did not reveal any more detail of the moraines located at these sites than earlier studies, which employed traditional aerial photograph interpretation and field mapping.

The study of landforms of the upper Forth Valley did however allow a correlation of sediments recorded in boreholes with the mapped location of landforms and the former ice limit, as interpreted from geomorphological evidence. Sediments within the moraine limit include a diamicts close to the surface. To the east of the moraines this diamict is not present, verifying the ice limit marked by the location of moraines. The morphology of the moraines and estuarine sediments are compatible with Thorps (1991a) theory that the large moraines in the upper Forth Valley were produced by glacitectonic processes by a glacier flowing rapidly over unconsolidated marine sediments. The morphology of the landforms was also found to be similar to thrust block moraines, in Iceland, produced by glacitectonic processes.

The poor quality of aerial photographs for the East Loch Lomond Basin had an adverse affect on aerial photograph interpretation as well as the quality of the D.E.M. produced by digital photogrammetry. The mapping and visualisation of the landforms therefore failed to reveal any more details of the morphology of the moraines than previously published. This study did however allow the presentation of previously unpublished sediment data for the outer moraine suggesting that, similar to the inner moraine, it has been subject to glacitectonic processes during readvance. This further verifies the oscillating nature of the ice margin at this location, as suggested by previous detailed studies of the inner moraine, at Drumbeg quarry (Benn & Evans 1996, Philips et al 2002).

9.3 Critical Assessment of the Application of Digital Photogrammetry and GIS to Glacial Geomorphology

Digital photogrammetry was employed in this study to produce geometrically corrected orthophotos as well as digital elevation models to investigate the morphology and spatial organisation of glacigenic landforms in the Scottish West Highlands. Aerial photographs were acquired from the aerial photograph library of the Royal Commission for Ancient and Historical Monuments Scotland (RCAHMS). These were used to produce orthophotos and digital elevation models using Helava Socet Set digital photogrammetric software. Using orthophotos has the advantage over aerial photographs that they are geometrically corrected to remove scale distortion due to height difference, parallax and aircraft tilt. This therefore results in more accurate mapping of features than is possible with uncorrected photographs. It is possible that distortion in the apparent spatial organisation of landforms, mapped from uncorrected aerial photographs, could lead to the misinterpretation of the spatial organisation if these features. It is therefore advantageous to map landforms from orthophotos to remove the possibility of inaccurate mapping.

Digital photogrammetry also allows the production of digital elevation models. These have the potential to allow detailed studies of the morphology of landforms. However, this was found problematic during this research. D.E.M.s produced by photogrammetry consist of a regularly spaced grid of points with location and elevation. No information on breaks of slopes are included in the D.E.M.s. Digital elevation models produced by field survey methods can include break of slope information and can use an irregular distribution of points based on the topography being surveyed. For example points can be surveyed at the breaks of slopes or on the crests of slopes, whereas the points on a D.E.M produced by digital photogrammetry are regularly spaced and therefore do not necessarily fall on breaks of slope. Although not as accurate as field survey, digital photogrammetry has the advantage that is can cover large area relatively quickly compared to field survey methods.

Three dimensional images derived from a D.E.M. use the elevation of points to derive contour lines, hillshading and aspect. Contours joining points of equal elevation can successfully model landforms and provide details of their morphology if the feature is located on flat ground. However much of the landforms investigated in this study are located on sloping ground. As contours join points of equal elevation they do not follow the outline or crests of landforms if the landforms are located on sloping ground as the outlines of the features are not at a constant elevation. Contours can also join points of equal elevation on adjacent features. During the research carried out for this project it was found that contours often gave a false impression of landforms and their spatial organisation. The use of images derived from the photogrammetrically produced D.E.M.s were therefore found to be of limited use. This highlights an important weakness in the application of D.E.M.s to geomorphological studies in areas of steeply sloping terrain. The use of D.E.M. derived images did produce better quality images in areas of flatter terrain. They were therefore found to be of more use for the flatter areas of the Tyndrum site than the on the steeply sloping ground of Torridon.

Despite the lack of detail in the D.E.M. derived images, images created by draping the orthophoto over the D.E.M. were found to be more useful to interpret landforms. These have the advantage of combining elevation and the ability to be viewed in three dimensions with the detail of an aerial photograph. This technique was found particularly useful for the Torridon site where it allowed the relative dating of moraines that had been overridden to produce flutings on their surface. For detailed studies of landforms on sloping ground, it is recommended that digital elevation models are used in conjunction with orthophotos as images derived solely from the D.EM. can give a false impression of the morphology of landforms.

The combination of orthophotos and D.E.M.s was also found useful for mapping landforms. Using the photogrammetric software Helava Leica Socet Set on a workstation with built in stereoscope allowed stereo viewing similar to that of a conventional stereoscope but with several advantages. As this technique uses digital images, these can be manipulated to assist the identification of landforms and their morphology by changing various parameters including height exaggeration, scale, contrast and brightness. The 3D model can also be viewed from various angles to identify features. This allowed the production of accurate maps from geometrically corrected orthoimages.

Both aerial photograph interpretation and the production of digital elevation models by photogrammetry are dependent on the quality of available aerial photographs. The photographs used for this study were of varying quality with the photographs for the east Loch Lomond site being of particularly poor quality. This is probably due to poor handling and storage of the photographs. Poor reproduction of the diapositives could also affect their quality.

The quality of the D.E.M.s is also affected by tree cover and buildings. The surface of a D.E.M. includes the height of any feature in the aerial photograph, including trees and buildings. The height of trees and buildings can be removed by lowering the height of point for example to remove the heights of trees. This is useful to allow contours to follow the ground on general topographic maps but does not reveal any information on landforms below the tree cover. It is therefore concluded that photogrammetry is not suitable for producing D.E.M.s for geomorphological studies in areas with substantial tree cover.

The GIS was found to be a useful tool to bring together information from various sources and combine this for landform interpretation and spatial analysis. Data from the photogrammetric work including maps of landforms, orthophotos and digital elevation models were combined with sedimentological data such as clast fabric and shape data and borehole data, and other information collected such as field notes and digital photographs.

9.4 Further Research

This research highlighted some important weaknesses in the use of photogrammetry to produce digital elevation models as well as problems deriving images from the D.E.M.s. As the technology of terrain modelling improves and new methods of producing D.E.M.s are developed research into their application to geomorphological studies would be useful. Other methods of terrain modelling include D.E.M.s produced from satellite data and from aerial survey using Lidar (aerial laser scanning). Lidar has the ability to scan the surface below tree cover, which would allow geomorphological studies in areas with extensive tree cover, such as the upper Forth Valley. Lidar also has the advantage of not being affected by aerial photograph quality. The use of new aerial photographs, especially if using digital photogrammetry, may provide better quality models and allow more detailed photograph interpretation. At the time of this study the only available aerial photographs had been taken twelve years previously and were not all in good condition. Higher resolution D.E.M.s could have been produced for this work but these would have been be very slow to process and would have required a large amount of computer storage. As computer become more powerful and increase their storage capacity it should be more practical to produce higher resolution D.E.M.s. It was found during this research that contouring is not suitable to visualise landforms on steeply sloping ground. Research into the development of GIS tools that can detect breaks of slopes rather than contouring could assist geomorphological studies.

The application of digital methods of mapping and terrain modelling could be applied to other sites of landforms traditionally interpreted as hummocky moraine. This may allow a better understanding of this type of topography, which has been interpreted in this research as polygenetic. Improved methods of terrain modelling may allow the relative dating of features and reveal other palimpsest landscapes as found in Torridon.

References

Alley R.B., Meese D.A., Schuman C.A., Gow A.J., Taylor KC., Grootes P.M., White JW.C. and Ram M. **1993**, Abrupt increase in Greenland snow accumulation at the end of the Younger Dryas event. *Nature* 362, 527-529.

Andersson G. **1998**, Genesis of hummocky moraines in the Bolmen, southwest Sweden. *Boreas* 27 (1), 55-67.

Atkinson T.C., Brifa K.R. and Coope G.R. **1987**, Seasonal temperatures in Bitain during the last 22,000 years, reconstructed using beetle remains. *Nature* 325, 587-592.

Avery T.E. **1977** *Interpretation of Aerial Photographs.* Burgess, Minneapolis.

Ballantyne C.K. and Benn D.I. **1994**, Paraglacial slope adjustment and resedimentation following recent glacier retreat, Faberstolsdalen, Norway. *Arctic and Alpine Research* 26, No3, 255-269.

Ballantyne C.K. and Benn D.I. **1996**, Paraglacial slope adjustment during recent deglaciation and its implicaions for slope evolution in formely glaciated environments. In *Advances in Hillslope Processes Volume 2.* Anderson M.G. Brooks S.M. (eds) John Wiley & Sons, Chichester, 1173-1195.

Bard E., Arnold M., Maurice P., Dupart J., Moyes J.and Duplessy J. **1987**, Rereat of the North Atlantic polar front during the last deglaciation by radiocarbon accelerator mass spectrometry. *Nature* 328, 791-794.

Bell D. **1892**, On a glacial mound in Glen Fruin, Dumbartonshire. *Transactions of the Geological Society of Glasgow ix,* 345-354.

Benn D.I. **1989**, Debris transport by Loch Lomond Readvance glaciers in North Scotland: basin form and the within-valley asymmetry of lateral moraines. *Journal of Quaternary Science* 4, 95-108.

Benn D.I. **1990**, Scottish Lateglacial moraines: debris supply, genesis and significance.
Unpublished PhD Thesis, University of St.Andrews.

Benn D.I. **1992** The genesis and significance of hummocky moraine: Evidence from the Isle of Skye. *Quaternary Science Reviews* 11, 781-799.

Benn D.I. **1993**, Scottish Landform Examples 9: Moraines in Coire na Creiche. *Scottish Geographical Magazine* 109, 187-191.

Benn D.I. **1994b**, Fabric shape and the interpretation of sedementary fabric data. *Journal of Sedimentary Research* A64, No 4, 910-915.

Benn D.I. **1995**, Fabric signatures of subglacial till deformation, Breidamerkurjökull, Iceland.
Sedimentology 42, 735-747.

Benn D.I. **1997**, Glacier fluctuations in Western Scotland. *Quaternary International* 38/39, 137-147.

Benn D.I. and Ballantyne C.K. **1993**, The description and representation of particle shape. *Earth Surface Processes and Landforms* 18, 665-672.

Benn D.I. and Ballantyne C.K. **1994**, Reconstructing the transport history of glacigenic sediments: a new approach based on the co-variance of clast form indices. *Sedimentary Geology* 91, 215-227.

Benn D.I. and Evans D.J.A. **1996,** The interpretation and classification of subglacially deformed materials. *Quaternary Science Reviews* 15, 23-52.

Benn D.I. and Evans D.J.A. **1998,** *Glaciers and Glaciation*. Arnold, London.

Benn D.I., Kirkbride M.P., Owen L.A. and Brazier V. **2003**, Glaciated valley landsystems. In *Glacial Landsystems,* Evans D.J.A (ed), 372-406, Arnold, London.

Benn D.I., Lowe J. and Walker M.J.C. **1992,** Glacial response to climatic change during the Loch Lomond Stadial and early Flandrian: geomorphological and palynological evidence from the Isle of Skye, Scotland. *Journal of Quaternary Science* 7(2), 125-144.

Benn D.I. and Ringrose T.J. **2001**, Random variation of fabric eigenvalues: implications for the use of a-axis fabric data to differentiate till facies. *Earth Surface Processes and Landforms* 26, 295-306.

Bennett M.R. **1990**, The cwms of Snowdonia: a morphometric analysis. *Queen Mary and Westfield College Research Papers in Geography 2.*

Bennett M.R. **1994**, Morphological evidence as a guide to deglaciation following the Loch Lomond Readvance: a review of research approaches. *Scottish Geographical Journal* 10, 24-32.

Bennett M.R. **1995**, The morphology of glacially fluted terrain: examples from the Northwest Highlands of Scotland. *Proceedings of the Geologists Association* 106, 27-38.

Bennett M.R. **1996,** *Glacial geology ice sheets and landforms*. John Wiley & sons Ltd., Chichester.

Bennett M.R. **1999**, Paraglacial and periglacial slope adjustment of a degraded lateral moraine in Glen Torridon. *Scottish Journal of Geology* 35, 79-83.

Bennett M.R. and Boulton G.S. **1993a**, Deglaciation of the Younger Dryas or Loch Lomond Stadial ice-field in the northern Highland, Scotland. *Journal of Quaternary Science* 8 (2), 133-145.

Bennett M.R. and Boulton G.S. **1993b**, A Reinterpretation of Scottish hummocky moraine and it's significance fo the deglaciation of the Scottish Highlands during the Younger Dryas or Loch Lomond Stadial. *Geology Magazine* 130(3), 301-318.

Bennett M.R. and Glasser N.F., **1996**, *Glacial Geology*. John Wiley & Sons, Chichester.

Bennett M.R., Hambrey M.J. and Huddart D., Glasser N.F. **1998**, Glacial thrusting & moraine-mound formation in Svalbard and Britain: the example of Coire a' Cheud Chnoic (Valley of a Hundred Hills) Torridon, Scotland. *Quaternary Proceedings* 6, 17-34.

Bennett M.R., Waller R., Glasser N.F., Hambrey M.J. and Huddart D. **1999**, Glacigenic clast fabrics: genetic fingerprint or wishful thinking? *Journal of Quaternary Science*14 (2), 125-135.

Birks H. H. and Mathewes R.W. **1978**, Studies in the vegetational history of Scotland. Late Devensian and early Flandrian pollen and macrofossil stratigraphy at Abernethy Forest, Invernessshire. *New Phytologist* 80, 455-484.

Birks H.J.B. **1993a**, Cam Loch. In *Quaternary of Scotland.* Gordon J.E. Sutherland D.G. (eds), Chapman, London, 134-137.

Birks H.J.B **1993b**, Loch Sionascaig. In *Quaternary of Scotland.* Gordon J.E. and Sutherland D.G. (eds), Chapman, London, 137-140.

Birks H.J.B. **1993c**, Lochan an Druim. In *Quaternary of Scotland.* Gordon J.E. and Sutherland D.G (eds), Chapman, London,141-143.

Birks H.B.J. **1993d**, Loch Maree. In *Quaternary of Scotland.* Gordon G.E. and Sutherland D.G. (eds), Chapman, London,143-146.

Birks H.J.B. **1993e**, Loch Ashik, Loch Cleat and Loch Meodal. In *Quaternary of Scotland.* Gordon J.E. and Sutherland D.G. (eds), Chapman, London,399-407.

Bluemle J.P. and Clayton L. **1984**, Large-scale glacial thrusting and related processes in North Dakota. *Boreas* 13, 279-299.

Boulton G.S. **1978**, Boulder shapes and grain-size distributions of debris as indicators of transport paths through a glacier and till genesis. *Sedimentology* 25, 773-799.

Boulton G.S. **1986**, Push-moraines and glacier-contact fans in marine and terrestrial environments. *Sedimentology* 33, 677-698.

Boulton G.S. **1992**, 'Hummocky moraine' on Rannoch Moor and in the Loch Tulla area. In *The south-west Scottish Highlands QRA field guide.* Walker M.J.C. and Gray J.M. (eds), Quaternary Research Association, Cambridge, 50-52.

Boulton G.S. **1996** Theory of glacial erosion, transport and deposition as a consequence of subglacial sediment deformation. *Journal of Glaciology* 42, 43-62.

Boulton G.S. and Dent D.L. **1974**, The nature and rates of post-depositional changes in recently deposited till form south-east Iceland. *Geografiska Annaler* 56a, 121-134.

Boulton G.S. and Clark C.D. 1990. A highly mobile Laurentide Ice Sheet revealed by satellite images of glacial lineations, *Nature* 346, 813-817.

Boulton G.S. and Eyles N. 1979, Sedimentation by valley glaciers; a model and genetic classification. In *Moraines and varves.* Schlucter C.H. (ed) 11-23, Balkema, Rotterdam.

Boulton G.S. and Paul M.A. 1976, The influence of genetic processes on some geotechnical properties of glacial tills. *Quarterly Journal of Engineering* 9, 159-94.

Boyle E.A. and Keigwin L.1987, North Atlantic thermohaline circulation during the past 20,000 years linked to high-latitude surface temperatures. *Nature* 330, 35-40.

Broecker W.S. and Denton G.H. 1990, The role of ocean-atmosphere reorganizations in glacial cycles. *Quaternary Science Reviews* 9, 305-341.

Brown T. 1870, On the old river terraces of the Earn and Teith, viewed in connection with certain proofs of the antiquity of man. *Transactions of the royal society of Edinburgh* xxvi, 149-176.

Brown D.G., Lusch D.P. and Duda K.A. 1998, Supervised classification of types of glaciated landscapes using digital elevation data. *Geomorphology* 21, 233-250.

Cameron I.B. and Stephenson D. 1985, *The midland valley of Scotland.* British Geological Survey, London.

Chandler J. 1999, Effective application of automated digital photogrammetry for gemorpohological research. *Earth Surface Processes and Landforms* 24, 51-63.

Charlesworth J.R. **1956**, The Late-glacial history of the Highlands and islands of Scotland.
Transcripts of the royal society of Edinburgh. LXII, 769-928.

Clark C.D. **1993**, Mega-scale lineations and cross-cutting ice flow landforms. *Earth Surface Processes and Landforms* 18, 1-29.

Clark C.D. **1994**, Large-scale ice-moulding, a discussion of genesis and glaciological significance. *Sedimentary Geology* 91, 253-268

Clark C.D. **1997**, Reconstructing the evolutionary dynamics of former ice sheets using multi-temporal evidence, remote sensing and GIS. *Quaternary Science Reviews* 16, 1067-1092.

Clark, C.D. **1999**, Glaciodynamic context of subglacial bedform generation and preservation. *Annals of Glaciology* 28, 1-20.

Clark, C.D. and Meehan, R.I. **2001**, Subglacial bedform geomorphphology of the Irish Ice Sheet reveals major configuration changes during growth and decay. *Journal of Quatenary Science* 16 (5), 483 –496.

Collins R. and Chisholm N. **1991**, *Geomorphological photogrammetry.* Photogrammetric Record 13, (78) 845-854.

Coope G.R. and Lemdahl G. **1995**, Regional differences in the Lateglacial climate of northern Europe based on coleopteran analysis. *Journal of Quaternary Science* 10, 391-395.

Coope G.R., Morgan A. and Osborne P.J. **1971**, Fossil coleoptera as indicators of climatic fluctuations during the last glaciation in Britain. *Palaeogeography, palaeoclimatology, palaeoecology* 10, 87-101.

Copland L., Sharp M.J. and Dowdeswell J.A. **2003**, The distribution and flow characteristics of surge-type glaciers in the Canadian high arctic. *Annals of Glaciology* 36: 73-81.

Croot D.G. **1988**, Morphological, structural and mechanical analysis of neoglacial ice-pushed ridges in Iceland. In *Glacitectonics, Forms and Processes* Croot D.G. (ed), 49-61, Balkema Rotterdam.

Curry A.M. **1999**, Paraglacial modification of slope form. *Earth Surface Processes and Landforms* 24, 1213-1228.

Curry A.M. and Ballantyne C.K. **1999**, Paraglacial modification of glacigenic sediment. *Geografiska Annaler* 81A, 409-419.

Dansgaard W., White J.W.C. and Johnsen S.J. **1989**, The abrupt termination of the Younger Dryas climate event. *Nature* 339, 532-533.

De Mers M.N. **2000**, *Fundamentals of GIS.* John Wiley & Sons, Chichester.

Derbyshire E. and Owen L.A. **1990**, Quaternary alluvial fans in the Karakoram Mountains. In *Alluvial Fans: A Field Approach.* Rachocki A.H. and Church M. (eds), Wiley, Chichester, 27-53.

Dix J.K. and Duck R.W. **2000**, A high-resolution seismic stratigraphy from a Scottish sea loch an its implications for Loch Lomond Stadial deglaciation. *Journal of Quaternary Science* 15, No. 6, 645-656.

Donner J.J. **1957**, The Geology and vegetation of Late-glacial retreat stages in Scotland. *Transcripts of the Royal Society of Edinburgh* LXIII part II, 221-263.

Doody J.J., Smythe D.K. and Watts D.R. **1993**, Geophysical investigations of the Blane Valley Pleistocene deposits. *Scottish Journal of Geology* 29, 201-204.

Drake L.D **1972**, Mechanisms of clast attrition in basal till. *Geological Society of America Bulletin* 83, 2159-2165.

Earp J.R., Francis E.H. and Read W.A. **1962**, Discussion of J.B. Sisson's paper on Late-glacial shorelines. *Transcript of the Edinburgh Geological Society* 19 (2), 216-220.

Embleton C. and Bochan **1990**, Geomorphological mapping, remote sensing and terrain models. *Zeitschrift fur Geomophologie supplementband* 80,

Evans D.J.A., Archer S. and Wilson D.J.H. **1999**, A comparison of the lichenometric and Schmidt hammer dating techniques based on data from the proglacial areas of some Icelandic glaciers. *Quaternary Research Reviews* 18, 13-41.

Evans D.J.A. and Benn D.I. **1999**, Glaciers as streamlining agents. *Geography Review* 12, 2-5.

Evans D.J.A. and England J. **1991**, Canadian Landform Examples 19: High Arctic thrust block moraines. *Canadian Geographer* 35, 93-97.

Evans D.J.A. and Rea B.R. **2003**, The surging landsystem. In *Glacial Landsystems.* Evans D.J.A. (ed) Arnold, London.

Evans D.J.A. and Rea B.R. **1999**, Geomorphology and sedimentology of surging glaciers: a landsystems approach. *Annals of Glaciology* 28, 75-82.

Evans D.J.A and Twigg D.R. **2002**, The active temperate glacial landsystem: a model based on Breiðamerkurjökull and Fjallsjökull, Iceland. *Quaternary Science Reviews* 21, 2143-2177.

Eyles N. **1983**, Modern Icelandic glaciers as depositional models for hummocky moraine in the Scottish Highlands. In *Tills and Related Deposits (INQUA).* Evenson B.E. and Schluchter C. A.A. (eds), Balkema, Rotterdam, 47-60.

Eyles N., Eyles C.H. and McCabe A.M. **1988**, Late Pleistocene subaerial debris-flow facies of the Bow Valley, near Banff, Canadian Rocky Mountains. *Sedimentology* 35, 465-480.

Eyles N. and Kocsis S. **1988**, Sedimentology and last fabric of subaerial debris-flow facies in a glacially-influenced alluvial fan. *Sedimentary Geology* 59, 15-28.

Falkner E. **1995**, *Aerial Mapping.* Lewis, London.

Flint R.F., **1971**, *Glacial and Quaternary Geology.* Wiley, New York.

Francis E.H. **1970**, The geology of the Stirling district. *Memoirs of the geological survey of the U.K.*

Gardnet T. **1990**, Automated extraction of geomorphic properties from digital elevation data.
Zeitschrift fur Geomoopholgie Supplementband 80, 57-68.

Gordon J.E. and Sutherland D.G. **1993**, Coire a' Cheud Chnoic. In *Quaternary of Scotland.* Sutherland D.G. and Gordon J.E. (eds), Joint Nature Conservation Committee, Glasgow, 123-126.

Graham D.J. and Midgley N.G. **2000**, Moraine-mound formation by englacial thrusting:the Younger Dryas moraines of Cwm Idwal, North Wales. In *Deformation of Glacial Materials.*
Maltman A.J. and Hubbard B. (eds), The Geological Society of London, London, 321-336.

Gray J.M. and Brooks C.L. **1972**, The Loch Lomond Readvance moraines of Mull and Menteith. *Scottish Journal of Geology* 8 (2), 95-103.

Gray J.M. and Lowe J.J. **1977**, The Scottish Lateglacial environment: a synthesis. In *Studies in the Scottish Lateglacial Environment.* Gray J.M. and Lowe J.J. (eds), Pergamon, Oxford, 163-181.

Hambrey M.J. Dowdeswell J.A. Murray T. and Porter P.R. **1996**, Thrusting and debris entrainment in a surging glacier: Bakaninbreen, Svalbard. *Annals of Glaciology* 22, 241-248.

Hambrey M.J. Huddart D. Bennett M.R. and Glasser N.F. **1997**, Genesis of hummocky moraine by thrusting in glacier ice: evidence from Svalbard and Britain. *Journal of the Geological Society of London* 154, 623-632.

Hanson J.D. and Evans D.J.A. **2000**, The Carse of Stirling. *Scottish Geographical Journal* 116 No1, 71-78.

Harker A. **1901**, Ice erosion in the Cuillin hills, Skye. *Transactions of the Royal Society of Edinburgh* 40, 221-252.

Heinrich H. **1988**, Origin and consequences of cyclic ice rafting in the Northeast Atlantic during the past 130,000 years. *Quaternary Research* 29, 142-152.

Hodgson D.M. **1982**, Hummocky and fluted moraines in part of NW Scotland. Unpublished Thesis, University of Edinburgh.

Hodgson D.M. **1986**, A Study of fluted moraines in the Torridon area, NW Scotland. *Journal of Quaternary Science* 1(2), 109-118.

Hodgson D.M. **1987**, Coire a' Cheud Chnoic. In *The Wester Ross Field Guide,* Ballantyne C.K. and Sutherland D.G. (eds), Quaternary Research Association, Cambridge, 127-135.

Holloway L.K., Peacock J.D., Smith D.E. and Wood A.M. **2002**, A Windermere Interstadial marine sequence: environmental and realative sea level interpretations for the western Forth Valley, Scotland. *Scottish Journal of Geology* 38, 41-54.

Holmes C.D. **1960**, Evolution of till-stone shapes, New York. *Geological Society of America Bulletin* 71, 1645-1660.

Hoppe G. **1952**, 'Hummocky moraine" regions, with special reference to the interior of Norbotten. *Geografiska Annaler* 34, 1-72.

Howarth P.J. **1968**, geomorphological and glaciological studies, Eastern Breiđamerkurjökull, Iceland. Unpublished PhD Thesis, University of Glasgow.

Huang Y.D. **2000**, Evaluation of information loss in digital elevation models with digital photogrammetric systems. *Photogrammetric Record* 16(95), 781-791.

Humlum O. **1985**, Changes in texture and fabric of particles in glacial traction with distance from source, Mydrdalsjökull, Iceland. *Journal of Glaciology* 31, 150-156.

Jack R.L. **1874**, Notes on a till of boulder clay with broken shells in the lower valley of the River Endrick near Loch Lomond and its relationship to certain other glacial deposits. *Transactions of the Geological Society of Glasgow* 5, 5-25.

Jones C.B. **1997**, *Geographical Information Systems and Computer Cartography*. Longman, Harlow.

Kalin M. **1971**, The active push moraine of the Thompson Glacier. *Research report (glaciology)*, McGill University, Montreal No4.

King C.A.M. and Gage M. **1961**, Note of the extent of glaciation in part of west Kerry. *Irish Geographer* 4, 202-208.

Klemen J. **1992**, The palimpsest glacial landscape in northwestern Sweden: Late Weichselian deglaciation landforms and traces of older west-centred ice sheets. *Geografiska Annaler* 74A, 305-325.

Klemen J. **1994**, Preservation of landforms under ice sheets and ice caps. *Geofiska Annaler* 9, 19-32.

Kraus K. **1993**, *Photogrammetry.* Dummler, Bonn.

Kruger J. **1987**, Track af et glaciallandskabs udviking ved mordranden af Myrdalsjokull, Iceland. *Dansk Geologisk Foreningens, Arsskrift for 1986 49.65.*

Kruger J **1993**, Moraine-ridge formation along a stagnant ice front in Iceland. *Boreas* 22, 101-109.

Lane S.N. James T.D. and Crowell M.D. **2000**, Application of digital photogrammetry to complex topographic for geomorophological research. *Photogrammetric Record* 16(95), 793-821.

Lewis W.V. **1960**, Norwegian cirque glaciers. *Royal Geographical Society Research Series* 4.

Lillesand T.M. and Keifer R.W. **1994** *Remote Sensing and Image Interpretation.* John Wiley & Sons, Chichester.

Lo C.P. **1976**, *Geographical Applications of Aerial Photography.* Crane, Russack & Co. New York.

Lowe J.J. **1993a**, Mollands. In *Quaternary of Scotland.* Gordon J.E. and Sutherland D.G. (eds), Chapman, London, 464-469.

Lowe J.J. **1993b**, Tynaspirit. In *Quaternary of Scotland*. Gordon J.E. and Sutherland D.G. (eds), Chapman, London.

Lowe J.J., Amman B., Birks H.H., Bjorck S., Coope G.R., Cwynar L.and De Beaulieu J.L. **1994**, Climatic changes in areas adjacent to the North Atlantic during the last glacial-interglacial transition (14-9 ka BP). *Journal of Quaternary Science* 9, 185-198.

Lowe J.J., Coope G.R., Sheldrick C., Harkness D.D. and Walker M.J.C. **1995**, Direct comparison of UK temperatures and Greenland snow accumulation rates 15000-12000 yr age. *Journal of Quaternary Science* 10, 175-180.

Lowe J.J. and Walker M.J.C. **1976**, Radiocarbon dates and deglaciation of Rannoch Moor, Scotland. *Nature* 264, 632-633.

Lowe J.J. and Walker M.J.C. **1980**, Pollen analyses, radiocarbon dates and the deglaciation of Rannoch Moor, following the Loch Lomond Advance. In *Timescales in Geomorphology,* Cullingford R.A. , Davidson D.A. and Lewin J. **1980** John Wiley & Sons Ltd. Chichester.

Lowe J.J. and Walker M.J.C. **1991**, Vegetational history of the Isle of Skye, The late Devensian Lateglacial period (13-10ka BP). In *Quaternary of the Isle of Skye Field Guide.* Ballantyne C.K. and Benn D.I. (eds), Quaternary Research Association, Cambridge, 98-118.

Lowe J.J. and Walker M.J.C. **1997**, *Reconstructing Quaternary Environments.* Longman Group., Harlow.

MacFarlane J. **1858**, Memorandum of shells and a deers horn found in a cutting of the Forth and Clyde Junction Railway. *Proceedings of the Royal Physical Society of Edinburgh* 1, 163-165.

Manley G. **1959**, The late-glacial climate of North-west England. *Liverpool and Manchester Geological Journal* 2, 188-215.

Matthews J.A. Mccarrol D. and Shakesby R.A. **1995**, Contemporary terminal-moraine ridge formation at a temperate glacier: Styggedalsbreen, Jotunheimen, southern Norway. *Boreas* 24, 129-139.

Nakawo M. and Yoing G.L. **1981**, Field experiments to determine the effect of a debris layer on ablation of glacier ice. *Annals of Glaciology* 29, 118-122.

Nye J.F. **1951**, The flow of glaciers and ice sheets as a problem in plasticity. *Proceedings of the Royal Society of London Series A* 207, 554-572.

Owen L.A. **1991**, Mass movement deposits in the Karakoram Mountains: their sedimentary characteristics, recognition and role in Karakoram landform evolution. *Zeitschrift fur Geomorphologie* 35, 401-424.

Owen L.A. and Derbyshire E. **1989**, The Karakoram depositional system. *Zeitschrift fur Geomorphologie Supplementband* 76, 33-73.

Peacock J.D. **1967**, West Highland morainic features aligned in the direction of ice flow. *Scottish Journal of Geology* 3, 370-372.

Peacock J.D. **1981**, Scottish Lage-glacial mariane deposits and their environmental significance. In *The Quaternary of Britain.* Neale J. and Flenley J. (eds), Pergammon Press, Oxford, 222-236.

Pelto M.S. **2000**, Mass balance of adjacent debris-covered and clean glacir ice in the North Cascades, Washinton. In *Debris Covered Glaciers.* Nakawo M. and Raymond C.F. (eds),
International Association of Hydrological Sciences, Wallingford, 35-42.

Pennington W. **1970**, Vegetation history in the north-west of England: a regional synthesis. In Walker D. and West R.G. (eds) *Studies in the vegetational history of the British Isles.* Cambridge University Press, Cambridge, 41-79.

Peteet D.M. **1993** Global Younger Dryas ? *Quaternary Science Reviews* 12, 277-355.

Peteet D.M. **1995** Global Younger Dryas ? *Quaternary International* 28, 93-104.

Phillips E.R. Evans D.J.A. and Auton C.A. **2002**, Polyphase deformation at an oscillating ice margin following the Loch Lomond Readvance, central Scotland, UK. *Sedimentary Geology* 149, 157-182.

Price R.J. **1975**, The glaciation of West Central Scotland : A Review. *Scottish Geographical Magazine* 91, 134-145.

Price R.J. **1983**, Scotland's environment during the last 30,000 years. Scottish Academic press, Edinburgh.

Razavi A.H. **1995**, ArcView Developers Guide. Onward Press, Santa Fe.

Renwick J. and Gregory J.W. **1909**, The Loch Lomond moraines. *Transactions of the Geological Society of Glasgow* 13, 45-55.

Rose J. **1981**, Field Guide to the Quaternary Geology of the South Eastern Part of the Loch Lomond Basin. *Proceedings fo the Geological Society of Glasgow* 122/123, 12-28.

Rose J. Lowe J.J. and Swithur R. **1988,** A radiocarbon date on plant detritus beneath till from the type area of the Loch Lomond Readvance. *Scottish Journal of Geology* 24 No.2, 133-145.

Russel A.J. and Marren P.M. **1998,** A Youger Dryas (Loch Lomond Stadial) jökulhlaup. *Boreas* 27 No 4, 231-242.

Seddon B. **1957**, Late-glacial cwm glaciers in Wales. *Journal of Glaciology* 3, 94-99.

Sharp R.P. **1960,** *Glaciers.* University of Oregon Press, Oregon.

Sharp M. **1984,** Annual moraine ridges at Skalafelljokull, South-east Iceland. *Journal of Glaciology* 30 No 104, 82-93.

Sharp M.J. **1985,** 'Crevasse-fill ridges: a landform type characteristic of surging glaciers. *Geografiska Annaler* 67A, 213-220.

Simpson J. B. **1933,** The Late glacial readvance moraines of the Highland border west of the River Tay. *Transcripts of the Royal Society of Edinburgh* 57, 633-645.

Sissons J.B. **1963,** The Perth Readvance in Central Scotland. *Scottish Geographical Journal* 79, 151-163.

Sissons J.B. **1966,** Relative sea level changes between 10.300 and 8,300 in part of the Carse of Stirling. *Transactions of the Institute of British Geographers* 39, 19-29.

Sissons J.B. **1967a,** *The evolution of Scotland's Scenery.* Oliver and Boyd, Edinburgh and London.

Sissons J.B. **1967b**, Glacial stages and radiocarbon dates in Scotland. *Scottish Journal of Geology* 3, 375-381.

Sissons J.B. **1973**, Loch Lomond Readvance in the Grampian Highlands of Scotland. *Nature* 244 No 135, 75-77.

Sissons J.B. **1974**, The Quaternary in Scotland : A Review. *Scottish Journal of Geology* 10, 311-337.

Sissons J.B. **1977**, The Loch Lomond Readvance in northern mainland Scotland. *In Studies in the Lateglacial Environment.* Gray J.M. and Lowe J.J. (eds), Pergammon, Oxford, 45-59.

Sissons J.B. **1979a**, The Loch Lomond Stadial in the British Isles. *Nature* 280, 199-203.

Sissons J.B. **1979b**, The Loch Lomond Readvance in the Cairngorm Mountains. *Scottish Geographical Magazine* 96, 18-19.

Sissons J.B. **1980**, Paleoclimatic inferences from Loch Lomond Advance glaciers. *In Studies in the Lateglacial of north-west Europe.* Lowe J.J. and Gray G.M., Pergamon Press, Oxford, 31-43.

Small R.J. **1983**, Lateral moraines of Glacier de Tsidjiore Nouve: form, development and implications. *Journal of Glaciology* 29 No 102, 250-259.

Smith D.E. **1965**, Late and postglacial changes of shoreline on the north side of the Forth Valley and estuary. Unpublished thesis, University of Edinburgh.

Smith D.E. **1969**, Post-glacial displaced shorelines in the surface of the carse clay on the north bank of the river Forth, in Scotland. *Zeitschift fur Geomorphologie* 12, 388-408.

Smith D.E. **1993**, Western Forth Valley. In *Quaternary of Scotland.* Sutherland D.G. and Gordon J.E. (eds), Chapman & Hall, London, 456-464.

Sneed E.D. and Folk R.L. **1958**, Pebbles in the lower Colorado River, Texas, a study in particle morphogenesis. *Journal of Geology* 66, 114-150.

Spedding N. and Evans D.J.A. **2002**, Sediments and landforms at Kviarjökull, southeast Iceland: a reappraisal of the glaciated valley landsystem. *Sedimentary Geology* 149, 21-42.

Sugden D.E. **1970**, Landforms of deglaciation in the Cairngorm mountains. *Transcripts of the Institute of British Geographers* 51, 201-219.

Sugden D.E. **1971**, The significance of periglacial activity on some Scottish mountains. *Geographical Journal* 137, 388-392.

Sutherland D.G., Gordon J.E. and Smith D.E **1993**, Western Highland Boundary. In *Quaternary of Scotland.* Sutherland D.G. and Gordon J.E. (eds), Chapman & Hall, London, 437-474.

Takeuchi Y. **2000**, Characteristics of ablation and heat balance in debris-free and debris-covered areas on Khumbu Glacier, Napal Hymalayas, in pre-monsoon season. In *Debris Covered Glaciers.* Nakawo M. and Raymond C.F. (eds), International Association of Hydrological Sciences, Wallingford, 53-62.

Temple P.H. **1965**, Some aspects of cirque distribution in the west-central Lake District, northern England. *Geografiska Annaler* 47, 185-193.

Thorp P.W **1981**, A trimline method for defining the upper limit of Loch Lomond Advance glaciers: examples from the Loch Leven and Glen Coe areas. *Scottish Journal of Geology* 17, 49-64.

Thorp P.W. **1986,** A mountain icefield of Loch Lomond Stadial age, western Grampians, Scotland. *Boreas* 15, 83-97.

Thorp P.W. **1991a,** Surface profiles and basal shear stresses of outlet glaciers from a Late-glacial mountain ice field in western Scotland. *Journal of Glaciology* 37, No 125, 77-88.

Thorp P.W. **1991b,** The glaciation and glacial deposits of the western Grampians. *In Glacial depostis in Great Britain and Ireland.* Ehlers J. and Gibbard P.L. (eds), Balkema, Rotterdam,137-149.

Tipping R.M. **1985,** Loch Lomond Stadial *Artemisia* pollen assemblages and Loch Lomond Readvance regional firn-line altitudes. *Quaternary Newsletter* 46, 1-11.

Tipping R.M. **1988,** The recognition or glacial retreat from palynological data: a review of recent work in the British Isles. *Journal of Quaternary Science 3, 171-182.*

Twigg D.R.**1998,** The global positioning system and its use for terrain mapping and monitoring. In *Landform Monitoring, Modelling and Analysis.* Lane S.N. amd Chandler J.H. (eds), John Wiley and Sons, Chichester, 37-61.

Twigg D.R. **2000,** Morphometry of glacial landforms of he ice marginal landsystem of Breidamerkurjökull and Kviarjökull, Iceland. *Modern & Ancient Ice-marginal Landsystems Symposium.*

Unwin D.J. **1973,** The distribution and orientation iof corries in northern Snowdonia, Wales. *Transactions of the Institute of British Geographers* 58, 85-97.

Vitek J., Giardino J. and Fitzgerald J. **1996**, Mapping geomorphology: A journey from paper maps, through computer mapping to GIS and virtual reality. *Geomorphology* 16, 233-259.

Walker M.J.C. **1995**, Climate changes in Europe during the last glacial-interglacial transition. *Quaternary International* 28, 63-76.

Walker M.J.C., Bjorck S., Lowe J.J. and Cwynar L.C. **1999**, Isotopic 'events' in the GRIP ice core: a stratotype for the Late Pleistocene. *Quaternary Science Reviews* 18, 1143-1150.

Walker M.J.C. and Lowe J.J. **1980**, Pollen analyses, radiocarbon dates and the deglaciation of Rannoch Moor, Scotland, following the Loch Lomond Advance. In *Timescales in Geomorphology*. Cullingford R.A. and Davidson D.A. (eds), John Wiley & Sons, Chichester, 247-259.

Wewetzer S.F.K. **1995**, A bathymetric resurvey of the Lake of Menteith. *Forth Naturalist and Historian* 18, 13-20.

Whittow J.B. **1977**, *Geology and scenery in Scotland*. Penguin books, Harmondsworth, England.

Wilson S.B. and Evans D.J.A. **2000**, Scottish Landform Example No. 24, Coire a' Cheud Chnoic, The hummocky moraine of Glen Torridon. *Scottish Geographical Journal* 116(2), 149-158.

Wise S.M. **1998**, The effect of GIS interpolation errors on the use of digital elevation models in geomorphometry. In *Landform Monitoring, Modelling and Analysis*. Lane S.N. and Richards K.S. (eds) John Wiley & Sons, Chichester, 139-164.

Wolf P.R. and Dewitt B.A. **2000**, *Elements of Photogrammetry*. McGraw-Hill, London.

Woodward J., Murray T. and McCaig A. **2002**, Formation and reorientation of structure in the surge-type glacier Kongsvegen, Svalbard. *Journal of Quaternary Science 17(3),* 201-209.

Wright H.E. **1989**, The amphi-atlantic distribution of the younger Dryas paleoclimatic oscillation. *Quaternary Science Reviews* 8, 295-306.

Appendix 1 Aerial photographs used

All aerial photographs were purchased from the Royal Commission for Ancient and Historical Monuments Scotland (RCAHMS). The aerial survey was carried out in 1988.

Study Site	No. of Photographs	Photo numbers
East Loch Lomond	6	51388 189 51388 190 51388 191 51488 049 51488 050 51488 051
Forth Valley	14	51288 127 51288 128 51288 129 51288 130 51288 233 51288 234 51288 235 51288 236 51488 091 51488 090 51488 089 51488 088 51288 232 51288 131
Torridon	4	62688 068 62688 069 62688 070 62688 071
Tyndrum	7	50988 090 50988 091 50988 092 50988 250 50988 251 50988 252 50988 253
Rannoch Moor	8	63688 233 63688 234 63688 235 63688 134 63688 135 63688 136 63688 137 63688 138

Appendix 2 Clast fabric eigenvalues

Torridon

Sample	S1	S2	S3
To1	0.435	0.407	0.158
To2	0.439	0.349	0.212
To3	0.473	0.346	0.181
To4	0.51	0.302	0.187
To5	0.707	0.166	0.127
To6	0.62	0.255	0.125
To7	0.461	0.376	0.163
To8	0.608	0.21	0.182
To9	0.605	0.219	0.176
To10	0.49	0.352	0.158
To11	0.574	0.331	0.095
To12	0.62	0.234	0.146
To13	0.544	0.345	0.11
To14	0.648	0.22	0.132
To15	0.546	0.34	0.114

Rannoch Moor

Sample	S1	S2	S3
R1	0.538	0.329	0.132
R2	0.524	0.296	0.18

Tyndrum and Strath Fillan

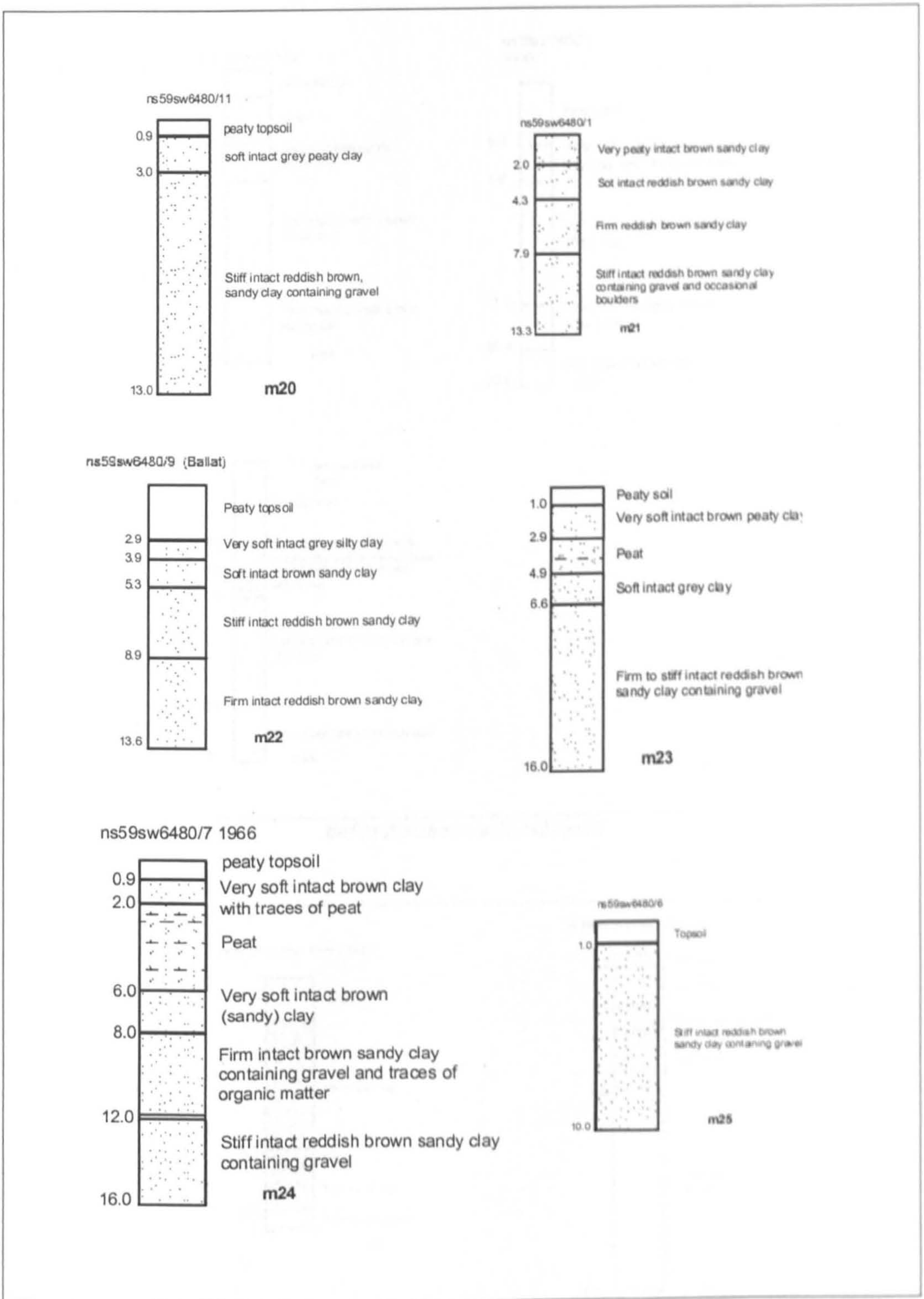
Sample	S1	S2	S3
Ty1	0.558	0.318	0.124
Ty2	0.485	0.352	0.163
Ty3	0.561	0.299	0.14
Ty6	0.514	0.324	0.161
Ty7	0.475	0.364	0.161
Ty8	0.486	0.331	0.183
Ty9	0.513	0.314	0.173
Ty10	0.562	0.288	0.15
Ty11	0.493	0.394	0.114
Ty12	0.536	0.315	0.149
Ty13	0.559	0.292	0.149

Appendix 3 Aerial triangulation RMS values

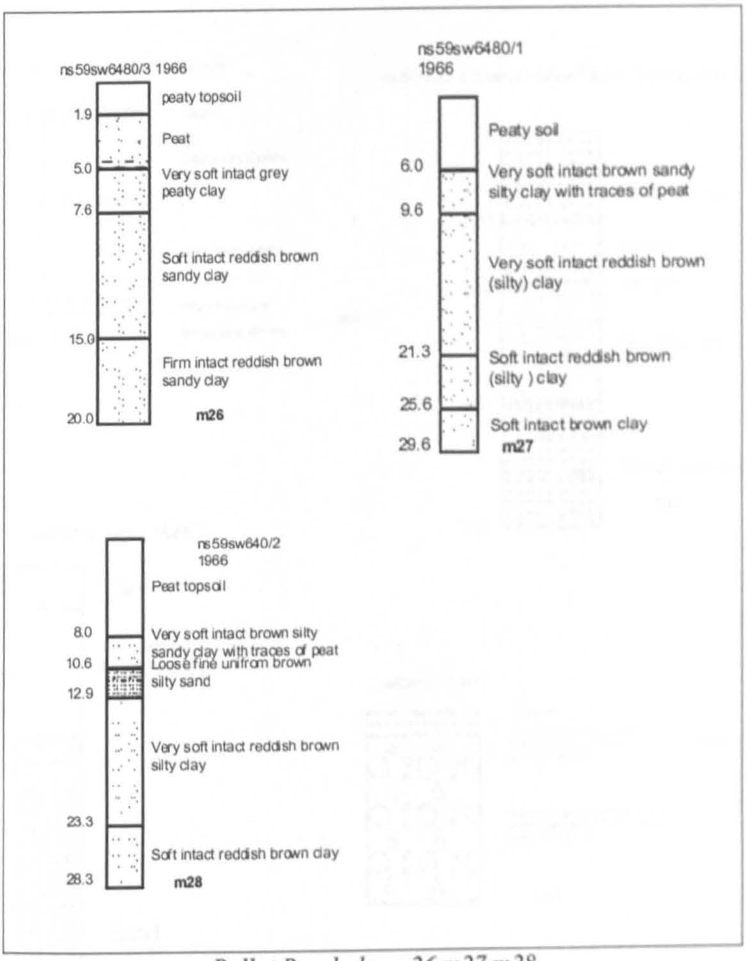
Root mean square error (RMS) values for aerial triangulation. RMS values are measured in pixels. RMS values for an accurate triangulation solution should not be significantly greater than 1 pixel.

Site	RMS (pixels)
Torridon	1.187
Rannoch Moor	data lost
Tyndrum	0.328
Upper Forth Valley	0.951
East Loch Lomond basin	0.855

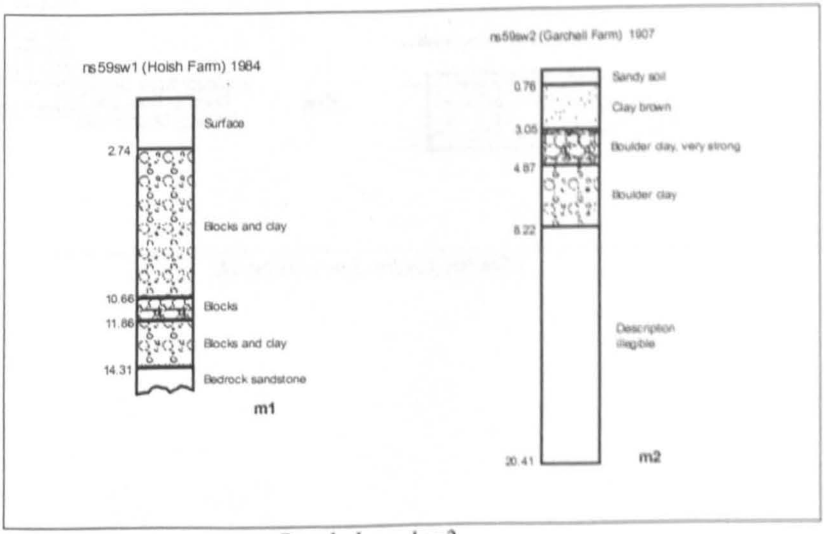
Appendix 4 Upper Forth Valley Borehole Records



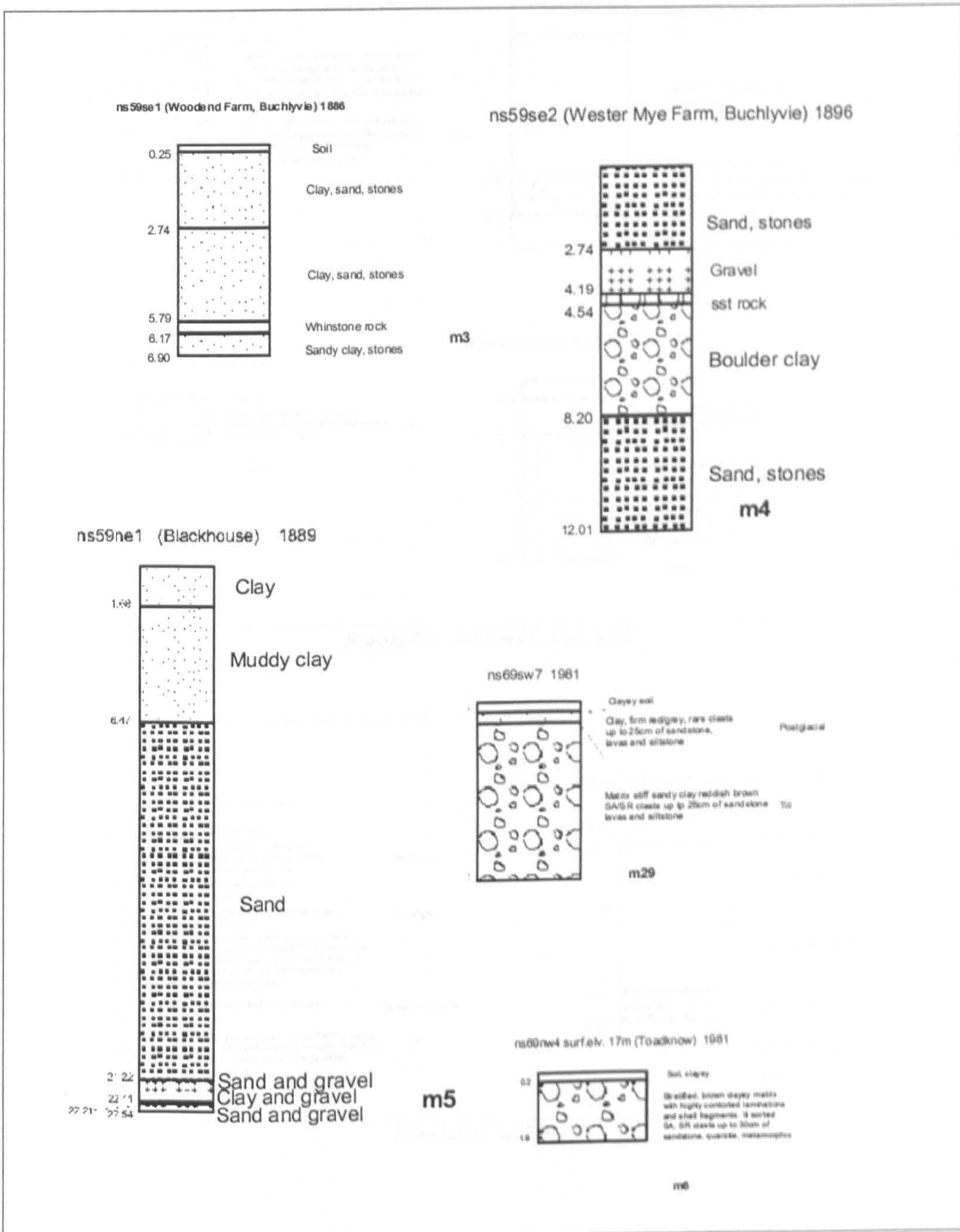
Boreholes m20,m21,m22,m23,m24,m25



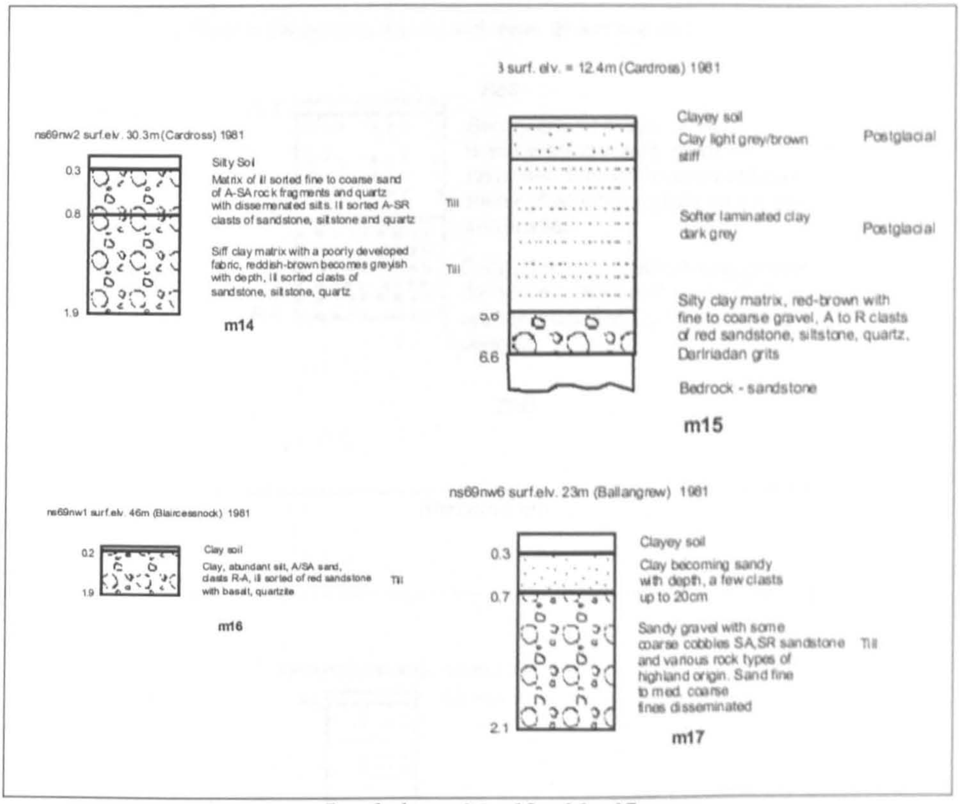
Ballat Boreholes m26,m27,m28



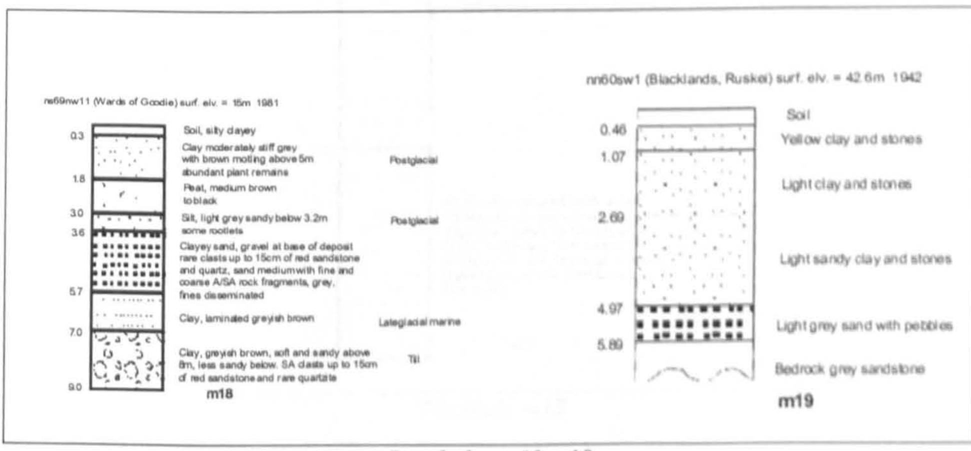
Boreholes m1,m2



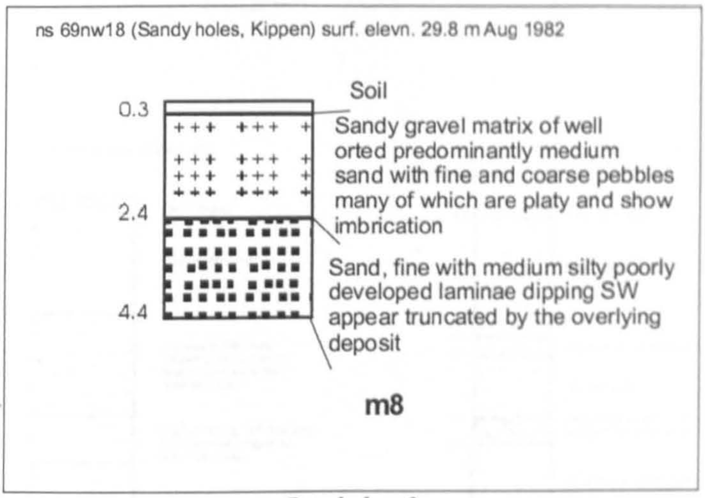
Boreholes m3,m4,m5,m6,m29



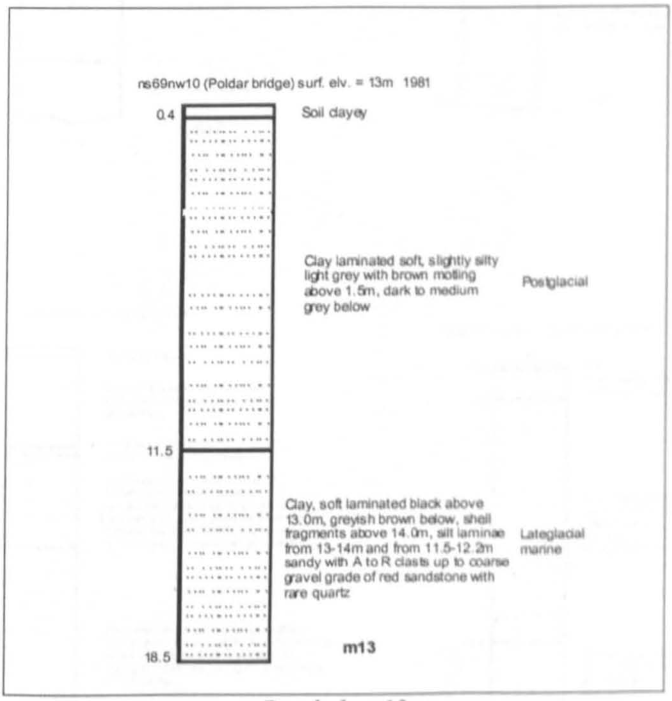
Boreholes m14,m15,m16,m17



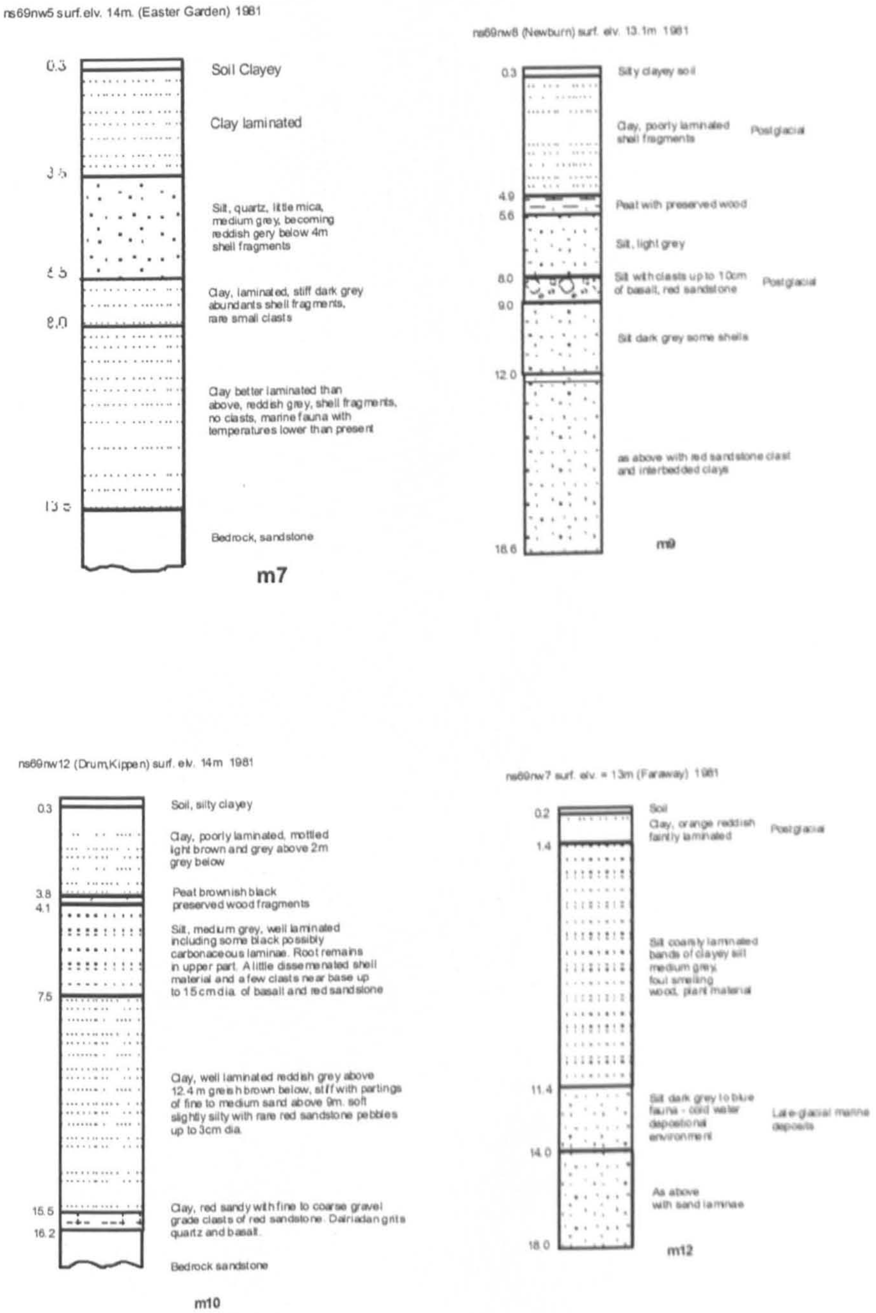
Boreholes m18,m19



Borehole m8



Borehole m13



Boreholes m7,m9,m10,m12