An holistic approach to mapping the Quaternary geology and reconstructing the last glaciation of West County Mayo, Ireland, using satellite remote sensing and 'conventional' mapping techniques

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An Holistic Approach to Mapping the Quaternary Geology and Reconstructing the Last Glaciation of West County Mayo, Ireland, Using Satellite Remote Sensing and 'Conventional' Mapping Techniques

Volume 1 of 2

by

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ABSTRACT

The Quaternary geology of West County Mayo, Ireland, has appeared in the literature over 30 times since Close's account in 1867. Various glacial reconstructions have been proposed due to i) the complex sedimentology and morphology of the area, ii) different approaches having been adopted by researchers, iii) models being tainted by theory-laden evidence as different glaciological concepts were in vogue at the time of publication.

Corroboration of existing information was undertaken in this research along with *de novo* mapping and identification of new data. An holistic approach was adopted, with 'conventional' mapping techniques integrated with digital image processing of satellite imagery. Over 2000km^2 were field-mapped where landforms such as drumlins, moraines, roche moutonnées, kames/kettle holes and eskers were recorded along with sedimentological data including till fabric analysis, deformation structure geometry, petrographic components, lithofacies etc. Radar (ERS-1) and optical multitemporal and multispectral Landsat-5 Thematic Mapper imagery were processed, evaluated and interpreted. Due to the absorption of H_2O molecules in soil and plants between 1.55-1.75μm, winter Landsat TM band 5 provided most information and was used for interpretation.

Geological information from conventional mapping and digital remote sensing were integrated using an inversion model. The landscape was spatially divided into assemblages of landforms and relative chronologies were determined by analysing cross-cutting landforms.

The data show that there was one ice mass with two 'domes' in the research area. The dome in Clew Bay had a north-south divide with ice flow towards the east in the eastern half of the bay and towards the west in the western half. The eastern margins of this dome diverted the Midlands ice to flow in a northerly direction. An older pattern of flow, towards the northwest, was recorded in the east of the area. The deposits indicate that a staged retreat occurred generally from north to south.

ACKNOWLEDGEMENTS

I must sincerely thank the Director and staff of the Geological Survey of Ireland for the provision of facilities and friendship. This gratitude is directed, in particular, to Dr. Willie Warren, head of the Quaternary Section. Apart from firing me 1278 times your encouragement was guaranteed and much appreciated! UCD was my acadamic base at the outset of the PhD and the successive Heads of Department deserve my gratitude for their support. Much credit is also due to the Director and staff of BGS for enabling me to continue this research with full use of its facilities.

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My family were extraordinary. Through thick and thin you've always there for me, not just for the PhD, but for everything in life. Your patience and fortitude always amazes me. Thank you.

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1 INTRODUCTION

This thesis was initiated as a pilot project within the Quaternary and Geotechnical Section of the Geological Survey of Ireland (GSI) in association with University College Dublin, to investigate the possible application of satellite remote sensing to Quaternary geology mapping and interpretation. A systematic mapping methodology has been developed within the GSI, and this research forms part of the long term objective of producing a more efficient mapping system incorporating digital mapping techniques such as satellite remote sensing.

The project involved mapping the Quaternary geology and geomorphology of 2010km^2 of west County Mayo in Western Ireland using the methodology adopted by the GSI. All existing data on the area were compiled and supplemented with detailed fieldwork and laboratory analyses. Moreover, it comprised scientific documentation and categorisation of all the sediments that were exposed, with the addition of drilling or trenching if sufficient outcrop did not exist. In addition to the location and description of the Quaternary deposits, areas where bedrock outcropped and where it existed within 1m of the surface were also delineated. A multidisciplinary approach was adopted to augment the GSI maps to include data relating to the environments of deposition and the directions of ice flow at the time of deposition.

An additional facet of the holistic approach undertaken was the use of satellite remote sensing and digital image processing to increase the speed of the mapping process, and also to increase the accuracy and the amount of data on the maps. Spatial accuracy increases were made possible by the fact that the image data was digitally geo-rectified to the Irish National Grid which precludes the use of hard copy map bases and problematic manual data transfer processes. Data amounts can be increased by a combination of the synoptic view afforded by the satellites which provide a new perspective for the geologist, and by the multispectral nature of the data which increases the amount of data available for interpretation over that provided by conventional fieldwork or aerial photography.

The reasons for undertaking this study were twofold. First, as part of a broad client base, Quaternary maps are required to produce groundwater vulnerability maps, which follow GSI guidelines (Daly & Warren, 1994). The demand for these has increased substantially since the enactment of the European Union Groundwater Directive (80/68/EEC) that aims to control the discharge of certain substances to groundwater. If this demand is to be met in a timely manner by the GSI, techniques such as satellite remote sensing had to be evaluated for their contribution to the mapping process. Second, it has been noted by Quaternary geologists working in Ireland that a full understanding of the geology of west Mayo is crucial in determining the form of glaciation that affected the island of Ireland as a whole (*e.g.* Close, 1867; Warren, 1992). For example, was Ireland affected by one large ice mass which spread from the north Midlands vis-à-vis the 'Great Central Snowfield' model (Hull, 1878) or was there a more complex pattern involving the convergence of at least two great ice sheets (Close, 1867)?

1.1 RESEARCH AIMS AND OBJECTIVES

There are two main aims driving this research:

1. to map the Quaternary geology of west Mayo (more than 2000km^2) using the GSI mapping system;
2. to enhance the maps by integrating the digital mapping technique of satellite remote sensing to produce a multidisciplinary yet holistic result.

Having produced the maps using a *tabula rasa* approach the sedimentology and morphological data will be impartially interpreted with the objective of re-evaluating the pre-existing, and conflicting, models / theories of glaciation in west Mayo by modelling the predicted patterns of ice sheet growth, flow, and decay.

The two main aims above have been sub-classified as follows:

1. the production of a Quaternary sediments map of west County Mayo using the Geological Survey of Ireland methodology;

2. the production of a geomorphological map of west Mayo from detailed fieldwork, aerial photography and the synoptic view obtained from orbital sensors, using a newly developed methodology;
3. the digital integration of the geomorphological and sedimentological data using computer aided drawing (CAD) and digital image processing (DIP) software packages;
4. analysis and interpretation of the integrated data to enable a model of glaciation to be formulated for the research area.

The objective of the project is to impartially model the glaciation of the area in an effort to test the existing hypotheses below which were defined by previous researchers, as outlined in Section 1.3.1:

1. A single ice mass produced the landforms in the study area. This ice mass flowed from the Midlands in a westerly direction across Mayo (arcing anti-clockwise around the Partry Mountains in the south and clockwise around Nephin in the north) to flow offshore through Clew Bay;
2. A single ice mass moulded the landforms as it progressed from the Midlands. The streamlined landforms in Clew Bay are not drumlins but are Rogen moraines, and therefore formed transverse to ice flow as it progressed in a northwesterly direction;
3. The research area was affected by more that one ice mass, one centred in the Midlands, and another centred in Connemara. An ice divide existed in Clew Bay (an extension of the Connemara dome) causing drumlins which are geographically close to have been formed by ice moving in differing directions;
4. The landforms in the area are the product of several non-contemporaneous glaciations.

1.2 STUDY AREA

1.2.1 Site and Situation

The study area for this thesis is situated on the western seaboard of Ireland (figure 1.1). It consists of over 2000km^2 of west County Mayo, bounded on the south by longitude 270000, to the north by longitude 310000, to the east by latitude 130000, and on the west by the Atlantic Ocean. The islands in Clew Bay (of which there are reputedly 365) are also included in the research.

The mapping area can be divided into a number of Ordnance Survey of Ireland (OSI) sheets of various scales. Fifteen 1:25,000 sheets were mapped; 08/27SW, 08/27SE, 08/27NW, 08/27NE, 08/29SW, 08/29SE, 08/29NW, 08/27NE, 11/29SW, 11/29SE, 11/29NW, 11/29NE, 11/27SW, 11/27NW & 11/27NE (Figure 1.2). Each of these maps covers an area of 15 by 10km. This research area corresponds to 1:50,000 Sheet 31 and portions of 1:50,000 Sheets 30, 37 and 38 of the OSI Discovery Series.

1.2.2 Physiography

This section contains a short summary of the physiography of the study area. The topography of the research area can be divided into three main regions, a northern region, a southern region and a central region.

1. The northern region comprises the highlands of the Nephin Beg Range which consists of the peaks and ridges of Claggan (383m), Glennamong (628m), Bengorm (582m), Buckoogh (588m), Birreencorragh (698m) and Nephin (806m). These mountains are separated from Loughs Conn and Cullen to the east by Glen Nephin, while to the west there is an area of lowland lying at 40m (MSL) stretching to the sea at Blacksod Bay. The highlands are underlain by Dalradian rocks.
2. The southern region is also a mountainous one, dominated by Croagh Patrick (764m), Mweelrea Mountain (803m), the Sheeffry Hills (762m), and Partry Mountain (391m). Several large glaciated valleys dissect this region, radiating

towards the northeast (Glen Erriff and Carrowbeg River Valley) and the northwest (Doo Lough Pass and Bunowen River Valley) from the centre of the mountain range. The area is underlain by Silurian and Ordovician rocks.

3. While the first two regions are mountainous, and are underlain by more resistant rocks, the third area consists of lower-lying topography underlain by Lower Carboniferous Limestone. It forms the Plains of Mayo on land and the offshore basin that is Clew Bay. This region is dominated by Quaternary landforms, including the much-cited drumlins. The interdrumlin zones are generally poorly drained and contain either boggy areas or lakes. This region is situated at the head of Clew Bay and continues inland to the Midlands with a mean altitude of 55m MSL. Only one more-elevated zone occurs in this region, at Sraheens where Upper Carboniferous Avonian shales and sandstones rise above the surrounding terrain to 262m MSL.

The physiography of pre-Quaternary ridges and valleys provided preferential route-ways for the ice, which covered the area at times in the Quaternary Period.

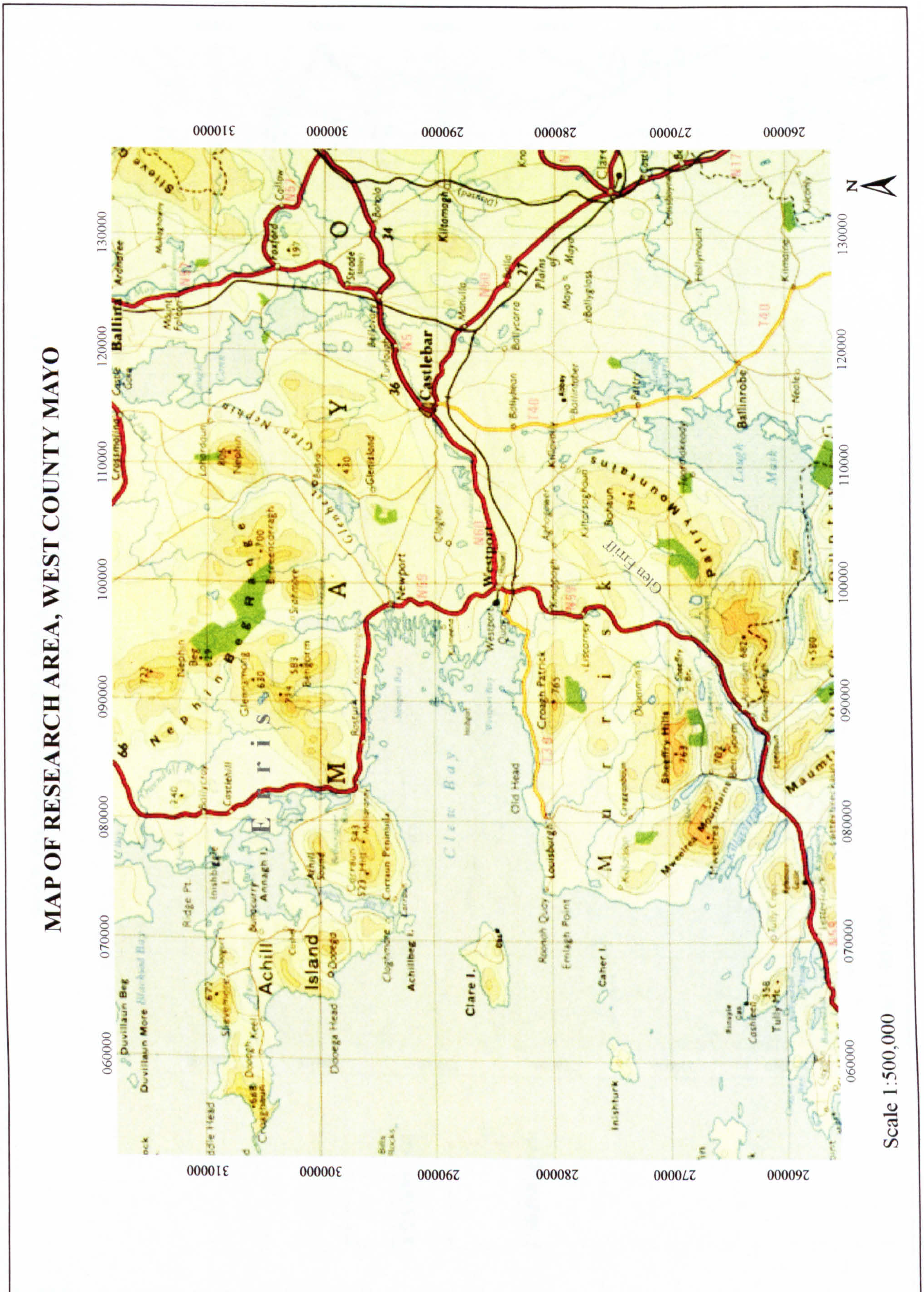

Figure 1.1. Map of research area, west County Mayo. (Adapted from the Atlas of Ireland, 1979)

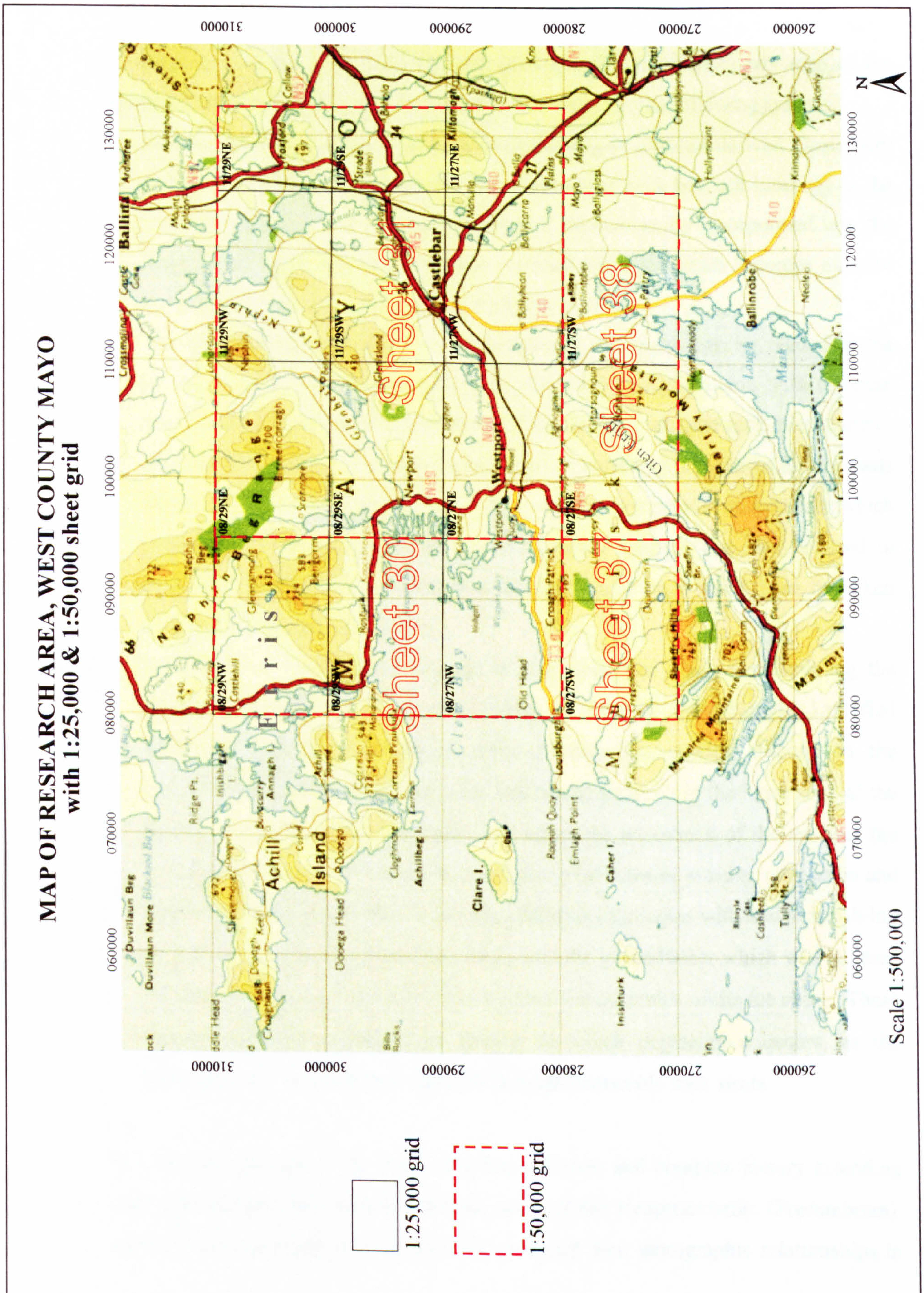

Figure 1.2 Location map of the research area showing index to 1:50,000 and 1:25,000 sheets

1.2.3 Bedrock Geology of the Study Area

A description of the underlying bedrock geology must accompany any map of the Quaternary geology and model of glaciation of an area for the following reasons.

1. Correlations between the source bedrock lithologies and the derived Quaternary sediments can be drawn in terms of the response of each bedrock lithology to the overriding ice, *i.e.* will the rock shatter and become easily incorporated into the basal layers of the ice, or is it a more resistant lithology which becomes rounded and smoothed by the overriding ice, with less erosion.
2. The geotechnical properties of the Quaternary sediments can be related to the parent material, *i.e.* limestone bedrock will produce a diamicton with different geotechnical properties to that produced from another rock type such as sandstone.
3. The directions of ice flow can be determined by locating provenances for the clasts within the Quaternary sediments. As well as provenance information which provides ice flow direction data, a petrographic analysis can also be used to determine whether the sediment was derived locally or if it had been reworked from a previous glacial episode.
4. Knowledge of the bedrock geology is also important when reconstructing the hydrological dynamics in the basal layers of the ice. For example, karstified limestone will allow subglacial water to percolate quickly through to the groundwater, which will decrease the hydrostatic pressure in the basal zone of the glacier. This reduction in pressure will affect the movement of the ice over the bedrock substrate, and consequently influence the rates of erosion, deposition and deformation (Hooke, 1998). In contrast, bedrock lithologies with low permeability rates will not allow water to drain freely into the groundwater which will increase the amount of basal sliding and thereby alter the dynamics of the ice sheet. These factors will also influence the fashion in which deglaciation occurs, as the meltwater will dissipate more quickly through permeable rock strata.

The bedrock geology of the study area has a diverse and complex history extending back 750 million years to the Dalradian rocks of the Neoproterozoic (Precambrian). Rather than describing each of the rock types and their stratigraphic relationships in great detail, a summary will be presented here to accompany Figures 1.3 and 1.4 and the published bedrock maps of the area (Leake & Tanner, 1994; Leake *et al.* 1981; Long et al. 1992; Long & McConnell, 1995; Max *et al.* 1992; Morris *et al.* 1995). More detailed descriptions of the bedrock geology, with reference to the local Quaternary geology accompany the descriptions of each 1:25,000 mapping sheet (Jordan, 1997b,c,d). Also, rather then becoming embroiled in the multiplicity of formation and unit names, the summary describes the spatial extent of generalised lithologies as this is the context which is most important to the Quaternary geologist for the reasons explained above.

The oldest rocks in the study area date to the pre-Dalradian, older than 750 million years ago, and consist of the pelitic and semi-pelitic schists of the Kinrovar Schists which belong to the Inishkea Division of the Grampian Group. As the area these rocks cover is too small to be shown in Figure 1.3, they have been combined within the Dalradian schist and gneiss classification. The Dalradian Supergroup comprises most of the metamorphic rocks of the study area, which in turn are included in a zone of metamorphics which continue through Tyrone and Antrim into Scotland (Long *et al.* 1995).

As can be seen from Figure 1.3, these metamorphics dominate the northern half of the study area encompassing Achill Island, Corraun, the Nephin Beg Range and extending in a band towards the northeast enclosing the Ox Mountains at Foxford. There are also localities where the age of the rocks is cited as Dubiously Dalradian, or possibly Cambro-Ordovician age (Long *et al.* 1992). Those of Dubiously Dalradian age are the Westport Grits (from the Formation of the same name, WG on Fig. 1.4) which are located to the southeast of Westport town.

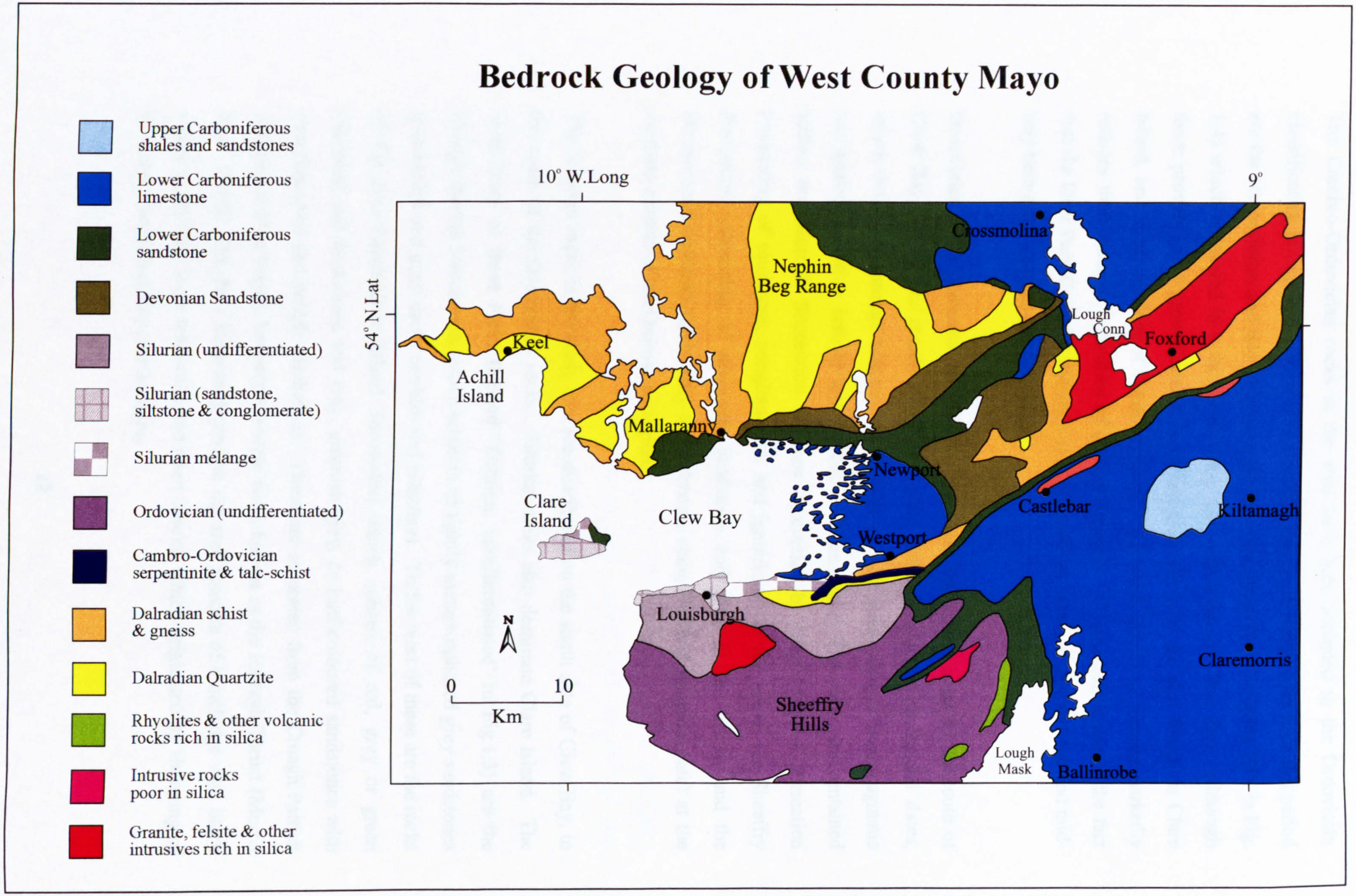

Figure 1.3. Bedrock geology of West County Mayo, compiled from Leake *et al.* (1981) Long & McConnell (1995) and Max *et al.* (1992).

The Cambro-Ordovician rocks in the area have been included in the Ordovician classification in Figure 1.3 to avoid cluttering. The noteworthy rocks from this period are the serpentinites and talc-carbonate schists of the Deer Park Complex (DX in Fig. 1.4) which is located in a thin band along the south coast of Clew Bay. Although these provide good provenance, it is unfortunate that they are also found on Clare Island, and in the vicinity of Westport town. This wide spread of sources markedly reduces their value as indicators of glacier transport. Compounding this is the fact that the Deer Park Complex outcrops in other isolated localities at Castlebar and mid-way between Castlebar and Newport.

Ordovician rocks dominate the Sheeffry Hills and the upland areas to the south of Clew Bay. The rocks consist of pillow lavas, tuffs, greywackes, shales and slates, which developed through volcanic arc \ island arc volcanism, deeper level magmatic arc igneous intrusive activity and oceanic sedimentation. The rocks are contained within the Murrisk Succession and are dominated by the Mweelrea Formation (consisting of sandstone, conglomerate, and ignimbrite) to the south, the Sheeffry Formation (consisting of mudrock, sandstone and tuff) in the centre, and the Derrymore Formation (consisting of sandstone, slate, tuff and conglomerate) at the northern extents of the Ordovician region.

The Silurian rocks in the study area are distributed on the south side of Clew Bay, to the north of the Ordovician rocks. Silurian rocks also dominate Clare Island. The main body of these rocks (termed 'Silurian, undifferentiated' in Fig.1.3) are the Croagh Patrick Succession, which consists of lightly metamorphosed grey sandstones (psammites and quartzites), marbles and siltstones. To the west of these are the rocks of the Louisburgh-Clare Island Succession which consist of red, grey or green siltstones and mudstones and grey, greenish-grey, or buff-coloured sandstones with conglomerates and pebbly sandstones. These are separated from the Croagh Patrick Succession by a major, low-angle reverse fault, known as the Emlagh Thrust (Morris *et al.* 1995). The final Silurian deposit in the area consists of a mélange with black shales containing large sandstone and chert blocks, which originated by slumping of sediments on an unstable marine slope.

The end of the Silurian and the beginning of the Devonian was marked by the intrusions of granite batholiths and satellite plutons. This time (the Caledonian) was a period of orogeny, and, as some rocks were pushed up to form mountains, others were simultaneously forced down to depths where they melted to rise upwards again under new buoyancy to be intruded into the upper crust where they cooled to form various types of granite. The two regions in this study area that experienced this intrusive deposition are the Corvock granite pluton south of Louisburgh and the larger area of granite which extends to the northeast from Lough Cullin past the town of Foxford, and comprises the Ox Mountains.

Sandstones in the study area have been dated to both the Devonian and Carboniferous Periods. The Devonian (Old Red) sandstones were laid down during a period when this part of Ireland was experiencing an arid climate with periodic torrential rainfall producing ephemeral rivers and lakes. The sediment was eroded from the Caledonian mountains and the coarser material was deposited in proximal situations as alluvial fans close to the mountains, while the finer sediments were laid down in distal environments as sand or mud as sheets on the plains or in the ephemeral lakes (Morris *et al.* 1995). The Carboniferous sandstones, on the other hand, were deposited during the inundation of shallow tropical seas. Most of these sediments in the mapping area were deposited by rivers on coastal plains, and consist predominantly of grey sandstones and siltstones.

Another large body of rocks deposited in the Carboniferous Period are the various limestone formations ranging from the Rockfleet Bay Limestone and Lough Akeel oolite at the head of Clew Bay to the Castlebar River and Aille limestones further inland. These rocks include dark fine limestones and shales, sandy oolites and calciferous shales. The deposition of these lithologies marks another environmental change for the area. During this period there was a change to marine conditions, with deposition on the landward side of a carbonate shelf. As one moves up through the strata, the limestones become cleaner, and shales decrease, culminating in the sandy oolites which represent an episode of delta building, perhaps to the northwest (Long & McConnell, 1995).

In the Tertiary Period dykes of various forms of dolerite and gabbro were intruded. These relate to the opening of the Atlantic Ocean in late Cretaceous and early Tertiary times (Long *et al.* 1992). They are located in a southwest-northeast trending line that runs through the town of Castlebar.

From this brief summary of the bedrock geology of the study area it is clear that there is a large diversity in rocks in the region, both in terms of their ages, their lithologies and their distribution. Although this complexity complicates the field mapping process (as there is more variability to map per square kilometre) it would suggest a higher likelihood of locating trains of erratic carriage through boulder sampling or through petrographic analysis of the tills and gravels.

One limiting factor regarding the bedrock geology of the study area is the lack of knowledge relating to the rocks beneath Clew Bay itself. The fault lines located on the mainland have been traced to islands such as Clare Island and Achill Island, and features such as bedding, dip and folding enable the geologist to predict the extent and distribution of the formations where there are no exposures. However, in areas where there are no outcrops (such as beneath Clew Bay) the map "..is at best an intelligent guess." (Long *et al.*, 1992, p.4). Figure 1.4 illustrates a generalised pattern of faults which is predicted to run through Clew Bay, along with the distribution of Precambrian and Lower Palaeozoic rock units on the land, however there are no real suggestions regarding the bedrock geology in the bay. For example, does the Louisburgh-Clare Island Succession of Silurian rocks link up beneath the Atlantic Ocean, or are they divided by another group of rocks? A series of faults would be expected to run in a generally north-south direction, thereby offsetting those indicated in Figure 1.4 resulting in a far more complex pattern of geology, but as there is no direct evidence for these, they have been omitted (C B Long, *pers comm.* 1998). These gaps in understanding may prove problematic when attempting to locate the provenances of some of the clasts in some of the Quaternary sediments.

PRE-DALRADIAN or DALRADIAN

IR	Kinrovar Schist

DALRADIAN

D1	Bangor Succession
D2	East Achill - North Corraun Succession
D3	South Corraun - West Nephin Beg Succession
D4	East Nephin Beg Succession
D5	Raheen Barr Succession (equivalent to D4)
D6	Ox Mountains Succession

DUBIOUSLY DALRADIAN

OD & SC	Ooghnadarve & South Carrowgarve Formations
CS	Callow Succession (Lower Lismoran, Callow & Upper Lismoran Formations)
WG, AR	Westport Grit Formation, Ardvarney Formation, Cloonygowan Formation (CG)

Faulted contact

Faulted contact (hidden, conjectural)

Thrust or slide

CAMBRO - ORDOVICIAN

AB	South Achillbeg Formation (also Bills Rocks Formation)
DX	Deer Park Complex & Deer Park Schist Formation, plus fragmented components in Ox Mountains Inlier
FN	Farnacht Formation

ORDOVICIAN

LE	Letter Formation

SILURIAN

BA	Ballytoohy Formation	Mélange
PR	Portruckagh Formation	
KI	Killadangan Formation	
S1	Louisburgh - Clare Island Succession	
S2	Croagh Patrick Succession	

South Achill Steep Belt (inset)

Claggan Bay Mylonite Zone (inset)

dextral mylonite zone (inset)

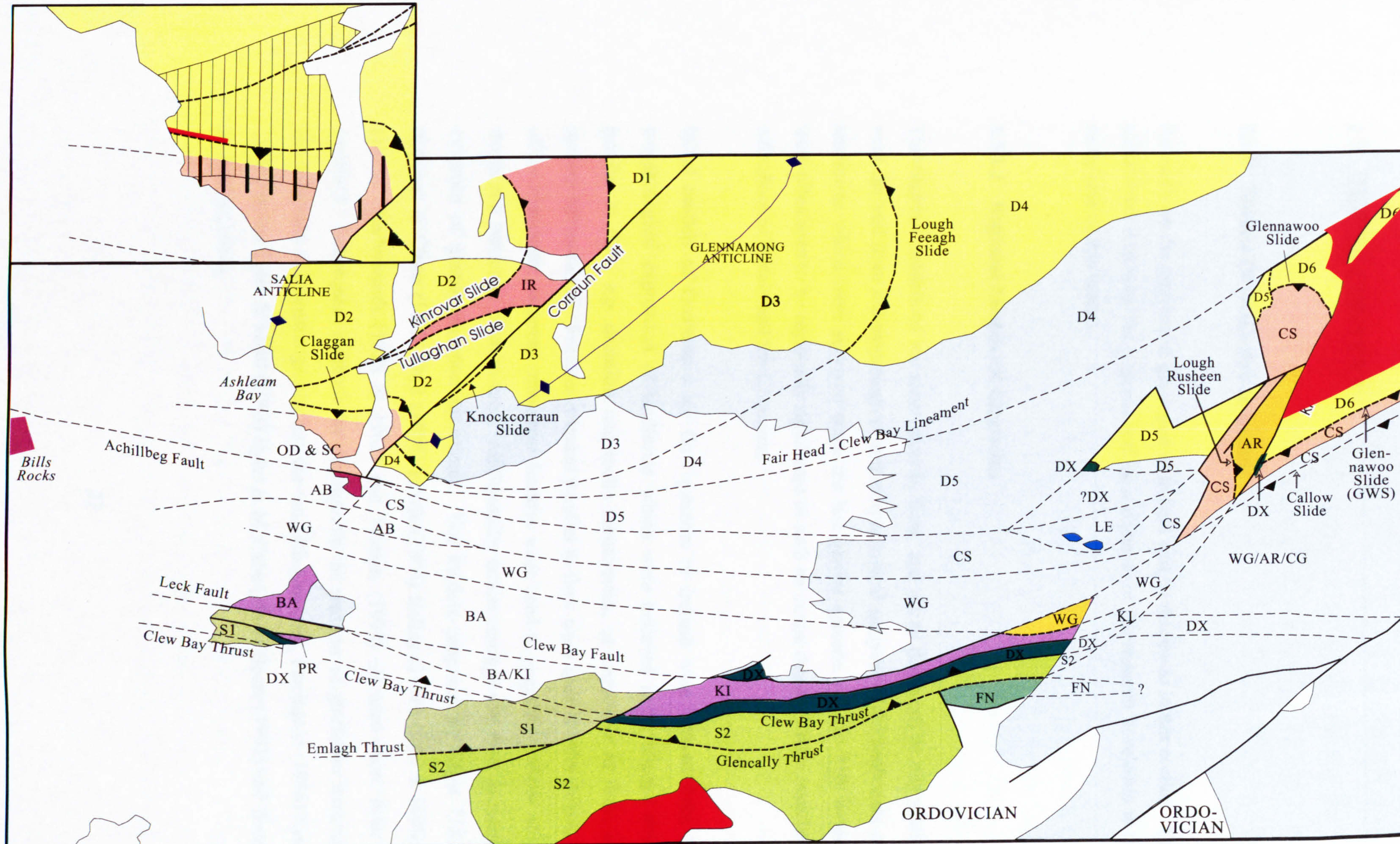

Figure 1.4
An interpretation of the distribution of Precambrian and Lower Palaeozoic rock units and major structures in the Clew Bay region (From Long *et al.* 1995)

1.3 THESIS CONTEXT

1.3.1 Models Of Glaciation In Ireland

Research on the patterns of glaciation in Ireland will be discussed in this section. The subsections deal with the regional and local contexts of the research in relation to the study area of this thesis.

1.3.1.1 Regional Models Of Glaciation

The regional models of ice sheet growth, flow, and decay discussed in this section were derived from sedimentological and morphological analyses of the sediments and landforms which have survived since the last glacial episode. These Irish models were often seen to be regionally significant to such an extent that they were correlated with those of Britain and the Continent.

Initial models of Quaternary ice flow patterns in Ireland were derived from the morphological expression of landforms which were believed to be aligned either parallel to flow, *e.g.* drumlins and roche moutonnées, or transverse to flow, *e.g.* recessional moraines. Features oriented parallel to flow were used to infer directions of ice movement, whereas transverse features were used to suggest locations of ice fronts at a particular point in time. Additionally, erratic carriage was used to provide evidence of glacial transport directions. The models proposed by Close (1867) Kinahan & Close (1872) Hull (1878) Lewis (1894) Sollas (1896) Cole & Hallissy (1914) Charlesworth (1928 & 1963) and Warren (1992) all used these lines of evidence. Subsequent methods for determining the patterns of glaciation integrated the technique of lithostratigraphy into the modelling process, Farrington (1966) Synge (1969) Eyles, Eyles & Miall (1983) Eyles & McCabe (1991) Hoare (1991) and Warren & Ashley (1994).

The first model, produced by Close (1867) introduced the term drumlin to the scientific literature, as a landform whose shape can be used as a direct indicator of the direction of ice flow. Using this premise, Close (1867) published a small scale map of Ireland outlining overall patterns of ice movement derived from drumlin long axes, striae orientation and the direction of glacially transported erratics. This model recognised a complex pattern of ice movement in the northwest and west Midlands and he interpreted this as the result of the convergence of at least two great ice sheets, one centred in the west of Ireland, and the other in the north Midlands. According to Warren (1992) a crucial region in the model is in County Mayo, the study area for this thesis, as it is the proposed location of a convergence zone between two ice masses and, as such, merits further study. The patterns suggested in Close's model were corroborated by studies carried out by Kinahan & Close (1872), Kinahan *et al.* (1876) and Symes *et al.* (1880).

However, the data (consisting of striae, roche moutonnées, and erratic carriage) were reinterpreted and later researchers altered this model. The source of the alteration originated from Hull's (1878) work which proposed a simpler model involving a single large ice mass which extended towards the southwest from Lough Neagh into the north Midlands and west central Ireland, along with a smaller snowfield in Connemara (Figure 1.5 A). Furthermore, it was suggested that this 'Great Central Snowfield' acted as the single source from which the ice radiated to cover all of Ireland, excepting the marginal mountain ice caps, so that *"..moving in a stately, unbroken stream it [the ice] moved along till it entered the lap of the ocean, in which its wanderings had their natural and peaceful end*" (p.227). An interesting point to note is that Hull claimed that the 'Great Central Snowfield' model followed Close's work of 1865, although with a much-simplified pattern of ice development and movement. It has been suggested that Hull's claim of following Close's hypothesis may have influenced others to follow the altered model more readily (Warren, 1992).

Most subsequent work has been based on, or assumed the general applicability of, Hull's model of 1878, while Close's model of 1867 was largely forgotten. The major consequence of this for subsequent Irish Quaternary studies was immense as all ensuing studies and models were based on the concept of a single country-sized ice sheet which formed large continuous end moraines, often the width of Ireland, such as the Southern Irish End Moraine (SIEM) as 'recognised' by Lewis (1894). Likewise, models of deglaciation were equally simplified with a pattern of ice retreat from south to north across the country returning to the source in the Great Central Snowfield (Charlesworth, 1963 and Synge, 1970, 1977, 1979).

Charlesworth (1928, 1929) made some alterations to Hull's model, including the addition of several local ice caps in the mountainous regions of Cork, Kerry and Wicklow, thereby suggesting that all of Ireland was not covered by a single ice mass at the same time. Of equal importance, Charlesworth recognised that the topography south of the SIEM was more subdued than that to the north, and surmised that the southern 'drift' of Munster must be stratigraphically older. His subsequent correlation of this stratigraphy with events in England was taken further by Synge (1963) who linked the major end moraines of Ireland to those in the UK and correlated them with the esker chains to propose a rapidly retreating ice front.

More recently, McCabe & Hoare (1978) employed lithostratigraphy in east central Ireland and supported the Hull model of retreat northwards to a single source. A similar lithostratigraphic approach was adopted by Coxon & Browne (1991) in central and western Ireland, who reached similar conclusions to those of McCabe and Hoare thirteen years previously. They named the two last glaciations the Munsterian and the Midlandian and identified a single northern ice dome as the source for both of these.

More recently still, Warren (1991 & 1992) has advocated a return to the more complex pattern of multiple ice masses proposed by Close (1867). This model postulates that several synchronous ice domes affected the Irish landmass. Using drumlin alignment, striae orientation and erratic distribution (as did Close, 1867, albeit with a much enlarged database) ice sheet flowlines were produced which show where the domes converged, and from where they originated. This model was developed further when the spatial extents of, and interactions between, the domes were studied (Warren & Ashley, 1994). The authors identified four domes, three on land, and a fourth off the east coast:

1. northern dome, affecting Ulster and the north Midlands;

2. central dome, affecting the central and southern Midlands and the western coastal regions;
3. southern dome, affecting Counties Cork and Kerry;
4. Irish Sea lobe, which covered the Irish Sea basin.

In this paper, Warren and Ashley studied the ridged landforms (*i.e.* 'eskers') of Ireland using analyses of lithofacies, sedimentary structures and palaeocurrent data in conjunction with the geomorphology to reconstruct the deglacial history. Their analyses showed that the traditional model of systematic ice retreat from south to north, towards the source of the 'Great Central Snowfield' is not compatible with the data. A new model is postulated where the ice fronts retreated back towards their respective domes of origin thereby producing subaerial and subaqueous glaciofluvial deposition in the intervening spaces that opened up. A comparison of the two models can be seen in Figure 1.5 (Warren & Ashley, 1994).

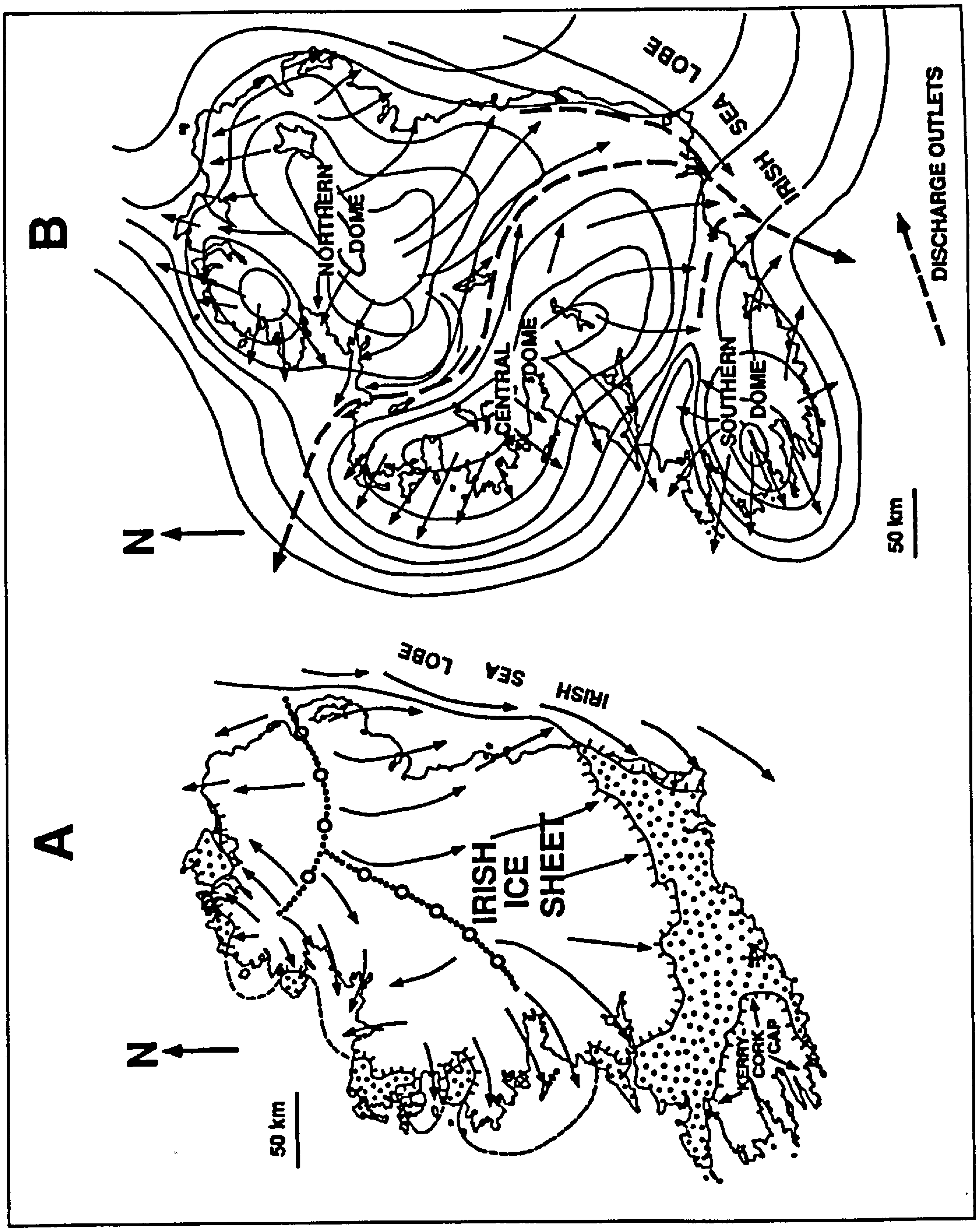

Figure 1.5 Comparison of the models for the most recent Irish glaciation. A) Great Central Snowfield model. B) Model comprising several synchronous ice domes.

(After Warren & Ashley, 1994).

1.3.1.2 Local Models of Glaciation

The section above summarises the development and composition of models for the glaciation of the island of Ireland in general. Here, proposed models will be reviewed in more detail, specifically the ice flow patterns in the west Mayo (Clew Bay) area.

The models will be dealt with in chronological order, starting with that described at length by Close (1867). Beginning in the east, in the area stretching from Lough Mask to Lough Conn (and beyond, to Killala), Close had no doubt that the ice flowed from south to north. This interpretation was derived from morphology, erratic drift carriage and 'numerous rock scorings'. The ridges in the area of Newport proved more of a puzzle. Close notes the cover of sandstone till on these drumlins and although he states that *'..it might seem at first most reasonable to think that that drift came from the sandstone ground above the head of the bay'* (Close, 1867, p.222) *i.e.* formed by an ice stream flowing offshore towards the southwest, he concludes that it is more probable that they were produced by ice which flowed onshore from the Atlantic towards the east which subsequently turned towards the north to join with the northward flowing stream progressing from Lough Mask to Killala Bay.

Furthermore, Close reports that there are numerous striae and roche moutonnées two miles east of Westport which at first may suggest that the northward flowing ice stream turned west and flowed out of the bay, but which in fact crossed the head of the bay and continued northwards without deviating from its course to flow offshore. In this situation he has no real evidence to support his hypothesis that ice flowed onshore at Westport apart from his interpretation of the drumlin morphology. Close supports his proposal by stating that there is no evidence to the contrary. The fact that the upper diamicton at the head of the bay is dominated by sandstone clasts presented no difficulty for Close's interpretation as he states that it exists on both sides of the mouth of Clew Bay, on Clare Island and *'..no doubt extends across (the bay) beneath the water'* (p.222) providing a large range of sources for this rock type.

Kinahan and Close (1872) altered this model and added a further complication. They identify ice flowing in a northerly direction from Connemara curving around the east side of Croagh Patrick and then flowing towards the west. It was proposed, however, that while ice flowed towards the west in the southern half of the bay, it simultaneously flowed in the opposite direction in the northern half of the bay, and extended in a northeasterly direction to merge with the ice flowing in a northwardly direction from the Midlands. It seems strange that one of the two co-authors, Close, would complicate a working model he himself proposed five years earlier. The new evidence for the turnabout is as follows.

- In the mountains to the north of the bay, all the lines of evidence pointed to ice flowing towards the north. This comprised Coolnabinnia, Lough Feeagh and Bellacragher Bay which served as passes for the ice streams to flow in a northerly direction, with corroborating evidence in the form of south-north striae at 1,100ft OD on Tristia, at 1,200ft on Buckoogh and similarly at an unspecified altitude on Corraun. Northward flowing ice was also evident by the distribution of red sandstone boulders.
- The authors found blocks of sandstone and metamorphic rock from the southeast in the drumlins situated on limestone ground in the area around Westport. An interesting point to note is that in his previous paper, Close stated that a definitive provenance could not be found for these boulders due to the distribution of bedrock lithologies in the area. Also, in the area around Louisburgh the authors recorded the presence of granite clasts that originated from the southeast.

Offering an interpretation of these data, the authors reaffirmed that ice moved towards the northeast in the area of Newport at the head of the bay where it met ice flowing northwards from the head of Lough Mask, as no new evidence had been uncovered to alter Close's previous pattern in that area. However, the newly acquired provenance for the clasts at Westport indicated that ice must have flowed over the site of Westport from the southeast, into Clew Bay, curving in the wake of Croagh Patrick to hug its lee side and flow towards the northwest.

As the ice expanded towards the north it flowed against the mountains at the north of the bay and was compelled to flow northeastwards at Newport. Accounting for the fact that this would require an additional barrier to stop the ice following the current gradient of the land and flowing offshore towards the west, the authors postulated the existence of an ice mass to the west. This would have grown as it preferentially received the snowfall carried on the prevailing southwesterly winds, depriving the remainder of the area of its accumulation rate. No hard data was presented to support this theory apart from the presence of a southwesterly prevailing wind at the time of writing.

The subsequent model, proposed by Hull (1878) has already been described as a much-simplified version of Close's work. The pattern can be seen in part A of Figure 1.5. This model entails ice flow from a dispersion centre in the west Midlands (part of the Great Central Snowfield) with the pattern of ice flow towards the west out of Clew Bay, following the present gradient of the land. It is interesting to note that in his work that Hull (1878) states that "*the westward movement of the ice along the shores of Clew Bay, and outwards into the Atlantic along the western coasts of Mayo, have been determined by the officers of the Geological Survey*" (p.241).

Hull uses evidence from Old Head which is on the western extremities on the south shore of the bay, stating that the bedrock surfaces are 'well glaciated' by ice which flowed from east to west at this location. His lack of data is also apparent from the map that accompanies his paper where directional indicators at Old Head and Corraun are the only two evident in the vicinity of Clew Bay. By using evidence from these locations only, and by ignoring the complex striae, morphology and nature of the sediments at the head of the bay which were studied by the previous authors, Hull is able to make the bold statement that ice flowed towards the west, offshore, through Clew Bay. As a result of this presentation of the data, most of the models which follow, and are based on, Hull's work advocate ice flow towards the west, out of Clew Bay.

By 1914 the GSI memoirs, covering west county Mayo and Clare Island, were published (Cole *et al.*, 1914). The author of the Quaternary geology section (Hallissy) was a proponent of Hull's 'Great Central Snowfield' theory stating that "*an Irish snow-field occupying an axis running north-east and south-west, and extending to the* *south of the Ox Mountain range contributed to the prevailing mer de glace*" (p.29). Hallissy uses morphology, striae and erratic carriage and the petrographic components of the tills to formulate his theory on the glaciation of the Clew Bay area. His model is twofold.

1. Ice from the Great Central Snowfield extended in a westerly direction across County Mayo and exited through Clew Bay, past Clare Island. This is attested to by the 'excellent east and west striations' in the area around Newport and the similarly aligned drumlin long axes in the area.
2. At a later period, the Great Central Snowfield was invaded by a local glacier from Connemara. When the local ice mass gained dominance it proceeded northwards over Mayo and realigned all the landforms in the lowlands around Castlebar. The drumlins in Clew Bay, however, were sheltered by Croagh Patrick and remained orientated towards the west. Hallissy used the existence of the upper till as evidence for the advance of a second glacier in the area, referring specifically to the erratic train of granite boulders from Corvockbrock to Louisburgh which overlie the local till and to the two facies at Roonah Point. He states that the lower till was formed by ice flowing from east to west, while the upper was formed by ice flowing towards the northwest.

Where Hallissy falls short in his interpretation is that he lacks ice flow direction data from the head of Clew Bay, having to extrapolate from the mouth of the bay. Also, he is forced to use the concept of Croagh Patrick as a shield to stop the drumlin realignment in the bay by the later ice mass flowing from south to north. While quoting his own pattern as "*the more obvious explanation*" (p.33) for the glaciation of the area he denounces the onshore ice flow pattern proposed by Kinahan & Close (1872) under the auspices of Occam's razor. In truth, Hallissy's offshore ice flow patterns for the head of the bay are determined by two sets of striae, which although capable of providing an axis of flow, cannot be fully relied upon to provide a resultant vector. However, Hallissy must be acknowledged for attempting to explain the complex morphology of the drumlins at the head of Clew Bay and also for recognising and explaining the two till facies present in those drumlins.

In 1929 Charlesworth presented a paper on the glacial retreat in Connemara, encompassing the southern half of Clew Bay. He modelled the pattern of glaciation and deglaciation using striae and moraine alignments and determined that there was an ice mass centred in Connemara which extended radially in all directions through a system of powerful glaciers which proceeded down the valleys. In his assessment the ice flowed towards the northeast at Lough Mask, northwards towards Clew Bay, and towards the northwest in the Louisburgh area. He avoided discussing the pattern of ice movements in Clew Bay and did not include any striae from the area on his accompanying map.

Synge & Stephens (1960) wrote a summary of the thoughts on the Quaternary period in Ireland at that time. Accompanying maps indicate ice flowing from south to north from Lough Mask, and then it arcs towards the west, around Croagh Patrick and flows west out of Clew Bay. In the north of the bay the ice is shown to flow in a westerly direction. As with the previous studies, an ice mass is shown extending in a radial pattern from Connemara. The same evidence was interpreted in the same manner in Mitchell's reviews of 1957 and 1960.

A curious interpretation of the landscape is undertaken when Synge & Stephens propose that northwest Mayo was outside the limits of the last glaciation. This is primarily a morphological distinction and is based on *"..the absence of sharp topographical features which suggest that it is an older deposit"* (Synge & Stephens, 1960, p.125). The authors state that the mountainous areas which contain fresh corries and associated moraines must have lain outside, and denote the limits of, the glacial maximum, as these features indicate that the area was not overrun by the general lowland ice sheet unlike Connemara and the mountains of Donegal which were overrun by ice and contain a notable absence of 'fresh' landforms. The proposal was adequate (although severely limited by the lack of sedimentological data) until Synge himself presented new data in his 1963 paper on the glaciation of the Nephin Beg Range.

In this study of 1963 he used corrie aspect and 'freshness' in conjunction with kame moraines, kame terraces and glacial meltwater channels to model the glaciation of the region. Several results were produced from Synge's work:

- the corries were occupied by glaciers at different times;
- the maximum extent of the last corrie glaciation preceded the greatest expansion of the lowland ice sheet;
- the central of the three moraines associated with the corries marks both the greatest spread of the lowland ice and readvance of the corrie ice;
- there is a continuous moraine skirting the Nephin Beg Range produced synchronously by the lowland ice sheet and those from the corries;
- the lowland ice sheet originated from the south as indicated by the sandstone erratics on the summits of Nephin Beg and Corslieve amongst others.

Of importance is the fact that the moraine around the mountain range, associated with the lowland ice sheet, was shown to be synchronous with the second series of moraines associated with the corries. The fact that the low-lying areas contain no 'fresh drift topography' is irrelevant, as is the occurrence of periglacial features, because it has been proven by the existence of the moraines and the erratics that ice was present in the lowlands, and that it originated from the south. The smoother topography is more likely a function of the fact that the area is covered by outwash sands and gravels (*i.e.* a sandur) which is characterised by low relief.

The dominance of the Great Central Snowfield model in the literature was maintained in 1964 when papers by Farrington & Stephens and Sissons persevered with its use. They used analyses of drumlin long axes to expand the western limits of the snowfield and proposed that ice flowed in a southwesterly direction up the Erriff Valley (against the gradient) suggesting that there was no ice source (or ice cap) in the Mweelrea Mountains, but that it all originated from the Great Central Snowfield. In fact they propose that the Connemara mountains acted as a barrier to the ice from the east. Therefore west Connemara, including the area around Louisburgh and south of Croagh Patrick was unglaciated during the last glacial maximum (the Weischel glaciation). This glacial limit was equated by Sissons with the South Irish End Moraine. It is unclear why one of the authors, Stephens, altered his previous view of four years earlier (Synge & Stephens, 1960) where he showed south Mayo and Connemara covered by an ice sheet as no explanation for the revised boundaries appeared in the texts. The limitations of these papers lie in their complete dependence on morphology, without the inclusion of any sedimentological evidence.

In his 1967 paper on the glaciation of Connemara and south Mayo, Orme examined the previous work carried out on the directions and extents of ice streams in west Mayo and Connemara. He immediately dismissed the work by Kinahan and Close (1872) stating that their interpretation *"was undoubtedly hindered by an imperfect knowledge of the glacial phenomena"* (Orme, 1967, p.262). He corroborated the ice flow patterns of the previous studies *i.e.* offshore in Clew Bay and to the north in the Plains of Mayo, although he added some detail in the Mweelrea area with a series of ice streams radiating from the highest ground in Connemara, arguing that Connemara did not lie wholly beneath an enveloping ice sheet (Figure 1.6). Curiously, he is inconsistent when he criticises Farrington & Stephens (1964) and Sissons (1964) as unjustified when they suggest that the area around Louisburgh was unglaciated, while he himself shows the same area as unglaciated during the last glacial maximum on the map accompanying his text and interpretation.

In 1968 Synge re-evaluated his earlier work in west Mayo and included interpretations of the drift sequences near Louisburgh along with information extracted from corrie morphology. He summarises previous works in the area in a four-stage model of glaciation:

1. widespread glaciation from the Midlands, represented by the basal tills at Louisburgh;
2. retreat stage of this glaciation, denoted by the Ballycastle-Mulrany 'moraine'
3. occurrence of a local glaciation centred on the highlands of Connemara, denoted by the upper tills at Louisburgh;
4. retreat stage of this glaciation, represented by the Kylmore 'moraine'.

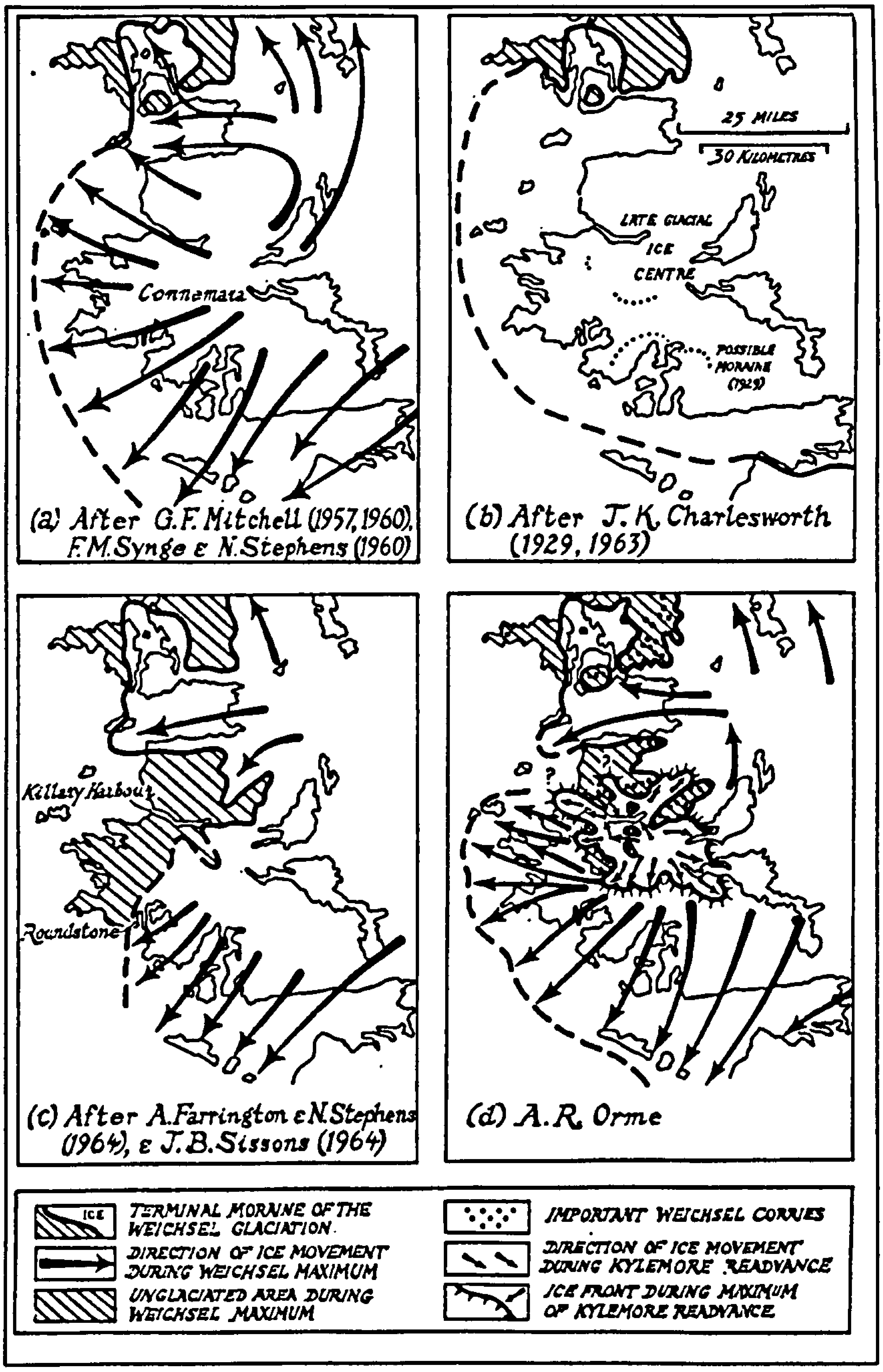

Figure 1.6 Four conflicting models of the patterns of ice flow during the last glacial maximum in western Ireland. From Orme, 1967.

The existence of an older drift sequence is proposed in terms of subdued morphology and the occurrence of periglacial forms, as observed by Synge in northwest Mayo and in the western part of the Murrisk peninsula. He corroborates this by stating that the older sequences do not include any fresh glacial landforms, such as eskers, kames, drumlins or kettles, although mapping for this research indicates that these are in fact present in the area.

Another problem lies in his work on the erratic train from the granite of Corvockbrock towards Louisburgh in the northwest. He claims that the train does not reach the shores of Clew Bay as it is interrupted by the newer drift end-moraine between Old Head and Roonah Quay. This moraine could not be located during the remote sensing or field mapping phases of this thesis, however the boulder train does clearly continue uninterrupted from Corvockbrock to the coast in the vicinity of Louisburgh. In fact Synge contradicts himself as he proceeds to state that "the foreshore in front of the drift cliffs west of Louisburgh, at Askillaun, is littered with exceptional numbers of large granite boulders from the Corvockbrock outcrop" (Synge, 1968, p.379). He interprets these as a third till (which he names the Killadoon till) at the base of the sequence. He has no additional evidence for this till apart from the boulders on the shore.

When discussing the two tills at the head of the bay he states that the contact between the two is generally sharp, sometimes emphasised by a thin band of sandy silt. He continues to say that the upper sandstone till, named the 'Newport Till', is not simply a weathered version of the lower limestone dominated till, the 'Roscahill Till'. This is based on the fact that there are no weathered limestone clasts in the Newport Till and that the removal of limestone by weathering is not apparent where the Roscahill Till is observed at or near the surface.

Synge's proposed pattern for the glaciation, as derived from the evidence summarised above, is quite different to the preceding ones. The Killadoon till is the earliest till recorded by Synge (equated to the Saale or Riss in Europe), with deposits only surviving in western Murrisk and northwest Mayo. This ice radiated from an ice shed extending across Killary harbour from the Sheeffry Mountains to the Maumturk Mountains. After this came the 'Louisburgh cool phase', or the 'Curaun interglacial' denoted by podsolic deposits, which have since been deemed 'dubious' (Coxon & O'Connell, 1994).

Synge postulates that Connemara did not act as a source for ice during the last glacial maximum but, in fact, it acted as a barrier to the ice flow that he envisaged extending from the east. For this reason he believed western Murrisk and northwest Mayo remained unglaciated. Ice from the Midlands was able to proceed in a westerly direction along the Clew Bay trough however, depositing a moraine along the northern flanks of Croagh Patrick. Two phases of glaciation were recognised, the earlier phase represented by the lower limestone (Roscahill) till, and the later by the upper (Newport) sandstone till. It was postulated that the drumlins in Mayo, and the swarms throughout Ireland, were associated with a major readvance of this ice towards the end of the last cold stage.

In essence, Synge reversed the previous understanding of the glaciation of the area. Instead of ice from the Midlands being superseded by ice from Connemara, he proposes the exact opposite. This interpretation is based on morphostratigraphy, which seems faulty. The oldest till, characterised by Synge as low relief and lacking drumlins or eskers, does in fact contain both. Its subdued relief is most likely due to the fact that the glacial sediments which compose these landforms were derived from different rock types to those where 'fresh' morphology was recorded. Also, the moraines which he mapped skirting all the higher elevations do not exist over much of the area. For example, exposures dug during aggregate extraction into the moraine along the flanks of the Partry Mountains indicates that it is in fact a kame terrace. It should also be noted that this model fails to account for the complex drumlin morphology at the head of the bay.

Synge reaffirmed this model the following year in his 1969 paper on the Würm ice limit in the west of Ireland. Using the same evidence as in his previous paper he reproduced the same results, but in the national context. Once again, Synge made some curious interpretations of the data. For example, he recognised a lateral moraine along the slopes of the Erriff Valley which he claimed was indicative of ice flow towards the southwest (against the current gradient of the valley floor) and related the contrasting evidence of erratic carriage in the moraine to an earlier glaciation with a northwesterly flow direction. Modern exposures in this moraine have shown that it is a kame terrace that was formed by glaciofluvial action from the southwest, consistent with the erratic carriage demonstrated by Synge. This rules out the complex model of two separate ice flows in the area that Synge proposed.

Coudé (1977) conducted an extensive bibliographic search relating to the west coast of Ireland and followed this by some detailed fieldwork. Starting with the preconception of a single ice mass spreading from the east, and reconstructing the supposed contours of the ice dome at its maximum, this study also indicates that ice flowed towards the west, out of Clew Bay, extending its maximum limits further west into the Atlantic Ocean than any previous study.

However, Coudé did not adhere completely to the previously accepted model and stated that the previous "*interpretation lays on a wrong analysis of the superficial formations*" (Coudé 1977, p.4). Rather than interpreting the low relief geology at western Murrisk and northwest Mayo as periglacial, and therefore unglaciated during the last glacial maximum, Coudé's analysis concluded that the sediments were formed by subglacial crushing in particularly fissile materials. He limited the periglacial areas to nunataks, and to the cold late glacial stage. Similarly, Coudé determined that the absence of landforms such as drumlins in what were previously termed periglacial areas was not due to the lack of glaciation, but the result of differing ice dynamics such as slower flow velocities.

The general conclusion reached was that the ice originated from the north Midlands and spread across Mayo, exiting through Clew Bay. The mountains acted as obstacles to flow, which slowed the ice velocity and resulted in the lower relief topography in the western areas. Although this appears to be a valid solution to the glaciation of the area, it does not account for the north-south drumlin morphology at the head of the bay, nor does it account for the evidence of an ice dispersion centre in Connemara.

In the same year an International Quaternary Research Association (INQUA) Guidebook (Bowen, 1977) with section leaders Orme and Synge, kept faith with Synge's 1969 model of ice flowing in a westerly direction out of Clew Bay, with the areas of Murrisk and northwest Mayo remaining unglaciated in the last glacial maximum (now termed the Midlandian). It was noted however that the different glaciations, the Munsterian (ascribed to the lower relief deposits in Murrisk and Erris) and the Midlandian were based on morphology and no "*Ipswichian (Eemian) interglacial deposits have yet been found separating the till (the Munsterian) from the Midlandian deposits that locally overlie it, for example along the southern shores of Clew Bay*" (Bowen, 1977, p.23).

A new explanation was proposed for the petrographic components of the tills at the head of the bay however. The lower till is dominated by limestone clasts, while the upper is dominated by sandstone, while the sandstone bedrock is located on both sides of the bay with limestone limited to the bay itself and its eastern end. This suggested to the authors that the lower till was deposited as the ice expanded towards the west in a radial pattern. As this advance waned, it was replaced by movement towards the east-west axis of the bay (*i.e.* from the north and the south respectively) which deposited the sandstone clasts across the present shoreline. This interpretation fails to take account of the geology beneath the bay itself, *i.e.* the occurrence of sandstone at the mouth of the bay, and also ignores the complex morphology of the drumlins at the head of the bay. Moreover this paper highlights the need for an integrated sedimentological and morphological approach to Quaternary mapping.

Synge's next contribution to the glaciation of Mayo was in 1979 when he wrote a text on the glaciation of Ireland in general. Here, he proposed no new data, and consequently did not alter his model in any way, except to rename the Munsterian glaciation the Connachtian. The existing model for the glaciation of the area was further promoted by McCabe *et al.* (1986) in their paper on Late-Pleistocene tidewater glaciomarine sequences in North Mayo. Although the article focuses on north Mayo (outside the area covered in this thesis), the accompanying map of major ice flow directions in Ireland during the 'drumlin substage' suggests that ice flowed from the Midlands in a northwesterly direction and subsequently flowed towards the west out of Clew Bay. Erris and Murrisk are shown as unglaciated. These ice flow directions are based on Synge's 1968 and 1969 papers.

Interest in the corries of the Nephin Beg Range was renewed by Kenyon in 1986 when he used well-developed corrie glacier moraines, ice sheet drift limits and periglacial features mapped from aerial photographs and fieldwork to reassess the glaciation of the area. He proposes that four phases can be recognised locally in the Midlandian glaciation:

1. a local ice cap built up over the Nephin Beg Range with nunataks above c.400m. This would have covered areas previously believed to have been ice-free;
2. this underwent downwasting, contemporaneous with a major advance of inland ice which produced a kame moraine around the mountains between heights of 215 and 310m;
3. extensive drumlin fields were deposited at the same time as a kame moraine complex on the north side of Clew Bay and could have involved active downwasting or be associated with a readvance of inland ice;
4. corrie glaciers returned to the Nephin Beg Range, correlated with the Nahanagan Stadial, and were more extensive than previously believed with a mean local firn line of 477m.

Kenyon dismisses previous works which stated that the areas affected by periglacial processes (*i.e.* Murrisk and Erris) must belong to the Munsterian glaciation by suggesting that the ice wedge casts and cryoturbation features were formed during the Nahanagan Stadial. He supports this claim using the evidence of erratic carriage within areas of periglacial activity, which indicate that the areas were under ice. Nevertheless, Kenyon himself lists the limitations of the evidence that he uses to support his hypothesis of glaciation:

1. the aerial photography was at c.1:30,000 scale, which was too coarse for the mapping scale of 1:10,560;
2. evidence of some corrie moraines was fragmentary;
3. no pollen stratigraphic sites were found;
4. delineation of ice sheet deposits was difficult due to the extensive peat cover, resulting in the need for extrapolation from known data;
5. the upper limits of the glaciers (trimlines) were difficult to define, with the limit drawn subjectively depending on local morphology.

Despite these limitations, his interpretation appears to be generally sound in so much as he supports the existence of an ice cap in the Nephin Beg Range and Midlandian ice in both Erris and Murrisk. Possibly the largest limitation of Kenyon's work is the ice flow direction which is suggested for Clew Bay, *i.e.* towards the west, from the Midlands. This is so for two reasons; firstly, he does not extend his ice cap beyond the uplands of the mountain range to link up with the Connemara ice and, secondly, he restricted his work to the uplands and studied none of the drumlins in the bay. This spatial restriction clearly limits the interpretation of the data and its regional significance.

McCabe published a summary of the models of glacial stratigraphy in Ireland in 1987. This paper was concerned with the location and description of type-sites that could be used to clarify the complex stratigraphy that was being debated at that time. Accompanying maps suggested the general directions of ice sheet movement in Ireland during the Munsterian and Midlandian cold stages. These maps did not take account of Kenyon's work but reverted to the pre-existing models which proposed that ice exited through Clew Bay in a westerly direction in both cold stages.

A similar situation occurred in 1991 when Eyles & McCabe published an article on the glaciomarine deposits of the Irish Sea Basin. The authors were not dealing with the west coast of Mayo, but a summary map was used to provide a context for the paper. In this map the ice was shown to flow towards the west across County Mayo, exiting through Clew Bay during the late Midlandian. Not only does this not account for the evidence provided by Kenyon in the Nephin Beg Range and by Coudé (1977) in south Mayo, but it ignores the north-south drumlin orientations in the Plains of Mayo in the vicinity of Castlebar.

Warren (1991) used "*standard stratigraphic procedures*" (p.79) to propose a differing view of Irish stratigraphy to that of McCabe (1987) stating that the Munsterian and Midlandian were of the same cold stage (which he named the Fenitian). This is important in the context of this thesis as it agrees with both Coudé's and Kenyon's views that the areas of Murrisk and Erris were in fact under ice during the last glacial maximum, but affected by periglacial action throughout the Nahanagan Stadial. Also, Warren summarises GSI data on erratic carriage, striae orientation and drumlin alignment to suggest that there was an ice mass radiating from Connemara which was synchronous with ice extending in an arc towards the north from Lough Mask and flowing west through Clew Bay. The weakness of this paper is that no new work was undertaken by Warren in the Clew Bay region, so the pervasive model of ice flowing towards the west was accepted, although it is curious that Warren, like his recent predecessors, did not account for the pattern of ice flow suggested by Close (1867) and Kinahan & Close (1872) where ice flowed onshore in Clew Bay.

Although in agreement with the proposed directions of ice flow out of the Bay, the complicated nature of the landforms, most notably the drumlins with their L-shaped crestlines which bend 90°, was alluded to by Coxon & Browne (1991) when they stated that *'the drumlins..do not all necessarily date to the same period but must have been produced by actively moving ice streams late in the last Glaciation'* (p360). The patterns of ice accumulation and flow were also considered too complex to unravel due *to "a lack of biostratigraphic marker horizons, detailed lithostratigraphic work and absolute dates*" (p.355). An interglacial site at Derrynadivva, near Castlebar was briefly referred to, however, and related to the Gortian Interglacial on the grounds of biostratigraphic evidence (Coxon & Hannon, unpublished). On the other hand, the Curaun Interglacial, stratigraphically located between the Midlandian and the Munsterian (Synge 1968) was dismissed as it was never published in detail and could not be shown to be unequivocally of interglacial status. This stratigraphical complexity was compounded by the acknowledgement by Coxon & Browne (1991) that a division of the tills in terms of morphological criteria and the absence or presence of cryoturbation structures was untenable.

Coxon & Browne (1991) also noted that nothing was known about the landform-sediment associations of the area due to the fact that no modern sedimentological studies had been published. Moreover, it was also acknowledged that many previous studies did not differentiate correctly between moraines and kame terrain and that "*detailed sedimentological research is the route to a better understanding*" (p.360). In general, the work by Coxon & Browne succeeded in asking many questions of the methodology of Quaternary mapping as applied to complex areas such as western Ireland and showed that more study was necessary.

In contradiction to the existing models of glaciation in western Mayo which were still based on the 'Great Central Snowfield' theory, Warren (1992) proposed a return to the complex flow patterns of Close's model of 1867 using drumlin orientation, striae alignment, roche moutonnées and erratic carriage to infer the patterns of ice flow for the last glaciation in Ireland. Warren stated that Clew Bay is one of '*the areas which provides crucial evidence*' (p359) relating to the developing debate regarding the patterns of glaciation in Ireland and therefore included a more detailed map and interpretation for the Clew Bay area. Warren substantiates Close's model by suggesting that ice radiating from Connemara merged with ice flowing in a clockwise loop from the north Midlands to flow in a northerly direction (Figure 1.7). Furthermore, within the bay itself, Warren postulates ice movement onshore at head of the bay and offshore (towards the west) at the mouth, indicating that the Connemara ice sheet encompassed Clew Bay with the divide running approximately north-south through the bay (Figure 1.8).

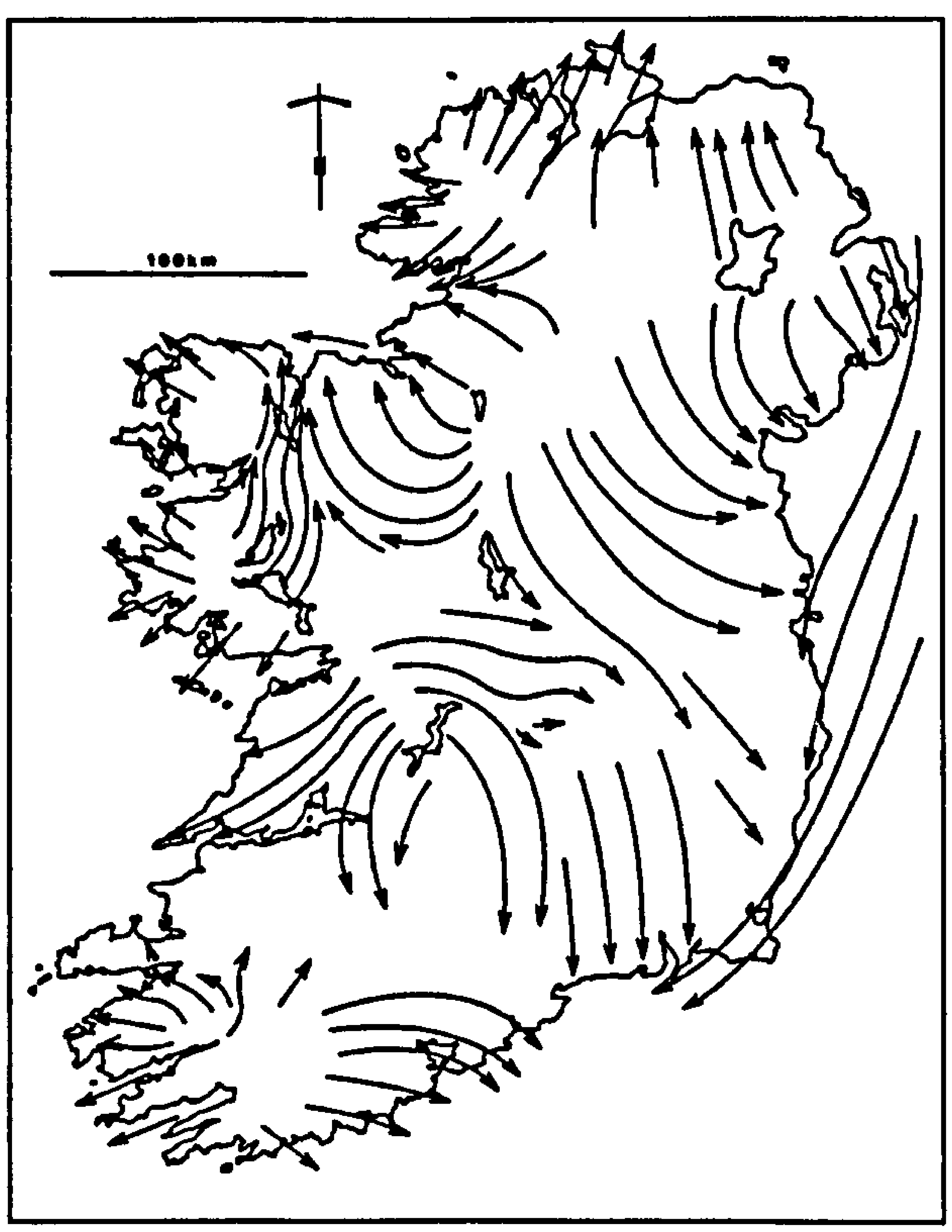

Figure 1.7 Pattern of ice movement inferred from drumlin alignment, striae orientation and erratic distribution. (After Warren, 1992).

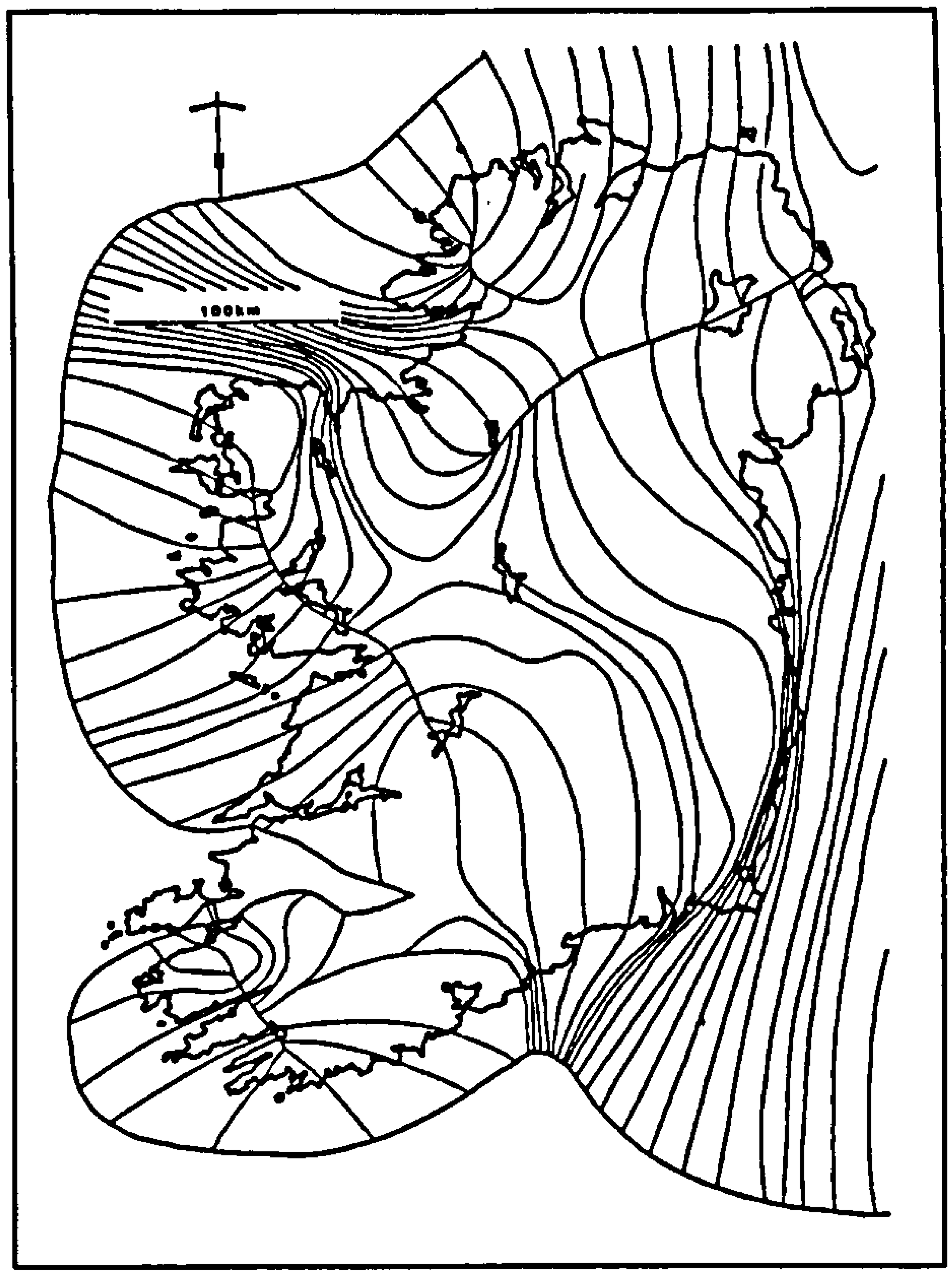

Figure 1.8 Model of the late Weichselian ice sheet showing major flowlines. (After Warren, 1992).

McCabe, as shown by his 1993 work on drumlins and Irish ice dispersions, did not accept this more complex model of multiple ice centres. McCabe persists with the Great Central Snowfield theory, which included ice flowing from the Midlands directly towards the west and offshore through Clew Bay (Figure 1.9). Interesting to note in this pattern of events is that ice is seen to flow up Erriff Valley and into the Mweelrea Mountains in Connemara suggesting that there was no ice centre in the mountains, and also that it flowed transverse to the crest lines of the drumlins in the Plains of Mayo in the vicinity of Castlebar.

In 1997 Hart undertook a fundamental review of the sedimentology of drumlins with special reference to the relationship between drumlin formation and other subglacial deforming bed processes over a wide geographical area from Iceland and North America to Ireland. Thirty three drumlins were studied in total with four included from the south coast of Clew Bay, at Pigeon Point, Turlin, Falduff and Thornhill.

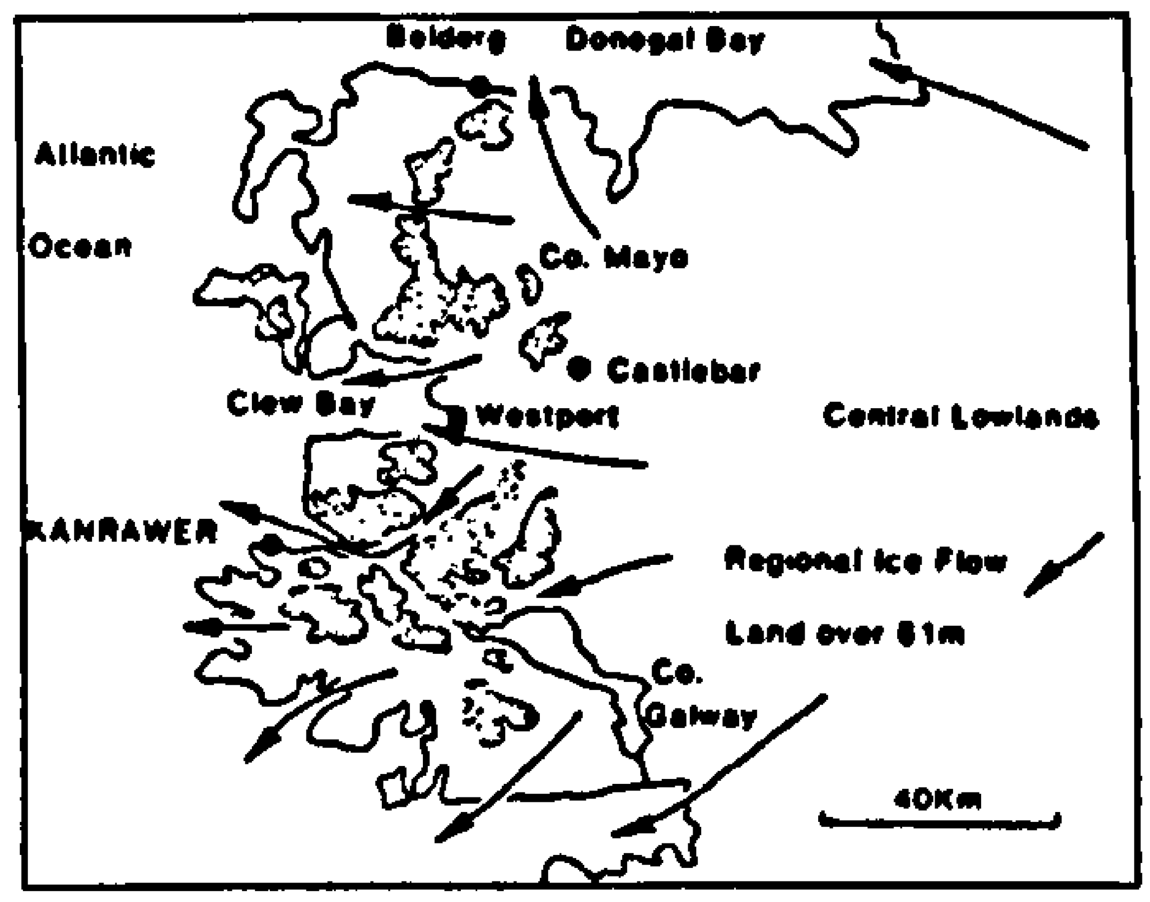

Figure 1.9 Postulated ice flow pattern in Clew Bay. (After McCabe, 1993 and McCabe & Dardis, 1994).

Using 'stacked units' in Pigeon Point, 'recumbent folding' in Thornhill, and 'a stoss side thrust sheet' at Falduff, Hart supports the model of ice flow in a westerly direction out of Clew Bay. No flow direction is given for the drumlin at Turlin, except that she says the fabric is aligned west-east, in the same direction as the drumlin long axis. There are two main shortcomings in this paper:

1) the grid references given for the sites in Clew Bay have been found to be incorrect, positioning two of them offshore. While this is not a large complaint, it throws doubt on the remainder of the data in the paper;
2) similarly, some of the site descriptions are inaccurate, such as the supposed existence of stoss side deformation in drumlins whose stoss sides have been extensively eroded by the Ocean, and open folding and backthrusting in Thornhill which may simply be thrust shearing. The sites discussed in this paper which lie within the study area of this thesis will be dealt with in detail in Chapter Five. Hart's interpretations of the deformation structures within the limited number of sites she reviewed in Clew Bay has further fuelled the belief that the drumlins were formed by ice flowing offshore, towards the west.

In their 1997 paper on the drumlin alignment of Donegal Bay, Knight & McCabe maintained their belief in the 'Great Central Snowfield' model and included a map showing ice flow in a westerly direction across Mayo from the Midlands and out through Clew Bay. No evidence was produced to support their hypothesis.

It is clear that the 'Great Central Snowfield' model became pervasive in the literature since it was first proposed by Hull in 1878 and has remained generally accepted, appearing recently in papers such as McCabe & Clark (1998) and in textbooks such as that by Benn & Evans (1998). The earlier and more complex model of Close (1865) postulating that ice could in fact have flowed onshore from Clew Bay has largely been ignored and rejected until the more recent work by Warren (1992, 1994). However, with such diametrically opposed ice flow directions promoted by the various 'schools', an holistic programme of objective, systematic and detailed studies involving both geomorphology and lithostratigraphy is necessary to solve the puzzle.

1.3.2 Glaciological Context

Clarifying the glaciological context of this research at the outset does not mean that each and every concept in glaciology will be explained, as that is clearly beyond the remit of this study. Instead, the geological terms that will be used in this text and on the accompanying maps will be defined so that the reader understands exactly what the author meant in a field where nomenclature is not always strictly followed. This section is divided into two main parts; the first deals with the glacigenic sediments, while the second deals with glacigenic landforms and associated sediments.

1.3.2.1 Glacigenic Sediments

1.3.2.1.1 Till

A till is a sediment which is deposited directly by a glacier that has not been disaggregated, although it may have undergone glacially induced flow either in the subglacial or supraglacial environment (Dreimanis, 1988). More generally it can be described as a 'diamicton', which is a non-genetic term for a poorly sorted or non-sorted unconsolidated sediment that contains a wide range of particle sizes. On the GSI Quaternary Sediments maps produced as part of this thesis (a sample of which is in the appendices) tills are sub-classified on the basis of dominant petrographic component and grain size. Till boundaries are drawn on these maps with reference to the till petrography, resulting in till types such as Limestone dominated, Lower Carboniferous sandstone dominated, granite dominated *etc*. Further subdivision exists on the basis of dominant grain size (Table 1.1). These textural properties are shown on the maps in the appendices symbolically and without boundaries.

Till Texture	**Texture Description**
Undifferentiated	Only applicable to those observed in the field, as sieving always resulted in a particle size classification
Clayey	>30% silt/clay or >20% silt/clay and >30% sand (clasts <50%); in both cases where field observations recorded the till as **clayey**
Silty	>30% silt/clay or >20% silt/clay and <30% sand (clasts<50%); in both cases field observations recorded the till as **silty**
Sandy	>40% sand or >30% sand and <20% silt/clay; in both cases where field observations recorded the till as **sandy**
Gravelly Stony	>55% clasts **and** <45% sand, silt and clay (with none dominant), where field observations recorded the till as gravelly/stony. In the case of gravelly and stony tills, field observations are very important
Sandy Gravelly	>50% clasts **and** >30% sand. Field observations again important
Silty Gravelly	>50% clasts **and** >30% silt/clay, where the matrix was recorded in the field as silt
Sandy Silty	>30% sand and >30% silt/clay, where the matrix was recorded in the field as very silty
Gravelly Clayey	>50% clasts **and** >25% silt/clay, where the matrix was recorded in the field as clayey and the till 'gravelly'
Stony Sandy	>50% clasts **and** >25% silt/clay, where the matrix was recorded in the field as 'stony'
Clayey Stony	>50% clasts **and** >25% silt/clay, where the matrix was recorded in the field as clayey and the till 'stony'
Stony Silty	>50% clasts **and** >25% silt/clay where the matrix was recorded in the field as silty and the till as 'stony'
Bouldery	>55% clasts **and** where the till was recorded in the field as 'bouldery'

Table 1.1 List of till textures and definitions, as defined by the Quaternary & Geotechnical Section of the Geological Survey of Ireland.

Although not denoted on the maps, the tills were also sub-classified according to their genesis. This is important for this thesis because the environment of deposition is required in order to reconstruct of the patterns of glaciation. In the dynamic glacial environment, sediments can be deposited either directly from the ice, or indirectly from meltwater produced from the ice. Therefore deposition can be from active or passive ice and from running or stagnating water in subaqueous, subaerial or subglacial environments leading to complex patterns of sediments deposited through time and space. Dreimanis (1988) subdivides tills by deposition process into a) primary tills consisting of melt-out till, sublimation till, lodgement till and deformation till and b) secondary till consisting of gravity flow tills.

More recently Bennett & Glasser (1996) state that there are six types of till: 1) lodgement till; 2) subglacial melt-out till; 3) deformation till; 4) supraglacial melt-out (moraine) till; 5) flow till; and 6) sublimation till (Table 1.2). New methods such as micromorphological analyses of tills are being applied to re-evaluate the recognition and interpretation of tills resulting in the belief that e.g. lodgement till and meltout tills are extremely rare, to the point of being non existent (van der Meer, Menzies & Rose, *in prep*). The approach adopted by Dreimanis (1988) has been used in this thesis.

	Lodgement till	Subglacial melt-out till	Deformation till	Supraglacial melt-out till	Flow till	Sublimation till
Particle shape	Clasts show characteristics typical of basal transport: rounded edges, spherical form, and striated and faceted faces. Large clasts may have a bullet-shaped appearance	Clasts show characteristics typical of basal transport, being rounded, spherical striated and faceted. These characteristics are less pronounced than those of lodgement till	Dominated by the sedimentary characteristics of the sediment which is being deformed, although basal debris may also be present	Usually dominated by sediment typical of high-level transport, but subglacially transported particles may also be present. The majority of clasts are not normally striated or faceted	Broad range of characteristics, but dominated by particles which are angular and have a non-spherical form. The majority of clasts are not striated or faceted	Clasts typical of basal transport, being rounded, spherical, striated and faceted
Particle size	The particle size distribution is typical of basal transport, being either bimodal or multimodal	The particle size distribution is typical of basal debris transport, being either bimodal or multimodal. Sediment sorting associated with dewatering and sediment flow may be present	Diverse range of particle sizes reflecting that found in the original sediment. Rafts of the original sediment may be present, causing marked spatial variability	The size distribution is typically coarse and unimodal. Some size sorting may occur locally where meltwater reworking has occurred	The size distribution is normally coarse and unimodal, although locally individual flow packages may well be sorted	The particle size distribution is typical of basal debris transport, being either bimodal or multimodal
Particle fabric	Lodgement tills have strong particle fabrics in which elongate particles are aligned closely with the direction of local ice flow	Fabric may be strong in the direction of ice flow, although it may show a greater range of orientations than typical of lodgement till	Strong particle fabric in the direction of shear; this may not always be parallel to the ice flow direction. High-angle clasts and chaotic patterns of clast orientation are also common	Clast fabric is unrelated to ice flow, is generally poorly developed, and is spatially highly variable	Variable particle fabric; individual flow packages may have a strong fabric, reflecting the former palaeo-slope down which flow occurred	Strong in the direction of ice flow, although it may show a greater range in orientation that a typical lodgement till
Particle packing	Typically dense and well-consolidated sediments	The sediment may be well packed and consolidated, although this is usually less marked than in lodgement till	Densely packed and consolidated	Poorly consolidated, with a low bulk density	Poorly consolidated with a low bulk density	Typically has a low bulk density and is loose and friable
Particle lithology	Clast lithology is dominated by local rock types	Clast lithology may show an inverse superposition	Diverse range of lithologies reflecting that present within the original sediments	Clast lithology is usually very variable, and may include far-travelled erratics	Variable, but may include far-travelled erratics	Clast lithology may show an inverse superposition
Structure	Massive structureless sediments, with well developed shear-planes and foliations. Shears or brecciated clasts (smudges) may be present. Boulder clusters or pavements may occur within the sediment, along with evidence of ploughing of clasts	Usually massive, but if it has been subject to flow it may contain folds and flow structures. Crude stratification is sometimes present. The sediment does not show evidence of shearing and overriding during formation	Fold, thrust and fault structures may be present if the level of shear homogenisation is low. Rafts of undeformed sediment may be included. Smudges (brecciated clasts) may also be present	Crude bedding may occur, but generally it is massive and structureless	Individual flow packages may sometimes be visible. Crude sorting, basal layers of tractional clasts, may be visible in some flow packages. Sorted sand and silt layers may be common, associated with reworking by meltwater. Individual flow packages may have erosional bases. Small folds may also be present	The deposit is usually stratified and may preserve englacial fold structures

Table 1.2. Summary table of the main sedimentary characteristics of various types of till. (After Bennett & Glasser, 1996).

Tills are also described in terms of their colour and consolidation properties. The colour is a useful and easy way of defining till types as long as an objective measure such as a Munsell Colour Chart is used and care is taken to measure both wet and dry samples. The colour may be misleading however where leaching and weathering can alter the colour and may cause confusion if this property is used on its own and not in conjunction with any other.

Consolidation heterogeneity is also influenced by a number of factors that should be addressed before any interpretations are made. For example, consolidation generally increases in a diamicton with decreasing matrix texture size *i.e.* a silty limestone till is generally more consolidated than a sandy limestone till. However, the level of consolidation is also a function of the mode of deposition, for example a lodgement till is generally more consolidated than an ablation till. This may be misleading however, as a lodgement till derived from sandstone bedrock may be less consolidated than an englacial or supraglacial till derived from limestone bedrock due to the texture of the source material.

Due to the absence of any quantitative instrument for field measurements of till consolidation/compaction in this research, a simple test involving the ease or difficulty of penetration of a knife into the deposit was used. Four levels of consolidation were determined; 1) under-consolidated, 2) normally consolidated, 3) well consolidated, and 4) overconsolidated (Paul, 1981; Eyles, 1983; Boulton & Hindmarsh, 1987; Dreimanis, 1988; Eyles & Eyles, 1992; Bennett & Glasser, 1996). A field test for the consolidation levels of sediments using a geological hammer in relation to the same four categories of consolidation is included in the Dames and Moore subsoil classification chart and was used in conjunction with the knife penetration test during field mapping (Table 1.3).

Class	**Strength**	**Field Test**	**Approximate range of uniaxial compression strength, kg/cm^3**
Highly overconsolidated	Extremely strong	Many blows with geological hammer required to break intact	>2000

		specimen	
Overconsolidated	Very strong	Hand held specimen breaks with hammer end of pick under more than one blow.	2000 - 1000
Well-consolidated	Strong	Cannot be scraped or peeled with a knife, a hand held specimen can be broken with a single moderate blow of a pick	1000 – 500
Normally consolidated	Moderately strong	Can just be scraped or peeled with a knife. 1mm-3mm indentations show with moderate blow of pick.	500 – 125
Under-consolidated	Moderately weak to weak	Material crumples under moderate blow with sharp end of pick and can be peeled easily with a knife	125 - 12

Table 1.3. Modified Dames and Moore subsoil consolidation classification chart.

1.3.2.1.2 Glaciofluvial sands and gravels

As with the discussion on tills, above, this section has been included in order to define the nomenclature regarding glaciofluvial sands and gravels and set their context within this thesis. Sand particles lie between 63 microns and 2mm while gravels range between the 2mm to 63mm sizes (Tucker, 1994). These sediments are deposited by glacial meltwater on, within, beneath or in front of the glacier. Sedimentological analyses of these deposits enable the mode of deposition and the depositional environment to be reconstructed in space and time. This was carried out through classification according to their dominant grain size, their petrographic component and through detailed logging of any sedimentary structures present.

An understanding of the modes of meltwater flow within the glacial environment is intrinsic to the recognition of the sediments that are left after the ice has retreated. Flow of water in glaciers is governed by variations in hydraulic potential, which is a measure of the available energy at a particular time and place (Benn & Evans, 1998). The hydraulic potential for supraglacial streams depends on elevation and gradient whereas the situation is more complex for water flowing englacially or subglacially because the hydraulic potential depends on both elevation and water pressure (Shreve, 1972; Paterson, 1981). The pressure within and below a glacier can range between atmospheric pressure and cryostatic pressure. Water flows from regions of high hydraulic potential towards regions of low potential, following the steepest hydraulic gradient.

Supraglacial drainage can occur in surface channels if there is sufficient discharge, with surface stream networks often well-developed on ice surfaces in glacier ablation zones. These streams commonly meander, exhibiting regularity of wavelength and amplitude (Knighton, 1972). However, straight channels predominate where structural control is strong, such as where cracks, crevasses or foliation are present (Sugden & John, 1976). Supraglacial meltwater may drain vertically down through moulins which form when crevasses open up across the line of a supraglacial stream (Stenborg, 1969). The influence of crevasse distribution on the location of moulins means that the patterns of englacial drainage are determined by glacier structure (Lliboutry, 1983; Fountain, 1993).

Subglacial meltwater drainage influences ice flow velocity, glacier stability, along with sediment erosion, transport and deposition. Benn & Evans (1998) classified subglacial drainage into two types of system, discrete and distributed. In discrete systems water is confined to a few channels or conduits, whereas water is transported over the whole of, or a large part of, the bed in distributed systems. Discrete systems include a) Röthlisberger channels (R-channels) - incised up into the ice (Röthlisberger, 1972); b) Nye channels (N-channels) - incised down into rock or sediment (Drewry, 1987); and c) tunnel valleys - incised down into rock or sediment (Boulton & Hindmarsh, 1987). Distributed systems include a) water film - between ice and bedrock (Hallet, 1979a,b); b) linked-cavity network - between ice and bedrock (Lliboutry, 1968); c) braided canal network - between ice and sediment (Walder & Fowler, 1994); and d) porewater flow (Darcian flow) - within subglacial sediment (Boulton *et al.*, 1974). It should also be noted that catastrophic flood events can occur (jökulhlaups) which are characterised by periodic or occasional releases of subglacial meltwater (Maizels, 1995).

Proglacial meltwater systems show wide variations in discharge rates due to fluctuations in meltwater supply combined with variations in rainfall and the release of stored water. Temporally, the variations occur in diurnal and annual cycles, over longer time periods reflecting changes in glacier mass balance, and in irregular intervals determined by the passage of weather systems. Spatially, proglacial meltwater systems usually form networks of shifting sediment-floored channels developed on outwash plains, referred to as 'sandar' as long as sediment is available for input to the system. Krigstrom (1962) noted that there are three systematic downstream changes in morphology:

a) *proximal zone*, where meltwater is confined within a few deep and narrow sediment-floored channels which may be extensions of Nye channels developed beneath the margins of the glacier;
b) *intermediate zone*, where flow is in a complex network of wide and shallow braided channels which frequently shift positions, and some of which may only contain meltwater during periods of high discharge;
c) *distal zone*, where channels are very shallow and may merge to produce sheet flow during periods of high discharge.

Although gravels generally dominate the proximal zone, grading into sand or silt in the distal zone, complex sedimentology exists due to the fact that the streams are braided with shifting channels and bars, with anastomosing and meandering patterns reported in distal reaches where banks are more stable (Boothroyd & Ashley, 1975).

The environments of sand and gravel deposition discussed above are terrestrial, but these sediments can also be deposited into subaqueous environments, whether they are lacustrine or marine. Sedimentation into subaqueous environments occurs through the following processes (Ashley, 1985; Lowe & Walker, 1987; Powell, 1984):

1. *deposition from meltwater flows,* which may be in the form of a plume if there is a density differential between the meltwater and the receiving body of water. The plume may be an underflow, an interflow, or an overflow. Interflow and overflow deposits generally produce deltas which contain topset, foreset and bottomset components;

2. *direct deposition from the glacier front*, where material is simply dumped into the water body resulting in irregular-shaped deposits of diamicton;
3. *'rain-out' from icebergs*, where calving icebergs float materials into the lake, depositing them as they melt;
4. *settling from suspension*, where sediments gradually settle into thin layers of mud and clay;
5. *re-sedimentation by gravity flows*, where sediments in unstable slopes slump under the force of gravity;
6. *current reworking*, where aquatic currents sort and rework the sediments which have already been deposited;
7. *shoreline sedimentation*, where wave action modifies the material which has been deposited;
8. *remobilisation by iceberg scouring*, where iceberg keels ground in shallow waters remobilise sediment, returning it to suspension.

1.3.2.1.3 Alluvium

While the sand and gravel deposits described in section 1.3.2.2 are glacigenic, alluvial sediments are determined by their Holocene (post-glacial) fluvial depositional environments, although the materials are often derived from glacial landforms. The deposits consist of gravel, sand, silt or clay in any variety of combinations characteristically deposited in beds or laminae. These are located along the river systems through deposition during flood episodes over the floodplains, or by meandering of the rivers across their retaining valleys. Boundaries are drawn on the Quaternary sediments map around areas of alluvium while further distinctions are noted with symbols regarding the dominant grain size of the deposits, but they are not delineated.

1.3.2.1.4 Peat

Peat is also a Holocene or interglacial sediment that consists primarily of organic remains (biomass) which has only partially decomposed in an anaerobic environment. Raised bogs developed in many small lake basins, spreading over time to the surrounding land. In this mapping area they are found most frequently in interdrumlin regions. Blanket bog, associated with poorly draining upland areas with greater than 1250mm of precipitation per annum, is more commonly found in western Mayo.

Peat deposits characterise warmer wetter climates than those experienced during glacial episodes. Therefore, if layers of compressed peat are found within glacial deposits they indicate an interglacial or interstadial, where the climate became warmer for a period.

Both the spatial extents and depths of peat areas are marked on the Quaternary sediments map although no differentiation was recorded between raised or blanket bog as the information does not contribute to the reconstruction of the glaciation of the area.

1.3.2.1.5 Outcropping rock within 1m of the surface

Outcropping rock, or areas of rock within 1m of the surface were delineated on the map. Although primarily recorded as a requirement of the mapping system carried out in the GSI, these boundaries were useful for calculating the altitudes reached by the ice and, subsequently, the ice mass contours. Outcropping rock on higher terrains, nunataks, provided unquestionable evidence of the limits of the ice as they are unaffected directly by glacial action and therefore have no diamicton cover, but are prone to shattering due to periglacial weathering. The morphology of the outcrops, together with any striae, are also of glacigenic significance as they provide excellent evidence of the directions of ice flow (MacClintock, 1953; Kleman, 1990; Clark, 1991).

1.3.2.1.6 Lacustrine deposits

Lacustrine sediments are composed of clay, silt or sand deposited in a lake. These may be massive, but are more characteristically bedded as varves or rhythmites that indicate seasonal changes in the depositional regime. Although subglacial lakes have been postulated (e.g. Shaw, 1983), lacustrine sediments are more generally indicative of proglacial sedimentation (Ashley, 1985). The lakes can form either in natural depressions in the landscape or as ice-dammed features consistent with a gradual ice retreat accompanied by high meltwater rates. Under these circumstances deltaic sedimentation occurs consisting of well sorted gravel, sand, silt and clay deposited in bottom sets, foresets and top sets in the classic Gilbertian model (Morgan, 1970). These remain as hills (generally flat-topped) when the ice melts and the lake drains, as described in van der Meer and Warren (1997).

1.3.2.1.7 Head / colluvium

This is a sediment deposited during periglacial climates, as defined in French (1976). Throughout these periods the frozen ground thaws in spring becoming more mobile, which enables the gradual movement of shattered rock fragments from higher to lower ground under the influence of gravity. Two related processes are solifluction, which is the rapid creep of materials downslope in periglacial areas, and gelifluction, which is the slow continuous movement of debris above frozen ground as defined in Summerfield (1991).

Therefore, it may be seen that these deposits are most common in upland areas of friable bedrock such as shale or schist that gives rise to head textures that are generally clast-rich. This process is substantially accelerated by periglacial action that causes the sediments to remain unconsolidated with low shear strengths. The distributions of these deposits are used to reconstruct the spatial limits of direct glacial activity (Sugden & John, 1976; Drewry, 1987; Lowe & Walker, 1987).

1.3.2.1.8 Marine deposits

These are composed primarily of sand, gravel, cobbles and boulders which have been deposited by marine action along the coastline. These can date to interglacial periods in which case they are most commonly found as cobble beds within glacial deposits or to late glacial times when they are found as raised beaches. Their form is dictated by the mode of deposition and the geographic location. Marine landforms in this study area date to the Holocene and include the following landforms:

- *beach* - unconsolidated material which extends landward from the low-water line to the high Spring-tide mark;
- *spit* - an extension of the land in point form which consists of sand or gravel and terminates in open water;
- *tombolo* - a spit that connects an island with another island or an island with the mainland.

1.3.2.2 Glacigenic Landforms

Once again, not all glacigenic landforms will be discussed here, only those which are found in the study area. The recognition and distribution of these landforms enable the extents of the glaciation to be determined, as some are associated with subglacial process and others with ice-marginal (Table 1.4).

	Ice-marginal	Subglacial
Glacial	Glaciotectonic moraines Dump moraines Ablation moraines Recessional moraines Lateral moraines	Flutes Megaflutes Drumlins Rogen moraines Mega-scale glacial lineations Roche moutonnées Whalebacks
Glaciofluvial	Outwash fans Outwash plains Kame terraces Kames Kame and kettle topography	Eskers

Table 1.4. Classification of terrestrial glacial landforms (Adapted from Bennett & Glasser, 1996).

1.3.2.2.1 Roche Moutonnées

Roche moutonnées are streamlined bedrock forms that have been smoothed by the glacier on the up-ice side and plucked on its down-ice side. As obstacles to ice flow, they become abraded, striated and polished by the progress of the ice while on the down-ice side their faces are quarried. High effective normal pressures occur on the stoss side of a bedrock hummock, but the pressure is sufficiently low on the down-ice side to allow a cavity to form (Boulton, 1974). As a result of this the up-ice side undergoes glacial abrasion, while the down-ice side is glacially plucked (Drewry, 1987). The existence of a lee-side cavity is a prerequisite for their formation which restricts them to areas where the ice velocity is high enough and the effective normal pressure sufficiently low to allow cavities to open (Sugden *et al.,* 1992). Therefore, it can be seen that they form preferentially in areas of thin and fast-flowing ice. Also, as glacial plucking is a function of variations in basal meltwater pressures, they also form preferentially in areas where meltwater is abundant (Iverson, 1991).

In scale they can range from small features less than 1m high or 1m in length to entire mountain tops which have been moulded by the ice. They are excellent indicators of ice flow direction. Care should be taken to note the bedrock structure, however, as this can effect the morphology of the roche moutonnées, and in some extreme cases may cause limited plucking on the stoss-side surfaces if favourably oriented joint systems exist (Glasser & Warren, 1990; Sugden *et al.,* 1992).

1.3.2.2.2 Eskers

Eskers are formed by glacial meltwater in tunnels and crevasses in stagnant or retreating ice masses and may have associated beads or fans of deltaic origin (Ashley, 1985). Their manifestation on the landscape is as long, narrow, sinuous ridges which demonstrate close links to the ice flow direction (Boulton, 1975). Generally they are composed of rounded boulders and cobbles with their mean clast size frequently larger than that of other glaciofluvial deposits. Sand need not necessarily be present. Stratification and bedding is also apparent in these gravels, although the beds are often slumped at the flanks of the feature which indicates a degree of collapse as the ice wall which retained the flow melted back (Warren & Ashley, 1994).

1.3.2.2.3 Ice-Marginal Moraines

Ice marginal landforms which are produced directly by the action of a glacier are known as ice-marginal moraines (Benn & Evans, 1998) and can form by the action of six processes: 1) ice pushing, 2) englacial and proglacial thrusting, 3) rockfall or debris flow onto or against the ice margin, 4) ice dumping, 5) supraglacial/ice-marginal melt-out, and 6) subglacial melt-out and lodgement (Bennett & Glasser, 1996). Bennett & Glasser recognised that in reality moraines may form by a combination of all five process, but that three broad categories of moraine can be identified: 1) glaciotectonic moraines, 2) dump moraines, and 3) ablation moraines.

1) *Glaciotectonic moraines* are formed by the tectonic deformation of ice, sediment and rock, generally through a pushing action, although also involving englacial thrusting (Aber, 1989). This requires forward momentum of the ice and results in an asymmetric cross-section with a shallow proximal and a steep distal side (Croot, 1988). Analysis of the moraine morphology (and sedimentology) enables the direction of ice flow to be determined.

2) *Dump moraines* are formed at a stationary ice front as debris is delivered to the ice margin where it accumulates along the side or in front of the glacier in the form of a ridge. The size of the moraine is dependant on three factors: 1) ice velocity - the faster the flow, the greater the amount of debris delivered; 2) the debris content within the ice - the greater the debris content, the larger the moraine; and 3) the rate of ice marginal retreat - a faster retreat means that the sediment is distributed more widely *i.e.* less concentrated (Croot, 1988).

3) *Ablation moraines* occur in similar circumstances to dump moraines but with a low gradient ice margin. Supraglacial sediments concentrate at the ice margin and are left *in situ* when the ice retreats. The morphology of the moraine is dependent upon the distribution of debris on and within the glacier (Aario & Peuraniemi,1992).

1.3.2.2.4 Kames And Kettle Holes

A kettle hole is simply an enclosed hollow formed by the melt-out of buried ice (Lowe & Walker, 1987). If the ice was buried in a sandur plain, and there is an extensive amount of buried ice, the resulting hummocky topography is termed 'kame and kettle topography' due to the resulting subsidence.

A kame is a steep-sided, variously-shaped mound composed chiefly of sand and gravel, formed by supraglacial or ice-contact glaciofluvial deposition (Holmes, 1947). As the ice melts the deposits may either be inverted to form kames or spread over the surface in a slumped manner to form an undulating hummocky surface. It should be noted that a continuum exists between the two. While an individual kame has two or more ice contact faces, a kame terrace has only one (Benn & Evans, 1998). These form when the ice is resting against a hill slope and glaciofluvial sediments are deposited in the intervening space. When the ice melts a continuous ridge remains. The glaciofluvial sediments in a kame or kame terrace are characterised by faulting due to settling of the deposits that occurs as the ice melts (Brodzikowski & van Loon, 1991).

1.3.2.2.5 Outwash Plains / Sandar

Outwash plains are proglacial features consisting of various sediments deposited by glacial meltwater. Outwash fans build up from the point at which the meltwater emerges from a stationary ice margin, however when these fans merge at a distance from the glacier and grade into large braided river sequences, it is termed an outwash plain *i.e.* sandur (Krigstrom, 1962). The fan surfaces may be subaqueous or subaerial, but are generally inclined at a shallow gradient. Fans will accumulate only if the ice contact zone is stagnant, otherwise a sandur will develop.

1.3.2.2.6 Glacial Meltwater Channels

Meltwater channels form in three environments: 1) subglacially, 2) along the ice margins, and 3) in proglacial locations where water flows away from the glacier or out of ice-contact lakes. Subglacial meltwater channels are different from the other two in the respect that the channel pattern is defined by the hydraulic potential gradient within the glacier which may bear little relation to the contours of the topography (Hooke, 1998). On the other hand the ice marginal meltwater channels generally flow parallel to the glacier margin while water from ice-dammed lakes may drain over cols or ridges in overspill channels. It is often quite difficult to differentiate between these three types in the field.

1.3.2.2.7 Drumlins

Drumlins are streamlined elongated shaped hills that are generally rounded at the up-ice end and elongated at the down-ice end. They generally occur in clusters or swarms giving rise to the term 'basket of eggs' topography. Although their general form remains similar, there is a degree of variability where some are more rounded, while others are more elongate. This variability has been measured in this research using an elongation ratio. Their widths vary from tens of metres to hundreds of metres while their long axes range from tens to thousands of metres. The drumlin long axes are aligned parallel to ice flow.

As drumlins are by far the most prevalent Quaternary landform in the study area it is felt that a brief synopsis of their sedimentology and their proposed methods for formation should be included. Their importance is also stressed by their use as indicators of ice flow direction in every proposed model for the pattern of glaciation in Ireland. Their usage has varied from purely morphological (their long axes are aligned parallel to ice flow) to sedimentological research involving till fabric analyses and deformation structure interpretation.

The term 'drumlin' was first introduced into the scientific literature by Close (1867) as a derivation from the Irish word *druimnín*, meaning small hill. Immediately the term can be seen as a morphological rather than sedimentological one, and this has continued throughout the literature, *e.g.* Dionne (1987) defined a drumlin as "..an elongated, dome-shaped hill, elliptical in basal outline, with a smoothly rounded summit, its profile being asymmetrical with the steeper side up-ice". Despite the lack of genetic significance given to the term, many have argued that drumlins are found only in glaciated terrains and therefore cannot be devoid of any genetic significance (*e.g.* Ashley *et al.* 1985; Muller, 1974).

It is also worth noting that there are several forms of streamlined glacial landforms, with the primary division based on whether the feature is composed of consolidated rock or unconsolidated Quaternary sediments (Dionne, 1987) Figure 1.13. The term 'drumlinoid' is an additional form of streamlined glacial landform defined by Dionne (1987). Although similar to drumlins, drumlinoids (or fluted drumlins) have a different morphology with a very elongate form and a length/width ratio from 10:1 to 20:1. Also, it is more difficult to distinguish between the stoss and lee sides, which makes it more difficult to determine the direction of ice flow that streamlined the features.

The complex and variable nature of drumlin sediments is commonly accepted, where the internal composition can range from stratified sand, to unsorted diamicton, to bedrock. The cores can consist of sand, gravel, till, boulders or rock. Structures range from unsorted homogenous, to shear and tectonic structures, to bedded or laminated deposits. This complexity and variability has lead to an equally variable array of models for drumlin formation. One point seems clear: any successful model will have to account for 1) drumlin morphology, 2) drumlin sedimentology, 3) spatial distribution, 4) local topographic factors while 5) taking account of the physics of ice as set out in glaciological theory. Literature reviews, such as that by Hiemstra (1994) inidcate that there are six main models postulated for the formation of drumlins, as summarised below.

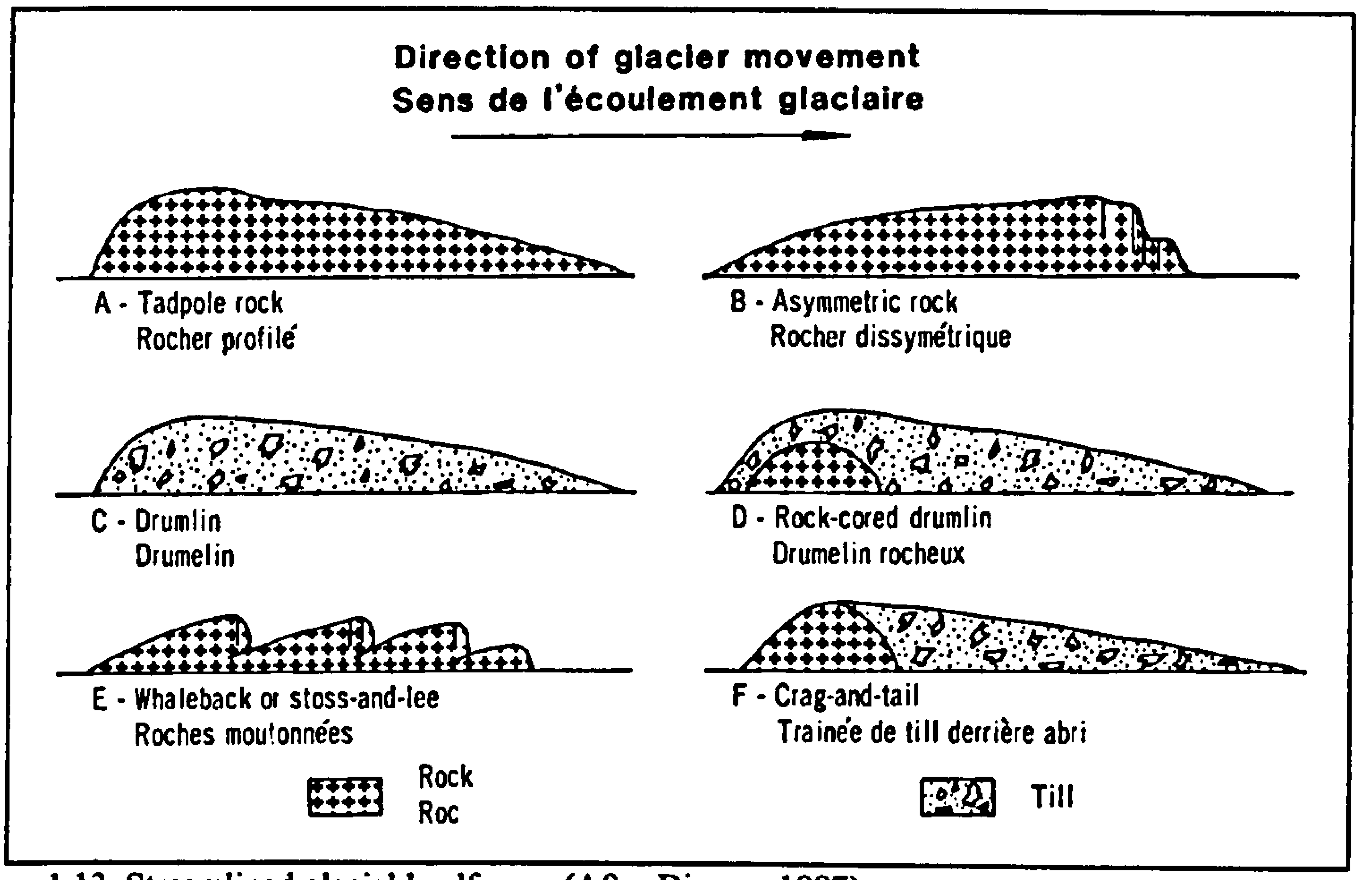

Figure 1.13. Streamlined glacial landforms. (After Dionne, 1987).

1. The Subglacial Lodgement Model

This model involves the concept that drumlins are constructed by the accretion of layers of sediment over time (Alden, 1918; Goldthwaith, 1924; Fairchild, 1929; Flint, 1948; Hill, 1968 & Hanvey 1992). A three-stage development is proposed:

- a bedrock knoll or other feature captures the till;
- accretion continues to build up around that object;
- a critical stage is reached when streamlining of the form occurs.

Objections to this model stem from the fact that firstly, the accretionary layer would not have the competence to avoid subsequent erosion and that secondly, as Menzies (1979) pointed out, "it would seem most unlikely that accretion layers would occur as large, complete shells encompassing the whole drumlin surface". However it is not necessary to have 'complete shells' of lodgement till, nor it is correct to question the competence of the till in relation to subsequent erosion. This applies to all lodgement tills.

2. The Squeeze-in Model

Advocated by Dyson (1952), Hoppe & Schytt (1953) and Vernon (1966) this model involves saturated till being squeezed into hollows in the glacier sole. The advancing ice subsequently streamlines this till. The squeezing of till into the spaces in the ice occurs simply through equalisation of pressure from high pressure in the till to low pressure in the cavities in the ice. Longitudinal cracks can form in a number of ways, such as subglacial crevasses during radial extension of the ice at valley mouths or by consolidated objects projecting upwards from the glacier bed into the basal layers of the overriding ice. Freezing of the extruded till ensures its competence with respect to the overriding ice.

Although this theory is glaciologically sound, the requirement of a saturated till followed by freezing of the extended mass prior to streamlining makes it unlikely over large areas. Furthermore, drumlins consisting of bedded sediments suggest that squeezing of deposits need not be a prerequisite. Nevertheless, it should be noted that small scale fluted surfaces under a modern glacier in Switzerland were concluded to have formed through subglacial squeezing of fine-grained particles from between coarse clasts in the bed (van der Meer, 1993). The importance of this discovery is that the overlying ice is debris-free, and therefore the fluted surfaces must have been generated from older material overridden by the glacier, with no requirement for simultaneous deposition from the ice sole (Piotrowski, 1997). This seems to strengthen the argument for erosional theories of drumlin formation.

3. The Frost Heave Model

The main proponent of this model, Baranowski (1969) focused not on individual forms, but on the pattern and spacing within swarms. He advocates the progression of a thermal cold front downwards through the ice (the result of a climatic change) which freezes the accumulated ground moraine and water that occurred when it was in a warm base situation. The freezing causes the interstitial water in the moraine to undergo frost heave and hummocks occur in the moraine due to the resultant expansion. The height of the heaving varies with the amount of water available for freezing. This creates a triggering mechanism that requires continued downward displacement of the cold front for formation of subglacial parallel ridges (drumlins).

This model seems rather unlikely due to the requirements of climatic change that would be necessary to send a progressive cold front downwards through the ice resulting in the amount of 'heave' that would be required to produce the scale of feature that is common throughout the study area of this thesis. It also necessitates a series of cold fronts over a large area to produce the drumlin swarms. Finally, if this model is correct, then one would expect a linear pattern to exist in the drumlin distribution aligned parallel to the ice front, and this has not been found, even with the help of Fourier transformations available in the digital image processing systems used in this thesis.

4. Glacial Kinematic Fluting Model

Shaw & Freschauf (1973) based this model on kinematic analogies with known features resulting from fluvial or aeolian processes that produce landforms parallel with fluid flow directions. Shaw & Freschauf (1973) propose that a sheet-like body of basal till may become concentrated in linear belts within the ice as a result of secondary circulation in the ice during transportation where flow is characterised by helicoidal flow cells (see Figure 1.14). This concept was tested in laboratory experiments by Folk (1971) who established the physical similarity between viscous fluids such as creeping ice and turbulent fluids where helicoidal patterns are expected. Rose (1989) confirmed the viability of this model through the use of three-dimensional till fabric analyses of elongate clasts in superimposed flutes.

There are several shortcomings in this model. The fieldwork carried by Rose in 1989 showed that clast alignment was pseudo-parallel to the drumlin long axis with a secondary orientation towards the axis, *i.e.* a herring bone pattern, but this does not necessitate helicoidal flow patterns in the ice as the process of formation of the flutings. Moreover, helicoidal flow patterns have not been observed in active ice sheets and there is no mention of their existence by workers involved in glacier mechanics (Drewry, 1987; Hooke, 1998; Paterson, 1981; Sugden & John, 1976). These factors must throw doubt on the validity of the glacial kinematic fluting model.

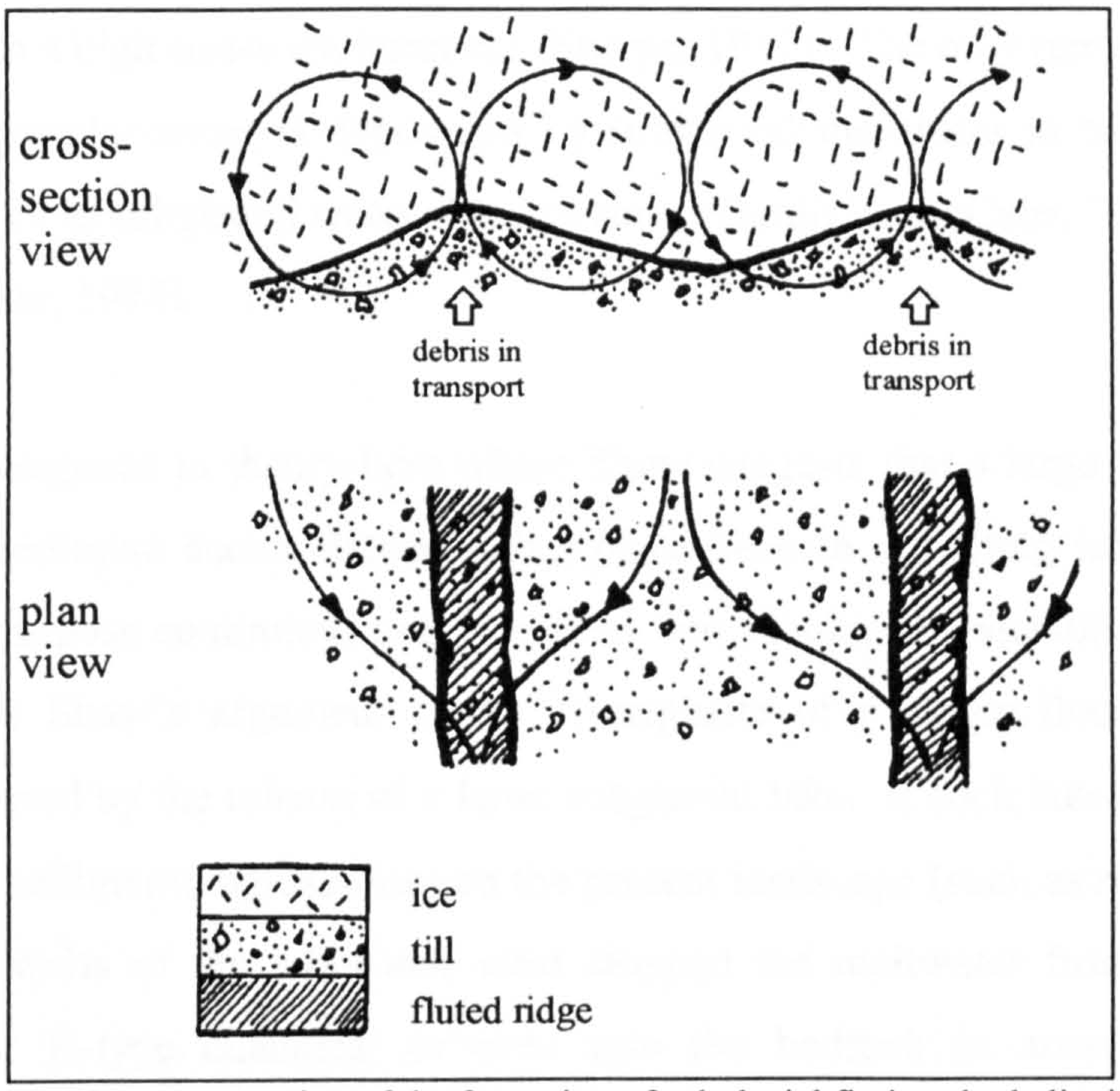

Figure 1.14. Schematic representation of the formation of subglacial flutings by helicoidal flow cells

5. Drumlins as Erosional Remnants of Subglacial Flooding (Shaw Wash Model)

Shaw (1983) drew an analogy between drumlin morphology and the casts of erosional marks associated with marine turbidity currents. He subsequently proposed the influence of subglacial meltwater in drumlin formation, where they are a product of subglacial erosion by glaciofluvial meltwater (Shaw *et al.* 1989). The crux of the model is the capacity for water storage in subglacial lakes that may be drained in a large event. Sedimentologically, Shaw establishes the plausibility of the model by discussing features which he proposes were initially stratified and subsequently eroded by fluvial actions, but could not have resulted from other subglacial processes such as lodgement.

The lack of observed internal glaciotectonic deformation structures has been suggested as support for this model as it implies that deposition of sediments under high stress conditions, such as lodgement, was not the major active process (Sharpe, 1987).

Therefore, it is suggested that as stratified sediments are common in drumlins (Krüger & Thomsen, 1984), and although many have been deformed by overriding ice (Hart, 1997; Whittecar & Mickelson, 1979), many are not deformed and therefore could not have formed in a high stress environment (Sharpe, 1987). The only remaining process for sediment emplacement is deposition by subglacial meltwater in turbulent flows (Shaw, 1983) or in subglacial water-filled cavities (Dardis & McCabe, 1983; Dardis *et al.* 1984; Muller, 1974).

There is a divergence in theory here where Shaw suggests that a large flood event is needed with sediment accumulation taking place beneath a melting ice sheet, while Dardis *et al.* propose continuous sedimentation into subglacial water-filled cavities. A weak point in Shaw's argument is the prerequisite of a single flooding episode, possibly triggered by the release of a large subglacial lake. If such lakes existed, then where are the sedimentological clues on the present landscape (such as ridges marking the retaining walls of the lake) and what stopped the meltwater from escaping in regular R- or N-type channels, or even into the bedrock in areas of fractured limestone? Work in Iceland (van der Meer *et al*, 1999) further casts doubt on the likelihood of subglacial floods because it demonstrated that 'it is very difficult for temperate glaciers with a temporary frozen bed in the toe region to retain subglacial meltwater' as it dissipates through water-escape structures. A problem with the 'Dardis model' is that subglacial water-filled cavities must be abundant and they must remain open until filled with sediments.

6. Dilatency Model

The 'dilatency' hypothesis (Smalley, 1966; Smalley & Unwin, 1968) proposes that stress in the glacier/bed interface could keep a layer of dilatent deforming till in motion, but that the dynamic stresses were not sufficiently high to reinitiate movement once the material had come to rest. Subsequently, in 1987 Smalley and Piotrowski withdrew the requirement of a dilatent till. The important relationship in this model is between the stresses applied by the glacier and the strength of the deforming layer. If the stresses are high relative to the internal strength of the sediments, then intense deformation will occur, but no hills (drumlins) will form. On the other hand, if the strength of the material increases, relative to the shear strength of the ice, then the competency of the sediments will result in the formation of smooth hills.

Importantly, the deformation velocity depends on the size and shape of the clasts in traction and affects the amount of 'collisions' and the formation of dense assemblages of clasts. The model is further complicated by the theory that there are two horizons of deforming material; the lower horizon which is jointed and relatively well consolidated and shows an elastic-plastic strain response to stresses, and the upper horizon which is dilettante with a high void ratio and responds to stresses in a non-linear, viscous manner (Aario & Peuraniemi, 1992). Boulton (1987) develops this to show that after rapidly deforming, the lower horizon progressively stiffens and stabilises. Variable shear strengths within heterogeneous sediments cause 'jamming' and hummock development, increasing the possibility for subsequent drumlinisation. The 'slurry' style (saturated debris) deposition of till in drumlins indicates moisture content of up to 40%. Free meltwater plays a minor part but porewater movement is fundamental and, if the drumlin is to survive, the yield strength of the slurry must be greater than the applied basal ice stresses. This could occur if there was any one of: localised sediment freezing; localised loss of porewater (dissipation); or differential basal stresses creating zones of over-consolidation.

It should be pointed out that none of the models above appears universal in answering the problem of how drumlins form: *i.e.* no single model can explain all the sedimentological or morphological features of the drumlin swarms. Likewise, the models are not mutually exclusive, but a degree of transition is seen between them. For example, sediment could be either squeezed or deposited by meltwater into cavities and subsequently deformed by the overriding ice into sediments that approximate those of lodgement tills or dilettante sediments. Furthermore, the meltwater present towards the end of the glaciation could remobilise sediments, lending support to the 'Shaw wash theory' (Shaw, 1983). However, the kinematic fluting and frost heave models stand on their own as they require complex scenarios for the formation of drumlins. The continuum that exists between the theories for drumlin formation suggests that the answer may lie in the concept of equifinality where different processes can produce the same morphological products. It is hoped that detailed study of both the sedimentology and morphology of the drumlins in the study area of this research, while keeping these models in mind, will help in the reconstruction of the glaciology and advance the understanding of the processes responsible for the formation of drumlins.

1.3.3 Environmental Remote Sensing Context

Remote sensing is defined as the acquisition of data about a body without actual physical contact with that body. Information is obtained through the study of the interaction of electromagnetic energy, either active or passive, and the body under examination. This process incorporates many forms, including geophysical methods such as Ground Penetrating Radar (GPR) and SOund Navigation And Ranging (SONAR). For the purposes of this thesis, the techniques will be limited to those involving orbital platforms such as the LANDSAT Thematic Mapper and ERS-1 satellite sensors.

1.3.3.1 Current Research In Quaternary Geology Using Remote Sensing Techniques

This section will discuss how remote sensing, and in particular orbital scanners, is being used as a tool for mapping previously glaciated terrains in temperate oceanic climates equivalent to that currently experienced in Ireland. The effects of climate on the imagery cannot be over-emphasised as climates such as Ireland's result in vegetation growth which masks the Quaternary deposits, and even makes morphological interpretation impossible at times. Also the levels of application of remote sensing techniques range from elementary interpretations of hardcopies (*e.g.* Coxon & Browne, 1991) to full digital image processing and interpretation, integrated within a customised GIS (*e.g.* Clark, 1997). This illustrates the two types of remote sensing generally carried out:

1. visual hardcopy interpretation;

2. digital analysis of multispectral data in a digital image processing software package.

Previous researchers have stated that satellite remote sensing has not proven an effective tool for mapping Quaternary deposits in Britain or Ireland (Warren and Horton, 1991). The lack of success achieved in northwestern Europe with remote sensing is due to the camouflaging effects of vegetation which mask the electromagnetic reflectances from the geological features of interest (Drury, 1986; Greenbaum, 1987; Jordan, 1994, 1997a,d; Marsh *et al.* 1995; Wright & Birnie, 1986). The masking occurs in two main ways, firstly the reflectance values captured by the satellite sensor originate from the surface biomass and do not relate directly to the geological features of interest. As a result of this the interpreter is forced to infer subsurface (geological) conditions from the heterogeneous growth patterns of the vegetation. However, this heterogeneity is becoming less discernible due to the influence of modern farming practices and the increased use of fertilisers. Secondly, the spatial pattern of field boundaries on Landsat imagery obscures other linear patterns, such as geological lineaments.

The recognition skills of the human eye are overpowered by the 'patchwork' effect of the high frequency field systems, to the detriment of the lower frequency geological data. This issue has become increasingly prominent with the higher spatial resolution satellites currently in orbit as they are more susceptible to the effects of high frequency disruptions.

The visible and near infrared portions of the electromagnetic spectrum are dominated by reflectances from vegetation due to plant pigments and cell structure. These qualities have been exploited, and many orbital scanners have been specifically designed with agronomy and botany in mind, such as Landsat MSS and TM, the MOMS system, SPOT and the metric and Large Format Cameras mounted on the space shuttle (Drury, 1986). This situation of the dominance of vegetation in the visible and near infrared wavelengths of the electromagnetic spectrum holds true for any mapping attempted using remote sensing in a zone of temperate climatic conditions where there is a substantial degree of biomass covering the soils, subsoils and bedrock geology.

The following sections review the work carried out which used satellite imagery to map previously glaciated terrains which currently experience a temperate oceanic climate similar to that in Ireland. These studies are categorised according to the type of sensor array that was used, *i.e.* passive, active or a combination of both. A passive satellite system is one in which the energy is not supplied from within the satellite sensor system. These depend on electromagnetic energy from the sun, in the form of reflected radiation which can only penetrate the earth's atmosphere in certain wavelengths, see Figure 1.15. The fact that the energy for the passive system is derived from reflected solar radiation must be reflected in the satellite orbital parameters, meaning that the imagery can only be captured during daylight hours, resulting in sun-synchronous orbits. The other disadvantage of passive systems is that they are highly susceptible to atmospheric interference and, for example, any cloud cover will completely obscure in the imagery..

Active remote sensing systems are those which use their own power sources, and therefore do not rely on reflected electromagnetic radiation from the sun or the emitted thermal energy from the Earth. This has a number of immediate advantages. As the system provides its own electromagnetic radiation it does not have to be deployed in a sun-synchronous orbit, and imaging can take place in the hours of darkness. The active system availed of in this study is RADAR, an abbreviation for Radio Detection And Ranging. In the sensor suite, pulses of microwave energy are emitted and the returned echo is recorded. As pulses whose energy characteristics are fully known are emitted from the satellite platform, the reflected radiation from that pulse contains less extraneous data of unknown origin. Another advantage of the active system is that the pulses are sent at relatively long wavelengths, such as in the microwave region (anything between 1mm and 1m). These longer wavelengths are not susceptible to the usual atmospheric effects of scattering and attenuation, resulting in imagery that can be captured through cloud cover, or even in the rain (and during the hours of darkness).

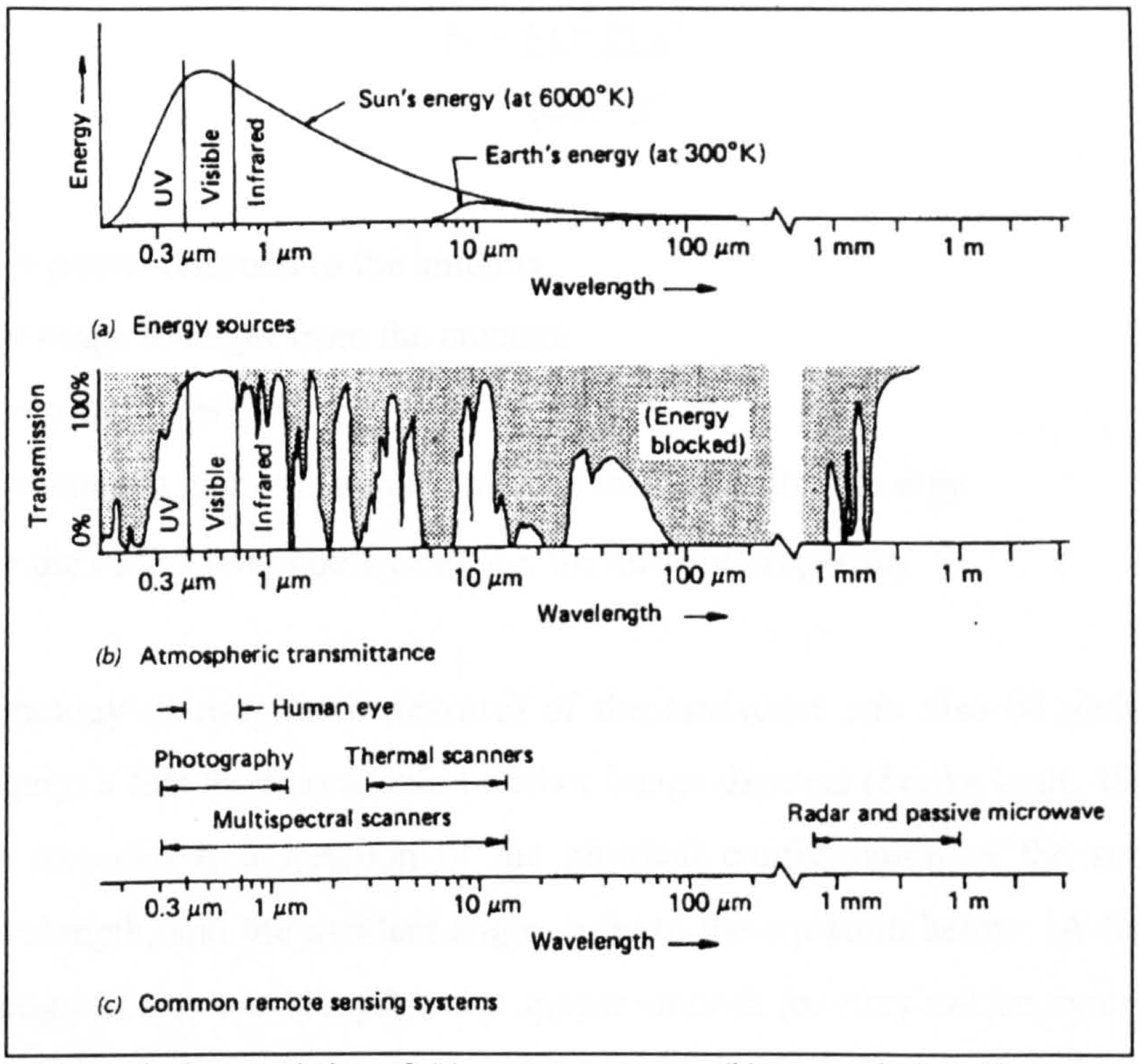

Figure 1.15. Spectral characteristics of (a) energy sources, (b) atmospheric effects and (c) sensing systems. (After Lillesand & Kiefer, 1994).

Another advantage of the radar system is its superior spatial and radiometric resolutions. Three-look ERS-1 imagery has a spatial resolution of 25m due to the application of the Doppler effect to create a synthetic aperture radar, a synthetically enlarged antenna (European Space Agency, 1989). Each ground point is imaged three times, and the results combined to produce a more exact image.

The reflected response to the pulses is unlike the passive system. The radar response is a function of several variables, such as the dielectric properties and texture (morphology) of the terrain. This is outlined in the equation below (after Cole, 1992). The dielectric properties affect the amount of energy that is backscattered from the surface cover. Materials with high dielectric constants, such as water or metals (*i.e.* substances with high electric conductivity), will reflect the energy well. This enables a relative measure of the water content of the materials (such as soils) to be estimated from the imagery, which in turn provides valuable data about the Quaternary sediments. For example, the drainage characteristics of gravels are different to those of tills *etc.*

$$Pr = \frac{\delta G^2 Pt \lambda^2}{(4\pi)^3 R^4}$$

Where: Pr = power returned to the antenna

R = range to target from the antenna

Pt = transmitted power

G = antenna gain, the ability to focus the transmitted energy

δ = the backscatter coefficient, *i.e.* the surface properties

The morphology or roughness (texture) of the landscape can also be gauged using radar imagery, a feature unavailable to other image datasets (Sonka *et al.* 1993). The roughness recorded is a function of the physical configuration of the surface, the signal wavelength, and the incident angle, refer to the equation below. A feature that appears rough in one wavelength, may appear smooth (or may not be evident on the imagery at all) when imaged with a different wavelength. By altering the frequency and polarisation of the pulse, different information can be distinguished from the sensor platforms.

$$\text{Std } h < \lambda / 8 \cos \theta$$

Where: Std h = the standard deviation of the height

λ = the wavelength

θ = the incidence angle

(After Campbell, 1987)

The incidence angle (equal to the depression angle) is essentially the angle at which the earth is imaged *i.e.* the angle at which the pulse hits the material under investigation, refer to Figure 1.16. If a low angle is used then the morphological effects will be exaggerated, similar to a low sun angle in aerial photography. A result of this is the fact that when the angle is reduced, the level of penetration of the pulse into the surface is also reduced. This effect is most apparent in arid terrains where microwave pulses have penetrated several metres below the earth's surface and have located relict features such as alluvial channels.

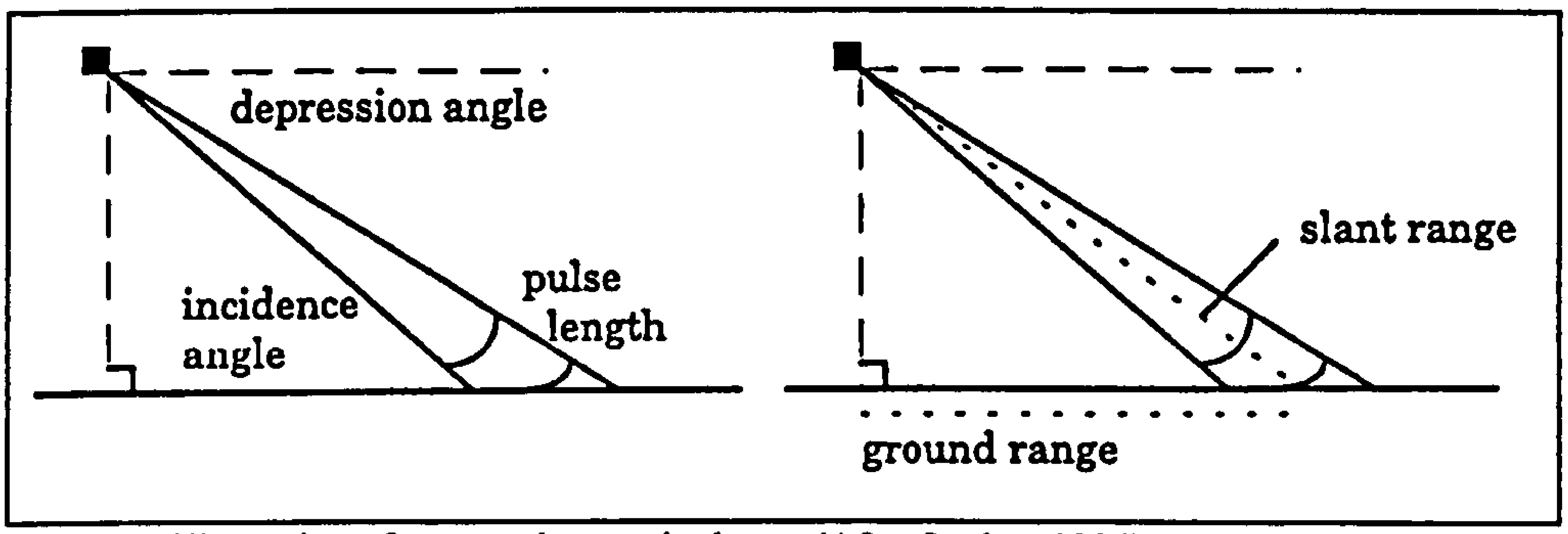

Figure 1.16. Illustration of some radar terminology. (After Jordan, 1994).

Radar imagery is not free from interference problems however. Point and volume scatter on radar images from dihedral reflectors (corner reflectors), points of extreme dielectric properties, and atmospheric interference or echoing (Kingsley & Quegan, 1992). A more problematic clutter is caused by the signal to noise ratio. A large amount of power is needed to generate the signal pulses, and this results in the characteristic 'salt and pepper' effect on radar images (Echard, 1987). Filtering techniques have been developed to reduce this speckling effect, but they are both CPU and time consuming.

Radar imagery also has its own range of geometric distortions. Layover occurs when the top of a tall object is closer to the antenna than its base. As a result of this the pulse reflection from the top of the object reaches the antenna first, implying through the principle of range detection that it is closer to the antenna in the ground range domain. On the image this is manifested as if the tall objects are leaning in towards the sensor, rather than standing as peaks or vertical buildings. Foreshortening occurs in terrain of modest to high relief at extended slant ranges. In this situation the slant to range representations are correct, but the distances between them are not accurately depicted. Therefore nearside slopes appear steeper, and lee-side slopes appear shallower (or in shadow). The concepts of layover and foreshortening are displayed in Figure 1.17. Due to these geometric and electronic distortions which affect synthetic aperture radar (SAR) data, the interpretation should be carried out by personnel experienced in radar data rather than optical systems (Clark, 1997).

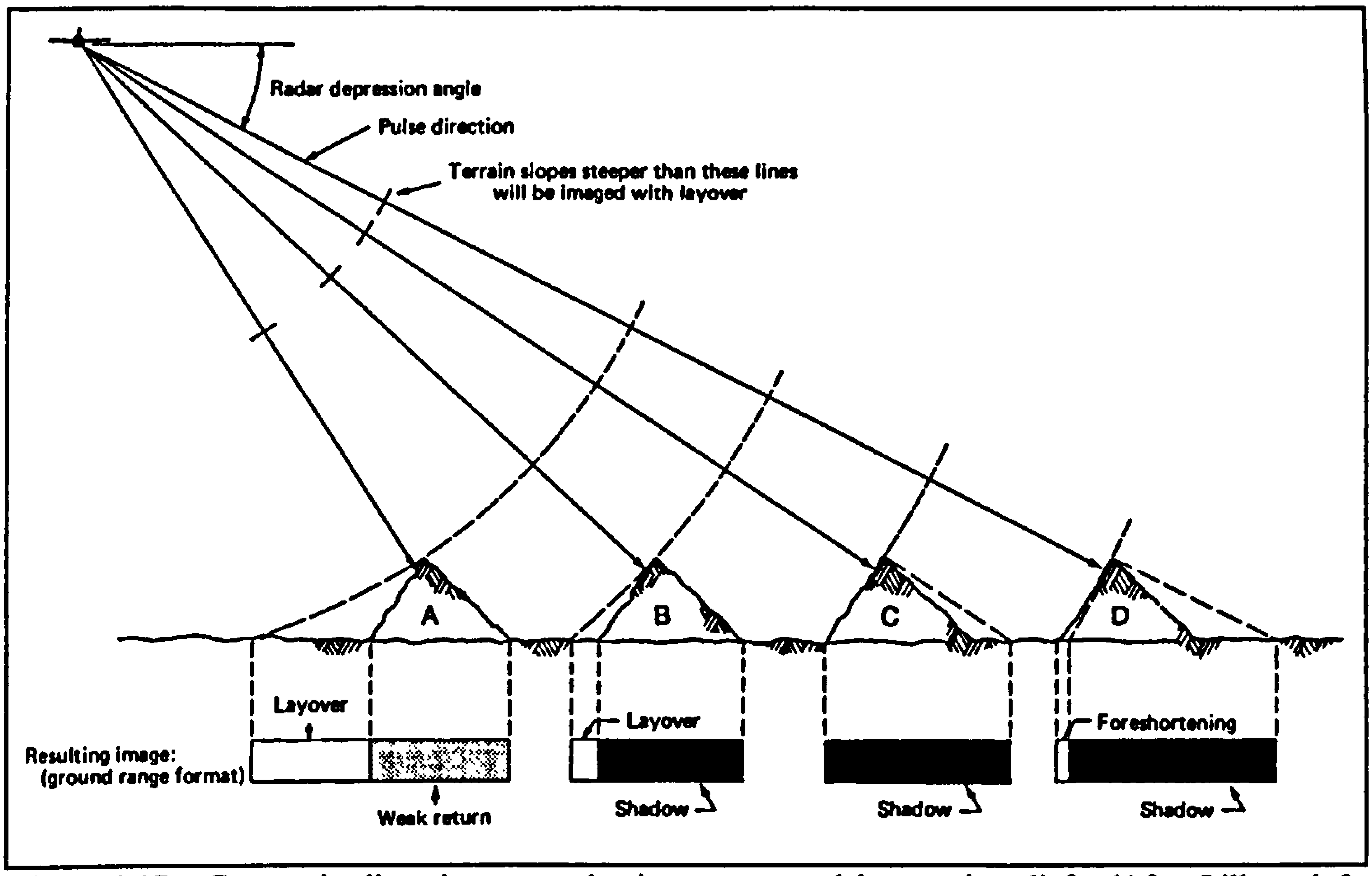

Figure 1.17. Geometric distortions on radar imagery caused by terrain relief. (After Lillesand & Kiefer, 1994).

1.3.3.1.1 Studies Using Passive Satellite Sensors

Several authors have used the synoptic qualities of satellite imagery to undertake regional geomorphological analyses in Ireland (Coxon & Browne, 1991; Knight & McCabe, 1997[a,b]). Coxon & Browne used Landsat TM imagery as a compilation tool (along with personal observations by the authors and data from several previous mapping studies) to produce a map of central and western Ireland showing major glacial depositional features. The published map is thematic in style where zones of landform assemblages are indicated, rather than the geographic locations of particular landforms or deposits. It is assumed that this is the result of the small mapping scale applied. No details were given in the paper regarding the method in which the remote sensing aspect of the study was applied, but it appears that simple hardcopy interpretation was undertaken from the Landsat TM imagery. It is therefore impossible to accurately gauge the relative inputs that the remote sensing techniques and the traditional methodology of compilation and field mapping had to the final map in the context of this study.

Knight & McCabe (1997[a]) used Landsat MSS imagery as an aid to bedform mapping in the area of Donegal Bay, northwestern Ireland. The long axis orientations of streamlined features (drumlins) and features transverse to the direction of ice flow (Rogen moraines) were recorded from the satellite imagery and compiled with both field evidence of morphology and field measurements from exposures to formulate a model of the directions of glacier flow in the area. The authors undertook a similar study in northern central Ireland using hardcopy Landsat TM data (which has a higher spatial resolution than the MSS they used previously) at a mapping scale of 1:250,000 (Knight & McCabe, 1997[b]). The bedforms were classified into three groups; kilometre-scale bedrock scallops, flow transverse ridges and streamlined bedforms. Rather than focusing on the production of a geomorphological map, the authors demonstrated how satellite remote sensing might be used as an aid to a better understanding of the regional distribution of Quaternary landforms. No details of the image data used, the techniques of image processing applied nor the field methodology were included in the published papers, although favourable comments regarding the contribution of the satellite imagery to the mapping process were noted.

Three papers by Punkari (1985, 1993 & 1995) report on the use of remote sensing techniques as a tool for mapping previously glaciated terrains. The earliest in the series (Punkari, 1985) uses Landsat-1 and -2 MSS grey-scale and colour imagery reproduced as photographic hardcopies at scales of 1:300,000 and 1:1,000,000. Interpretation was carried out from the hardcopies with the data subsequently compiled onto a map base at a scale of 1:1,000,000 for generalisation and glaciological interpretation. Pattern recognition analysis was carried out on the grey-scale photographs while the colour were used for vegetation mapping and interpretation. The vegetation analysis proved successful in the study area (Soviet Karelia) where vegetation heterogeneity allows till, sand, clay, peat and bedrock outcrops to be distinguished and mapped. The remote sensing data were substantiated using information gathered in the field, specifically of the morphology and internal structures of marginal formations, interlobate complexes, eskers and morainic forms. Aerial photographs and maps of the Quaternary deposits also provided control. Although this paper was written in the earlier days of remote sensing of Quaternary geology when digital image processing was restricted, it provides useful information regarding the process of regional (small-scale) interpretation from satellite imagery.

Punkari (1993) used visual interpretation of Landsat TM, MSS and SPOT imagery to model the dynamics of the Scandinavian ice sheet. Bedforms including drumlins, transverse and longitudinal moraines and glaciofluvial features were mapped from the satellite data at the scales of 1:500,000 to 1:1,000,000. More detailed mapping was also undertaken, however the satellite imagery was found to contribute less at these scales. As in his previous paper, Punkari found that whilst vegetation cover analysis was possible in the Scandinavian context using multispectral data which enabled morphology to be mapped from vegetation and moisture conditions, the imagery could not be used in three-dimensional topographic interpretation despite digital image processing such as Fourier analysis carried out to enhance the images interpretability. An additional improvement from Punkari's earlier work was the introduction of GIS methods to the analysis of the data where streamlined forms of similar orientation could be compared to those with different alignments in an effort to determine relative age sets. Although the image processing techniques and mapping scales are different to those necessary in the Irish context due to differences in vegetation cover and landform scales, the methodology of data compilation and analysis are comparable and applicable to the Irish context.

In the third paper in the series, Punkari (1995) used Landsat MSS imagery at a scale of 1:200,000-1:1,000,000 to produce glacial geomorphological maps of an area 1,000,000km^2 consisting of the eastern Kola peninsula and northwestern Russia. The map included drumlins, erosional basins, transverse moraines and glaciofluvial landforms. Once again the data obtained from the remote sensing aspect of the study were transferred into a GIS for integration with data from other sources before final interpretation. The development from the previous paper was the increase in size of the mapping area and the increased complexity of the GIS which enables rose diagram maps to be generated of the directions of ice flow.

Although the vegetation cover in the study area does not demand the same techniques of image processing before information can be extracted, in contrast to the Irish context, the approach to the compilation of the data used by Punkari is similar in structure to that used in the Geological Survey of Ireland. Also, the mapping scale required by the GSI (1:25,000) demands that the image data must be processed at a higher spatial degree in order to make satellite imagery a useful tool for the Quaternary geologist.

Drury (1986) conducted an important study on the use of remote sensing of geological structure in agriculturally vegetated terrains. This paper outlines the problems encountered in terms of the camouflage effects of the vegetation, and although it is aimed at mapping bedrock structures, the methodology proposed for image processing is applicable in Quaternary geology mapping. Landsat-4 TM Winter imagery is put forward as the solution, whereby the lower sun angle increases the morphological content of the imagery. However, it is stated that 1:250,000 is the optimum scale for visual interpretation of the imagery in subdued topography, although with improved contrast enhancement the scale of 1:50,000 can be used for interpretation with the subsequent loss of regional context and the intrusion of residual cultural features such as roads.

Two subsequent papers followed Drury's research of 1986. Gibson (1993) carried out a case study using Drury's methodology in four small areas of Northern Ireland measuring approximately 15km by 15km. Gibson also focused on structural information, but included some geomorphological interpretation as well, stating that a pervasive trending fabric formed of streamlined topography, probably an indicator of ice movement direction could be distinguished on the imagery. Nevertheless, only simple visual interpretations were attempted, with no GIS techniques employed. The main benefits of satellite imagery were given as a reconnaissance tool for targeting areas where fieldwork can be concentrated.

A British Geological Survey (BGS) report (Marsh *et al.* 1995) describes how the BGS Remote Sensing Group also used Winter Landsat TM imagery for geological surveying. This report advocates the use of Winter TM data as false colour composites with bands 4, 5 and 7 displayed through the red, green and blue bands of the display device respectively. These bands were chosen because their long wavelengths are less susceptible to atmospheric scattering and attenuation than the shorter wavelength bands in the Landsat TM sensor, and also because the colour combinations in the resultant image aided in the interpretation phase. After geo-rectification and edge-enhancement, the images were reproduced as high quality photographic prints at a scale of 1:50,000 and 1:100,000 for hardcopy interpretation. It was demonstrated that a large-scale map of the distribution of drumlins could be produced for Northern Ireland, which were subsequently used to infer the pattern of ice flow and retreat. One limiting factor stated is that there must be no snow on the landscape when the image is captured, and the best results are obtained from imagery from November, December and February. It should be noted however that there were no sedimentological controls on the interpretation that was undertaken entirely using geomorphological analyses.

1.3.3.1.2 Studies Using Active Satellite Sensors

Ford (1984) evaluated SEASAT synthetic aperture radar imagery (initially designed for marine applications) for the purpose of mapping Quaternary landforms and found that the sensor was useful in this field of study. With a spatial resolution of 25m, a wavelength of 23.5cm and a depression angle of 20°, it was possible to locate and map landscapes such as drumlin swarms, in both Alaska and parts of counties Cavan, Fermanagh and Monaghan in Ireland. In fact, the quality of image produced enabled a Muller Classification (a width/length ratio) to be carried out on the drumlins. Such a level of accuracy was not sustainable from satellite sensors however once SEASAT failed to operate in October 1978 after only 106 days in orbit (Mather, 1993). Ford also attempted to use Landsat MSS data to map the same features but failed due to the poor spatial resolution of that sensor (60m).

The success of the SEASAT synthetic aperture radar satellite in the 1970's inspired a new breed of orbital active microwave radar sensors; ERS-1 (European earth resource satellite), JERS-1 (Japanese earth resource satellite), RADARSAT (the Canadian equivalent), ALMAZ-1 (the Russian system) and the SIR-A, -B and -C (Shuttle Imaging Radar) missions.

Although they are all microwave sensors, their characteristics differ significantly (*i.e.* their wavelengths, depression angles and polarisations) which results in different information contents. Comparisons of ERS-1 and ALMAZ-1 (Marek & Schmidt, 1994) have demonstrated the superior capability of ALMAZ-1 for recognising linear patterns because of its higher spatial resolution of 10m, compared with 25m for ERS-1. Also, with its longer wavelength, ALMAZ-1 penetrates deeper through vegetation layers while the ERS-1 shorter wavelength results in backscatter from the surface of any biomass encountered, an effect accentuated by the lower incidence angle of the ERS-1 sensor.

Boulton & Clark (1990) carried out work on the Laurentide ice sheet, mapping glacial lineations over many hundreds of kilometres. They used a combination of ERS-1 satellite imagery and conventional aerial photography to establish the relative ages of the landforms. Unfortunately no details of the imagery or the image processing techniques were given in the paper which focused on the glaciological implications of the lineations for ice dome reconstruction. The study noted the importance of the integration of stratigraphic and chronological (absolute dates) information with morphological data before a complete reconstruction can be undertaken.

The RADARSAT system, launched by the Canadian Space Agency in 1995 improved on those already in orbit, with several beam modes enabling combinations of depression angles (31-70°), resolutions (10-100m) and imaging swath widths (450-500km) (Dekker & Nazarenko, 1994). As yet, no work has been published on the application of this sensor to mapping previously glaciated terrains.

The most recently published work relating to remote sensing of previously glaciated terrains is the research carried out on the reconstruction of the evolutionary dynamics of former ice sheets by Clark (1997). A comparison of orbital sensors indicated that the most detailed mapping scales possible were: 1:120,000 for Landsat MSS, 1:45,000 for Landsat TM, and 1:40,000 for ERS-1 SAR while the digital image processing requirements prior to interpretation ranged from "easy" to "medium" to "hard" (author's terms!) respectively. Nevertheless, the most detailed mapping scales quoted in the paper are subject to Clark's premise that "it is unusual in glacial geomorphology to worry about accurate locations of features, as the regional distribution and orientations are usually more important" (Clark, 1997 p1079). This may be the case for regional modelling of ice flow patterns, but when detailed geomorphological and material resource maps are to be produced, a very high accuracy of mapping scale and interpretation is required to enable the precise location of morphological features on fully rectified satellite imagery for subsequent transfer to a GIS.

Clark did not substantially alter the methodology for information extraction from the optical sensors, except to state that snow cover does enhance the morphological content of TM data, in contrast to the claim by Marsh *et al.* (1995) that TM data with snow cover should be avoided. The author includes radar image data from the ERS-1 satellite that requires substantially increased image processing and interpretation skills. A customised GIS was also used to integrate the information gained from various datasets to enable improved interpretation and modelling.

The main benefits postulated for the use of remote sensing in geological applications are:

a) many landforms can be detected more easily than through aerial photograph interpretation or field work;
b) the large view area, combined with the synoptic qualities of the imagery, enables patterns to be discovered;
c) a range of scales can be interpreted when the data are in digital form;
d) the speed of mapping is increased, and a single user can systematically map the geomorphology of a large area.

1.3.3.1.3 Studies Using Thermal Imagery

Thermal infrared data from the Explorer-A HCMMR (heat capacity mapping mission radiometer) satellite sensor (Bonn, 1978) and the thermal band of the TM sensor (Ottlé & Stoll, 1993) have also been applied to Quaternary mapping projects. Despite the success of these sensors in other application areas, they are not suitable for mapping at a scale of 1:25,000 as their spatial resolutions of 600m and 120m respectively are too coarse for the level of detail required. Generally the thermal band (*i.e.* band 6) of the Landsat TM sensor is deleted from the image database due to its low information yield, and with one less band the processing speed is increased.

1.3.3.1.4 Studies Involving Image Dataset Integration

Each satellite image dataset contains specific information which that particular sensor suite was designed to capture. Although many of these image datasets have limited suitability for mapping in isolation, when integrated to produce a hybrid dataset, useful geological information can be compiled. Daily *et al.* (1979), Harris *et al.* (1990), and Grasso (1993) attempted to integrate the spatial and textural content of high resolution panchromatic with the spectral qualities of multispectral imagery, using techniques such as forward and reverse intensity hue saturation transformations, see Table 1.5. The authors found that the process was successful as it increased the interpretability of the image datasets. Although these projects were carried out in arid areas where conditions are quite different to those experienced in the Irish context, the methodology of image processing is transferable to Irish data as long as the datasets used in the integration process are carefully chosen.

Author	**Multispectral Imagery**	**High resolution imagery (non multispectral)**
Daily *et al.* 1979	Landsat-2 MSS	Side looking airborne radar VV and VH, L-band (23cm)
Harris *et al.* 1990	Landsat TM	12.5m resolution x-band radar imagery
Grasso 1993	Landsat TM and Mss	Aerial photography (scanned)

Table 1.5. Image datasets used during evaluations of data integration between multispectral imagery and datasets with high spatial resolutions.

The integration process was taken one step further by Corbley (1994) by merging Landsat TM and radar data with airborne magnetic surveys and gamma ray spectrometry. Corbley attributed the high level of results attained in this study to the clarity of the geological features in the northwest territories of Canada, the small mapping scale chosen, and the dedicated digital image processing software.

It would be impossible to discuss data integration without referring to geographical information systems (GIS). A GIS is a spatial database which contains relational data including maps/imagery with tabular data of relevance to that area (Burrough, 1998). The process of digital mapping has been accelerated through the use of GIS techniques where paper maps have become redundant, and layers of data can be retrieved and queried at will (Goossens, 1991). Remote sensing, as input to map layers, enables the databases to be updated quickly (Deekshatulu & Hebbar, 1992). Trotter (1991) who integrated GIS and remote sensing successfully in natural resource management and mapping also proved this. Most digital image processing software packages currently available include a GIS module where external data sources can be integrated with the satellite image data for interpretation and analysis.

2 METHODOLOGY

2.1 INTRODUCTION

The methodology for this thesis comprises two main elements: one using the established procedures for the production of Quaternary geology maps as specified by the Quaternary and Geotechnical Section of the Geological Survey of Ireland (GSI), and the second using satellite remote sensing and digital image processing techniques to extract Quaternary geology information from satellite imagery. The GSI mapping system was used because this research was initiated as a pilot mapping project within the GSI and because it provided an objective system for mapping Quaternary sediments and morphological features.

The 'traditional' mapping procedure carried out in the Quaternary Section of the GSI and in other surveys, both national and private, has developed from the early 1800's to include digital mapping techniques, such as computer aided drawing (CAD) packages, and Geographical Information Systems (GIS) to the extent that they are accepted as routine in modern Quaternary geology mapping programmes (Jordan, 1992, 1997a,d; Lowe & Walker, 1987; Clark, 1997; Warren & Horton, 1991). Despite this progression to a digital regime, the mapping operation has remained largely unchanged. This begins with initial compilation of all available relevant information for the study area and its environs and is followed by detailed field mapping to validate the accuracy of the existing data, leading to a final compilation phase delineating the geological boundaries.

It has been shown however, that the traditional mapping process can benefit from the introduction of another tool which is becoming increasingly available to the Quaternary geologist, that of satellite remote sensing. Satellite imagery has been assessed in this context in a number of ways, whether through elementary hardcopy interpretation (Coxon & Browne, 1991; Knight & McCabe, 1997[a,b]; Knight & McCabe 1997; Punkari, 1995) or more complicated techniques involving digital image processing (Boulton & Clark, 1990; Clark, 1997; Drury, 1986; Gibson, 1993; Jordan, 1992, 1997, Marsh *et al*, 1995; Punkari, 1985, 1993). With the increasing availability of satellite imagery and modern advances in computer technology, both on the hardware and software sides, it is clear that there are possibilities for

a) deriving additional information than hitherto known
b) increasing boundary accuracy
c) speeding up the mapping process / reducing the cost of mapping programmes.

This structure of this chapter attempts to reflect the sequence of the work as it was carried out through the duration of this study, see Table 2.1. As with all analyses this begins with a listing and description of the raw data sources, and continues with a description of how that data was handled and interpreted. The main body of this chapter deals with the acquisition of new data through field mapping, drilling and trenching and the subsequent analysis of the data in the laboratory. This is followed by a general review of the methodology undertaken when utilising satellite remote sensing techniques for geological mapping. The final section of the chapter relates to the integration of the data collected using traditional mapping techniques with those gathered using satellite remote sensing. This section is included to affirm the importance of a holistic approach using both traditions to the process of Quaternary geology mapping.

One of two approaches can be utilised when undertaking a mapping project. The first is *tabula rasa* where all previous work is ignored and one starts with no preconceptions, while the other involves compilation of all previous research, used as the basis for further analysis. The latter approach was adopted in this thesis, as it was felt that a *tabula rasa* method would be of no benefit, while knowledge of previous studies, maps and glacial models would provide the context for a better understanding of the region.

PHASE	TASK
1. Compilation of…	Archival data
	Initial stereoscopic aerial photograph interpretation
	Satellite image analysis and information extraction
1a. Formulate hypotheses	Formulate hypotheses of patterns of glaciation for field testing
2. Field corroboration to verify data obtained in Phase One	Reconnaissance field mapping
	Ground 'truthing'
3. Data analyses	Analyses of data obtained during Phase 2 (till fabrics, shear plane alignment, fold reconstruction *etc.*)
4. Final compilation	Re-checking using aerial photographs and satellite imagery
5. At times it may be necessary to repeat step 2	Return to the field to re-check sediment boundaries and morphological features
6. Digitise final boundaries and point data	Digitise the maps to enable all the data to be integrated for interpretation
7. Formulate hypothesis for pattern of glaciation	Using the digitally integrated maps (sedimentology and morphology) to postulate models for the pattern of glaciation in the research area

Table 2.1. Outline of methodology for the research

Although the methodology outlined above is listed as a sequence of steps, it is in fact iterative, with a degree of repetition when it is necessary to return to certain phases as boundaries are re-established and corroborated. Similarly, after phase one, hypotheses were conceived, and tested during phase two. If the hypothesis was found to be invalid, it was necessary to return to phase one in order to construct a more robust model.

2.2 DATA SOURCES

Data were compiled in order to produce a series of Quaternary geology maps of the study area, to model the pattern of glaciation, and to fulfil the research aims as outlined in Chapter One. The data can be divided into two types; a) archival, and b) newly acquired or interpreted during the course of the research. The archival data include:

- Quaternary & bedrock geology maps;
- borehole data;
- topographic maps;
- literature on the area or the field of research;

while the second set of data were acquired during the course of the research through the processes of:

- aerial photograph interpretation
- digital image data and interpretation
- reconnaissance mapping

Each of these data sources will be reviewed in turn below in terms of their contributions, usefulness and accuracy. This is followed by descriptions of how they were used during the research.

2.2.1 Literature

Geological Survey of Ireland memoirs, published in 1885 to accompany the six-inch-to-one-mile county map series, provided anecdotal evidence for the location of some Quaternary deposits and landforms. The interpretation of the genesis of the sediments has changed dramatically since the publication date but the objective descriptions of the deposits contained in the memoirs still provide beneficial data regarding location and sedimentology. Care must be taken when terms such as 'boulder-clay' are encountered however, as it can often refer to a variable suite of deposits from tills to dirty gravels. Their accuracy and reliability, however, far outweigh this disadvantage once experience is gained in interpreting the texts.

Additional texts included any articles or volumes of relevance to the field of research or to the geographic region. Clearly it is not possible to list these here, however, they consisted of both academic papers dating from the 1800's to the present day, and recent textbooks which summarise current thoughts. Both sets were felt to be important if they referred specifically to the geographical area or the field or research, such as subglacial processes or satellite image interpretation in previously glaciated terrains. The texts are referenced in the text at the appropriate point and cited in the bibliography.

2.2.2 Quaternary and bedrock geology maps

The first compilation source used was the 1:10,560 drift and bedrock maps produced by the GSI in the 1800's (Geological Survey of Ireland, 1871). Bedrock geologists produced these maps and therefore the description of Quaternary sedimentology and morphology is not always accurate or systematic. Also, their date of production limits their applicability at times as descriptive terms such as boulder clay is used at times to describe sediments that have been seen in the field to vary from gravels to diamicts. At best these maps delineated peat bogs, alluvium, bedrock outcrops and suggested locations of 'drift' and gravels. The boundaries delineating Quaternary sediments were used as a basis from which the field survey phase began. Care had to be taken though, as they were often found to be inaccurate or incorrect and could serve to mislead rather than aid the mapping process. However, one of the most important bodies of data to be recorded on the six-inch maps are the locations of gravel pits. These may well have been either filled in or mined to extinction in the intervening time since the maps were published but the maps therefore provide an important clue to the locations of gravel deposits which may no longer be readily visible on the modern landscape.

Bedrock maps were also used as data sources during the initial compilation, field mapping and final compilation stages of the project to aid in the location of provenances for erratics and clasts within the Quaternary sediments. These maps are the Geological Survey of Ireland 1:100,000 series, sheets 6 & 10 (Long *et al.* 1995 & Max *et al.* 1992), and the 1:63,360 (one inch to one mile) series, sheets 63, 64, 65, 74, 75, 76, 84, 85 & 86. The 1:63,360 maps were only used to supply information for areas which have not yet been mapped in the 1:100,000 bedrock series. A bedrock map which was used in addition to the Geological Survey of Ireland data was the geology map of Connemara produced by the University of Glasgow at the scale of 1:63,360 (Leake *et al.* 1981).

2.2.3 Borehole Data

Archival borehole information consisting of depth to bedrock data (if bedrock was reached during drilling) and sedimentology (if logs were kept) was gathered from "Dataflex", the Geotechnical database of the Geological Survey of Ireland. Unfortunately this produced few records, as borehole data for much of the mapping area is extremely sparse, with less than 30 registered in the database. An additional 7 boreholes were drilled (to a total length of 125.1m) as part of this study to bolster this data deficiency. Ideally, several more boreholes would have been drilled, however financial and time constraints ruled this out. Nevertheless, even when borehole data are obtained, there are several limitations to this data source that must be noted:

- depending on the drilling system employed, variable depth to bedrock values may be achieved. A shell and auger system may fail at a large boulder which may be misinterpreted as solid bedrock by some workers;
- sedimentological structures, such as shear planes *etc.* cannot be discerned from auger holes into soft sediments;
- at best, this source provides point information, which needs correlation for regional analyses.

2.2.4 Topographic Maps

Ordnance Survey of Ireland topographic maps, published at scales ranging from 1:25,000 to 1:126,720 were used during compilation and reconnaissance field mapping. Geological boundaries and point information were drawn onto the O.S. 1:25,000 scale maps which were utilised as the base scale for both field mapping and digitising purposes. This map series was chosen as the map base for the following reasons:

- it is a commonly available format, both within the GSI and amongst the County Council engineers and consulting engineers who may be providing data and may also use the completed maps;
- this map series is used within the GSI in the compilation phase of mapping programmes, and as this research was carried out under the auspices of the GSI, it was necessary to maintain their mapping system;
- the maps contain all the geographical features necessary for accurate location while in the field, such as field boundaries;
- the Irish Ordnance Survey copyright for these maps is no longer valid, thereby enabling direct reproduction and digitising from this base.

Despite the production of these maps onto stable bases there is still a problem of geometric errors that must be addressed. The series was produced by photographically reproducing the 1:10,560 maps, resulting in radial distortion of each portion and poor fitting (or even gaps) where they should fit together. Compounding this is the fact that although the maps should be rectangular, of dimensions 10kmx15km, they are often distorted into trapezoids with offsets of as much as 6mm, which equates to 150m on the ground. Linked to these errors is the grid inaccuracy which means that a grid reference obtained from such a map could be as much as 150m off target. This will cause the largest amount of concern when the satellite imagery is integrated with the Quaternary geology maps produced using the 1:25,000 map base. Moreover, with such an old map series in use, the new road systems and other landscape features which have changed over the last 150 years (most notably the field boundaries) are not included on the maps.

Two other map series were used in this research; 1:126,720 (half inch to one mile) maps which were most useful for synoptic perspectives of the topography of the mapping area and the *Discovery Series* maps at 1:50,000 scale. The 1:50,000 were most useful in two respects; a) having been produced in their first edition in 1994 they contained recent landscape changes including forestry trackways and river patterns, b) their contour intervals of 10m enable some morphological features to be distinguished, *e.g.* drumlins, moraines, corries and large roche moutonnées.

2.2.5 Photographic Sources

Initial morphological mapping was undertaken using the Geological Survey of Ireland 1973 aerial photography with a nominal scale of 1:30,000. Viewed stereoscopically, landforms were traced onto clear overlays and transferred onto the 1:25,000 stable base using features such a field boundaries as ground control points common to both the photography and the maps. The resulting map shows drumlins, eskers, kames, kettle holes, kame terraces, moraines, meltwater channels, terraces, breaks in slope and other features which may be non-glacial such as ridge crests, valley axes, and escarpments. Initial mapping was purely morphological, followed by morphogenetic analysis where sedimentology was inferred from surface topography, *e.g.* kame and kettle topography comprises sand and gravel deposits. The skill and experience of the photogeologist in recognising landscape assemblages and landforms define the accuracy of this data source.

2.2.6 Digital Image Data

The digital image data processed for this study includes one ERS-1 RADAR image and two sets of Landsat-5 Thematic Mapper data. These were processed and interpreted on a number of software and hardware systems. The radar data was captured on July 7th 1992 at 22:38:39 hours while the Landsat Summer and Winter images were captured in May 1989 and 24th January 1989 respectively.

ERS-1 RADAR summary data:

Date of Capture: 07 July 1992

Time of capture: 22:38:39 GMT

Date of processing by ground receiving station: 30 March 1994

Image centre coordinates: N 53.602842 W 9.292798

Number of looks: 3

Spatial resolution: 25m

Orbit/frame number: 5113 /1071

Ground track heading: +343.443

Mid swath incidence angle: +22.932

Geocoding map projection: World Geodetic System, 1984, UT29

Altitude: 783km

Orbital inclination: 98°

Wavelength: 5.3 Ghz, C band, 5.6cm

Polarisation: VV

Radiometric resolution: 16 bit, 65536 grey levels.

ERS-1 data was used in this study for a number of reasons;

- it has an excellent capacity for distinguishing morphology and texture
- it has a high spatial resolution (25m)
- it is relatively unaffected by atmospheric distortions so common in Irish imagery

Disadvantages linked with ERS-1 imagery;

- large disk space requirement, large volumes of data
- complicated digital image processing is necessary

Landsat-Thematic Mapper summary data:

Spectral band	Wavelength (μm)	Spectral location	Spatial res. (m)	Temporal res. (days)	Principal application
1	0.45 - 0.52	Blue	30	16	Water body penetration, soil/vegetation discrimination, forest type mapping & cultural feature identification
2	0.52 - 0.60	Green	30	16	Designed to measure peak green reflectance of vegetation, for vegetation discrimination and stress assessment
3	0.63 - 0.69	Red	30	16	Designed to sense chlorophyll absorption, aiding in vegetation monitoring
4	0.76 - 0.90	Near infrared	30	16	Soil moisture discrimination, determination of vegetation types and stress, and delineation of water bodies
5	1.55 - 1.75	Mid-infrared	30	16	Designed for sensing soil moisture content, and vegetation moisture content. Differentiates between snow and clouds
7	2.08 - 2.35	Mid-infrared	30	16	Designed to discriminate between mineral and rock types and to sense vegetation moisture content
6	10.4 - 12.5	Thermal infrared	120	16	Vegetation stress analysis, soil moisture discrimination and thermal mapping applications

Table 2.2. Landsat TM sensor characteristics.

Satellite sensor: Landsat-5, Thematic Mapper

Orbit: near-polar, sun-synchronous

Altitude: 705km

Inclination: 98°

Equatorial crossing time: 0945

Swath width: 185km

Radiometric resolution: 8 bit, 256 levels per band

Image capture dates: May 1989

Jan 24th 1989

Advantages of Landsat TM:

- the data are multispectral;
- relatively high spectral and spatial resolution;
- does not require vast amounts of disk space;
- in this situation the data are also multitemporal.

Disadvantages:

- the data are prone to atmospheric effects.

2.3 TRADITIONAL MAPPING PROGRAMME

2.3.1 Initial Compilation

Compilation was carried out on an area that consisted of fifteen 1:25,000 sheets, comprising a total area of $2010km^2$. Four overlay maps were produced for each sheet comprising:

1) boundaries defining the spatial extents of the classified Quaternary sediments. In addition to this features such as striae and roche moutonnées are also included;
2) borehole and geotechnical data;
3) geomorphological map;
4) the distribution of outcropping rock locations.

This collection of maps was combined to produce a complete Quaternary geology map for each sheet, containing both sedimentological and morphological information.

The 1:25,000 base topographic maps and each overlay were printed onto transparent stable bases. This process enables all four overlays and the base map to be collated and compared using a light table. Stable bases were used to retain the geometric accuracy of the maps, as regular paper bases have are known to stretch under certain conditions. The boundaries were drawn in coloured ink with internal colour shading in pencil relating to the enclosed deposit. Symbols were used where necessary to reduce any clutter and unnecessary text that may affect the interpretability of the final map.

2.3.1.1 Quaternary Sediments Map

The sediments map of the area consists of boundaries which delineate the following categories of Quaternary deposit, which have previously been defined in section 1.3.2.1.

1. Tills
2. Glaciofluvial sands and gravels
3. Alluvium
4. Peat
5. Outcropping rock, or rock within 1m of the surface
6. Lacustrine deposits
7. Head \ colluvium
8. Marine deposits

These categories not included on the Quaternary sediments map unless their depth is equal to or greater than 1m, and their spatial extents must be large enough to be clearly discerned on a 1:25,000 scale map. The classification utilised is genetic, as it is the process of formation that defines each sediment class. Each of the categories above is further subdivided using the textural analyses described in the glaciological context section of this thesis.

2.3.1.2 Borehole Geology Maps

A map of borehole locations was produced on the second overlay by plotting data from the Geotechnical database (Dataflex) and from data supplied by the Groundwater Section, both within the Geological Survey of Ireland. Limited information exists for the study area due to its rural, undeveloped nature. Two levels of borehole data exist on the map, those which are composed of depth values (generally from the

Groundwater Section database) and those which also include stratigraphical logs. Care must be taken when compiling the logs as driller's, engineer's and geologist's nomenclature vary. Additional borehole data was obtained through drilling during the fieldwork phase of the study. Drilling is discussed in Section 2.3.2.7.

2.3.1.3 Geomorphological Map

Traditionally the geomorphology of a substantial mapping area is undertaken through the interpretation of stereoscopic vertical aerial photographs during the Compilation Stage of the project. Morphological mapping is concerned with the recognition of individual slope elements in the landscape and the nature of the junctions between them (Goudie, 1990), while geomorphology relates to landform mapping. A morphogenetic interpretation is also shown, for example, a kame terrace has a distinctive mode of formation and generally consists of sand and gravels. The aerial photographs used in this study are panchromatic, black and white, from the Geological Survey of Ireland series, which were flown between April and September 1973 to 1977 inclusive. Flown at an altitude of 4,560m with block adjustment for mountainous areas and captured onto negatives of 23cm x 23cm (inside frame), they have a nominal scale of 1:30,000 (GSI circular 81/1, 1983). Each photograph covers an area of 47.2 sq. km, but due to overlapping flight lines over 300 photographs were interpreted stereoscopically.

A clear overlay was placed over the photographs, onto which the morphology was drawn. Changes and breaks in slope were traced using both lines and symbols as outlined in Gardiner & Dackombe (1983). The features outlined were subsequently transferred manually onto the 1:25,000 overlays using ground control points. This proved a relatively simple task where there was a good concentration of field boundaries that could be used as reference points. However, the process was substantially less accurate where no geographic locators exist, such as in the extensive Mayo uplands that are covered in little other than blanket bog. In such an area there are no field boundaries, roads or trackways to help locate the boundaries when transferring the linear data onto the map base. A zoom transfer scope was not utilised due to the time constraints imposed during the research. Although possibly more accurate than manual transfers, a transfer scope was not viable with more than 300 aerial photographs to interpret in the time available.

The effects of vignetting and radial geometric distortion on the aerial photography also complicated data transfer. The main result of this distortion is the change in scale of the photographs in a radial pattern extending outwards from the centre. Therefore the shape of the feature outlined on the photograph may not be exactly the same as that produced when it is transferred to the map base, despite the expectations of some photogeologists.

Two categories of Quaternary geology features can be mapped from stereoscopic aerial photograph analysis: those having clear morphological expressions and those inferred from relative radiance values. Morphological features include those such as drumlins, eskers, kames \ kettle holes, alluvial terraces and meltwater channels *etc.* which can be directly mapped from their topographical expressions. Landcover features such as the areal extents of peat can also be mapped from aerial photography in certain circumstances. Located primarily through their reflectance values in the panchromatic visible range of the electromagnetic spectrum, they generally appear as areas of lighter tonal contrast than their surroundings.

The end product of this sequence is a morphological map from which morphogenetic qualities are interpreted. For example, drumlins are outlined with red lines along their lower breaks in slope. Morphologically these may be described as elongate hills, but morphogenetically they have been shown to indicate deposition in a subglacial environment and denote the direction of ice flow at the time of formation (*e.g.* Boulton, 1987; Boulton & Clark, 1990; Clark, 1993; Menzies, 1982, 1989; Menzies & Rose, 1987; Punkari, 1985). Unlike drumlins, each of which is defined individually on the maps, kames are shown in symbol form. Where the mapping scale is not of sufficient detail to show each kame in a zone of kame and kettle topography (indicating a dead ice zone) symbols are used to denote their general locations, with a boundary line defining the limits of the landform assemblage area.

2.3.2 Reconnaissance Field Mapping

All boundaries or items of point information, compiled as described above, must be checked through detailed fieldwork. This consists of covering the field area by vehicle (jeep or boat) and on foot and recording exposures in all quarries, gravel pits, stream cuttings, drains, ditches, house foundations, trenches, construction sites, ocean-cut cliffs or any other sections into glacial \ postglacial sediments in an effort to log all possible Quaternary geological deposits and check the aerial photograph and satellite image interpretation. In this phase of the research, corroboration of extant information is undertaken along with *de novo* identification and mapping of new data. In some cases it may possible to infer the underlying sediment type from the morphology, *e.g.* kame terraces are generally composed of gravels. Nevertheless, it is imperative to locate exposed sediments in order to confirm, interpret and classify the deposits systematically.

2.3.2.1 Field Mapping

To undertake the reconnaissance mapping phase, all the compiled data were transferred using a light table onto a paper copy of the 1:25,000 stable base map. It would have been impractical to work with the stable base and film paper overlays while in the field. Photocopying was undertaken on an A1 drum copier rather than the more common flatbed system in an effort to retain as much of the geometric qualities of the map as possible. Summary notes symbols and boundaries were written directly onto the paper map during field mapping, with more extensive notes recorded in field notebooks.

2.3.2.2 Morphological Mapping

Morphological features that were compiled from previous studies and the new ones located during the aerial photograph interpretation and satellite image interpretation stages were checked in the field. Features which were unclear or not evident on the imagery (due to extensive areas of shadow or thick vegetation cover) were drawn onto the 1:25,000 map. Nevertheless, the overview of the landscape obtained from stereoscopic aerial photographic interpretation and processed satellite image data are often superior to the view obtained while in the field.

2.3.2.3 Sediment Mapping

Reconnaissance mapping of the sediments and other 'point features' which were plotted onto the Quaternary overlay involved systematic fieldwork to confirm the existence and locations of the boundaries compiled from the archival data sources. The compiled boundaries were also used as a basis to plan fieldwork as they often gave an indication of the complexity of the sedimentology of the area, while pits located on the imagery indicated the degree of exposure in the area. The mapping area was covered by a series of traverses by vehicle and on foot. Every road and trackway was driven in order to locate exposures that could be studied. In areas with limited road networks (such as the upland areas) traverses were made on foot. Ideally every field would have been traversed on foot, however due to time constraints and the size of the mapping area, this was not possible, with an estimated one third of the area directly observed on foot. GSI boats were used to reach the islands in Clew Bay. Point locations where the geology was known were accumulated through the reconnaissance fieldwork phase and these were amalgamated until boundaries could be defined around areas where the deposit was deemed homogeneous in terms of its petrography.

Each of the 1:25,000 sheets was treated as a mapping area and they were mapped in sequence. Every section, located by direct observation, was logged and described. This involved recording the following data about each exposure.

- National Grid Reference (10 figure)
- Townland name
- 1:25,000 & 1:50,000 sheet numbers
- Exposure dimensions; length, height & orientation
- Weather conditions (which may affect the sediment details)

- Morphological context
- Vegetation cover
- Sediment details (see Figure 2.1)
    - colour
    - petrography (field estimate) and erratic list
    - matrix composition (field estimate)
    - clast/matrix ratio
    - clast shape, presence of bullet boulders or striated clasts
    - level of consolidation
    - degree of sorting
    - presence of imbrication, bedding or structures
- General description *i.e.* diamicton, glaciofluvial gravel, alluvium *etc.*

The extent of these sections ranged from over 1.5km in length and 30m in height at the coast to less than 1m long and 1m high at other locations. Through the description and analysis of each exposure, areas of homogeneous deposit were delineated to produce a sediments map of the area.

Sections that were well exposed and contained bedding or deformation structures were drawn to scale and logged. Generally these were coastal sections where marine erosion has produced near vertical till cliffs. Further analyses on these sites included till fabric analyses, which is used as an indicator of the direction from which the ice travelled, and shear strain analyses that also serve to indicate the direction from which the ice was pushing. These are described in detail in Section 2.3.3.2 below.

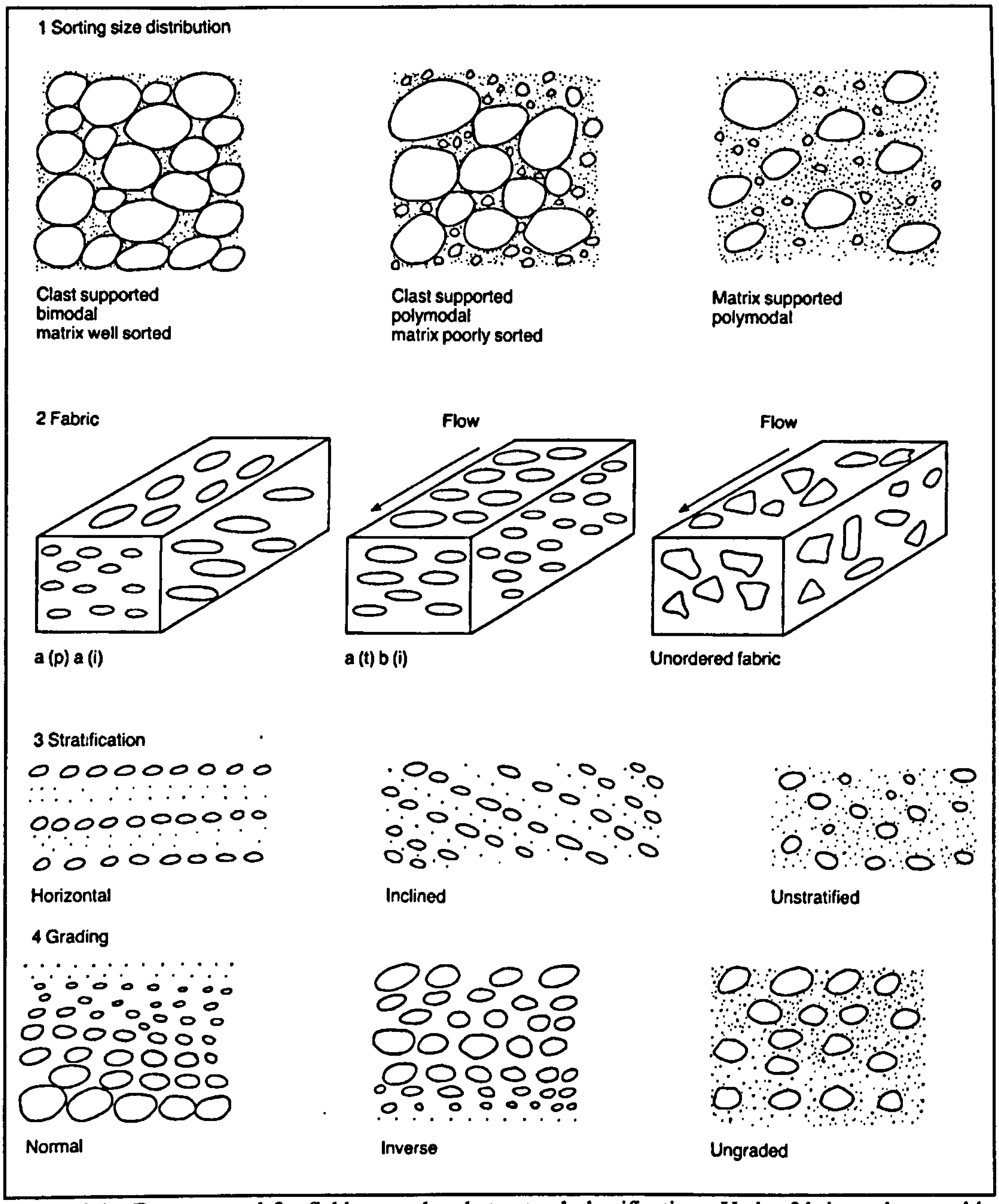

Figure 2.1. Features used for field textural and structural classification. Under fabric, codes a and b refer to long and intermediate axes respectively; p = parallel to flow, t = transverse to flow, i = imbricate. (After Tucker, 1991).

2.3.2.4 Record of Indicators of ice flow direction

Indicators of ice flow direction exist at a variety of scales (Table 2.3). Several types of data that provide information about the carriage direction of the sediments (and therefore the ice flow direction) were recorded in the field. Certain landforms are known to be aligned parallel to ice flow such as drumlins, roche moutonnées, whalebacks and fluted moraines while other features are oriented transverse to the direction of ice flow (such as Rogen moraines, De Geer moraines and recessional moraines) (Punkari, 1985, 1993; Boulton & Clark, 1990; Clark, 1993; McCabe *et al.*, 1999). The features of macro scale (Table 2.3) were defined from aerial photography and satellite imagery. While each of the direction indicators in Table 2.3 provides data on the direction of ice flow, it is best to use a combination of these features so that they may corroborate each other.

Scales of features which indicate the ice flow direction	
Scale	**Feature**
Micro	Thin sections Till fabric analyses Petrographic analyses Shear / thrust planes (these can exist in the micro and macro scales) Fold alignment (these can exist in the micro and macro scales) Heavy mineral provenance Striae alignment Slickenside alignment
Medium	Boulder erratics
Macro	Drumlin alignment Moraine alignment (lateral or transverse) Roche moutonnées Crag & tail Flutes Whalebacks / tadpole rocks

Table 2.3. Features which indicate the direction of ice flow, with reference to scale.

Smaller scale features supplying information relating to ice transport directions are outlined above. Till fabric data relate to the imbrication of clasts within a till which occurred as the till was in transport or as it was deposited. Subsequent analysis of the clasts yields data enabling reconstruction of the flow directions. This is dealt with in more detail in Section 2.3.3.2, which relates to the Analysis Phase of the research. Similarly, analysis of the deformation structures is included in Section 2.3.3.3.

The orientations of striae on clasts were generally not measured unless they were located on bullet boulders, because clasts without a defined long axis tend to rotate during transport (Drake, 1974; Mark, 1973; Murray, 1997). Stoss-lee boulders (also known as bullet boulders) have up-ice ends with tapered down-ice sides thus providing the means to ascertain the alignment of the clasts with respect to the direction of ice movement. The striae are aligned parallel to the long axes of the boulders. Striae on bedrock surfaces are more reliable sources of ice flow direction, with several types occurring:

a) wedge striae, where they gradually widen down-glacier due to progressive blunting of the identity asperity;
b) nail-head striae, as above, but the widening an abrupt end. Striae can become narrower down-glacier, but this is rare (Benn & Evans, 1998);
c) rat tails occur as small residual ridges down-glacier from a resistant nodule, *e.g.* a quartz clast in a sandstone conglomerate as at Old Head (SW Clew Bay).

Chattermarks, gouges and fractures, formed by subglacial quarrying of rock flakes were also mapped. Chattermarks are generally only a few centimetres wide, and occur at the base of shallow bedrock features with their concave sides facing down-glacier (Harris, 1943). Larger than these are crescentic gouges and lunate fractures that may measure from a few centimetres to more than a metre across. The horns on crescentic gouges point up-glacier while those on lunate gouges point down-ice (MacClintock, 1953).

The orientation of P-forms (plastically moulded forms) was also recorded on the maps. Although there are several types of P-form included in the transverse, longitudinal and non-directional broad categories (Kor *et al.* 1991) only furrows were found in the study area. These are longitudinal erosional forms that are aligned parallel to ice flow.

Slickensides are polished and smoothly striated grooves caused by slippage along a plane of displacement. In Quaternary sediments these are seen to occur in two-dimensional surfaces, most frequently along shear planes where laminae of silt or clay are situated. Although providing information regarding the alignment of slippage, it cannot be determined from slickensides alone in which direction the movement occurred (Park, 1986). Slickensides must therefore be used in combination with other sources of evidence if successful reconstruction of glacier movements is to be undertaken from glacigenic sediments.

Review of erratic carriage can be one of the easiest and best ways of determining the transport direction of the ice. This involves recording the locations and lithologies of boulders that have been transported by the glacier. These boulders are often described as 'strewn boulders' in the Geological Survey of Ireland memoirs and contemporary maps. Mapping is undertaken by plotting their present geographical positions and relating these to the bedrock geology maps in an effort to determine their region of origin. If the source can be ascertained it provides definitive evidence for the direction of glacier movement. This is similar to petrographical analysis (Section 2.3.3.3), although at a different scale.

2.3.2.5 Sediment Sampling

Sediment sampling was carried out throughout the reconnaissance mapping phase. Samples were taken to acquire quantitative values of the sediment properties *e.g.* the sediment petrography and matrix composition. Petrographic analysis was the more important enabling: a) a provenance to be found for the deposit; and b) classification of the deposits using the GSI standard. Knowledge of the matrix composition was useful in lithofacies analyses.

The sample design was dictated by the GSI who were funding the research. Samples were taken from surface exposures and purpose-dug trenches and boreholes. Each sample taken weighed approximately 4kg, although this varied with the matrix and clast content. Where sampling was undertaken on vertical sections, the exposure was cleaned back and the sample was taken below the weathering profile and at least one meter above bedrock in order to minimise any contamination. The locations of the sample sites are marked on the GSI Quaternary sediment maps with a symbol and a unique sample number.

There was no predefined sampling grid, but at least one sample was taken every $8km^2$. When the terrain and geology are taken into account the density of the sampling grid was better than one sample every $8km^2$ resulting in over 250 samples. Much of the mapping area is covered by deep blanket bog or consists of outcropping rock where samples could not be taken, therefore the grid was increased elsewhere. Although it was felt that this did not provide sufficient data to enable quantitative textural analyses between the sediment types, the samples were useful for erratic carriage data.

Each sample was wet-sieved to produce particle size distribution curves, printed in Jordan 1997[b]. After sieving, clasts between 5mm and 10mm were retained for petrographical analysis. The petrography of each stone present in the sample was recorded, and the sum of each petrography was counted to produce pie charts of percentages for each sample (Jordan, 1997[b]). These percentages enabled quantitative analyses of the dominant petrography within each sample to enable an areal subdivision of tills and gravels into petrographically similar units. Stone counts also enabled erratics to be recorded for provenance purposes. Phenoclast petrography was determined using a x10 hand lens, a microscope and 10% dilute HCL when dealing with calcareous samples.

Sediment samples were also taken for micro-fossil analysis. It has been stated that the sediments in Clew Bay were deposited in a glaciomarine environment as part of an ice shelf that uncoupled from the bed as eustatic changes occurred, thus accounting for the clay laminae at the base of the till sequences (Dardis *pers comm.* 1995). To test this hypothesis, four samples were taken in these clay layers along the western side of the bay for foraminifera analysis in the University of Maine, Institute for Quaternary Studies. The existence of foraminifera would indicate that the sediments were laid down in a region of shelf seas, whereas the lack of foraminifera would suggest that they were not deposited in a glaciomarine environment (Lowe & Walker, 1987).

2.3.2.6 Trenching

Trenching was undertaken at the end of the reconnaissance mapping phase at locations where there were gaps in the exposure into the Quaternary deposits. Additional trenching was also carried out along geologic boundaries that were in doubt. Trenching was undertaken using an Hitachi EX60 on tracks, to enable bogland and softer sediments to be crossed. Depths of the trenches varied between 1.5m and 5m depending on the consistency of the material and the risk of slumping and infilling while the trench was being analysed. Samples were taken from each trench for wet-sieving (particle size analysis) and petrographical analyses. In this way a more complete reconstruction of the glacial patterns of the area can be carried out without having to rely on extant sample location.

2.3.2.7 Drilling

As with trenching, drilling was used to bolster the number of exposures and sample locations that were evident during the reconnaissance mapping phase. Drilling was carried out using the Geological Survey of Ireland drilling rig equipped with both wireline auger and continuous flight auger rigs to ascertain depth to bedrock, and in some cases the stratigraphy of the Quaternary deposits. In total 125.1m of drilling was carried out for this study. Samples where retained from the boreholes at regular intervals and also whenever the characteristics of the sediments appeared to change. These were used for wet-sieving (particle size analysis) and petrographical analyses.

2.3.3 Data Analysis

2.3.3.1 Petrographic Analyses

Petrographic analysis of samples collected from exposures, trenches and boreholes was carried out on all clasts in the 5-10mm size range that were retained after wet sieving. Clast petrography was recorded in a computerised spreadsheet (Excel) where the sum and percentage of each petrography was calculated. Pie charts were subsequently produced in CorelChart. These results are included on the maps as arrows indicating ice flow direction as inferred from erratics within the sample.

2.3.3.2 Fabric Analyses

Till fabric analyses are used in this research as a tool for the identification of the direction of ice movement at the time of till deposition. Till fabric is the arrangement of particles of any size in a till (Lowe & Walker, 1987). These particles include all sizes from boulders down to fine-grained clay particles. The correlation between clast dip/orientation and the mode of sedimentation was noted as early as 1884 by Miller, although the relationship was not quantified until the 1930's (Lowe & Walker, 1987). Till fabric analysis has subsequently become one of the most commonly used techniques in glacial geology (Boulton, 1971). The method relies on the assumption that the particles in the sediments are aligned so that their long axes lie either parallel or transverse to the direction of glacier movement, in a similar fashion to imbrication of clasts in a fluvial environment (Rust, 1972).

Till fabric analysis is generally carried out on pebble or larger sized clasts and has been used to infer both the direction of glacial transportation and the processes of deposition (Curray, 1956; Dowdeswell & Sharp, 1986; Mark, 1973; Mills, 1991). It has been shown that a sample of 25 pebbles is sufficient as this number provides a statistically reliable sample (Bennett & Glasser, 1996; Domack & Lawson, 1985; Woodcock & Naylor, 1983). The dip and orientation are measured for each pebble and only prolate clasts (those with axial ratios b\a < 2\3 and c\b > 2\3) are chosen. The orientations of these elongate shapes are found to display higher correlation with the direction of ice flow than more spherical clasts (Drake, 1974).

The till face must be cleaned back to a depth where it is undisturbed by weathering or cryoturbation. The sample area must also be of sufficient depth from the surface to avoid the effects of weathering and cryoturbation. Clasts were not measured if they were in direct contact with other clasts in the deposit as this may bias their dip and orientation. A similar effect of fabric bias will occur if clasts in the lee of boulders are sampled. The location of the sample site in relation to other local features will affect the samples and special note is taken of these in the field:

- proximity and form of deformation units such as fold structures, faulting and shear planes in the till;

- local bedrock relief, if known;
- sample situation in relation to glacial landforms as, for example, compressive and extensional forces are applied at the stoss and lee side of drumlins which may substantially alter the till fabric results.

There are several ways in which till fabric data can be plotted and analysed. Mark (1971, 1973) recommends beginning with a simple visual analysis of the data which is carried out by plotting the data from each clast onto a Schmidt equal-area lower hemisphere. The purpose of a preliminary visual analysis is to evaluate the statistical distribution of the data. If the points are bimodally or multimodally distributed certain approaches such as the rotational vector and eigenvalue methods should be avoided as the mean vectors will always lie between the modes (Andrews, 1971).

Curray (1956) proposes that four basic requirements should be fulfilled by the analysis technique used to process the till fabric data.

1. There should be a measure of central tendency or preferred orientation. This arises from an inclination to treat fabric data like a linear normal distribution where mean, standard deviation and variance are descriptive statistics. However, with circular data, an origin must be chosen to divide the circular distribution into a linear frequency curve, and this cannot be done *'a priori'*.
2. There should be a measure of dispersion that is independent of origin.
3. The results should be tested in terms of their statistical significance against a model of non-uniform or random data.
4. A model distribution of data, such as circular normal should be used to test the deviation within the till fabrics.

These requirements are best fulfilled by the eigenvector model (Mark, 1973) which is used throughout this study. This method treats each pebble dip and orientation as a single unit vector and uses this information to undertake three dimensional vector statistics using principal components analysis. The computer programme into which the data are input tests each vector for dips ranging from 0° to 90° and for azimuths ranging from 1° to 360°. After each iteration (or rotation in terms of spatial statistics) the length of the vector is recorded until the maximum vector is found. The angle of the vector is termed the eigenvector defined by the variance-covariance matrix while the length of the vector is termed the eigenvalue.

The eigenvectors, of which there are three (due to three-dimensional nature of the data) are labelled V_1, V_2 and V_3. V_1 refers to the direction of maximum clustering about the mean and V_3 to the minimum. In terms of till fabrics and glacial deposition, this implies that V_1 is the direction of maximum orientation, or statistically the most likely direction from which the ice was moving when the sediment was deposited, while V_3 is normal to the preferred plane of the fabric. The eigenvalues are labelled S_1, S_2 and S_3 and quantify the degree of clustering of the data about their respective eigenvectors and may be seen to summarise the fabric strength.

Woodcock and Naylor (1983) explored a test for randomness using the S_1, S_2 and S_3 values produced in the eigenvalue method. It was found that a shape parameter *C* could be calculated where $C = \text{In}(S_1 \backslash S_3)$. A perfectly uniformly distributed dataset would have $C = 0$ whereas distributions with low *C* values can be described as randomly distributed, which display no clear palaeo-flow direction. This correlation can be plotted onto a modified Flynn strain plot (Everdingen *et. al.* 1992) see Figure 2.2. In this diagram, uniform distributions are plotted where the x and y axes intersect, while those with increasing preferred orientation are plotted progressively farther from the intersection. Also included in this strain plot is a measure of the spatial form of clustering, whether locally clustered, or girdled. Benn (1995) reached a similar conclusion when analysing dataset randomness, although he named the clustering shape 'elongation index' (*E)* which was defined as $E = 1\text{-}(S_2{:}S_1)$. The elongation index is a measure of the preferred orientation of a fabric in the $V_1 \backslash V_2$ plane. Figure 2.2 is useful as it indicates the information which can be gained from a simple visual analysis of the data obtained in the field when attempting to determine the ice flow direction.

Eigenvalues (S_1, S_2 & S_3) have also been used by several authors as quantitative descriptors for the mode of deposition, whereby various till types are automatically classified according to their S_1 strength (Benn, 1995; Bennett & Glasser, 1996;

Boulton, 1971; Dowdeswell & Sharp, 1986; McCabe & Dardis, 1994). Dowdeswell & Sharp (1986) who compiled till fabric data from modern glacigenic environments in order to correlate fabric data with known depositional environments produced Figure 2.3 in its original form.

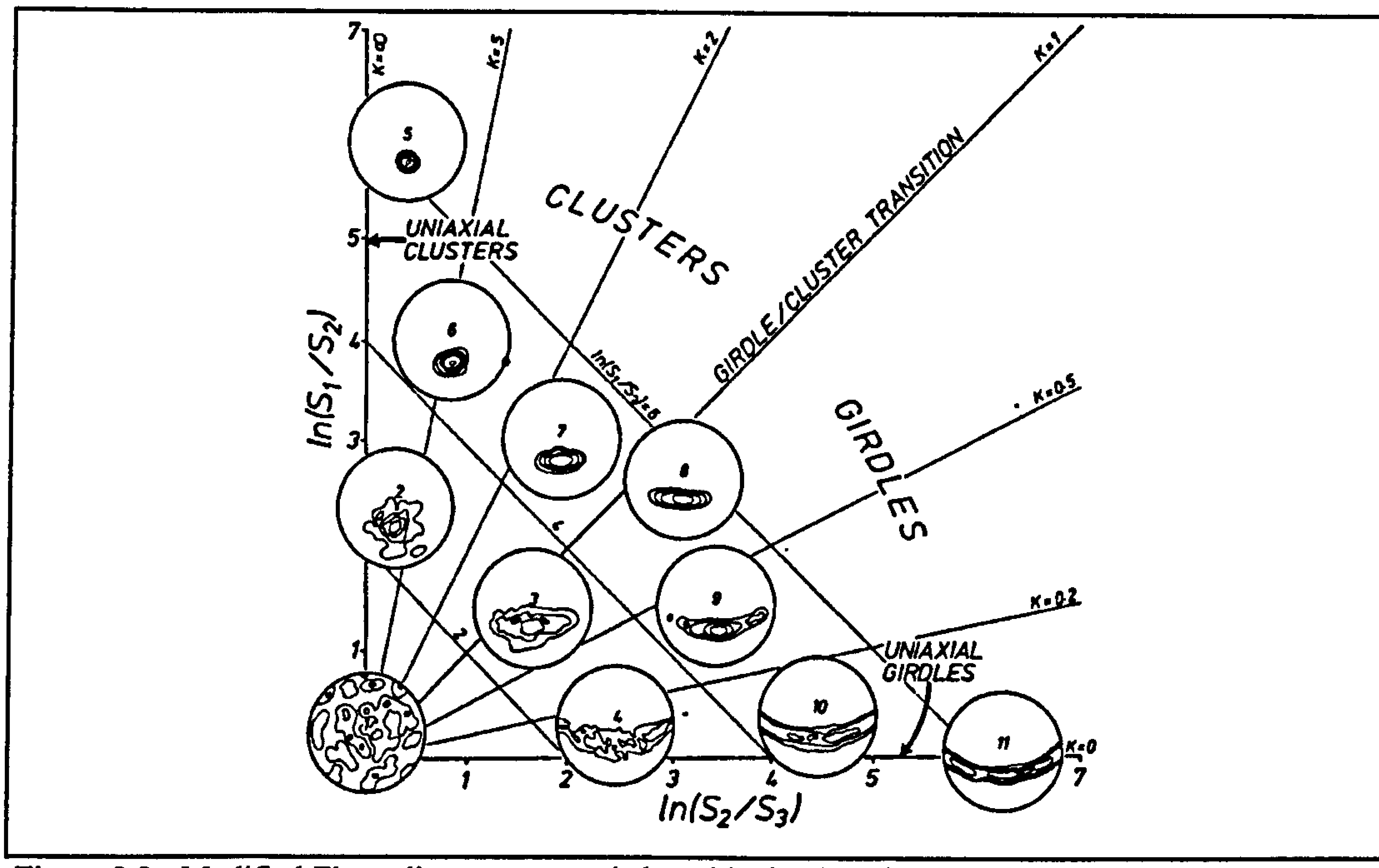

Figure 2.2. Modified Flynn diagram: two axis logarithmic plot of ratios of normalised eigenvalues S1, S2 and S3 with examples of fabric shapes included in the graph. (From Woodcock, 1977)

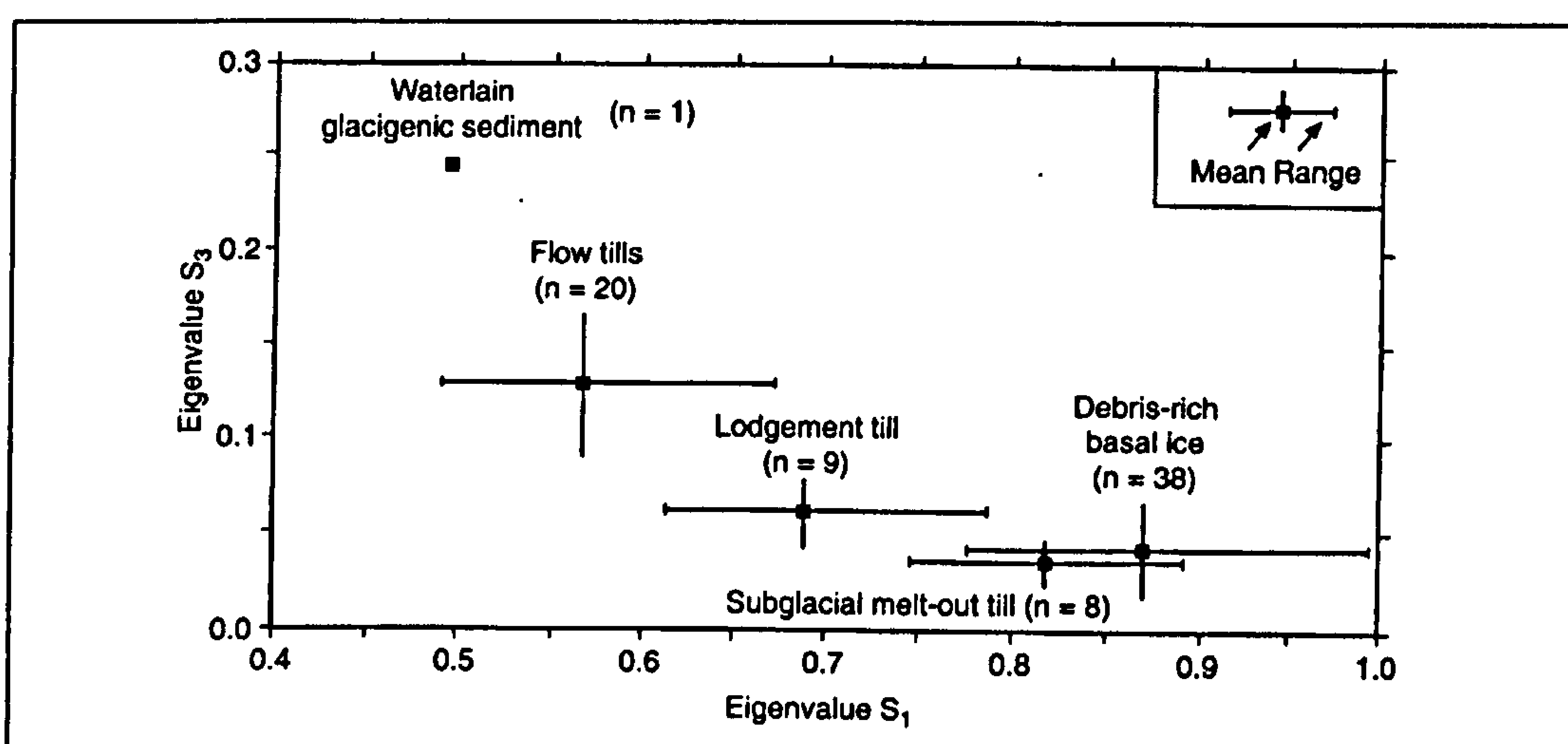

Figure 2.3. Plot of eigenvalues S1 and S3 as a method for differentiating till types, where *n* is the number of sample sites in modern glacigenic environments. (From Bennett & Glasser, 1996).

The eigenvalue method was chosen for the purposes of this thesis for a variety of reasons. As explained above, it provides useful data regarding both the dominant orientation and the degree of clustering of the three-dimensional datasets produced during till fabric surveys. Care was taken however to plot the data initially on an equal area projection (Schmidt equal-area lower hemisphere was used) in order to examine the data points visually before commencing statistical operations. For this reason, Schmidt equal-area projections are included with the contoured data and the eigenvalues and eigenvectors when till fabric data are displayed in the thesis. Modified Flynn diagrams and $S_1 \backslash S_3$ plots are also included to increase the interpretability of the results.

Also, the eigenvalue technique was chosen for this project as it has been used extensively by other authors (listed above) and this enables direct comparisons between the results achieved in this study and those obtained elsewhere in deposits from previously glaciated terrains.

The computer programme used to process the raw data was QUICKPLOT (Everdingen *et. al.*, 1992). Within this programme each sample was plotted on equal area projections while multiple datasets were plotted onto a modified Flynn diagram for comparisons. Ice flow directions which were indicated from till fabric analyses were included on the maps in symbol form (as arrows which bisect a circle) in a similar fashion to directions determined from striae or roche moutonnées.

2.3.3.3 Deformation and Shear Structures

As glaciers move over their substrate there may be coupling between the glacier and the bed material, be it soft sediment or bedrock (Hooke, 1998). If the material is composed of soft sediments, *i.e.* tills or gravels, deformation of the sediments (whether brittle, ductile, or a combination of both) may occur, depending on the sediments and the pore water pressures involved (Hart & Boulton, 1991; van der Wateren, 1995). Ductile deformation refers to folding of materials while brittle deformation involves sediments moving along discrete planes of failure, called shear planes or thrust planes. Table 2.4 is a summary of the various structures found in brittle and ductile deformation zones.

Deformation Type	Structure
Brittle	Ramp thrusts, flat thrusts, piggyback thrusts, overthrust step sequences, duplex imbricate thrusts, pop-up structures (formed by back thrusting), anastomosing jointing, conjugate faulting and thrust in asymmetric folds.
Ductile	Folds: open, recumbent, kink band, upright, overturned, box, inclined, isoclinal, overturned, chevron, sheath, disharmonic, dome, basin and periclines.

Table 2.4. Brittle and ductile deformation structures in glacial sediments. (Compiled from Benn & Evans, 1998 & Park, 1986).

The study of subglacial tills and their deformation has been well documented in the literature (*e.g.* Boulton, 1987; Clarke, 1987; Hart, 1995). Boulton (1979) discovered that nearly 90% of the motion of the Icelandic Breidamerkurjökull glacier may be accommodated by deformation of the soft sediments in the bed which has clear implications for any glaciological reconstruction undertaken through the analysis of soft sediments where there is evidence of deformation. An analogy can be drawn between what appears to be a chaotic assemblage of sediments in Clew Bay and a study undertaken by Brodzikowski and Van Loon (1985). Through systematic mapping of deformation structures, and linking these to the deformation processes which formed them, the authors were able to unravel the 'chaotic character' of the sediments in the Jaroszów area of Poland to reconstruct the ice flow patterns of the region.

Similarly, a regional picture of the forces which deformed the sediments was formed by recording the deformation and shear structures that are visible in many of the deposits in Clew Bay. This enabled the direction of ice flow during deposition to be determined throughout the study area. Once these forces are understood and plotted, their properties can be utilised to model the pattern of glaciation of the area. Features named as shear planes in this study can be defined as planes of weakness that are often characterised in the exposures as thin joints some of which contain a silt band.

Strain is the geometrical expression of the amount of deformation caused by the action of a system of stresses on a body (Park, 1986) or more simply, the change in size and shape of an object due to an applied stress field. There are four possible results when strain is placed on a volume of sediments, they can undergo dilation, distortion or rotation, or a combination of the three. Dilation occurs when the volume of the sediment changes, either in a positive or negative manner, due to tensile or compressive strains respectively. Distortion is the change in shape of the sediments, while rotation describes a change in the attitude. If the amount of strain is equal throughout the deposit it is described as homogeneous, with the result that primary parallel bedding, if any exists, will remain parallel after deformation. Heterogeneous strain describes unequal forces acting on the deposit, and this results in parallel beds becoming non-parallel and straight lines becoming curved when exposed to deformation. Clearly, heterogeneous strain is a closer approximation to reality. The concept of pure and simple shear must also be introduced at this point. If there is no rotation of the sediment mass during shear, it is called pure shear, but if there is a change in orientation, the process is described as simple shear, see Figure 2.4.

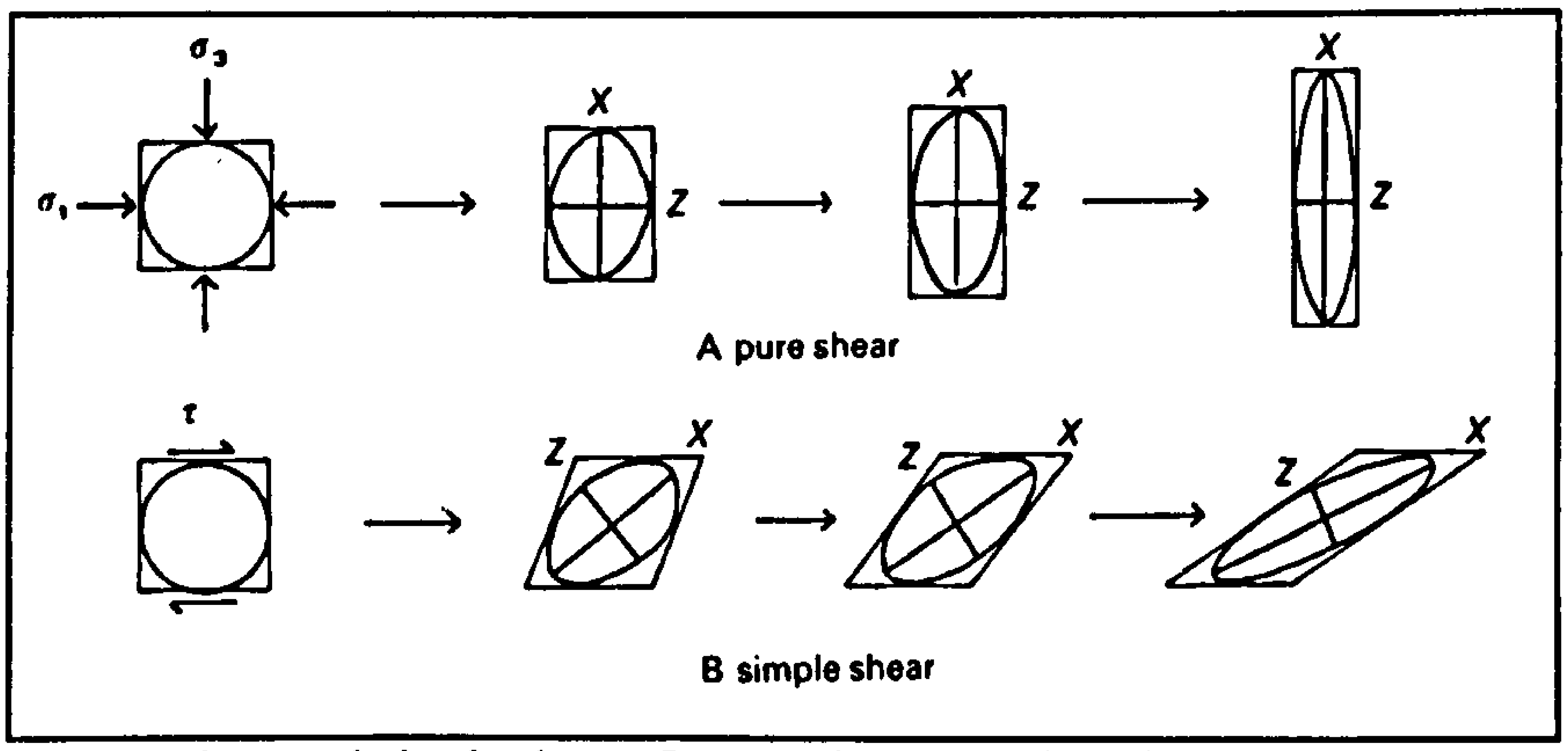

Figure 2.4. Pure shear and simple shear. In pure shear the orientation of the x and z axes do not change, whereas in simple shear, the axes rotate clockwise. (From Park, 1986).

Figure 2.4 is also of use as it demonstrates the idea of a strain ellipse, which can be used to reconstruct the forces and their stress vectors that acted on the sediments. Visually, the perfect circle refers to a sediment which has not undergone any form of deformation. When strains act upon the circle, as indicated by the arrows, it is distorted into a new form, thus reflecting the alterations that a deformed sediment has undergone.

A development of the strain ellipse above is shown in Figure 2.5. In this diagram the instantaneous shape change, or distortion, is described by the ellipse (Xi,Zi,) relating to each of the three shear types illustrated. The difference in the particle distribution between their initial state and their deformed condition is given as (Xf,Zf) and is described as finite deformation. The angle α refers to the amount of rotation the sediment has undergone in the direction of the strain arrow, and is measured in degrees. The arrows in the far right column give the strain vectors. Of special note are the quadrants, labelled 1-4 in the lower instantaneous flow ellipse. Quadrants 1 and 3 refer to the extensional zone of deformation while numbers 2 and 4 refer to the compressional zones (shaded in the first column of ellipses).

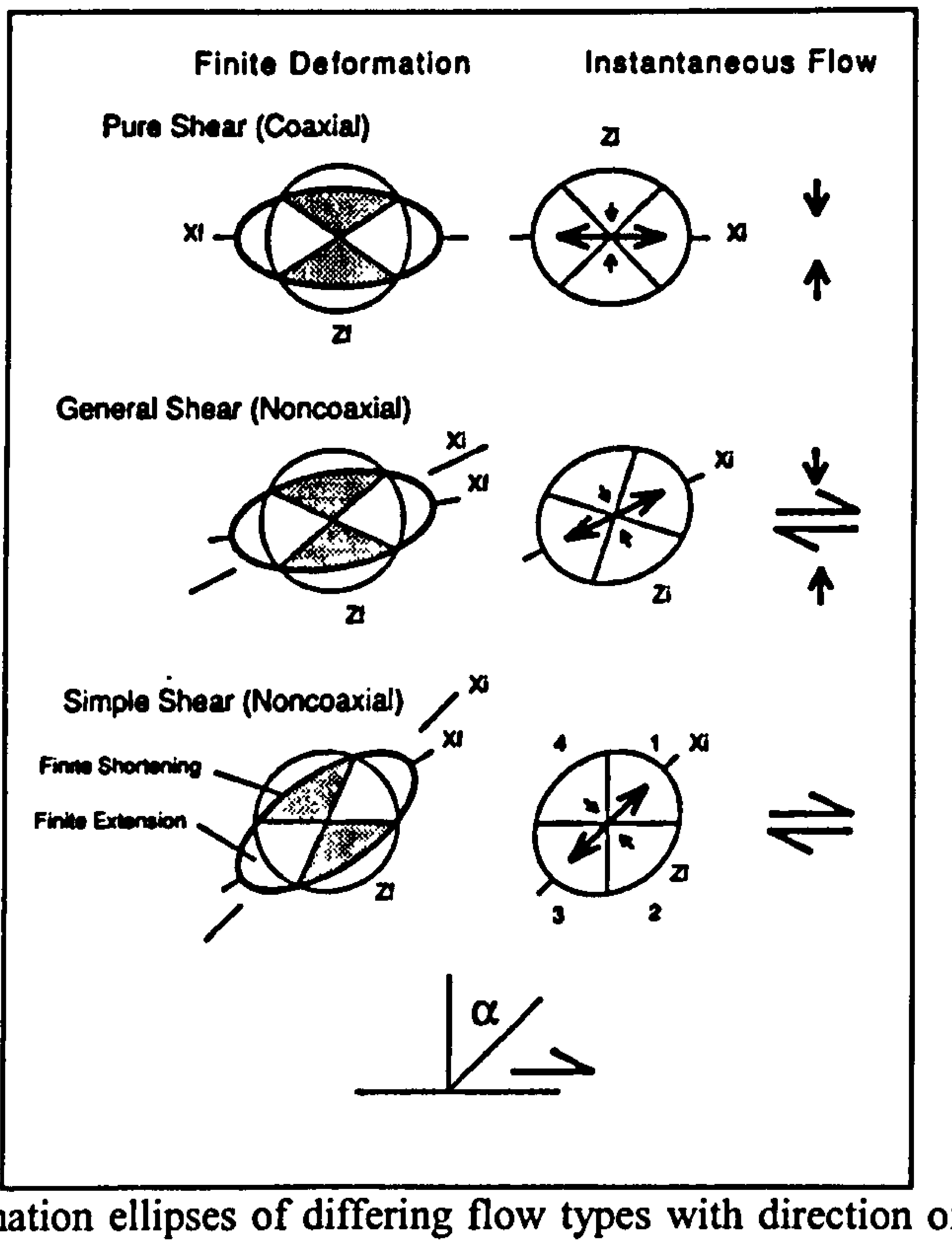

Figure 2.5. Deformation ellipses of differing flow types with direction of shearing shown. (From Hanmer & Passchier, 1991).

Analysis indicates that along the axis (Xi) where extension is indicated, one would expect shear-slip to develop. Alternatively, along the Zi axis, where shortening is indicated, one would expect tensile shearing to occur where the sediment is 'pulled apart' into conjugate fractures, boudinage and extensional crenulation features (Park, 1986, Van der Wateren, 1995). Systematic measurement of all shears and fracture zones in the sediments deposited in previously glaciated environments may be used to test this model and attempt a reconstruction of the glacial episode under which deformation occurred.

The methodology for measurement of the shear planes is relatively elementary. One cleans back the exposure where a shear plane is evident and records the largest dip, using a clinometer. The maximum dip is used to avoid taking the measurement at a point oblique to the shear plane. When the dipping bed curves in either a convex or concave manner, several measurements are taken along its full length. The vector perpendicular to direction of maximum dip (called the strike) is measured using a compass that has been corrected for magnetic declination. This is normal to the direction in which the shearing has taken place and may be assumed to be the direction of ice flow where the up-glacier side corresponds to the dip direction (as in till fabric measurements). Note must also be taken of the stratigraphical context of each deformation unit as they display different characteristics under different strain forces. For example, at low shear strains simple patterns of glaciotectonic deformation occur, such as overturned beds, at higher strains there may be highly attenuated folds whereas at higher shear strains again the till may become homogenised making it difficult to differentiate between a deformed (homogenised) till and an undeformed till (Hart, 1995; Hart & Boulton, 1991).

For the purposes of this study, each section containing deformation structures was drawn to scale before any measurements were taken as this enabled the structures to be plotted in three dimensions as the exposures (especially the coastal ones) were eroded. It is important to fully record all the structures both spatially and temporally to gain a full understanding of the glaciological processes that acted on the section as a whole. These processes may then be related to those catalogued in the other exposures in the area to gain a regional understanding of the glacial geology with the ultimate aim of ice sheet reconstruction.

Deformation structures were used both to provide information on the patterns of ice movement at the regional scale and, when analysed sedimentologically, to provide important evidence regarding the glaciological processes which acted to produce each landform under scrutiny. For example an analysis of the stresses a till undergoes during drumlin deformation may help to clarify their mode of formation.

2.3.4 Final Compilation

Once the final boundaries are drawn, following the iterative phases of initial compilation, aerial photograph interpretation and field mapping, they are transferred to film paper overlays. All other information including, roche moutonnées, striae, exposure locations, trench locations, drilling locations, sample locations along with vectors interpreted from till fabric analysis, erratic carriage and deformation structure analyses *etc.* were also included on their respective overlay bases. These overlays acted as stable bases when the maps were digitised.

2.3.5 Digitising the Quaternary Geology Information

Both the altered boundaries and the locations of point data from all four film paper overlays, consisting: a) the Quaternary sediments and ice flow vectors; b) morphological map; c) borehole and depth to bedrock data; and d) locations of outcropping rock, were digitised into a computer aided drawing (CAD) package. A customised version of AutoCAD (version12) was used. The digital nature of the data ensures that the maps are easier to query and alter whereby specific layers of data can be turned 'on' or 'off' and plotted at will to any scale. Each of the four film paper overlays was digitised individually and saved as a separate drawing file which could be combined and overlaid digitally at a later stage for printing or interpretation purposes.

2.4 SATELLITE AIDED GEOLOGICAL MAPPING

The methodology outlined in this chapter is a description of the techniques routinely undertaken when processing digital satellite imagery, and serves as a development from the general introduction to satellite remote sensing which was outlined in Chapter One. The methodological developments specific to this study in terms of the production of a Quaternary geology map are dealt with in full detail in Chapter Three. The allocation of a specific chapter to this section of the study enables full discussion to be given to the digital image processing methods undertaken in the context of each sensor under evaluation. Furthermore, it permits an interpretation of the techniques to be included in the same section for ease of reference.

The methodology followed in the course of this study involves a comparison and subsequent integration of the Quaternary geological information that can be mapped purely by traditional techniques as described above, compared to the speed and accuracy of mapping that may be achieved through the application various satellite sensors and digital image processing techniques. The purpose is not to choose between one or the other of the traditional or satellite methodologies, but to formulate a holistic procedure through which the current mapping process may be developed via the application of digital remote sensing techniques.

Digital image analysis was undertaken for two main purposes:

1. To map the aerial extents and patterns of Quaternary materials and morphological facies
2. To map the linear patterns of directional indicators such as drumlins and moraines.

2.4.1 Data Acquisition

Data acquisition is a relatively elementary section of the methodology, assuming that sufficient funds have been made available. Most image datasets can be purchased over the internet, or from commercial companies. Ideally, one would evaluate each and every satellite image sensor for its possible Quaternary geology information content, although this would incur high costs, both in terms of finance and time and is therefore unfeasible. Three image datasets were evaluated in this study, ERS-1 RADAR, and multi-temporal Landsat Thematic Mapper-5 (Summer and Winter). These were deemed to be representative of those commercially available at present. ERS-1 RADAR was taken to be representative of the active sensors such as RADARSAT (the Canadian system), JERS-1 (the Japanese system) and ALMAZ-1 (the Russian system) while the TM data are typical of the most commonly used passive multispectral sensors such as Landsat MSS (Multi-Spectral Scanner) and SPOT (Système Pour l'Observation de la Terre).

2.4.2 Image Processing System Selection

There is a large selection of digital image processing packages available 'off the shelf' at present. Each system has merits and relative disadvantages, both in terms of the graphic user interface (GUI) and processing algorithms employed, however, it must be stated that in general the software packages are remarkably similar. ERDAS Imagine v8.2 and ERMapper v5.5 were used in this study.

The selection of a suitable image processing system is limited by the time that is needed to familiarise oneself with the software and, more importantly, the cost of the software packages. The suitability of the software package must not be underestimated as the algorithm quality and the processing time required by each package for the same process varies. Both of these factors affect the speed of the mapping process and the level of information that can be extracted from the imagery, thereby affecting the quality of the geology map.

2.4.3 Image Display and Enhancement

2.4.3.1 Introduction

Each image dataset requires different digital image processing techniques to enable the geologist to extract the information within. Before deciding on which techniques to use, two tasks were undertaken. Firstly, the image statistics and histograms were viewed. This gave an indication of the spread of the raw data across the possible range of digital numbers (0-255 for 8-bit, and 0-65536 for 16-bit) and demonstrated the degree of clustering that must be resolved for display purposes. Secondly, the stretched imagery was viewed on-screen to assess the image quality and the level of preprocessing that was necessary before Quaternary geological information could be extracted from the data.

2.4.3.2 Digital Image Preprocessing

Preprocessing is the term given to image treatment that is carried out before a scientific user can interpret the data. This commonly includes a) primary cleaning, and b) registration / geo-rectification.

A) *Primary cleaning* is necessary when the satellite image is degraded through a mechanical error in the satellite. For example, if a detector is incorrectly calibrated or malfunctioning, the image will contain a sequence of lines which contain erroneous values. This is manifested on the image as striping. When this occurs, values have to be inputted to those pixels by the image processor. These values can either be dummy digital numbers, or can be derived from nearby pixels, in an effort to minimise the damage. Although the correction of striping has been referred to as a purely cosmetic operation (Lillesand & Kiefer, 1994) the stripes can pose serious problems for geologists if they interfere with the interpretation of linear features such as bedding. Striping is more prevalent in the shorter wavelength bands of Landsat-TM imagery, and as these bands were only used from the Summer dataset, destriping was only carried out on that image dataset.

B) *Image registration.* Raw remotely-sensed data are representations of the earth's surface in the form of a two-dimensional array consisting of rows and columns of digital numbers (pixels). The images must be processed to enable them to be represented on a planar surface, conform to other spatial data, and ultimately have the geometric integrity of a map. Rectification is the process of data transformation from one grid system into another using an *n*th order polynomial equation, where *n* is normally a number between 1 and 3. Resampling of the pixels must be undertaken because the pixels of the new grid may not align with those of the original grid.

Georeferencing is the process of assigning map coordinates to image data. By itself, georeferencing involves changing only the map coordinate information in the header file of the imagery. The data must be projected onto the desired plane, and referenced to the proper coordinate system. A map projection system is a design to represent a spheroid (the earth) on a plane surface. Flattening a sphere to a plane causes distortion to the surface, therefore each map projection system compromises accuracy between certain properties, such as conservation of distance, angle or area. The system used in this project is the same as that employed by the Irish Ordnance Survey; Transverse Mercator projection, Airy Modified spheroid, 1975 adjustment. Through the use of the same projection system, the digital maps (both raster and vector) can be easily compared in a Geographical Information System (GIS) and external datasets, such as Ordnance Survey topographic maps, can be integrated to increase the speed and ease of interpretation.

There are two methods used in digital image rectification. Correction can be undertaken using the flight parameters of the satellite platform at the time of imaging, or by using points of known geographic location on the ground (Ground Control Points) to which the image is referred. The latter method was used for this study because it provides more reliable results because as the platform parameters vary randomly (such as the attitude of the sensor platform) and are never truly known.

However, even if the attitude of the sensor is known, this method does not account for topographical variations that are meaningful for geological interpretation.

The choice and distribution of the ground control points (GCPs) are of paramount importance. The GCP's used were features that could be easily and definitively located on the satellite image to within a single pixel width, with corresponding full national grid references, such as road or rail junctions, or possibly field boundaries if it could be ascertained that they had not moved. Features such as river meanders, lake shores and coastal zones were avoided for obvious reasons. The distribution of the GCPs was also chosen so that they were evenly spaced across the image.

The number of GCPs is also an important factor to reconcile when rectifying an image. Each GCP takes a great deal of time to accurately locate, therefore there are the dual concerns of having enough GCPs to rectify the image exactly, versus the amount of time taken which is spent locating each GCP. A mathematical model to dictate the minimum amount of GCPs states that:

$$\frac{((t+1)\,(t+2))}{2}$$

where t = transformation order.

Polynomial equations are used to convert the original raw image file coordinates to map space coordinates. The complexity of the equation varies with the distortion of the imagery, the number of GCPs and their relative locations. The degree of complexity of the polynomial is expressed as the order of the polynomial. A transformation matrix of coefficients, computed from the GCPs is used in the polynomial equations to convert the coordinates. The aim, when calculating the coefficients, is to produce polynomial equations for which there is the lowest possible error when used to transform the imagery.

Each GCP influences the calculation of the coefficients. The distance between the polynomial curve and the GCPs is the RMS (root mean square) error, see Figure 2.6. On the image, the RMS error is the distance between the known GCP and it's transformed location *i.e.* the difference between the desired location of the pixel in coordinate space and the transformed location.

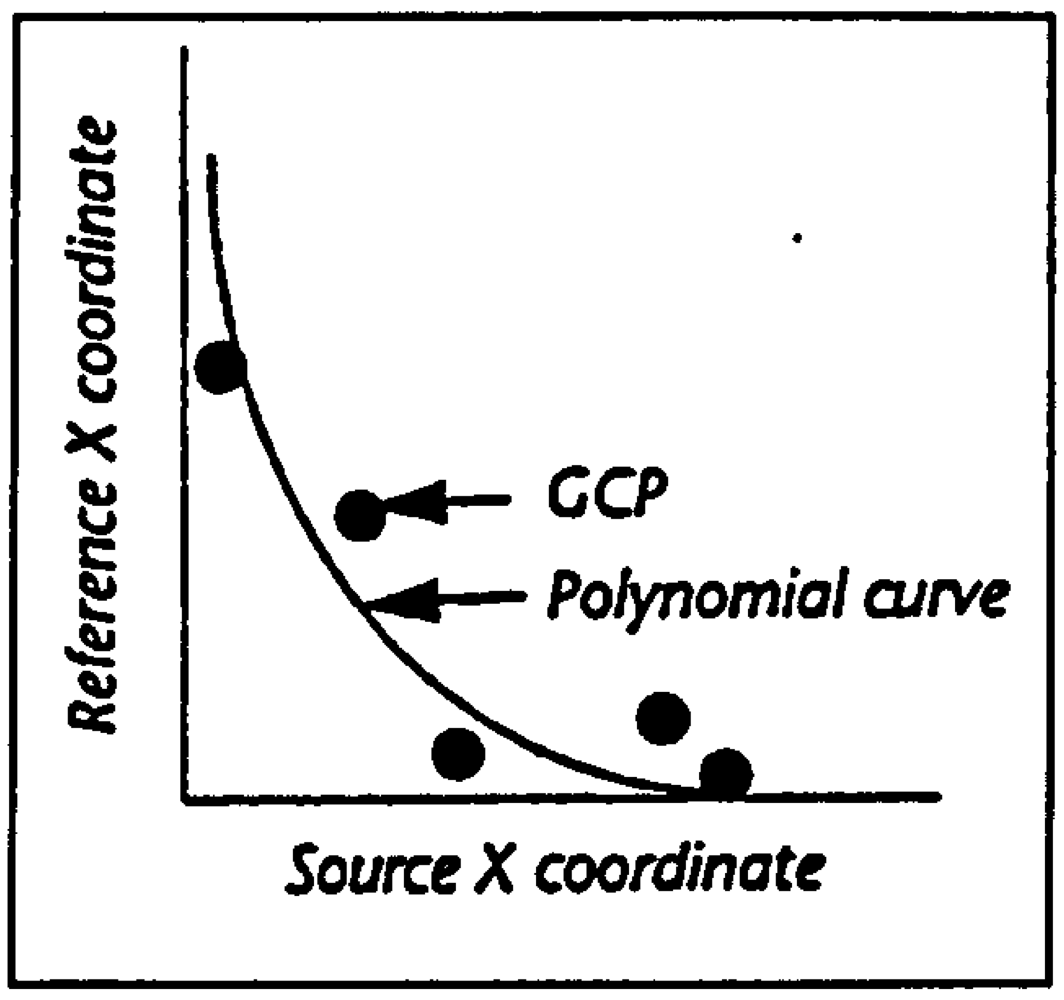

Figure 2.6. Polynomial curve plotted against hypothetical GCPs. (After ERDAS Field Guide, 1994).

The degree of tolerance in terms of the RMS error was decided in relation to both the imagery in question and the mapping scale. The field mapping scale in use throughout this study was 1:25,000, therefore with 1mm on the map equating 25m on the ground, it is reasonable to expect the digital image accuracy to be better than 25m. In fact, a 10m accuracy level was imposed to allow for the integration of datasets of higher resolutions at a later date, such as digital elevation models from the Irish Ordnance Survey, which have a gridding space of 10m. Therefore, the RMS error desired from the Landsat TM transformation matrix was less than or equal to 0.3. As this is a pixel measurement, and each pixel (excepting the thermal band) is 30x30m, this equates to a 10m accuracy tolerance. The RMS error tolerated from the ERS-1 radar data was 0.6, which would give the same level of accuracy as achieved from the TM data.

Once the transformation matrix was computed, and the order of transformation chosen, the process of resampling the data was undertaken. This involved 'transferring' the raw data onto a new grid (Figure 2.7). There are three possible methods for carrying out this task: a) nearest neighbour; b) bilinear interpolation; and c) cubic convolution.

a) The merit of the nearest neighbour technique is that it uses the original data values (digital numbers) in the output image by assigning the value of the pixel that is spatially closest to it from the original dataset. An additional advantage of this method is its low computational requirements, which results in shorter processing times. A corollary of this however is the fact that the resultant image has a pixelated effect, with some digital numbers dropped while others are duplicated. An important inference linked to this is that linear information, such as moraines or faults can become disjointed in the resampled image in contrast to their continuous patterns in reality.

b) Bilinear interpolation is more sophisticated than the nearest neighbour technique as it uses values from several surrounding pixels in the original image to produce a new digital number which is transferred to its corresponding pixel in the transformed image. In this system, data values from the four nearest pixels (in a 2x2 window) are used to calculate the transformed pixel values with a bilinear function. The advantages of this technique is the lack of subsequent pixelation resulting in a smoother image and the fact that there is a higher degree of spatial accuracy as this is a two-dimensional equivalent to the linear interpolation method. On the negative side however, the pixel values are averaged, in a similar fashion to a low-frequency convolution filter, which serves to smooth edges and average any high or low values which may be of interest to the interpreter.

c) The cubic convolution method is similar to bilinear interpolation resampling except that the surrounding 16 pixels are averaged, and an approximation of a cubic function is applied rather than a linear function. In general this process avoids the pixelation and disjointing which results from nearest neighbour resampling and provides a slightly sharper image than bilinear interpolation. However, a hybrid digital number is produced from the 16 pixels that are sampled resulting in highly altered (averaged) cell values. An additional disadvantage of this method is the large amount of processing time required for resampling. Therefore, bilinear interpolation was used as the method for resampling in this study as the image data are not as pixelated as in the nearest neighbour method and they are not averaged to the same extent as in a cubic convolution resampling algorithm.

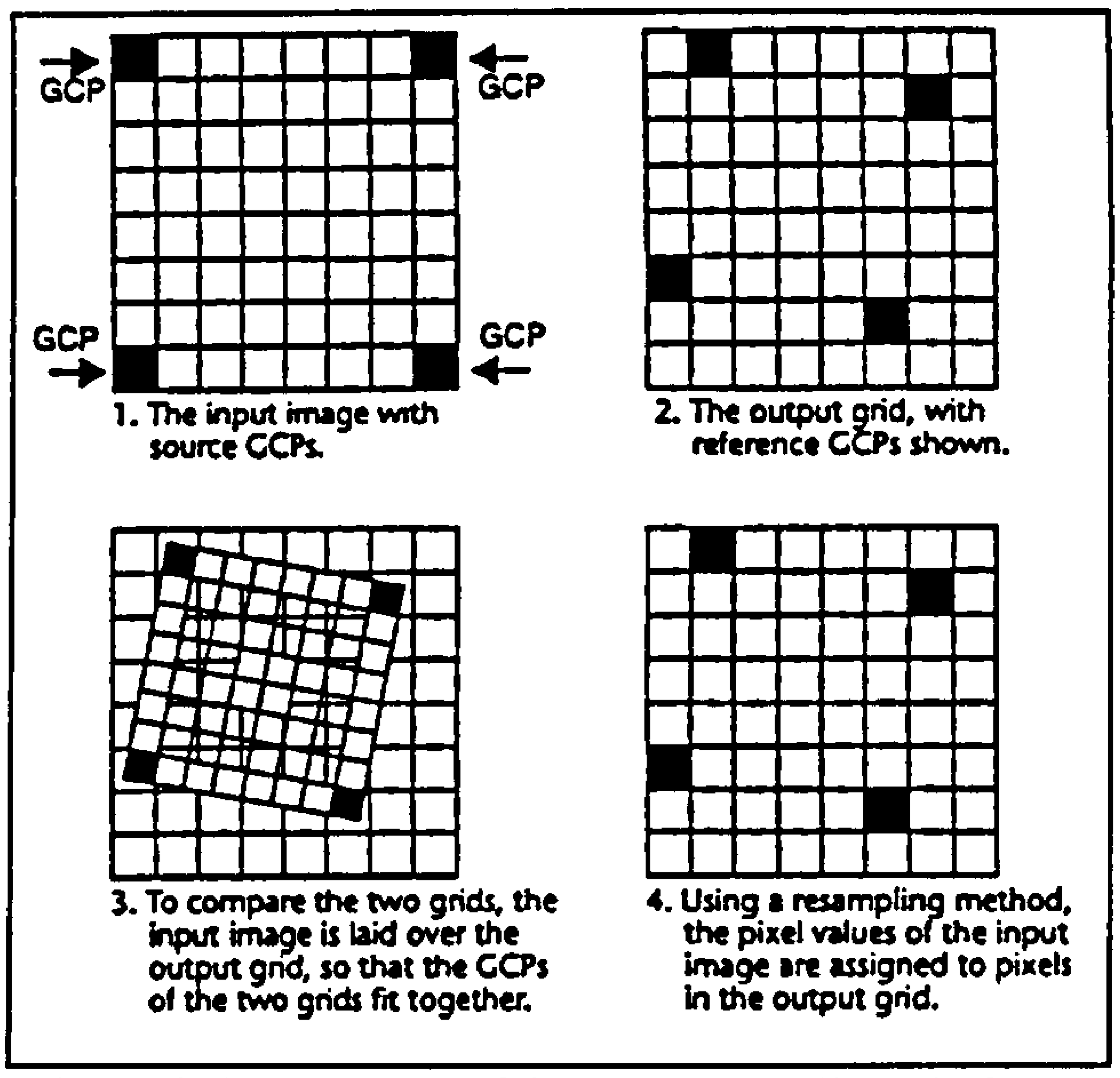

Figure 2.7. Illustration of the process of image resampling during rectification. (After ERDAS Field Guide, 1994).

2.4.3.3 Digital Image Processing

Even when the spectral information sought by the geological interpreter is visible within the image, it is not always possible to extract this information readily (Gillespie *et al.* 1986). Image processing is the method used to reveal the information in the image dataset for interpretation purposes. There are numerous digital image processing techniques available to extract the information content from the satellite imagery. These techniques are refined for each satellite sensor, each individual dataset, and each application. Rather than simply pressing icons on screen in order to run the digital image processing algorithms which are supplied with each software package in the expectation of producing an interpretable image, it was more efficient to begin by analysing both the image data and the reflectance properties of the earth surface features under scrutiny, and to subsequently choose which image processing techniques were most appropriate for the given application.

A complication, which had to be resolved in this study, is the fact that two conflicting sets of information are required from the satellite imagery, resulting in the need for two contradictory approaches to the digital image processing methodology. The two approaches are as follows.

1. To eradicate all vegetation reflectances (and their camouflaging / masking effects) and concentrate on enhancing features primary to Quaternary geology mapping, such as the geomorphology. Excessive backscatter from vegetation will serve to mask any geomorphological features.
2. To enhance the radiance patterns from the vegetation. Working on the assumption that vegetation growth (encompassing both the vegetation type and its state of health) is partly dictated by the subsoil conditions, the resultant image can be used as a basis for interpreting subsurface drainage characteristics, and by inference, the sediment type.

Before any image enhancement or interpretation was undertaken, an evaluation of the digital image data was carried out to assess the quality of the data and the degree of digital image processing that was necessary. The first such data evaluation method was a review of the summary statistics of the imagery. Although providing no actual information regarding the information content of the imagery, it enables the statistical distribution of the data, the level of skewness *etc.* to be established. Generally satellite imagery is normally distributed (Gaussian), although it is bi-modal in some bands if there is cloud cover or if there are water bodies. Multi-modal data are an indication of heterogeneity within the scene, *i.e.* a number of contrasting landcover types (in terms of their spectral reflectances). This preliminary investigation indicated the amount of contrast stretching and atmospheric corrections necessary for optimum display.

The best method for image evaluation was to display it on screen. The process of image display is much the same as that employed by television systems. The image on screen is made up of combinations of three colours, red, green and blue (the RGB system). Each of these three are produced by a different gun in the cathode ray tube of the display device or monitor. Through combinations of these three colour guns, a full colour palette is available for display. However, due to the statistical spread of the digital numbers in a raw satellite dataset, the image displayed on screen would be too dark to distinguish any features unless enhancement was undertaken. Although Landsat TM has an 8-bit radiometric resolution (ERS-1 has 16-bit radiometric resolution) entitling digital numbers from 0-255 to be used, the full range of these values is rarely utilised as few scenes will include landcover types from both the darkest and brightest ranges of the sensor in that particular band. The concept of histogram enhancement involves 'stretching' those digital numbers that have been sensed in order that they may fill the entire dynamic range available within the specifications of the display device (Figure 2.8).

The process for stretching the contrast of the data is undertaken using histograms. The stretch need not be equal across the input range, which means that areas of interest can be highlighted, and unwanted data can be visually discarded with ease. By performing this operation interactively on screen with one display gun being altered at any one time, the optimum image can be achieved in a short space of time. The final result of this procedure is to refine the image so that areas of interest are displayed more clearly, while simultaneously reducing the contrast in the remainder of the image thereby making the image more interpretable for the given application.

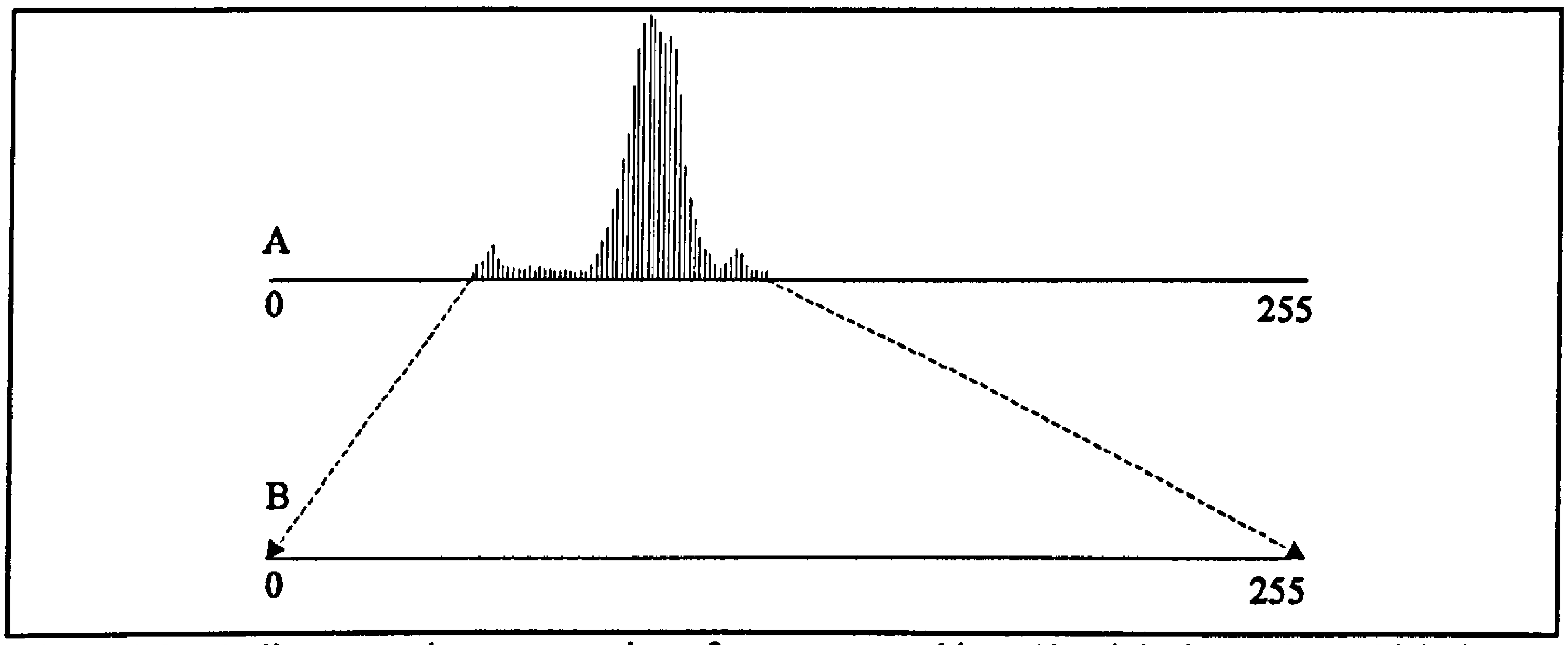

Figure 2.8. A diagrammatic representation of contrast stretching; A) original raw data which do not extend the full 8-bit range, and B) the digital numbers have been stretched to fill the entire dynamic range which may otherwise be left unused. The Y axis represents the data frequency for each digital number.

The range of colours available is limited by both the radiometric resolution of the imagery and that of the display device. However, if interpretation is undertaken from hardcopy format (printouts) then the relevant resolution is that of the printing device. During this study, interpretation and digitising was carried out on-screen, while hardcopies were used only for demonstration purposes and fieldwork. This methodology was followed due to the flexibility of the image processing software that enables panning and zooming into areas of interest for detailed analyses and interpretation combined with the option of small scale synoptic views when regional analyses are required.

As every display device is limited to three colour guns, a maximum of three bands of data can be viewed simultaneously on the computer monitor (while Landsat TM comprises 7 bands of data). If the red, green and blue bands of the TM sensor are displayed through the red, green and blue guns respectively of the display device, the result is a true colour image of the area. This approximates the landscape as it would be seen from orbit with the naked eye. False colour composites are produced by combining spectral bands outside the range of normal human vision. The unusual colour scheme produced in a false colour composite image requires detailed knowledge on the part of the analyst before interpretation can be undertaken. For example, a false colour infrared image composed of bands 4, 3 and 2 of the TM sensor (infrared, red and green respectively) displayed through the red, green and blue bands respectively will have the following results; vegetation reflects very strongly in the near infrared and absorbs a high percentage of visible light, thereby appearing as various shades of red. Water acts like a blackbody in the infrared and also absorbs nearly all incident energy in bands 3 and 2, so bodies of standing water will be black. Soil with a high moisture content will reflect partly in bands 3 and 4 producing a cyan colour on screen.

With seven bands to choose from in Landsat TM data there is always the problem of which band combinations will provide the optimum information display for the purposes of geological interpretation. Each author appears to have their own preferences such as bands 5, 4 and 3 (Siegal & Gillespie, 1980), bands 4, 5 and 7 (Marsh *et al.* 1995), to those who prefer to interpret from a single band rather than any set of combinations (Drury, 1986). There are three main methods for deciding which band combinations will be useful for a given application:

1) One can experiment with every band combination by displaying them on screen and evaluating the results. This is a time consuming process and does not account for *a priori* knowledge.
2) The second is to approach the problem with a 'ground up' approach where knowledge of the reflectance properties of the landscape features of interest are used to define which band combination will be used for interpretation.
3) Alternatively, the image statistics can be used. An Optimum Index Factor (OIF) ranks all possible three band permutations of the six bands (the thermal band is generally omitted because of its poor spatial resolution) based on the amount of total variance and correlation within and between the band combinations (Jensen, 1986). The three bands with the highest OIF will generally have the most information, as measured by variance, with the least amount of duplication, as measured by correlation. The OIF is calculated using

$$OIF = \frac{\sum_{k=1}^{3} S_k}{\sum_{j=1}^{3} Abs(r_j)}$$

(After Jensen, 1986)

where S_k is the standard deviation for band k, and r_j is the absolute value of the correlation coefficient between any two of the three bands being evaluated. In general the best combinations include one of the visible bands (TM 1, 2 or 3), one of the longer wavelengths bands (TM 5 or 6) and TM band 4 (Jensen, 1986). These bands can be displayed through whichever colour gun combinations are preferred by the image interpreter. Despite the statistics involved in this operation, the combination with highest information content, as defined by the OIF, may not necessarily contain the information sought by the analyst, therefore detailed visual analyses of the results must be undertaken. For this reason, the second approach was used during this study.

The multidimensional nature of the imagery illustrates one of the problems encountered when working with multispectral data. The number of bands in the dataset may not equal the dimensionality of that dataset. In general, multispectral datasets have more spectral bands than there are dimensions within the data (Jensen, 1986). Therefore it may not be possible to display the required information in the RGB system. It is for these reasons that Principal Components Analysis (PCA) was undertaken during the course of this study.

PCA (also known as Karhunen-Loeve analysis) works on the premise that spectrally similar bands in a multispectral remotely-sensed image are generally correlated (Mather, 1983). In simple terms, this means that certain bands in the dataset are 'seeing' and recording the same information, although in different ways. The implication of this is that there is an amount of repetition of information within the image datasets that inevitably leads to data loss. For example, if two bands (X and Y) are perfectly correlated then their values will plot in a straight line in a graph of X against Y (Figure 2.9). Therefore these two datasets can be plotted along that single line |AB| thereby reducing the dimensions of the data while still retaining the same amount of information.

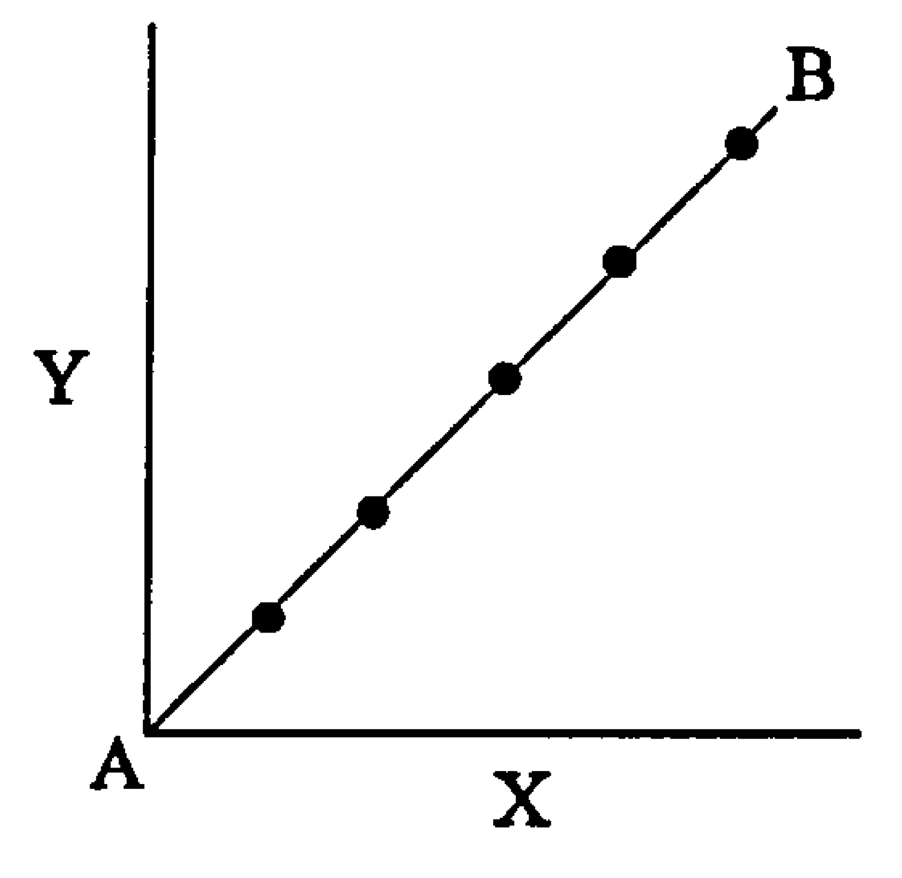

Figure 2.9. Graph of perfect correlation between two bands of multispectral imagery, X and Y. (After Mather, 1993)

Even if correlation between the bands is not perfect, as in reality in TM imagery, there is still a dominant direction of variability. This variability is expressed in the form of an ellipse when the two bands are plotted on a graph (Figure 2.10). The two maximum directions of variability on such a plot are defined by the major axis |AB| and the minor axis |CD|. These are the new components of the dataset. The image produced by plotting the new components will expose any variability in the data more clearly.

The scatter of data points, as in Figure 2.10 below, can be enclosed by an ellipse whose shape is defined by the variance-covariance matrix derived from the spectral bands. The principal axes of these ellipses are defined by a set of quantities called eigenvalues, while their orientations are defined by the eigenvectors. The data are scaled and rotated into a new (Cartesian) coordinate system that is defined by the eigen components calculated from the original data. Mather (1993) has shown that the first three components of the PCA may contain over 95.5% of the data, which illustrates the data redundancy within many multispectral image datasets. Nevertheless, it must be noted that the remaining data in the other components may contain information of interest and they should therefore be displayed on screen to assess their contents. One of the disadvantages of this process is that the colours on the PCA image do not relate to any known qualities, and may require a large amount of interpretation. Also, the unusual 'psychedelic' colour schemes produced by a combination of three of the components tend to confuse those unfamiliar with the process of PCA. Additional disadvantages include the amount of intensive computing time necessary, which is compounded by the additional filespace required by the newly created dataset (in some software packages).

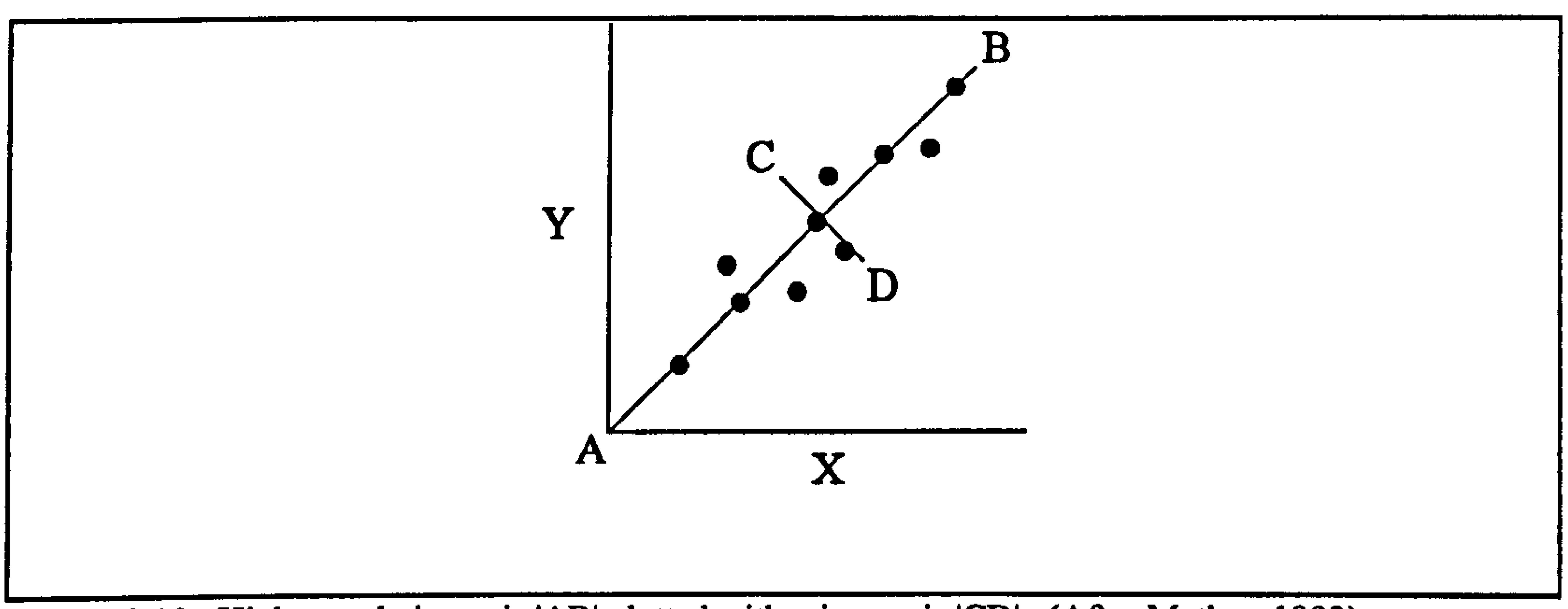

Figure 2.10. High correlation axis |AB| plotted with minor axis |CD|. (After Mather, 1993)

A further problem, which has to be accounted for in any remote sensing methodology, is the concept of information extraction from several diverse datasets. The method that was used to integrate chosen aspects of various digital image datasets was Intensity Hue Saturation (IHS) transformations. This model uses intensity, hue and saturation values to explain and display colours as a cone rather than the traditional RGB cube (Harris *et al.*, 1990) see Figure 2.11. Hue is the dominant wavelength of colour that we see (such as green, red *etc.*) while saturation is a description of the purity of the colour, *i.e.* whether it is a pastel shade or not. A pure colour is 100% saturated. The intensity component is a measure of the brightness of a colour, and is often equated with the actual spatial content of the imagery.

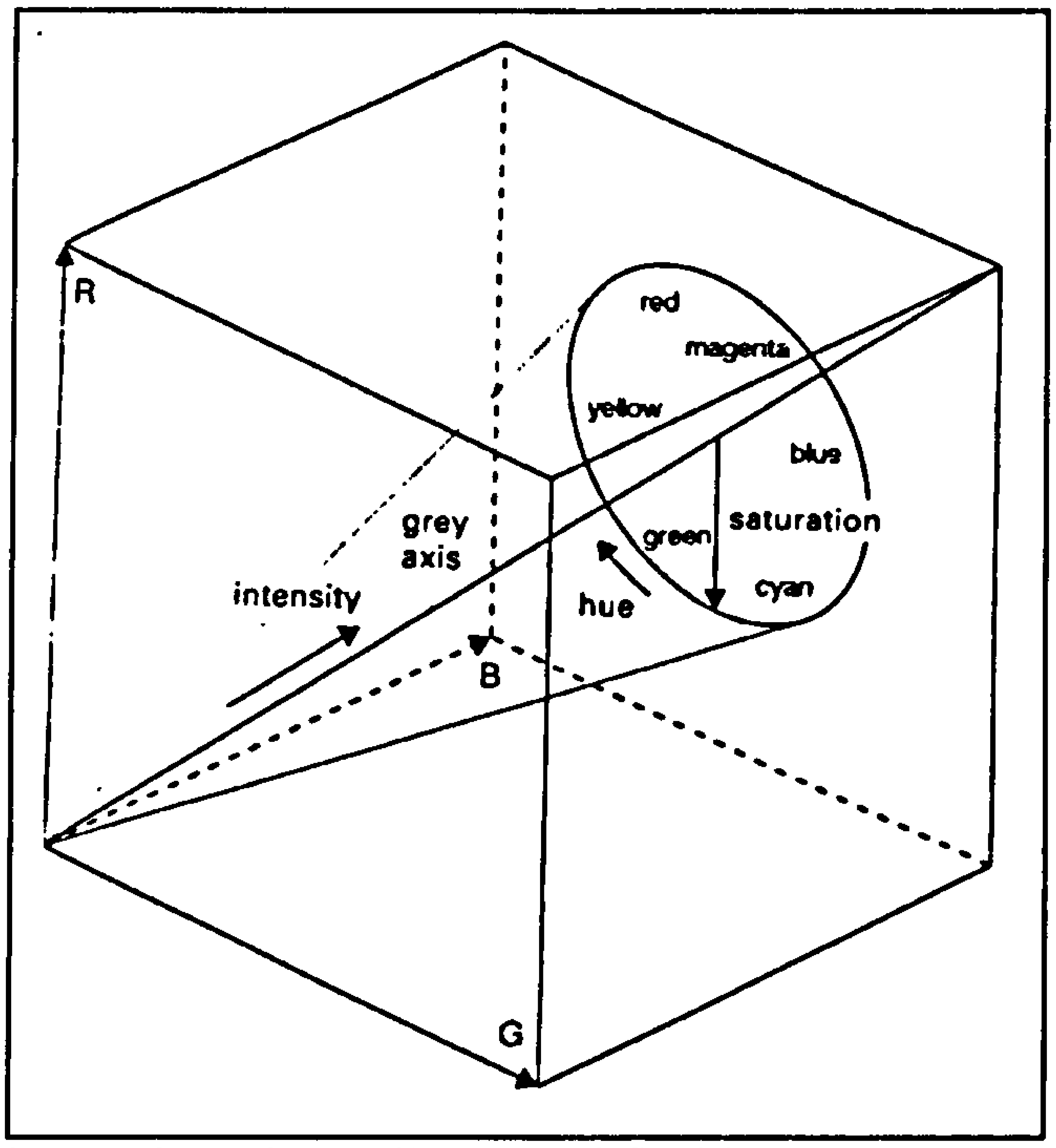

Figure 2.11. Intensity Hue Saturation (IHS) cone as defined in the RGB colour space cube. (After Drury, 1993).

IHS transformations were used in two ways. Firstly, the RGB display was transformed to IHS and simple histogram stretching is applied to each component before the data are transformed back to the RGB mode. This served to stretch the display of the data in a way that is not possible in a pure RGB coordinate system. The data are transformed back to RGB for ease of interpretation. Secondly, an IHS transformation was used in a more complex manner. Before the reverse transformation, a grey-scale image with a higher spatial resolution than the multispectral dataset (or a different sensing technique) may be inserted in place of the intensity component (Grasso, 1993). After the reverse transformation, the image should retain its initial spectral qualities, but have the increased spatial resolution of the grey-scale image. This process was carried out using the spectral qualities of the Landsat TM and the textural and spatial qualities of the ERS-1 imaging radar data.

There are certain digital image processing techniques such as atmospheric correction and band ratioing which are generally recommended in the textbooks as applicable under most circumstances (Barrett & Curtis, 1992; Cracknell & Hayes, 1991; Drury, 1993; Jensen, 1986; Mather, 1993). Although neither of these methods was carried out in this study, it is felt that their omission must be explained. Atmospheric correction is utilised when multitemporal imagery is to be quantitatively analysed, or where a single set needs to be corrected for cosmetic purposes before information extraction can be undertaken. Quantitative analyses are not required in geological interpretations of this type where relative differences in radiance values are suitable for distinguishing both landform types and areas of homogeneous vegetation, also preliminary visual evaluations indicated that correction was unnecessary for cosmetic purposes. Although the shorter wavelength bands in the Winter TM imagery do suffer from haze and other atmospheric scatter, this cannot be suitably resolved by atmospheric correction. Moreover this interference was unimportant, as these bands are not used in the geological interpretation methodology utilised in this study.

Band ratioing involves dividing the digital numbers of one band by those of another, and has a number of uses in the field of geology. For example, a high reflectance for all minerals is found in TM band 5 while the molecular rotational effects associated with clays and other hydroxylated minerals results in their absorption in band 7, therefore, by ratioing band 7 against band 5 clay-rich rocks will show up as dark areas (Drury, 1993; ERDAS Field Guide, 1994; Jacobberger & Hooper, 1991; Jensen, 1986). Although this would prove useful for certain aspects of this study, the main disadvantage of ratioing far outweighs any of the benefits. One of the main consequences of producing ratios is the reduction of shadowing effects in the image (Figure 2.12) however, the expression of topographic features is used for the interpretation of geomorphology, which is of prime importance for geological mapping thereby proving that band ratios should not be used in the context of this study.

The methodology for processing digital satellite imagery varies with both the application and the dataset being analysed. ERS-1 RADAR captures data in a different way to the passive sensors onboard the Landsat series of satellites and therefore different image processing techniques must be applied. One of the commonly accepted drawbacks of radar data is the fact that it is plagued by point and volume scatter and signal interference (Cole, 1992; Kingsley & Quegan, 1992). These combine to result in a low signal to noise ratio which produces the characteristic 'salt and pepper' effect seen on radar imagery (Echard, 1987).

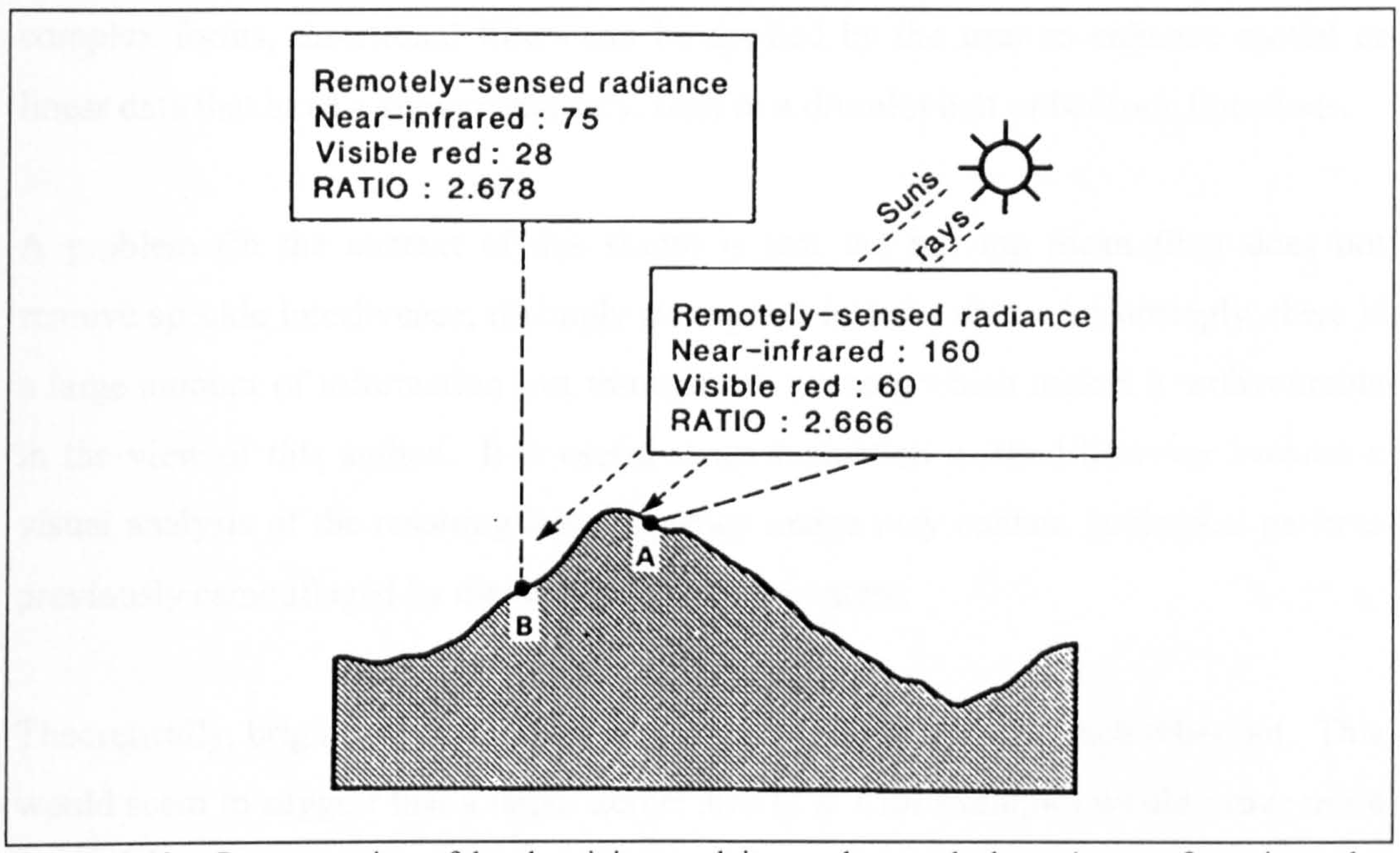

Figure 2.12. Representation of band ratioing, and its results on shadows (areas of varying solar irradiance). (After Mather, 1993).

All of the above interfere with the purity of the data, and consequently with the quality of the information acquired during interpretation. It was therefore necessary to enhance the imagery by reducing the effects of the interference. Several methods are available within the radar modules of the image processing software and a number of additional techniques were attempted.

The most basic enhancement technique (following standard contrast enhancement, as previously described) is that of filtering. A moving mean filter (low pass) consists of a matrix of numbers which is passed over the image array while the pixel being operated on, at the centre of the filter kernel, is replaced by the arithmetic average of all the values within the window. By changing the values and the dimensions of the filter kernel variable results can be achieved. The effect of this filter is to smooth the image and reduce any pixelation that may be evident. Although this is useful and necessary for many mapping scales, it reduces the high frequency component of the imagery resulting in a loss in some large scale detail. More complicated low pass filters exist which have weightings to reduce the averaging effect to the data values and yet smooth the image. Filters can also be used to increase the high frequency component of the data and enhance any fine detail in the imagery. In their more complex forms, directional filters can be applied by the user to enhance spatial or linear data that have a known tendency, such as a drumlin belt or bedrock lineations.

A problem (in the context of this study) is that the moving mean filter does not remove speckle interference, it simply averages it into the data. Accordingly, there is a large amount of information lost through this process which makes it unfavourable in the view of this author. It is useful as an evaluation method however because a visual analysis of the resulting low-frequency image may contain geological patterns previously camouflaged by the higher frequency content.

Theoretically, bright and dark pixels within the kernel will cancel each other out. This would seem to suggest that a larger kernel size (7 x 7 for example) would prove more successful at eradicating the 'salt and pepper' effects. However, this would simply average the values out even more, thereby smoothing the image and decreasing the high frequency content. This is contrary to the requirements of the study. Rather than using a larger filter kernel, the methodology followed in this study was to use several passes of a 3 x 3 low pass kernel.

A median filter was also passed over the raw radar data in an attempt to reduce the speckling effects. This algorithm operates by ranking the digital values of a user-defined area (the filter kernel array) in sequential order. The pixel at the centre of the kernel is replaced by the mode value *i.e.* the values at the centre of the ranked distribution. The advantage of this process over the averaging filter is that the original data are retained while extreme values are discarded.

Adaptive filters, which work by weighting the operating functions with the data on which they are working were also used as a method for reducing the interference in the radar imagery. The two filters used in this methodology are a) local statistics filters and b) sigma filters. These use the statistical distribution of the digital number values to estimate the output pixel value. The local statistics filter assumes that the mean and variance of the centre pixel within the moving window is equal to the mean and variance of all pixels within that window. The size of the window is user selected.

The sigma filter bases its calculations on the likelihood of a Gaussian distribution *i.e.* it assumes that 95% of the data are within two standard deviations, or a two sigma range of the mean (Shaw & Wheeler, 1985). The filter kernel size, range of standard deviations and coefficient of variation are user-specified variables. The filter operates by replacing the pixel at the centre of the moving window with the average of digital number values within the defined range. Consequently, extreme values are replaced by others that fall within the normal distribution expected of the data. This serves to reduce the effects of high point-reflectors such as dihedral reflectors by replacing them with values within the normal range as defined by the coefficient of variance. The results obtained by the processed described above are detailed in Chapter Three.

2.4.4 Information Extraction

Once the digital satellite images were processed to reveal geologically relevant material, the procedure for information extraction was undertaken. Digital information can be distinguished through automated or manual methods. Thus far, studies dedicated to automated classification procedures of generic terrain features have proved unsuccessful (Graff & Usery, 1993; Wu *et. al.* 1993) with results falling short of maps produced through traditional interpretation by photogeologists. For this reason geological interpretation was carried out in this study by manual means rather than attempting to develop automated techniques.

Interpretation can be carried out either by completing the image processing and subsequently printing hardcopies to work from, or by working directly with the image on-screen. The latter method was chosen for three main reasons; 1) unless photographic quality prints are available there will be a substantial reduction in image quality (compared to the high resolution display system) which is inevitably followed by poorer quality interpretation; 2) digitising on-screen allows more flexibility to view regions of interest and to zoom in or out to gain a variety of perspectives of the area, from the detailed to the synoptic; 3) by digitising directly one is working in digital format and by-passing the need to use hardcopies thereby reducing the risk of errors and increasing the compatibility with other digital datasets for the purposes of comparison.

Quaternary geological features were interpreted and digitised using the vector annotation and overlay modules in ERMapper and ERDAS Imagine. This enables lines and symbols of chosen colour and thickness to be drawn, delineating both points and features of interest. Interpretation was undertaken using standard photo-geological techniques (Paine, 1981; Verstappen, 1977) as outlined in Section 2.3.1.3 which deals with the methodology of morphological mapping from aerial photography.

2.5 DIGITAL INFORMATION INTEGRATION FOR INTERPRETATION

The task carried out in this phase of the research was to integrate all the information obtained from both the traditional mapping and the satellite remote sensing procedures so that the data could be analysed in a holistic manner. For this reason it was necessary to integrate the lineation map produced from the satellite imagery with the information (such as striae, erratic carriage, till fabric analyses and deformation shear analyses *etc.*) gathered through the traditional techniques described above.

The data integration was achieved using the GIS functionality of the image processing software packages combined with the drawing package, AutoCAD v12. The

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The second approach, which uses glacial isostatic rebound to gauge the locations of ice masses, was not adopted because it has been stated that '*the north Mayo sites are the only raised glaciomarine sequence documented from the west of Ireland*' (McCabe *et al.*, 1986 p.82). Moreover, whether a deposit is glaciomarine is interpretation and thus prone to interpreter-bias. Furthermore, it has even been argued that relict beaches above sea level near a diminished ice mass may in part be due to the gravitational attraction of the ice upon the ocean, and it is therefore difficult to separate these instantaneous effects from isostatic components (Clark, 1976). Moreover, information on eustatic changes is poor for this period (Clark, 1980), and in any case it has been suggested that sea level changes cannot be measured anywhere (McCabe *et al.*, 1986). More fundamental questions regarding this approach have been asked by Andrews (1982) such as how far the deformation of shorelines mirror former ice sheets? In short, these data do not exist for west Mayo, and even if they did, there is a large degree of scepticism regarding their validity for ice sheet reconstruction.

By default, this leaves the third approach that uses glacial geological data to reconstruct former ice sheets. A review of this methodology was carried out by Kleman & Borgström (1996) where they define the process of glacial inversion where 'time-slice ice sheet flow patterns are extracted from the patchy and partly overprinted landform record in former ice sheet areas'. Although elements in the geomorphological and geological record aligned parallel to flow are potentially the most powerful tools for reconstructing palaeo-ice sheet flow patterns and mass distribution, an inversion model is required to extract the information from the metachronous nature of the landform systems which contain inherent patchiness and complexity.

This model is important because it recognises that older glacial landscapes may have been preserved in many glaciated areas that were previously thought to contain only landforms from the late stages of the last glaciation (Kleman, 1994) providing key evidence on the configuration and evolution of older ice sheets. Similarly, this time-slice approach would be useful in an area of dynamic ice domes with shifting ice divides where the margins buttress against each other and produce superimposed landforms. An important factor to bear in mind when applying this model is that a comprehensive knowledge of the genesis of the glacial landforms used in the inversion model is required if a successful reconstruction is sought (Figure 2.13).

An inversion model was applied by Boulton *et al.* (1985) to the Laurentide and Fennoscandian ice sheets, while Boulton & Clark (1990) focused on the Laurentide ice sheet and improved the model by defining spatially coherent lineation sets and arranging them in a relative-age stack using cross-cutting landform relationships. Absolute dating was carried out at a number of key stratigraphic sites and preservation of older landforms was attributed to their location under ice divides. Importantly, however, neither Boulton *et al.* (1985) nor Boulton & Clark (1990) used landforms created by glaciofluvial meltwater, such as eskers and drainage channels as a source of information. Meanwhile, Kleman (1990) applied the inversion model to striae data and meltwater landforms, which he used as deglacial markers in the relative-time stack.

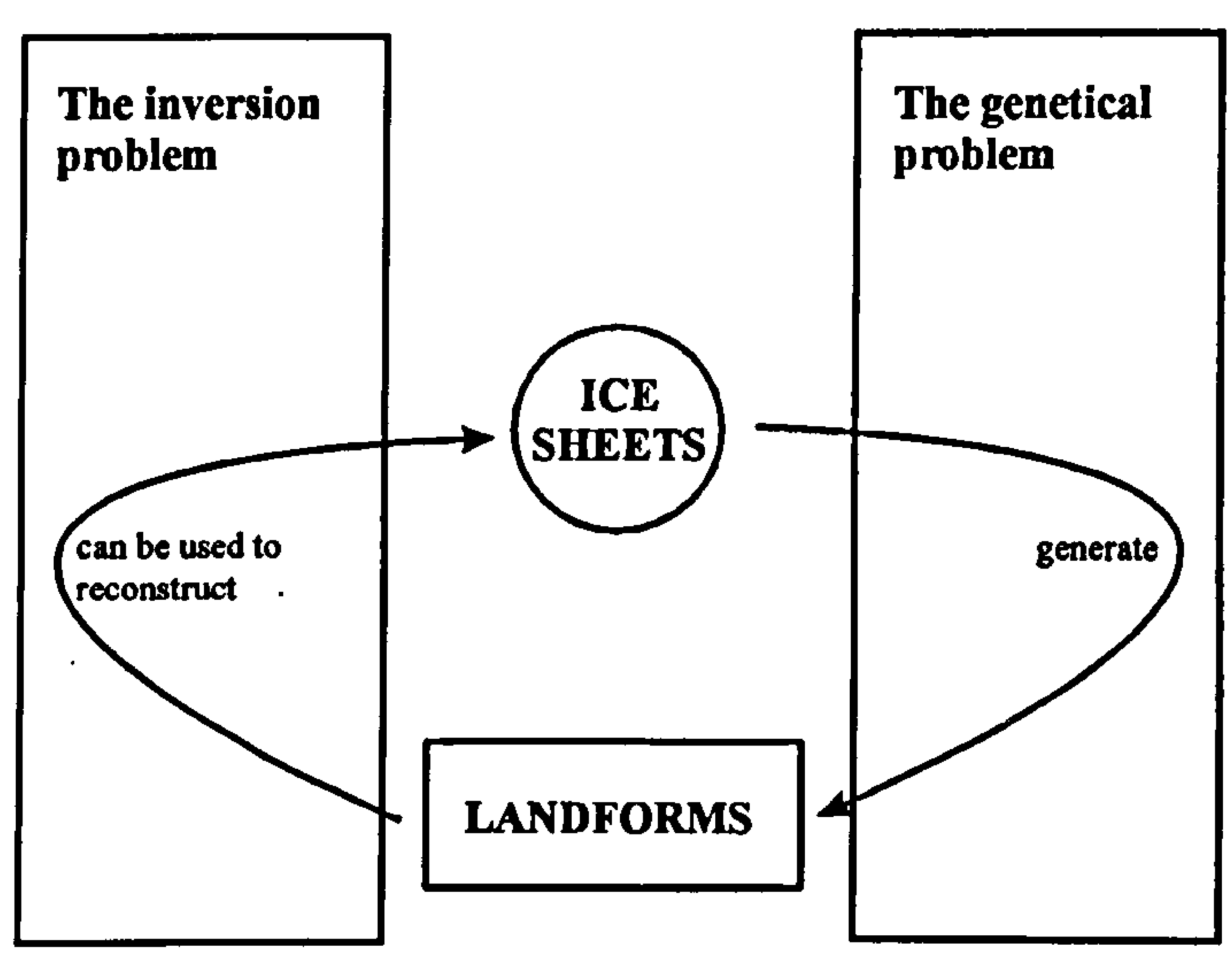

Figure 2.13. Successful solution of the inversion model requires a comprehension of the genesis of the landforms that are used in the model. (From Kleman & Borgström, 1996).

Ice-surface form/contour lines can be produced when cross-cutting or superimposed relationships in the flow-directional record are used in a relative dating system (Kleman & Borgström, 1996). These can be used to infer assemblages of landforms that were produced approximately synchronously. Similarly, isochrons can be drawn transverse to the direction of ice flow in these synchronous assemblages, and used to infer the ice sheet morphology. However, absolute dates should be used if available to define stratigraphical contexts and attribute absolute values to the isochrons. This is most important because it is often assumed that ice sheets always erode or reshape their beds (Kleman & Borgström, 1996) whereas there is a large body of evidence which demonstrates that under dry-bed (frozen-bed) conditions, old delicate landforms can survive ice-sheet overriding (Sugden & Watts, 1977; Punkari, 1985; Lågerback, 1988; Kleman, 1994). This is not to say, however, that cross-cutting or superimposed landforms are the result of different glaciations, but may be due to changes in flow direction during a single glaciation (Punkari, 1993). Recently, the accepted applicability of this model to ice sheet reconstruction has seen a number of papers that have adopted this approach (Punkari, 1997a,b; Clark, 1997).

Care was taken when using the inversion model in this research however so that account was taken of the following factors that were outlined when the model was used by Clark (1997).

1. The data must not be fragmented *i.e.* there is a danger that spatially separate studies, with many contradictions between areas, exist in the literature and may be incorporated into a single model. This is one of the main reasons for the *tabula rasa* approach adopted throughout this research.
2. Much of the data may be what Rhoads and Thorn (1993) refer to as *'theory-laden evidence'* where information was collected in the past when different glaciological ideas were in use that are no longer considered valid, but have tainted the evidence. This source of error is further confused when some theory-laden evidence has propagated through the literature. This is another reason for adopting a *tabula rasa* approach to research.
3. Poor dating control is another factor of weakness where, on land, such techniques only tell us when an area became ice-free, enabling us to constrain the ice margins. But evidence recording information from within the margins, *e.g.* from striae, cannot be dated, thereby limiting our knowledge about ice build-up and dynamics.
4. The assumption that all the landforms were formed synchronously, providing maximum information about the ice sheet at one point in time, is another source of error, as seen by cross-cutting bedforms or glaciologically impossible configurations, *i.e.* incorrect temporal grouping of evidence.

5. This leads to the final point, that the reconstruction of ice sheet flow and geometry must be glaciologically plausible.

The following lines of evidence were input to the inversion model for ice sheet reconstruction; a) flow traces, and b) meltwater traces. Flow traces include features such as till lineations (including drumlins), striae, and lateral moraines, all of which are parallel to ice flow; and recessional moraines and Rogen moraines, which are transverse to ice flow. Meltwater traces include eskers, kame terraces, De Geer moraines, and meltwater channels. Spatial patterns of subglacial landforms as well as marginally created meltwater forms are noted as assemblages of flow sets, called 'fans' in the inversion model. If the fans overlap or are cross-cutting then relative chronologies are established at the intersections, and the fans are grouped into relative-age stacks according to the relative chronologies (Figure 2.14). Through this procedure, the ice flow can be plotted over both space and time enabling the ice sheet to be reconstructed and the pattern of glaciation/deglaciation to be determined. Moreover, the environments of deposition of the sediments are determined and used in the interpretation stage of the modelling when the ice sheet dynamics are being reconstructed.

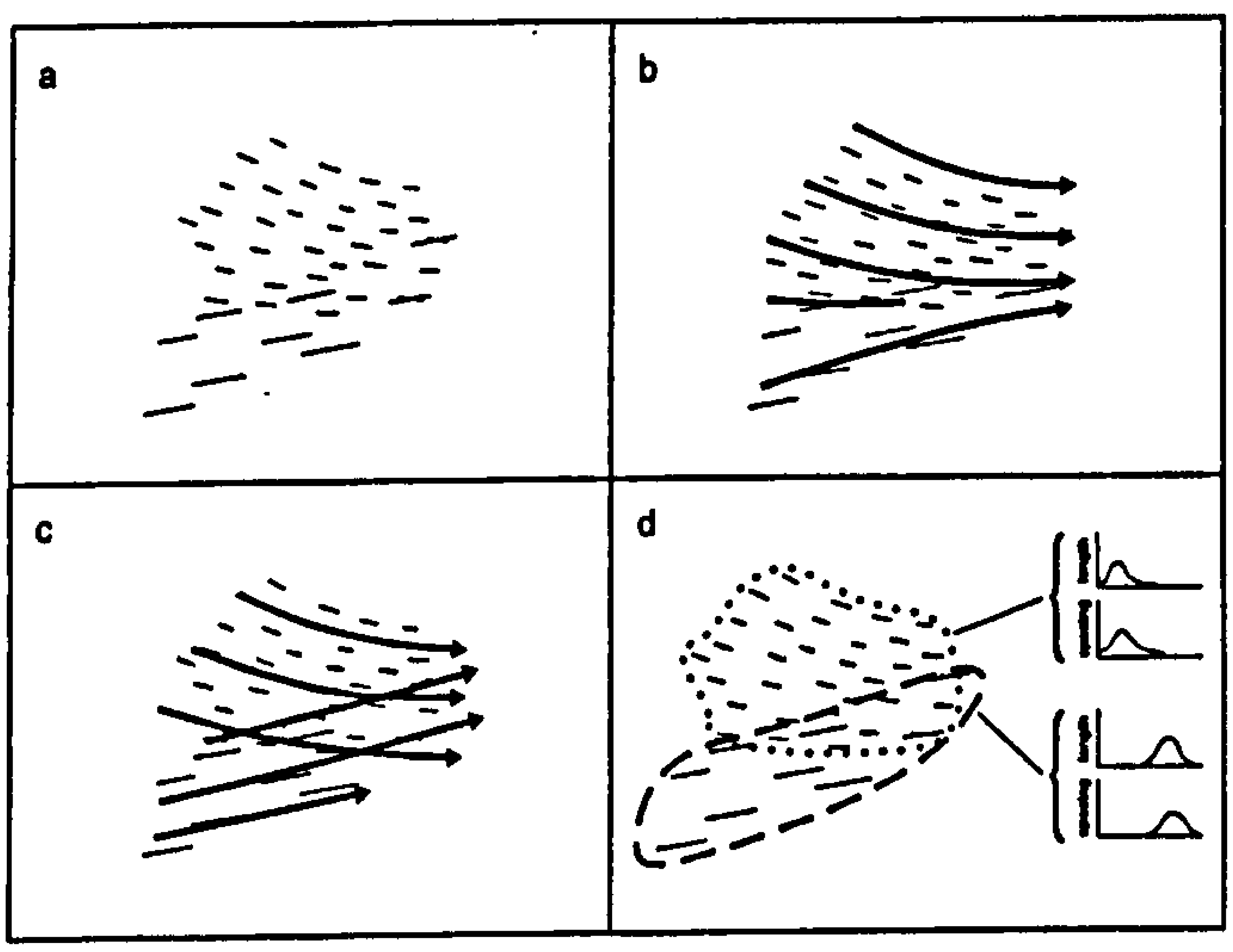

Figure 2.14. The figure shows the principle of grouping glacial landform swarms or assemblages into fans that are employed in the inversion model; a) represents a hypothetical lineament pattern, b) an interpretation that assumes all of the flow evidence is synchronous, c) an alternative that takes account of cross-cutting lineaments, and d) shows how delineated fans from spatial patterns and morphometry assist in discriminating metachronous flow events. From Clark (1997).

It should be noted that the inversion models in the published literature focus on glacial lineations defined from morphological mapping, whereas sedimentological data obtained through detailed field mapping throughout the entire research area were incorporated fully into the model used in this research. This adds an important component to the database of ice flow directions over time and space. For example, the directions of flow determined from drumlins were not reliant on the morphology of the drumlin landform, but were also obtained and corroborated by data including till fabrics, striae on bullet boulders, phenoclast petrography, deformation structure geometry and lithostratigraphy. This means that even if only one direction of ice flow can be determined from the morphological data due to reworking of the sediments during the most recent glaciation, previous directions of flow can be distinguished and related to their stratigraphical contexts assuming net accretion of till, or constructional deformation (Hart & Boulton, 1991; Hart, 1995).

2.6.1 Flow Traces

Flow traces were used as direct evidence for the direction of ice flow at a particular location at one point in time. These exist at a variety of scales, and they were mapped from a combination of satellite imagery, aerial photography and fieldwork. The aerial photography and satellite imagery complimented each other by contributing various (and often overlapping) datasets comprising both sedimentological and morphological information at a variety of scales. The flow traces include; till lineations, erratic trains, phenoclast petrography (in relation to the provenance of the component clasts) till fabric data, deformation structure geometry, bedrock lineations, striae, corries and erosional scouring. The location of each flow trace type in the context of ice flow directions and the environments of deposition has already been discussed in the sections describing the morphology and sediments maps and the satellite imagery. Here I will discuss each flow trace type in terms of the quality of data it contributes to the inversion model. The flow traces will be plotted on scale maps of the research area for interpretation.

2.6.1.1 Till Lineations

Till lineations are elongate ridges which are wholly or partly composed of till. They may be aligned parallel to the direction of ice flow, such as drumlins, flutings, crag-and-tail ridges and lateral moraines or they may be transverse to ice flow, such as recessional moraines or Rogen moraines. This highlights the importance of a comprehensive knowledge of the glacigenic processes which combine to produce the landforms, so that correct interpretations are made regarding the directions of ice flow (*i.e.* whether the features are aligned parallel or transverse to ice flow) and also regarding the environments of deposition *i.e.* subglacial, englacial, supraglacial, paraglacial or periglacial.

Drumlins form the largest body of evidence of streamlined ice flow indicators in the research area but have been used in the past as evidence in models that support opposing directions of flow. To increase the accuracy of these data, the lineament vectors have been integrated with sedimentological data such as till fabrics and deformation structure geometry analyses relating to the internal structures of the drumlins to define the ice flow directions throughout the stratigraphic column. Application of this holistic methodology enabled the true direction of ice flow to be determined for drumlins that had accessible exposures.

Erratic carriage has been used extensively to provide information on ice flow directions in this area. Erratic trains are generally associated with a fan-shaped distribution of glacially-transported boulders from a known provenance, such as that which extends towards the northwest from the Corvock granite to the town of Louisburgh, or the train comprised of Devonian sandstone boulders from the northern shores of Clew Bay that are distributed north along the shores of Furnace Lough. Several far-travelled erratics were mapped in Foxford, consisting of granite with a provenance in Connemara, a transport distance of over 60km. Erratics are symbolised on the Quaternary sediments maps as crosses with the colour of the cross denoting the lithology of each boulder.

In combination with erratic boulders, the phenoclast petrography was calculated for bulk samples from exposures, trenches and boreholes and used to determine the provenance of the sediments where possible. This line of evidence did not always prove useful however. For example, the origin of the Lower Carboniferous sandstone till drape on the drumlins in Clew Bay is unsure because the bay is encircled by Lower Carboniferous sandstone bedrock (Figure 1.3).

Moraines aligned parallel to flow, *e.g.* lateral moraines, and those transverse to flow *e.g.* Rogen, recessional and terminal moraines are an important body of evidence in the reconstruction of both the glaciation and deglaciation of the area. Included within this group are the till ridges consisting of glaciotectonised limestone bedrock to the east of Westport town, within 1:25,000 sheet 08/29NE and 1:50,000 sheet 31. These landforms are important in the glaciological reconstruction because similar landforms in Soviet Karelia were interpreted as having been formed in a zone of compression where ice masses converged (Punkari, 1985).

2.6.1.2 Bedrock Lineations

Bedrock lineations were also used as data input to the inversion model. These exist in a wide variety of scales from large-scale streamlined or faceted hills and roche moutonnées down through tadpole rocks, to striae. Streamlined hills and large-scale roche moutonnées are conspicuous on both satellite imagery and stereoscopic aerial photography and provide good evidence regarding the directions of ice flow. Tadpole rocks and whalebacks are best located through fieldwork when their orientations can also be measured with respect to true north.

Glacial striae were recorded both on bedrock surfaces and on clasts within the tills. Nevertheless, extreme caution was exercised when evaluating striae on clasts as the clasts can rotate during glacial transport giving false values. For this reason, striae on bullet boulders were used as their long axes are aligned parallel to ice flow with their stoss sides located up-ice and their tapered side located down-ice. Striae from bedrock outcrops were a particularly useful line of evidence because old striae can be left untouched in locations on the bedrock surface that became protected when flow directions changed. This is in stark contrast to till landforms that can be reoriented by overriding ice of a later flow direction.

Corries and nivation hollows were also included in the model, and were easily mapped from satellite imagery, aerial photography and fieldwork. These provided evidence relating to the sources of smaller ice masses that aided the interpretation of overall ice flow directions in the area. These are of best use when interpreted in combination with their associated moraines that indicate the aerial extents of the corrie glaciers.

Erosional scour lineaments have been included within the bedrock lineations section. Erosional scours are negative features on the landscape, produced when the passing glacier gouged sediments out of the landscape leaving elongate troughs in their wake. These were not recognisable on the aerial photography, but the synoptic view and increased morphological data afforded by satellite imagery enabled them to be mapped with relative ease.

2.6.2 Meltwater Traces

Meltwater traces were input to the inversion model so that the pattern of deglaciation, as well as that of glaciation, could be spatially and temporally reconstructed. Meltwater traces include eskers, kames, glacial lake traces and glaciofluvial meltwater channels. As with the landforms used in flow tracing, the environment of formation of the meltwater traces must be known if the objective is a defensible reconstruction of the deglaciation. Eskers are glaciofluvial anastomosing ridge deposits associated with an ice sheet drainage system. In Ireland, these landforms have been used both as evidence for a systematic ice retreat from south to north (Delaney, 1997) and as evidence for glaciofluvial meltwater activity in the zones of convergence in an Irish ice sheet composed of ice coalescing from a number of distinct ice centres (Warren, 1991, 1992) during an ordered, rapid retreat of active ice (Warren & Ashley, 1994). However, both schools of thought are in agreement that eskers are formed transverse to the ice margin in an inward-transgressive fashion close inside retreating margins. It has also been stated that the mean esker orientation within a swarm is a good flow direction indicator, while coherent swarms are indicative of temperate, wet-based glacial systems (Kleman and Borgström, 1996).

Of less use are kames and glacial lake boundaries because neither provide the same quality of information directly relating to ice flow patterns, but they do provide control on segments of the ice-margin outline, and the approximate location of shrinking dispersal centres. Typical glacial lake traces are shorelines, perched deltas and glaciolacustrine sediments. Stepped sequences of these features enable a more complete reconstruction of the deglaciation to be produced, whereas a distinct lack of these features may indicate retreat under frozen bed conditions (Seppälä, 1980).

Data such as imbrication, particle size components and phenoclast petrography were obtained from kame terrace sequences to yield information regarding the conditions of deposition and the palaeocurrent direction. These were also used in the inversion model for reconstructing the meltwater depositional sequences along the glacier margins. For example, the mean particle size of the large kame terrace along the eastern flanks of the Erriff Valley reduces towards the north, grading from boulders in the south to fine sands deposited into a subaqueous delta in the north. Furthermore, the phenoclast petrography indicates that the clasts have a southerly provenance and imbrication is towards the south, indicating palaeocurrent flow from the south. These data indicate the meltwater flowed from south to north along the flanks of the glacier (between the ice and the valley wall), parallel to the ice flow direction in the valley that was determined from till fabric analysis, erratic carriage and landform morphology.

Not included in this list, but equally important in the deglaciation record are spillways, which are landforms produced when topographic lows (often cols) enable decanting of ice-dammed lakes by facilitating water escape across a watershed.

2.6.3 Data Visualisation and Interpretation

The next step in the reconstruction process is to plot the data onto a scale map of the area prior to both interpretation and comparison with the existing models. Both sets of flow traces and meltwater traces were plotted onto a 1:500,000 scale map of the research area with arrows depicting the direction of ice flow derived from those traces. Rather than produce a separate map for each of the flow traces they were incorporated along with till fabrics, striae, deformation structure geometry and erratic carriage data onto a single map to enable an holistic interpretation of all lines of evidence. The information interpreted from the satellite imagery and that obtained from the conventional mapping techniques was integrated in a Geographic Information System.

3 REMOTE SENSING - SATELLITE IMAGE PROCESSING, ANALYSES & INTERPRETATION

3.1 INTRODUCTION

In this chapter, the digital image pre-processing and processing techniques applied to the three image datasets, which have been outlined previously, will be described in sequence. The pre-processing and processing algorithms will be dealt with in separate sections, with an analysis and interpretation of the imagery following the discussion of processing for each dataset. A lineation map is produced from the imagery, and this will be combined with the geological data obtained from the initial compilation and reconnaissance mapping phases for overall analysis, interpretation and modelling. Plots of the imagery referred to in this Chapter are bound in Volume 2.

Three sets of image data were used:

1. Landsat-5 Thematic Mapper (TM) captured in the Summer
2. Landsat-5 TM captured in the Winter
3. ERS-1 RADAR data, captured in the Summer.

3.2 PREPROCESSING

Preprocessing involved transforming the three image datasets to the same map projection so that they and their derivative maps could be integrated digitally at a later stage for interpretation purposes. The Transverse Mercator Projection, using Airy Modified Spheroid datum with the 1975 adjustment was chosen as this is the projection used by the Irish Ordnance Survey. The first dataset, TM Summer, was already rectified when it was obtained from the CORINE (Co-Ordination of Information on the European environment) database, however it was necessary to retransform it to the projection and datum listed above. The level of accuracy of the data was tested using the Ordnance Survey 1:50,000 digital Discovery Series maps (which were available for Sheet 31 of the research area) by linking the satellite imagery with the map on the computer screen and comparing the National Grid Coordinates obtained for a number of points on both images. The error, of less than or equal to 10m, was found to be within acceptable limits for 1:25,000 mapping.

The Summer TM image was subsequently used as a source to rectify the remaining two satellite images using Ground Control Points (GCP's) which are points of reference which can be accurately located on both the raw and the transformed imagery. GCP's were generally features such as road or rail junctions. A transformation matrix was computed to warp the raw data onto the transformed grid and applied using a polynomial equation of chosen order, varying with the degree of warping which was required. It was found that band combinations of 4, 3, 2 (displayed through the red, green and blue guns respectively) in the Summer imagery and 7, 4, 3 in the Winter imagery were optimum for locating the GCP's.

As the research area straddles two TM path rows, a total of four TM sub-scenes (or quadrants) were required to cover the area. Only three of these were available, and it was necessary to rectify each of these three Winter TM images individually, and subsequently mosaic them together. Dotted lines on the final image delineate where the scenes hace been joined in the mosaic. The number of GCP's varied in relation to the land area of the sub-scene, with a larger number of GCP's needed to correct the larger images:

1. TM 208_23_Q1. This covers the southwest region of the research area including Clew Bay and Connemara. Fifteen GCP's were necessary to provide a complete distribution across the area of the satellite image, see Table 3.1.

Table of GCP's for TM 208_23_Q1								
	Source, raw coordinates		Destination, map coordinates		Residual		RMS Error	Contri-bution
GCP Number	X	Y	X	Y	X	Y		
1	2703.863	2118.292	91737.298	278890.72	0.024	-0.293	0.294	0.958
2	2358.310	2071.188	81356.054	280240.02	-0.221	0.292	0.366	1.194
3	2452.517	1743.075	81507.226	269968.95	0.152	-0.183	0.238	0.777
4	2802.773	1784.945	91985.791	268473.60	-0.108	0.018	0.109	0.356
5	2945.693	1843.321	96592.647	269067.07	-0.046	0.263	0.267	0.870

6	3123.559	2224.409	104729.37	278706.84	0.150	-0.290	0.326	1.064
7	2772.845	2342.117	95494.992	284849.00	0.304	0.230	0.381	1.243
8	3184.672	2733.008	110432.94	292946.25	-0.056	0.006	0.057	0.184
9	2511.619	2722.438	91253.895	299344.62	-0.330	0.182	0.377	1.230
10	2203.550	2674.102	81599.299	298925.60	0.218	0.001	0.218	0.711
11	2725.630	2669.171	96661.021	294695.05	0.003	0.540	0.054	1.759
12	2998.728	2807.116	105631.22	296527.66	0.298	-0.162	0.339	1.106
13	2562.483	2470.214	90386.395	290189.65	-0.098	-0.286	0.302	0.985
14	3207.532	2581.250	109921.45	288390.52	-0.213	0.191	0.286	0.931
15	2998.553	2513.250	103345.80	288036.43	-0.077	-0.144	0.163	0.533
X RMS error = 0.184553 Y RMS error = 0.244948 Total RMS error = 0.306691								

Table 3.1. Table of GCP's for TM 208_23_Q1, including individual and total RMS errors.

The RMS error of 0.3 refers to pixel dimensions, therefore this transformation is accurate to within 10m.

2. TM 208_23_Q2. This covers the southeast portion of the research area including the Plains of Mayo and Lough Mask. Eleven GCP's were necessary to provide a complete distribution across the area of the satellite image, see Table 3.2.

Table of GCP's for TM 208_23_Q2								
	Source, raw coordinates		Destination, map coordinates		Residual		RMS Error	Contri-bution
GCP No.	X	Y	X	Y	X	Y		
1	555.859	2025.039	111779.83	270603.76	0.186	0.081	0.203	0.632
2	692.891	2291.989	117808.11	277270.75	-0.129	-0.358	0.381	1.187
3	1095.996	1970.057	126989.84	264759.83	-0.055	-0.217	0.224	0.697
4	985.004	2560.091	128367.52	282761.63	-0.059	-0.172	0.182	0.568
5	1088.026	2215.151	128674.84	271955.32	0.113	0.345	0.363	1.133

6	258.922	2225.039	104727.72	278705.31	0.171	-0.402	0.437	1.363
7	723.197	2894.017	123385.77	294490.24	0.120	-0.211	0.242	0.756
8	319.980	2732.102	110429.17	292954.44	-0.133	0.266	0.297	0.926
9	722.938	2533.961	120568.63	284079.66	0.081	-0.103	0.131	0.407
10	266.919	1944.206	102781.31	270514.46	-0.176	0.258	0.312	0.973
11	325.003	2563.078	109263.98	288004.88	0.081	-0.103	0.131	0.407
X RMS error = 0.129097 Y RMS error = 0.293616 Total RMS error = 0.320743								

Table 3.2. Table of GCP's for TM 208_23_Q2, including individual and total RMS errors.

An RMS of 0.32 means that the transformation is accurate to within 10m.

3. TM 208_22_Q3. This covers the northwest portion of the research area including Achill Island, the Nephin Mountain Range and west Lough Conn. Nine GCP's were necessary to provide a complete distribution across the area of the satellite image, see Table 3.3.

Table of GCP's for TM 208_22_Q3								
	Source, raw coordinates		Destination, map coordinates		Residual		RMS Error	Contri-bution
GCP No.	X	Y	X	Y	X	Y		
1	3154.898	40.417	112111.09	290465.63	0.118	-0.194	0.228	0.818
2	3027.916	575.453	112590.40	306965.72	0.042	0.069	0.080	0.289
3	2586.019	192.442	96778.509	299314.62	0.255	-0.404	0.477	1.717
4	2475.886	546.554	96328.140	310447.82	-0.000	-0.205	0.205	0.737
5	2098.916	48.495	81570.057	29827.975	-0.032	-0.143	0.146	0.527
6	2149.958	355.398	85411.913	307446.84	0.053	0.223	0.230	0.826
7	2050.844	559.500	84120.533	314133.49	-0.052	0.044	0.068	0.246
8	2916.868	209.430	106497.65	297244.62	-0.309	0.271	0.411	1.478
9	2643.990	10.496	97050.568	293615.00	-0.074	0.339	0.347	1.246

X RMS error = 0.144519 Y RMS error = 0.237584 Total RMS error = 0.278086

Table 3.3. Table of GCP's for TM 208_22_Q3, including individual and total RMS errors.

The RMS value of 0.27 means that the transformation was accurate to within a nominal value of 8m across the image. A second order transformation was used on all three images, with bilinear interpolation. A second order transformation was required as it both warps and rotates the image, while bilinear interpolation was chosen because the result is not as pixelated as a nearest neighbour transformation nor are the digital values as averaged as in the cubic convolution technique. A useful test for the accuracy of the transformation was to check continuous features such as roads, railways, rivers and coastlines when the three quadrants were mosaiced together to see if they joined up. This visual test corroborated the statistical tests of accuracy as linear features crossed the seams with no disjointing effects.

The ERS-1 radar image was purchased in geo-coded format, rectified to the 1984 World Geodetic System, Zone UT29. This was carried out at the ground receiving station at Oberpfaffenhofen, Germany using the sensor parameters at the time of imaging, rather than GCP's. As the radar image was already rectified, six GCP's were located, both to transform the image to the same projection as the maps and the TM data, and to check the spatial accuracy of the data, see Table 3.4.

Table of GCP's for ERS-1 5113/1071								
	Source, raw coordinates		Destination, map coordinates		Residual		RMS Error	Contri-bution
GCP No.	X	Y	X	Y	X	Y		
1	3863.781	3188.781	111669.57	283697.01	0.033	-0.030	-0.044	0.070
2	2679.156	1936.281	96995.692	299574.62	0.413	-0.642	0.764	1.212
3	1472.016	1732.150	81890.625	302336.63	-0.065	-0.219	0.228	0.362
4	4602.781	1405.156	121160.35	305854.59	-0.299	0.756	0.813	1.291

5	3928.886	4242.014	112348.13	270525.38	0.153	-0.639	0.657	1.042
6	1533.937	4348.938	82319.375	269597.88	-0.234	0.773	0.807	1.282
X RMS error = 0.239272 Y RMS error = 0.582851 Total RMS error = 0.630053								

Table 3.4 Table of GCP's for ERS-1 5113/1071, including individual and total RMS errors.

The RMS value of 0.63 means that the transformation is accurate to within a nominal value of 15m across the image. As the imagery was already geo-coded, a first order transformation was utilised which is required to rotate but not warp the image array so that it correctly fits the chosen map projection.

3.3 IMAGE ENHANCEMENT AND ANALYSIS

This consists of enhancing the image data through a variety of digital image processing techniques so that any information which may be of use to the interpreter can be readily extracted. These processing techniques will be dealt with separately for each of the three satellite image datasets.

3.3.1 ERS-1 Microwave RADAR Imagery

Active microwave imagery requires more digital image processing and is harder to analyse than optical sensors such as Landsat TM (Clark, 1997). The processing techniques utilised in this study have followed on from work carried out by Jordan (1994), Vencatasawmy *et al.* (1997), and Clark (1997). The first process carried out was spatial frequency filtering which decreased the effects of speckle which is characteristic of raw radar image data. Modern digital image processing software packages are equipped with a wide range of speckle suppression and filtering algorithms that have been specifically designed for radar imagery. As many of these, such as the sigma filter, have been developed for agricultural applications they do not produce suitable results for geological mapping. Also, these complex algorithms are both computationally and time demanding. Despite these doubts, the full range of filters in both image processing software packages (ERMapper 5.5 and ERDAS Imagine 8.2) were evaluated, and the best results were obtained by two passes of a 3x3 kernel low pass filter. Vencatasawmy *et al* (1997) recommend three passes of such a filter, but as bilinear interpolation resampling was utilised during geocoding, this already reduced the data frequency so that only an additional two passes of a low frequency filter were required.

Although geocoding was carried out at the ground receiving station, and transformation to the Irish National Grid was subsequently applied, the additional geometric distortions of foreshortening and layover had to be addressed. To compensate for layover and foreshortening effectively in radar data, a high resolution DEM (digital elevation model) is required (Curlander & McDonough, 1991), and as this could not be obtained, these distortions were ignored. This was not expected to be problematic as these distortions only affect areas of higher elevation and would not distort the drumlin swarms.

Contrast was increased within the image using a linear contrast stretch that truncated the data at both ends of the frequency scale. This was carried out visually using a histogram contrast stretch, and by truncating the data distribution at a point where the positive tail of the Gaussian distribution was seen to flatten. This decreased the large dynamic range that high scatterers and corner reflectors created, thereby increasing the overall contrast within the image. This did not eradicate the problem of radar shadow however, which is one factor of active microwave data which cannot be 'processed out' and must be accepted and by-passed using either another satellite image dataset or aerial photography.

Conversion from 16- to 8-bit is also recommended by Vencatasawmy *et al* (1997) as an aid to decreasing both the radiometric resolution of the data and its file size. However, this technique was also evaluated by Jordan (1994) using a FORTRAN conversion programme, and resulted in a degraded image with reduced interpretability. It was therefore decided that the length of processing time and file space required by the 16-bit data was offset by the resolution it contained.

The specialist radar image processing algorithms available with the software packages were supplemented by manually entered algorithms. An example of one such process was to mathematically square all the digital numbers, resample each four pixels to one, and derive the square root of the result. This served to reduce any speckling which specifically affects image degradation from objects of point interference such as corner reflectors, while simultaneously increasing the contrast of the image. This reduced the amount of high frequency interference that remained after the low pass filters were applied.

Even after image enhancement processing, it was found that the ERS-1 radar image had a very low information content, see Image 1. The effects of layover, foreshortening and radar shadow are clear in the mountainous areas, where the peaks seem to lean towards the west, in the direction from which the image was captured. The lighter grey-scales in the mountains indicate a higher dielectric conductivity, due to the increased moisture content of the soils in these areas. With the exception of this information, and the fact that corries could be delineated, no other geological data could be discerned in the higher elevations.

Although the drumlin swarms can be seen on the image, and at times individual drumlins ridges can be mapped from the higher reflections on the western slopes (especially on north-south aligned drumlins) the image clarity is not sufficient to enable mapping to be carried out. This can be seen on Image 2 which is a 1:50,000 plot of sheet 11/27NW of the research area, with a digital overlay of Quaternary geological lineaments which were digitised from Landsat-5 TM Winter imagery. The overlay has been included to demonstrate the amount of Quaternary geological information which is present on the landscape but which cannot be seen on this satellite image.

There are several reasons why this image is of inferior quality, despite state-of-the-art image processing efforts.

1. Irish Meteorological Office Reports state that there were eight days of near-continuous rainfall previous to the capture date. In fact, the sea squalls visible

along the Atlantic coast and in Clew Bay indicate that there was rain falling at the time when the image was being captured. Despite claims that active microwave sensors are unaffected by clouds and rainfall, it has been shown that heavy rain does interfere with the signals (Kingsley & Quegan, 1992), further demonstrated by the low quality of this image.

2. The high rainfall, while directly affecting the microwave signals in the ether, also affected their interactions with the Earth's surface. The high amount of moisture on the landscape increased the overall backscatter to the point where it dominated and negated the more usual dielectric interactions with the biomass and soils and 'drowned' the image reflectances.
3. Despite positive published results from ERS-1 radar data (*e.g.* Clark, 1997), some practitioners would argue that the depression angle of the ERS-1 sensor is too large, thereby reducing the reflectance due to slope angle which is necessary to view clearly relatively minor Quaternary geomorphological features (B. Loughlin, *pers comm.* 1997). This factor is compounded by the relatively short wavelength microwaves employed (C-band), which are better at sensing textural features at scales larger than those required in geological mapping, unlike, for example L-band which has a wavelength located in the bandwidth between 15 and 30cm. For example, in this ERS-1 image, individual waves in the Bay can be discerned easily, as can their flow patterns around the islands, indicating that the wavelength is more suited to mapping features of that scale.
4. As has happened elsewhere, the geocoding algorithm applied by the ground receiving station may have degraded the image to the unusable state in which it arrived (C. Clark, *pers comm.* 1997). If this is the case, then no amount of image processing could render the image interpretable.

For these reasons, none of the image processing techniques which were applied from both the specialist radar software algorithms and from manually entered algorithms were capable of producing an interpretable image which could be used for geological mapping. No interpretation was attempted from the radar image, as it would not have a beneficial expenditure of time or effort.

3.3.2 Landsat-5 TM Summer

Owing to non-uniform changes in the satellite sensor over time, caused by deterioration of the charge couple devices (CCD's), differing signals are recorded by the sensor array, which means that even if a homogenous landcover type is within the instantaneous field of view (IFOV) it is recorded with a series of lines of varying intensity which run transverse to the orbital path. By displaying each band on screen it was noted that this affects the shorter wavelength bands preferentially, and would only cause an interpretation problem for bands 1, 2 and 3. Therefore, the linear interference was removed from these bands by replacing them with pixels averaged from a surrounding 3x3 pixel window. By using a small window the interference was filtered out while the image lost little of its spatial definition. Digital image processing packages have more complex methods for removing these variations in the scan lines, but evaluations of these on the imagery provided unsuitable results with a loss of high frequency geological data.

Real-time linear histogram adjustments (in ERMapper) were used to redistribute the digital numbers recorded by the sensor so that they fill the 0-255 colour range available with 8-bit radiometric resolution. This increased the interpretability of the imagery by reducing the contrast in bright areas (*e.g.* quartzite exposures such as the summit cone of Croagh Patrick, NGR 90608, 280150) while increasing the contrast in dark areas on the imagery (*e.g.* in peat-covered regions or areas affected by shadows behind mountains). Without this image processing, the bright areas would simply appear white and the dark areas would be black, with no chance for geological interpretation in either.

As minor filtering was carried out during the transformation stage of geo-rectification, it was not necessary to undertake extensive spatial filtering, with the exception of a single pass of a low pass filter. After experimentation with several types and sizes of filter, a 7x7 kernel was chosen as this reduced any of the remnant pixelation, which made linear features easier to distinguish while not substantially reducing the high frequency content of the data.

The next stage of image processing was to choose a suitable band combination that revealed the geological content within the image data. Immediately band 6, the thermal band, was ruled out because although its spatial resolution of 120m is suitable for regional studies, it is too coarse for detailed mapping at 1:25,000 or 1:50,000. More importantly however, the thermal band contains no useful information when imaged at 0930hr, as the landscape no longer displays the heterogeneous temperature profiles of late evening or pre-dawn. This was corroborated by a visual analysis of band 6 that showed that the radiance values were relatively uniform across the image with practically no information content. Band 6 was deleted from the dataset to increase the speed of processing for future operations.

The vegetation cover that masks the geology on Summer TM imagery dictates the approach taken to band choice and processing techniques. Two approaches can be attempted; a) reduce the reflectance characteristics of the vegetation, and attempt to 'see through' the biomass to the geology, or b) enhance the vegetation responses, working under the premise that the growth patterns are partly a function of subsoils conditions such as drainage, and use this to infer the type and composition of the sediments.

A) Reduce the reflectance characteristics of the vegetation. This involves attempting to by-pass the vegetation and negate its masking effects to enable the Quaternary sediments to be mapped, either directly or in a morphogenetic fashion. Direct mapping is not possible with this imagery as there is no way to penetrate the vegetation which camouflages the geology (Drury, 1993; Jordan, 1994, 1997; and Marsh *et al.* 1995). Morphogenetic mapping is carried out by delineating Quaternary landforms and correlating each type with a certain category of sediment, such as kames with sand and gravel deposits. As TM is a passive sensor system, the morphological content is dictated by the illumination angle, *i.e.* the solar azimuth and zenith angles at the time of imaging. The imagery was captured in May at approximately 0930hr, which means that the solar zenith was too high to enable most morphological features to be clearly identified, with the exception of some of the higher mountains which have ridges aligned transverse to the solar azimuth. Nevertheless, even if morphogenetic mapping was possible from this image dataset, there is still the complication of correlating landforms with sediment categories, a process made difficult be the heterogeneous nature of the sediments in a drumlin landscape. This indicates that although Quaternary geological information can be obtained from Summer TM imagery processed in this way, the quality is not sufficient to warrant its continued use.

B) Enhance the vegetation reflectances so that variations in the edaphic cycle, which may be due to geological conditions, can be mapped. The rate of plant growth and the stresses on plants can be mapped from satellites with little difficulty (Clevers & van Leeuwen, 1996; and Kimes *et al.* 1991) while the role of subsurface conditions has been recognised as a major influence in vegetation reflectances from passive orbital sensors (Rondeaux *et al.* 1996). However, a problem when linking vegetation growth to subsurface geological conditions is that increasingly this effect is being minimised by fertilisers and agricultural drainage schemes. This is illustrated well in Plates 1.1 and 1.2 that show two drumlins composed of well-drained limestone till with an inter-drumlin peat deposit. Plate 1.1 shows the drumlins when the surface vegetation has been stripped off prior to drainage, while Plate 1.2 shows the homogeneous vegetation growth after reclamation of the inter-drumlin bog. On Image 3, at NGR 099054 286205, the pre-drainage vegetation digital numbers reflect the subsurface Quaternary geology while an image captured after drainage works would incorrectly indicate that the vegetation of the entire area was underlain by a sediment of uniform drainage characteristics, till.

Plate 1.1. Two drumlins at Derrynanaff (NGR 0991 2863) with surface vegetation stripped to reveal tills and interdrumlin peat.

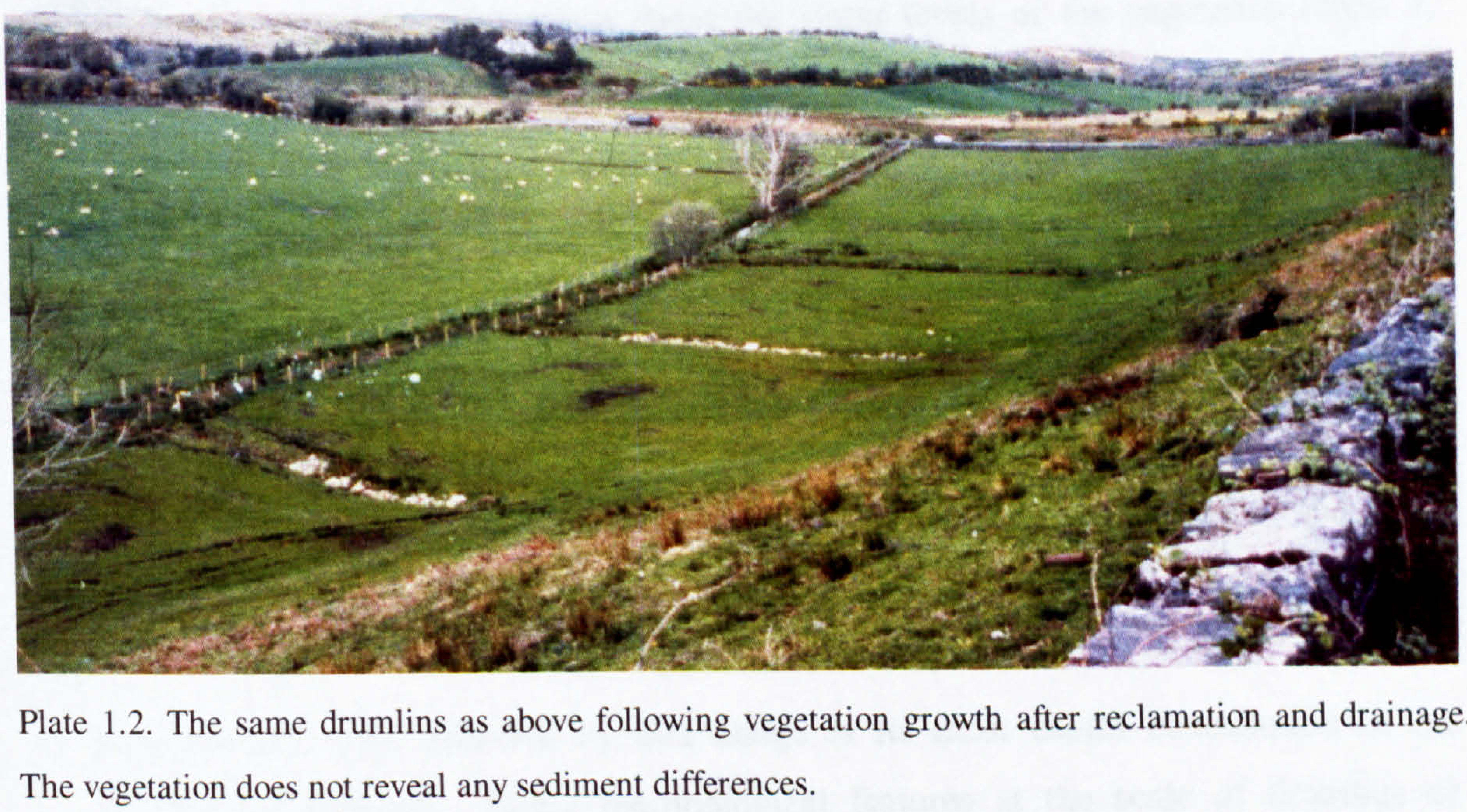

Plate 1.2. The same drumlins as above following vegetation growth after reclamation and drainage. The vegetation does not reveal any sediment differences.

Despite these complications, Quaternary mapping was attempted with Summer TM imagery by inference from the vegetation reflectances. The vegetation can be assessed either by using an automatic vegetation index available with the image processing software or by creating a similar product by manipulating the software algorithms, both were carried out. The most commonly used vegetation index is the normalised difference vegetation index which takes the general form of VI = (NIR-R)/(NIR+R), where NIR is the near infrared and R is red (ERDAS Field Guide, 1994). The NDVI has been proved to be the most susceptible to soil background effects in comparison to the SAVI, soil-adjusted vegetation index, the TSAVI, transformed soil-adjusted vegetation index, the ARVI, atmospherically resistant vegetation index, the GEMI, global environment monitoring index and the MSAVI, modified soil-adjusted vegetation index (Rondeaux *et al.*, 1996) and was therefore used in this research. Nevertheless the NDVI is a function of the LAI (leaf area index) which is a measure of the area of leaf surface per unit area of soil surface. Within the research area, the LAI was so high (>3) that the NDVI reached saturation level, and the final image had the 'patchwork quilt' effect from agricultural fields while the upland areas, which would be unaffected by modern agricultural practices, contained little heterogeneity. This method was deemed unsuccessful.

The second procedure for extracting vegetation information from the dataset is to select appropriate bands and interpret them on screen. Bands were chosen which displayed contrasting information about the stress levels of the vegetation: band 3, which designed to sense chlorophyll absorption, aiding in vegetation monitoring; band 4, which detects soil moisture discrimination, determination of vegetation types and stress, and delineation of water bodies; and band 5, which was designed for sensing both soil moisture content, and vegetation moisture content. When these are displayed as a false colour composite, healthy vegetation with a high LAI is shown in various shades of green, less active vegetation is shown in various shades of pink while vegetation under stress, or agricultural fields being tilled, are shown in shades of brown, see Image 3.

The synoptic view afforded by this image is its most useful contribution to the research programme. Single morphological features at the scale of drumlins or moraines *could not* be mapped from this image as their forms cannot be distinguished due to the solar elevation at the time of imaging. Nevertheless, larger landforms such as corries, arêtes and kilometre-scale roche moutonnées were mapped and interpreted, as well as drumlin assemblages that showed similar orientations and were therefore recognisable on the imagery. It should be noted that interpretation was carried out on the digital screen image, and the hardcopies included in this text are of inferior quality, plotted at 300dpi.

Three main patterns were identified in the mountains to the south of Clew Bay, *i.e.* in the Partry and Sheeffry ranges;

1. The corries have northerly aspects. This is not unusual in the northern hemisphere where the north faces of mountains experience colder micro climates, however, if the Nephin Mountains did act as a source for an ice dome, corries should occur at all aspects. The north-facing corries suggest that locally the ice flowed towards the north.
2. The U-shaped glaciated valleys display a herring bone pattern with dispersion towards the northeast and the northwest from a line running from south to north through the centre of the mountains. It is not proposed that the valley physiography is due to glacial erosion alone as these valley axes would have existed in the Neogene and would have acted as preferential routeways for ice streams in the Quaternary period. However, the ice streams did erode these valleys to deepen and widen them, producing U-shaped valleys characteristic of previously glaciated terrains.
3. The gentle slopes which exist on the south sides of the mountains in contrast to the steeper, notched northerly faces suggest that glacial deposits were 'plastered' against these slopes while there was erosion on the north-facing slopes. While this morphology can be produced in non-glacial environments the context suggests that a glacial origin is more likely.

While none of these three factors provide concrete evidence for the direction of ice flow when considered individually, it is their combined testimony that enables a viable interpretation to be proposed. This interpretation indicates that an ice mass existed in Connemara, and while it was moving in a generally northerly direction, it also spread out towards the northeast and the northwest from a north/south divide centred in the mountains.

Interpretation is not as clear in the Nephin Beg Range to the north of Clew Bay, where the topography is more rounded. The few corries that do exist however have northerly aspects, and as in the south, there is a gentle gradient on the south facing slopes, most notably on Nephin Beg mountain (NGR 110462, 307895) and Corraun (NGR 77623, 296113) where the north face is notched and plucked. This would strongly suggest a generally south to north ice flow direction in this area.

In the low-lying areas, individual drumlins can be distinguished by the vegetation heterogeneity that is exposed in the infrared bands which enables drumlin fields with homogeneous long axis orientations to be differentiated by the alignment of the inter-drumlin bogs and lakes. Two separate assemblages were distinguished, one encompassing all the lowlands on the eastern portion of the imagery and the second at the head of the bay between the towns of Westport and Newport. To the east there is a sweeping drumlin pattern which bends around Lough Mask, turns towards the north, and then proceeds towards the north-northeast in an 'S' pattern. Although the direction of ice flow (towards the north, or towards the south) cannot be determined from this satellite image, if this is part of the ice mass which affected the mountains, the ice flow direction may be towards the north. The drumlins at the head of the bay display different long axis alignment with a curved pattern extending first to the east, and then to the northeast. Once again, the imagery alone will not provide definitive evidence relating to the direction of ice flow and detailed field mapping is required.

Although variations can be distinguished between and within vegetation types, so that well drained drumlins can be differentiated from poorly drained inter-drumlin zones and alluvium, and raised bogs can be differentiated from blanket peat, this image cannot be used to map variations within till type, or even to differentiate tills from gravels. This is due to the influence of modern farming practices that override any variations that a sandy or silty till may have effected on vegetation growth. One exception to this is in the area around Sraheens at (NGR 12800, 29000) where the elevated Lower Namurian silty-stony till is more poorly drained than the surrounding limestone deposits, resulting in a difference in the vegetation growth which can be discerned on the satellite image.

Peat, even though covered by vegetation, can clearly been seen as a pink colour on the image, however it should be noted that no depths could be inferred, simply their spatial extents. Marine sediments reflect well in all three visible bands, and are therefore represented by the bright digital numbers along the coastal zones. Alluvium can be recognised by its proximity to rivers, and its level topography *e.g.* the Bunowen River deposits at NGR 081996, 278998. Outcropping rock is obvious in some locations, such as the quartzite outcrop on the cone of Croagh Patrick (NGR 90608, 280150) though less easy to map in others, such as the karst limestone pavement to the east of Lough Mask (NGR 116046, 268289).

Principal components analysis (PCA) was carried out on the image dataset in order to redistribute the data spatially in an effort to extract more geological information. Six of the seven bands were used in the PCA, the thermal band was omitted. Most of the information in the dataset, as measured by variance, is displayed in the first principal component. This primarily contained data relating to agriculture, with reflectances from fields and field boundaries dominating the image to the detriment of any geological information. Moving through the principal components, very little geological information was visible as atmospheric and sensor interference was more pronounced. Practically no landcover data could be distinguished on the higher order principal components as they were dominated by atmospheric scattering and sensor interference. Therefore interpretation was not attempted from any of the principal components.

3.3.3 Landsat-5 TM winter

There were two main features of the Landsat-5 TM Summer imagery which reduced the capacity to distinguish any Quaternary geological information, the vegetation cover and the high angle of solar illumination. Winter TM imagery was obtained in an effort to overcome these obstacles, however it must be noted that it is more difficult to acquire than Summer imagery, especially in temperate climates, because there is increased cloud cover and haze. For these reasons few Winter images for Ireland exist on archive.

As the Landsat platform captures data at the same local solar time during each orbit, the only way to reduce the angle of solar illumination was to acquire Winter imagery. This increased the effect of shadows on the imagery, which enhanced the morphological features. It is important to note that in the high latitudes in the northern hemisphere where the study area is located (between 53:34:54.4N and 54:7:11.26N), this preferentially illuminates features which are oriented SW-NE, and may make landforms aligned parallel to the solar azimuth more difficult to distinguish.

Through the application of Winter TM imagery, the masking effect of the vegetation which dominated the Summer scenes can be negated. Band 5 of TM (1.55-1.75μm) includes the absorptive area of H_2O molecules in both soil and plants (Hunt, 1980). In Ireland, all green vegetation, except coniferous forestry, has a similar water content when soil moisture is constant, therefore, on a planar surface, biomass reflectance in band 5 should be homogeneous, producing a grey-scale image of uniform digital values. Any variations in the image tones may consequently be attributed to insolation levels (dependant on slope aspect and gradient) and the moisture content of the soil. These are important variables for Quaternary mapping as they can be used to produce a morphology map, and the variations in soil moisture content may be used to infer the sediment type.

A corollary of these facts is that one band (TM 5, near-infrared) contained most of the geological information within the data, while the redundant data, such as the urban fabric and agricultural landcover was held elsewhere. This single band is displayed through the red, green and blue guns of the display device as a grey-scale image, with two distinct advantages:

1. A grey-scale image is similar to a black and white aerial photograph, therefore time is not needed to familiarise oneself with the variable colour schemes which are associated with false- or pseudo-colour composites from multispectral satellite imagery.

2. It has been shown that the human eye responds differently to colour and monochrome imagery. The modulation transfer functions (MTF) for the human retina show the chromatic response to decrease above 1 cycle degree^{-1}, whereas maximum modulation occurs at a frequency of 7 cycles degree^{-1} for achromatic imagery (Drury, 1993), see Figure 3.1. The effect of this on the information extraction process is that high frequency data such as drumlins, eskers and moraines can be distinguished more easily on monochrome rather than colour displays.

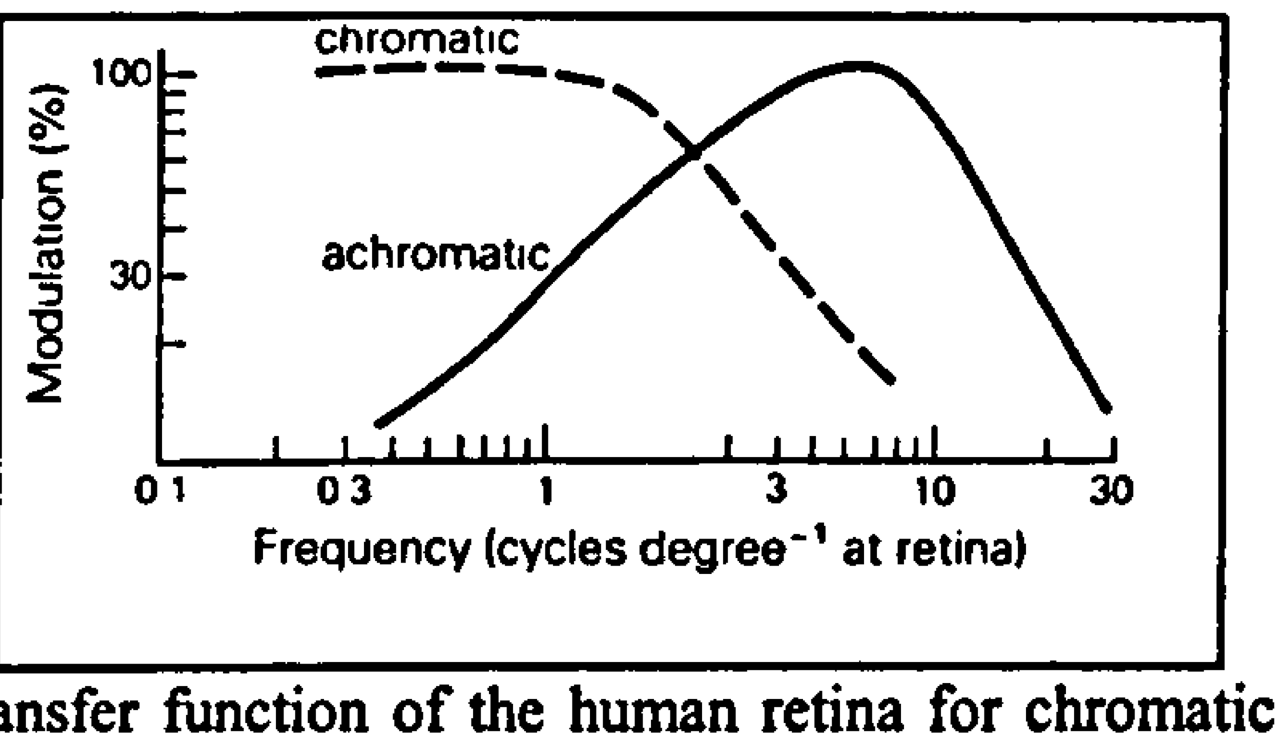

Figure 3.1. Modulation transfer function of the human retina for chromatic and achromatic imagery (Drury, 1993).

Digital image processing of TM band 5 consisted of an interactive histogram stretch to achieve the optimum contrast within the image, followed by low pass filtering using a Sobel function to reduce any pixelation which remained after resampling to aid interpretation. Although a visual analysis of the image dataset revealed that it was heavily affected by atmospheric scattering, this was only a problem for the shorter wavelength bands (as explained by $Rs \propto 1/\lambda^4$, which states that Rayleigh scattering in inversely proportional to the fourth power of the wavelength) and therefore only had minor effects on band 5. These digital image processing techniques were carried out on a mosaic of the three Winter scenes, rather than on each individual quadrant so that a single image of the entire research area could be produced to avail of the synoptic qualities of the satellite imagery, see Image 4.

The disjointed shape of the image is because it is formed by mosaicing three quadrants together, while the angle of the borders is due to the fact that the image was rotated in reference to a map coordinate system. The predicted increased effects of shadow on Winter imagery can be seen clearly to the north of Croagh Patrick (NGR 90608, 280150) where its peaks cast a series of large shadows over the land. This is one disadvantage of this type of imagery, in mountainous areas extensive regions cannot be mapped as they are cloaked in shadow. Similarly, it is often found that southeast facing slopes have such high reflectance values that little geological information can be extracted. However, on the plus side, although it was unclear if drumlins with their long axes parallel to the solar zenith could be imaged, it is clear from the image that this was not a problem as their short axes provided suitable angles and elevations for competent solar reflectance.

It is also important to note that coniferous forestry is shown in darker tones than the remainder of the land surface (except shadows) because of the absorption spectra of the foliage in this wavelength. Coniferous forestry can also be recognised by their geometric shapes and the trackways which dissect them, *e.g.* Tonlegee forest at NGR 105821 278882. Unfortunately, absorption by the forestry foliage dampens the reflectance signals that would occur due to aspect and slope, therefore reducing the morphological content of the imagery in forested areas.

Another disadvantage associated with this band choice is that bathymetry is not possible. Water bodies act like blackbodies in the infrared wavelengths and absorb all the incident radiation, appearing black on the image. Unfortunately this meant that a survey of the seabed could not be undertaken to ascertain if there were fully submerged drumlins in the bay. In theory, band 1 could be used to penetrate the water bodies and search for subaqueous morphology, however this short wavelength band was dominated by atmospheric attenuation and sensor interference.

A major advantage of imagery which has been processed in this way is the fact that the general masking effects of the vegetation, along with the 'patchwork quilt effect' of the agricultural boundaries, and even the infrastructure networks have been eliminated, thereby clarifying the image prior to geological interpretation. Features such as field boundaries are high frequency spatial data and their occurrence on imagery distracts the interpreter from other data of similar frequency such as moraines and drumlins.

A review of the image shows that it contains an extensive amount of Quaternary geological information, both on the regional and local scales. Locally, individual drumlins and kames can be mapped, see Image 5, while regionally, the synoptic view afforded by the image enables spatial patterns to be discerned within the drumlin field, see Image 4. Interpretation began at the local scale by drawing the long axis of each streamlined landform onto an annotation layer on the screen, thereby using a 'ground up' approach to the data in order to build up an understanding before final interpretation and modelling. Each type of landform was delineated with a different colour to aid in the interpretation process. Drumlins were marked in red, bedrock ridges and roche moutonnées in black, moraines by broken green lines, eskers in continuous dark green lines, erosional flutings in blue, and sinuous ridges which fieldwork indicated were composed of glacio-tectonised bedrock in pink, see Image 6.

A variety of drumlin forms were mapped: spindle, classic, parabolic barchanoid and superimposed. The distribution of these forms has been used to infer ice flow mechanisms as well as the directions of ice flow. Spindle-shaped drumlins dominate the eastern half of the research area. At Lough Mask their long axes are aligned towards the northeast, subsequently veering to the north and then to the northeast, in an extended 'S' pattern. Their stoss ends are to the south. Within this region of the drumlin field the dimensions of the landforms are remarkably uniform with a length/width ratio of 5.3. This uniformity of shape would seem to suggest a relatively constant speed of ice flow over homogenous topography, while their spindle shape would indicate a thick ice mass (Mills, 1987). This hypothesis is corroborated by the fact that their forms become shorter and wider with a length/width ratio of 2.2 as they get closer to the hills at Sraheens (NGR 127428 286649). This shortening of form, corresponding to increasing altitude, has been catalogued elsewhere and attributed to thinner ice at higher elevations (Rose, 1987).

To the west of this, there is an assemblage of drumlins in the Erriff Valley at NGR 10562, 25720. Previous research has suggested that ice flowed towards the southwest, up the valley (McCabe, 1993; McCabe & Dardis, 1994), however the drumlin morphology indicates that the opposite is the case. First, the elongation ratio of the drumlins at the top of the valley is 3.6, whereas at the valley opening they are significantly shorter with an elongation ratio of just 1.6. As the drumlin shortening is not a result of an increase in elevation which would have caused the glacier velocity to decrease (Rose, 1987), it may be attributable to converging flow where an ice stream flowing down-valley converged with the ice mass which was moving in an arc around the Partry Mountains at NGR 109410, 276000. This assumes that the ice streams in the valley and in the lowlands were synchronous. Second, a northeasterly flow direction is also indicated by the fact that the drumlin stoss ends are to the southwest.

At the head of the bay, the geomorphology is more complicated, with the occurrence of arcuate landforms consisting of barchanoid, superimposed and megadrumlins which could have been formed by one of four ice flow scenarios, see Figure 3.2.

A. Ice flowed in a southeasterly direction but was subsequently diverted towards the north. The ice flows need not be synchronous. This scenario is unlikely when the scale and morphology of the feature are considered, as it would be necessary for the ice stream to change direction by 330° with a 0.5km area.
B. The features may be polygenetic, formed by ice converging from two ice centres. This could be the same ice mass which has undergone an ice centre shift, *i.e.* asynchronous formation.
C. The landforms are barchanoid drumlins \ Rogen moraines with a single ice flow direction from the southeast. This seems unlikely as it does not account for the superimposed drumlin patterns oblique to each other, which seem to suggest an asynchronous process of formation.
D. It is proposed that the landforms could have been produced by ice flows transverse to one another, similar to Boulton's (1987) model, where an earlier flow produced landforms aligned SW-NE while a later flow, from the southeast, deformed these sediments around resistant cores. In this situation there is no need to postulate that the two flow directions are the result of different glaciations or different ice sheets, but that ice moving towards the east, from a divide in Clew Bay, was in contact at this location with ice moving in a northwesterly direction from the Midlands. With an active junction in a dynamic zone between the two, and each ice mass gaining superiority at different times, several episodes of deformation would have taken place which would account for the multiple flow directions indicated by the

morphology. These processes could have led to the development of these landforms which lie somewhere between drumlins and Rogen moraines.

An interpretation of the morphology suggests that a combination of B and D was responsible for the production of the landforms. The variation in direction, postulated in B and D, would have been due to shifts of the interlobate zone between the two ice masses. As the ice moving eastwards from the bay gained dominance, the ice from the Midlands was forced further towards the north and northeast, and *vice versa*. The ice sheet dynamics would have been forced by a number of variables including eustatic changes, variations in the basal temperatures of the ice masses and regional/local climate changes affecting the accumulation and ablation rates which would affect the two ice masses in different ways.

Although useful discussion regarding ice flow directions can be undertaken using morphology alone, it should be reaffirmed that a holistic approach including sedimentological research is needed before the depositionary environment can be reconstructed with a high degree of certainty. It is for this reason that remote sensing image analyses were integrated with traditional Quaternary geology mapping techniques in this thesis before a model for the regional glaciation of West Mayo was proposed.

To the west of the arcuate drumlins, described above, is a series of east/west aligned drumlins located between the towns of Westport and Newport and also partially submerged in the bay itself. These show a radiating pattern from the bay towards the east, in classic ice dispersion form. These drumlins are unusual, however, as they are curved in plan. Their western ends are aligned west-east, but they subsequently bend towards the north. This would be most easily explained by postulating ice from the Midlands forcing the ice in Clew Bay to divert from its preferred path inland and progress in a more northerly direction, thereby remoulding the landforms.

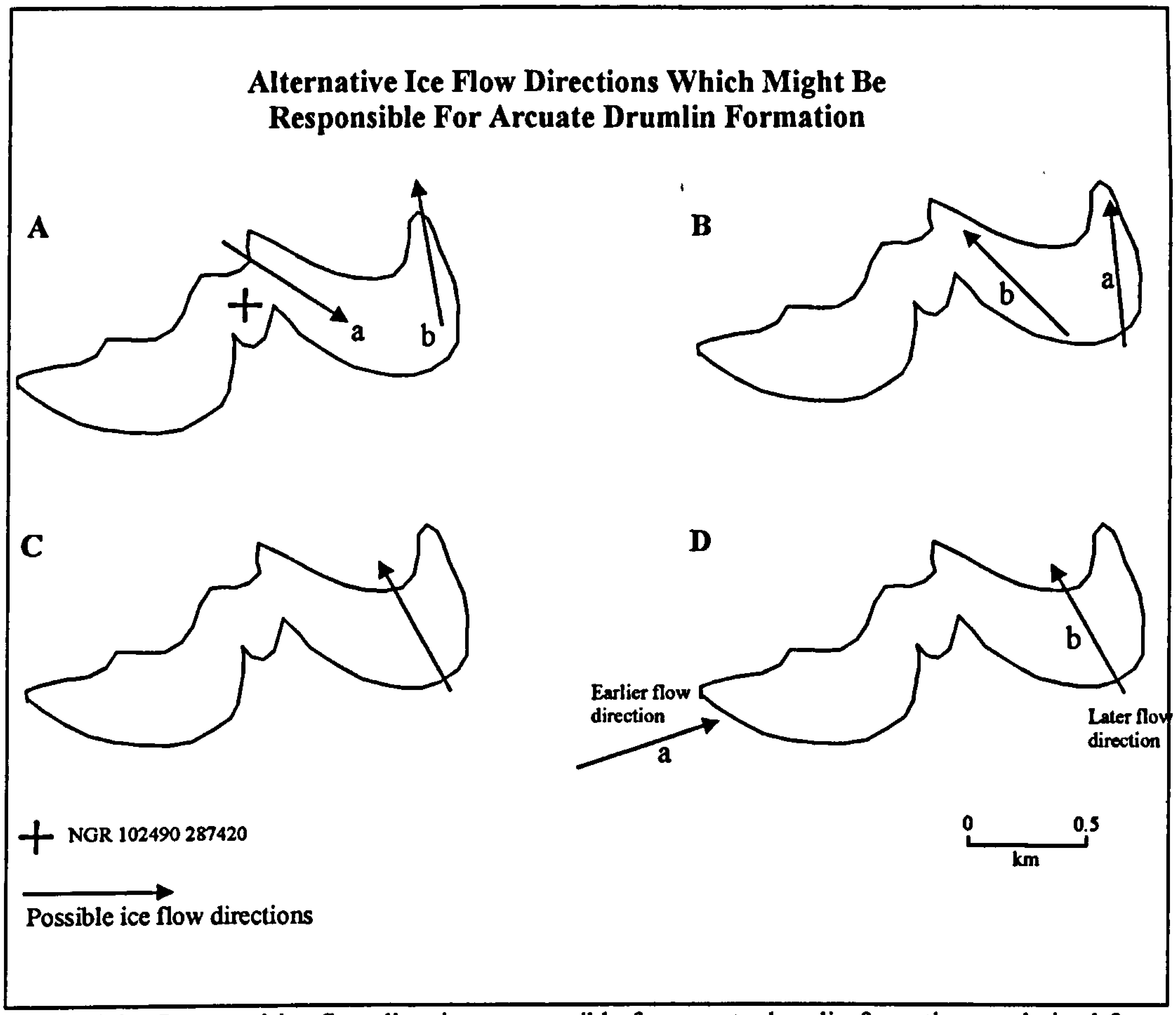

Figure 3.2. Suggested ice flow directions responsible for arcuate drumlin formation, as derived from morphology. The drumlin is a scale plan of one located at the head of Clew Bay near Westport town, NGR 102490, 287420.

There is another pattern of drumlin morphology of note, situated along the northern shores of the bay, between the towns of Newport (NGR 098201, 293890) and Mallaranny (NGR 082903, 296577). Many of these landforms are 'megadrumlins', defined by Rose & Letzer (1977) and Riley (1987) as drumlins superimposed on larger streamlined hills. The pattern comprises a diverging system with the streamlined bedrock hills aligned towards the northeast in the Newport region of the bay (*e.g.* at NGR 093092, 296890) and aligned towards the northwest along the Mallaranny coast (*e.g.* NGR 086155, 297319) while the superimposed drumlins are oriented in a more east/west alignment, tangential to that of the bedrock hills.

Working on the premise that megadrumlins are a geomorphological response to the stresses applied by ice at the glacier bed (Rose & Letzer, 1977) then the main variables that control shear stress, *i.e.* glacier thickness and surface slope (*e.g.* Boulton, 1975; and Hooke, 1998) may be considered as responsible for the formation of the streamlined hills and the superimposed drumlins. A decrease in either of these two factors would result in a decrease in the shear stress at the glacier bed, producing smaller drumlins superimposed on the streamlined hills. The superimposed drumlins could therefore reflect a time of bedform development during a deglacial phase when the ice was thinner than at the time when the streamlined hills were formed. Similarly, the streamlined hills could have formed when the glacier surface slope was higher (when they were closer to the snout) in contrast to the superimposed drumlins which would have formed under a gentler surface slope when the ice divide was directly above *i.e.* under an ice plateau. These conditions need not be mutually exclusive, but in any case the morphology suggests that there was an earlier ice dispersion pattern from the south which formed the larger streamlined hills. This ice flow pattern was gradually replaced by an ice divide in the centre of the bay as the whole ice mass expanded in a northerly direction, causing the ice to flow in a more west-east orientation, forming the smaller, superimposed drumlins on top of the streamlined hills. This suggests an active late glacial phase with continued drumlin formation in the area. Alternatively, the morphological pattern could be the result of two separate glaciations, but this is not corroborated by evidence from elsewhere in the research area.

Further west along the northern coast of the bay, the drumlin pattern is more controlled by local topographic features. Corraun Mountain, at 541m (MSL), NGR 078278 295483, was a formidable obstacle to ice flow. On the eastern end of the mountain, the long axis lengths are reduced to a mean value of 0.52km, with an elongation ratio of 1:2.8, while to the west of the mountain the long axis mean length increases to 1.1km and the elongation ratio rises to 1:5.8. This indicates that ice flowed in a generally westerly direction at this location, and as the ice banked against the mountain slope it became thinner and formed smaller bedforms. Also, the drumlin morphology displays a curved pattern, indicating that when the ice stream came in contact with the mountain it was diverted towards the southwest, around the mountain, and that it subsequently veered northwest towards a zone of lower pressure when the obstacle was passed. The orientation of the landforms in the lee of the mountain also indicates that while ice streams were diverted around the mountain, some ice overtopped the mountain and flowed directly towards the northwest.

To the east of a line between NGR 132048, 293105 and NGR 122696, 261824 the morphology, although dominated by drumlins, is different to rest of the research area. The drumlin long axes have a mean length of 1.07km and an elongation ratio of 1:3.8, which makes them the same length, but with a longer b axis than those to the west. Their long axes are also parallel to the drumlins to the west. Of importance in this area is the fact that the morphology is more subtle, to the extent that the drumlins are difficult to delineate on the satellite imagery. Also, the density of drumlins is substantially lower, decreasing towards the north, and terminating altogether in an area of moraines at the north of the imagery. A second morphological pattern also occurs in this region, a series of elongate erosional scour marks that are aligned southeast-northwest. Many of these depressions are now lakes.

The esker complex, aligned parallel to the drumlins at NGR 136297, 277947 also provides evidence relating to the glaciation of the area. Working under the assumption that the eskers were deposited generally perpendicular to the ice sheet margin (Warren & Ashley, 1994), and that they are indicative of the last glacial event, it can be assumed that the drumlins (which are parallel to the eskers) were also formed in the last glacial event. The erosional flutings, which are oblique to these, must therefore precede the formation of the drumlins, though not necessarily from an earlier glaciation. This is corroborated by the fact that one of the eskers overlies one of the flutes, at NGR 134906, 278660, thereby establishing the proposed sequence of formation.

In combination with the drumlins, other morphological features provide evidence relating to the pattern of glaciation in the area. Streamlined hills and roche moutonnées are common in the region and are good indicators of the directions of ice flow. Two similar examples are Buckoogh and Nephin, located at NGR 098986, 300912 and NGR 110176, 307451 respectively. These are both wedge-shaped hills, with their wide ends facing northeast, and have been streamlined along their long axes. Moreover, they have corries on their northeastern faces that also indicate that ice flowed towards the northeast at these locations. The five streamlined hills to the west of Buckoogh are of similar morphology and orientation, but are smaller in scale. These indicate that ice flowed from south to north in this area. Further evidence substantiating this pattern of ice flow in the environs of Lough Furnace is the roche moutonnée along its western shoreline, at NGR 094236, 299838.

In the centre of the Nephin Beg Range, the geomorphology of the roche moutonnées indicates that the ice flowed directly from south to north, along pre-Quaternary valleys and ridges aligned in that direction. The western section of the range mirrors the east, with morphological evidence suggesting that ice flowed towards the northwest. This is shown most clearly at Claggan Mountain (NGR 84388, 299612) and Corraun Hill (NGR 78318, 296389) which have gentle slopes on their southeastern faces where the till was emplaced by the passing glacier and ice-plucked northwestern slopes. The streamlined hills at NGR 80469, 207583 indicate that the col in the mountains at Mallaranny (NGR 82903, 296577) served as a conduit for a northerly-flowing ice stream.

Moraine ridge forms are common in the Nephin area, being interpreted as (a) lateral moraines along mountain sides (*e.g.* NGR 113461, 308492 along the flanks of Nephin), (b) arcuate terminal moraines from corries (*e.g.* NGR 89838, 305391 at Corryloughaphuill Lough) or (c) recessional moraines in valleys (*e.g.* 97957, 303587 to the north of Furnace Lough). The form of the recessional moraines can be clearly distinguished on the computer screen display and has been partially dictated by the wedge-shaped hill to the south of it. The hill acted as an obstacle to ice flow giving the moraine a sinuous outline. Fieldwork has shown that there is a series of recessional moraines located even further up the valley, parallel to that described above, but they are cloaked in shadow and cannot be seen on the satellite imagery.

Other Quaternary geology features of interest include two assemblages of sinuous ridges; the first to the east of Westport town at NGR 104779, 283309, and the second, smaller series, to the northeast at NGR 103247, 288393. They are aligned generally southwest/northeast. Reconnaissance fieldwork was utilised to identify these features as their morphology did not accord with that of eskers or moraines, and led to their identification as glacio-tectonised bedrock ridges. Similar features were identified by Punkari (1985) who proposed that their formation was through the fragmentation of the bedrock between active glacial lobes, due to convergent and compressive flows. This would suggest that these mark the location of an active interlobate area with ice flowing towards the northwest from Lough Mask, and ice flowing towards the northeast from the Clew Bay.

Solid bedrock features which may be confused for glacial landforms are located in an area around NGR 118310, 285639, see Image 6. A pattern of linear features crossing the image in a SW-NE alignment have been identified as limestone bedding, visible through the till, while the circular feature which surrounds the grid location is the expression of a syncline. Neither bedding nor syncline were visible during field visits, or from aerial photography. The larger bedrock feature, also oriented SW-NE, between NGR 099366, 283798 and NGR 125095, 295092 is the Moyne Thrust which marks the boundary between the Lower Carboniferous Sandstone to the south and the Dalradian rocks to the north.

Chromatic images were also created from the Landsat-5 TM winter dataset. This was undertaken because if the achromatic imagery is superior for interpreting high frequency data, then it follows that lower frequency data, such as regional patterns of soil moisture can be interpreted preferentially from chromatic multispectral data. The shorter wavelength bands, 1, 2 and 3, were displayed on screen for preliminary visual analyses after they had been corrected for atmospheric scattering. This analysis showed that the reflectance values in these bands were primarily from the surface vegetation, with the same suite of problems that this posed for the Summer imagery. Therefore, permutations of the longer wavelength bands were evaluated (except for the thermal band) *i.e.* bands 4, 5 and 7. Ironically, bands 4, 5 and 7, displayed in that order through the red, green and blue guns of the display device provided the most interpretable image, see Image 7.

The colours on the image need either ground truth or knowledge of the wavelength characteristics before interpretation can be undertaken. A combination of both was used in this study. The bright red colour is snow on the mountain tops, while black is water bodies. Vegetation is imaged as various shades of pink which vary with the subsurface moisture content, but it does not have the overpowering effect that it has on Summer or shorter wavelength Winter TM imagery. Coniferous forestry has a unique signature and is imaged as a rust colour. The remainder of the landcover can be divided into three main types:

1. bright turquoise, which shows poorly drained mountain areas;
2. dull turquoise, showing poorly drained low-lying terrain;
3. pale red / pink, which shows well-drained areas.

Apart from the obvious divide on the image between the plains and the higher altitudes, indicating that the mountains are poorly drained in contrast to the lower elevations, there is another pattern of note. There is a band of poorly drained land extending in an arc towards the north-northwest from the northern shores of Lough Mask, parallel to the drumlin morphology. This marks an area where there is a notable lack of drumlins, and appears to indicate a zone of glacial erosion which contained a postglacial lake. Similar drainage can be seen at the eastern extents of the image where the density of drumlins decreases, and the erosional scour flutings appear. The dull turquoise pattern in this area is parallel to both the erosional scours mapped from the grey-scale Landsat TM band 5 Winter image and the long axes of the lakes in this area. Another interesting point to note is that the gravel areas to the northwest of the Nephin Beg Range are shown as poorly drained. This is because, despite the gravel's texture, the surface drainage is poor with the result that blanket bog developed in Holocene times.

To summarise, following interpretation of the satellite imagery, several patterns have been postulated which require testing using field geological methods. Primary amongst these are the suggested directions of ice flow which have been determined from the morphology and sediments interpreted from the satellite imagery but which need to be corroborated by sedimentological techniques applied during fieldwork and laboratory analyses. The postulated directions of ice flow for various locations in the study area are as follows:

- towards the north, through Lough Mask and Lough Conn in an extended 'S' pattern;

- radiating from the southern mountain ranges of the Partry and Sheeffry Mountains
- radiating from the Nephin Beg Range;
- radiating from a north-south divide in Clew Bay towards the east and the west;
- flowing towards the northeast up the Glenhest Valley at the northeast head of the bay;
- flowing up Bellacragher Bay between Corraun Hill and Claggan Mountain with ice streams diverted around the mountains.

Hypotheses relating to the thickness of ice and the mode of formation of landforms were also suggested from the satellite imagery and need to be tested using field and laboratory analyses. It was determined that the shape of the drumlins varied with altitude and also at the confluence of ice streams where they became shorter and more rounded, relative to the up-ice drumlins. Moreover, their situation in relation to the local topography affected their morphology, where, for example, their elongation ratio decreased at the up-ice side of large obstacles to ice flow such as hills. This may have been a function of a reduction in the ice flow velocity and/or a thinning of the ice, both of which would have been due to increasing altitude.

4 SUMMARY QUATERNARY GEOLOGY OF CLEW BAY

4.1 INTRODUCTION

Between November 1994 and September 1997, detailed field mapping of the Quaternary deposits and geomorphology of west County Mayo was carried out by the author while working for the GSI. 2010km^2 were mapped to GSI publication standards at 1:25,000 scale (figure 1.2). As detailed descriptions of the Quaternary geology of each 1:25,000 sheet have been outlined in Jordan (1997b) no more than a short summary will be included in this chapter. Data forming the basis of the descriptions such as 105 stone counts (in spreadsheet and pie chart form) and over 250 bulk sample descriptions and sieve analyses results have also been reported upon (Jordan, 1997c) and will therefore not be repeated here. Jordan (1997b) describes the geology under the following headings.

1. Surface morphology
2. Bedrock geology
3. Quaternary sediments
    - diamictons
    - glaciofluvial deposits
    - glaciolacustrine deposits
4. Glacial features
    - drumlinoid landforms
    - eskers
    - kames/kettleholes
    - roche moutonnées and whalebacks
    - striae
    - crag and tail landforms
    - corries

They will here be treated under the headings 'Landforms' and 'Sediments'.

Research that has not been documented in the GSI reports such as data relating to directional indicators of ice flow, till fabric analysis, deformation structure logging and striae collected from outside the fifteen 1:25,000 sheets, at locations on Clare

Island in the mouth of Clew Bay, and Roonah Point on the mainland to the southeast of Clare Island will be outlined in this chapter. These additional sites were chosen to ensure a complete distribution of data from the area surrounding the bay were obtained so that there would be no geographical data 'blanks' which could reduce the interpretability of the results. All ice flow direction data have been compiled onto figure 5.21 following discussion of the 11 exposures along the coast of Clew Bay.

The overlay maps described in the methodology chapter (*i.e.* Quaternary sediments, Morphology and Depth to bedrock) were amalgamated in AutoCAD into two maps for interpretation in this thesis. The first is a surface materials map showing Quaternary sediments and outcropping rock locations, while the second is a morphology map. During the course of sediment mapping, the deposits were categorised according to their genesis and this classification has also been used here because it provides the most straightforward method of both describing and analysing the sediments. As the sediments and morphology maps are available from the GSI, only representative 1:50,000 sediments and morphology maps have been included in the Appendices of this thesis.

Holocene sediments, consisting of peat, alluvium and marine deposits are recorded on the Quaternary sediments map due to GSI mapping requirements. However they are not discussed in this summary as they do not contribute to the reconstruction of the glacial geology of the area.

4.1.1 Landforms

Figure 4.1 illustrates the geographic distribution of glacial landforms in Clew Bay, derived from a combination of remote sensing and field mapping. The most striking feature of the Quaternary geology is the abundance of drumlins which occur across the low-lying plains and in the valleys. The axial trends of the drumlins contribute strongly to the understanding of the flow pattern of the ice in the area, and provide information relating to the directions of ice flow if one assumes that the stoss sides were up-ice and the tapered sides were down-ice. The drumlin morphologies were not used in isolation but were integrated with till fabric data and striae *etc.*

Immediately clear is the pattern in the eastern half of the area where the crestlines of the drumlins are aligned in an extended 'S' pattern. Of note in this drumlin field is the fact that the drumlins become shorter and more rounded at the southern extents of any elevated areas and regain their pre-existing elongation ratios to the north of the high ground. In the far east of the area at Claremorris this drumlin pattern aligned towards the northeast superimposes a series of erosional scours in bedrock that are aligned towards the northwest.

At Murrisk, in the southwest quadrant of the research area, the crestlines of the eastern drumlins are aligned towards the northeast, while the long axes are aligned towards the northwest in the western half of this region. This pattern of diverging flow is mirrored in the north of Clew Bay where the drumlin long axes are aligned towards the west and northwest in Corraun and towards the northeast at Furnace Lough (northwest of Newport).

The most complex drumlin morphology occurs at the head of Clew Bay, between the towns of Westport and Newport. The features in this area are megadrumlins with east/west crestlines on their west sides and north/south trending axes on their east sides. The south of this area is characterised by barchanoid-shaped drumlins with their horns extending towards the north and northeast. There are no exposures into these barchanoid drumlins.

Bedrock lineations, in the form of rock drumlins, roche moutonnées, tadpole rocks (Plate 4.1) and crag and tails are found throughout the mapping area. These are parallel or sub-parallel to the drumlin pattern described above. Smaller bedrock features, striae are also common, both on bedrock outcrops (Plate 4.2) and on clasts within the tills. Striae on clasts, unless they are stoss-lee boulders, are unreliable indicators of ice flow direction as the clasts rotate in transport. However striae in general display more variation in orientation than the drumlins, but are generally sub-parallel to them in the project area.

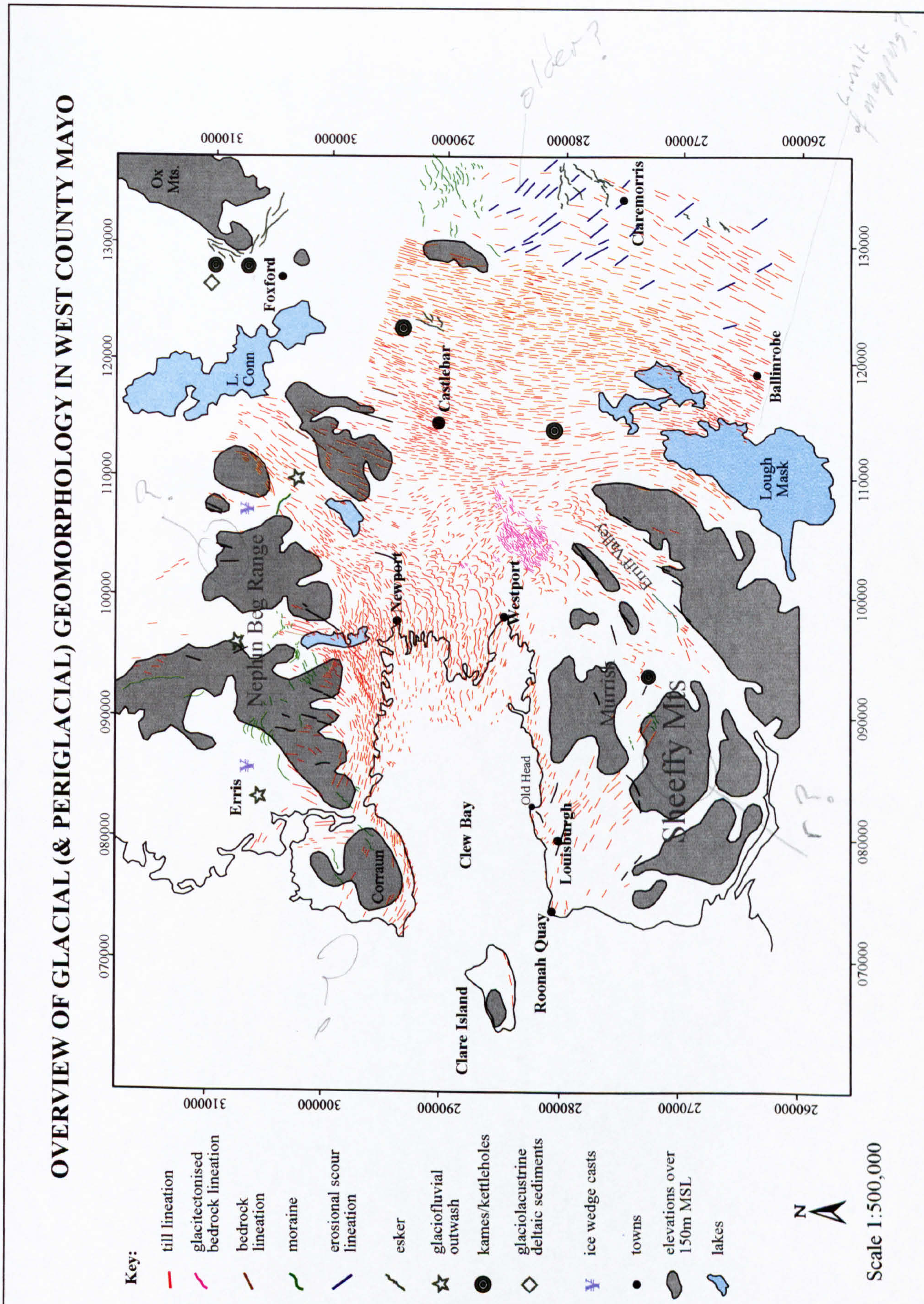

Figure 4.1. Distribution of landforms derived from remote sensing interpretation and field-mapping.

Plate 4.1 Croaghrimcarra tadpole rocks. Ice flow was from left to right.

Plate 4.2 Striae on limestone bedrock. Rat tails indicate ice flow away from the viewer.

Sub-parallel, sinuous ridges composed of tectonised limestone bedrock were mapped at two locations to the east of Westport town. Though sinuous, they are generally aligned southwest-northeast. They contain a small percentage of sandstone clasts whose nearest provenance is towards the south. Glaciotectonic features with similar sedimentological and morphological properties were recognised by Punkari (1985) in Soviet Karelia and attributed to formation through the fragmentation of the bedrock between active glacial lobes due to convergent and compressive ice flows.

Moraines were recorded in the mountainous regions of the research area *i.e.* in the Nephin Beg Range and in Murrisk, but were notably absent from the remainder of the research area. The moraines can be divided into two main types, those associated with corries, and those associated with 'lowland' ice. The corrie moraines are arcuate with the concave sides facing the corries. A sequence of three corrie moraines was mapped in the Nephin Beg Range, which have previously been attributed to the Nahanagan stadial (Kenyon, 1986). The lowland moraines extend in a discontinuous line from the west of Nephin Mountain to Bengorm in the east marking the boundary between the till to the south and the stratified sands and gravels to the north. Their steeper southern sides indicate that these were the ice-contact faces as the ice receded towards the south.

Both flanks of the Erriff Valley, northwest of Lough Mask, have extensive kame terraces composed of sands and gravels. Kame and kettle topography occurs to the northeast of Foxford where it is associated with the terminus of eskers and the location of deltaic landforms. Eskers also appear in association with kames and kettleholes to the northeast of Castlebar. Isolated kames were also mapped in valleys of the Sheeffry Mountains in the south of the research area, while eskers also exist to the northeast of Claremorris where the frequency of drumlins decreases substantially.

Erris, to the northwest side of Glenamong is a large expanse of stratified sands and gravels in the form of an outwash plain. This region is characterised by subdued morphology where the gravels are overlain by thick blanket bog.

4.1.2 Sediments

The sedimentology of the deposits constituting the drumlins is very varied, and a full discussion on this topic is deferred to the following chapter where logged drumlin exposures will be dealt with in detail. However, a summary of the till types and their general characteristics, including composition and stratigraphy will be included here. The GSI mapping system categorises tills by their dominant phenoclast petrography and as these maps form the basis for this study the same criteria will be used here. The following general patterns can be concluded: the limestone till is gravelly sandy silty/clayey; the Lower Carboniferous sandstone till is silty/clayey gravelly sandy; the Lower Palaeozoic till has fairly equal components of silt/clay sand and gravel; the granite till is gravelly sandy; the metamorphic till is silty/clayey sandy gravelly; the quartzite till is silty/clayey sandy gravelly; the Lower Namurian till is sandy silty/clayey while the Mélange till is gravelly. These are clearly bi-modal or multi-modal distributions. Nevertheless, while there is some correlation between the till types (as defined by the dominant phenoclast petrography) and particle size, there is in fact too much overlap to enable the petrography of the tills to be categorised by particle size (figure 4.2). Therefore, for example, one cannot conclude that simply because a till is silty/clayey it is a limestone dominated till or *vice versa.*

The structure of the tills at the inland sections is consistently massive, apart from rare horizontal fissility, while the till at the coastal exposures is highly deformed. This deformation will be described and interpreted in the following chapter. It is believed that deformation also exists in the inland tills but that the form of erosion at the coast has highlighted the structures there. A good example of glaciotectonics exists at Turlin Strand (to the northwest of Louisburgh) where the bedrock has been sheared up into the till, which itself has undergone deformation (Plate 4.3).

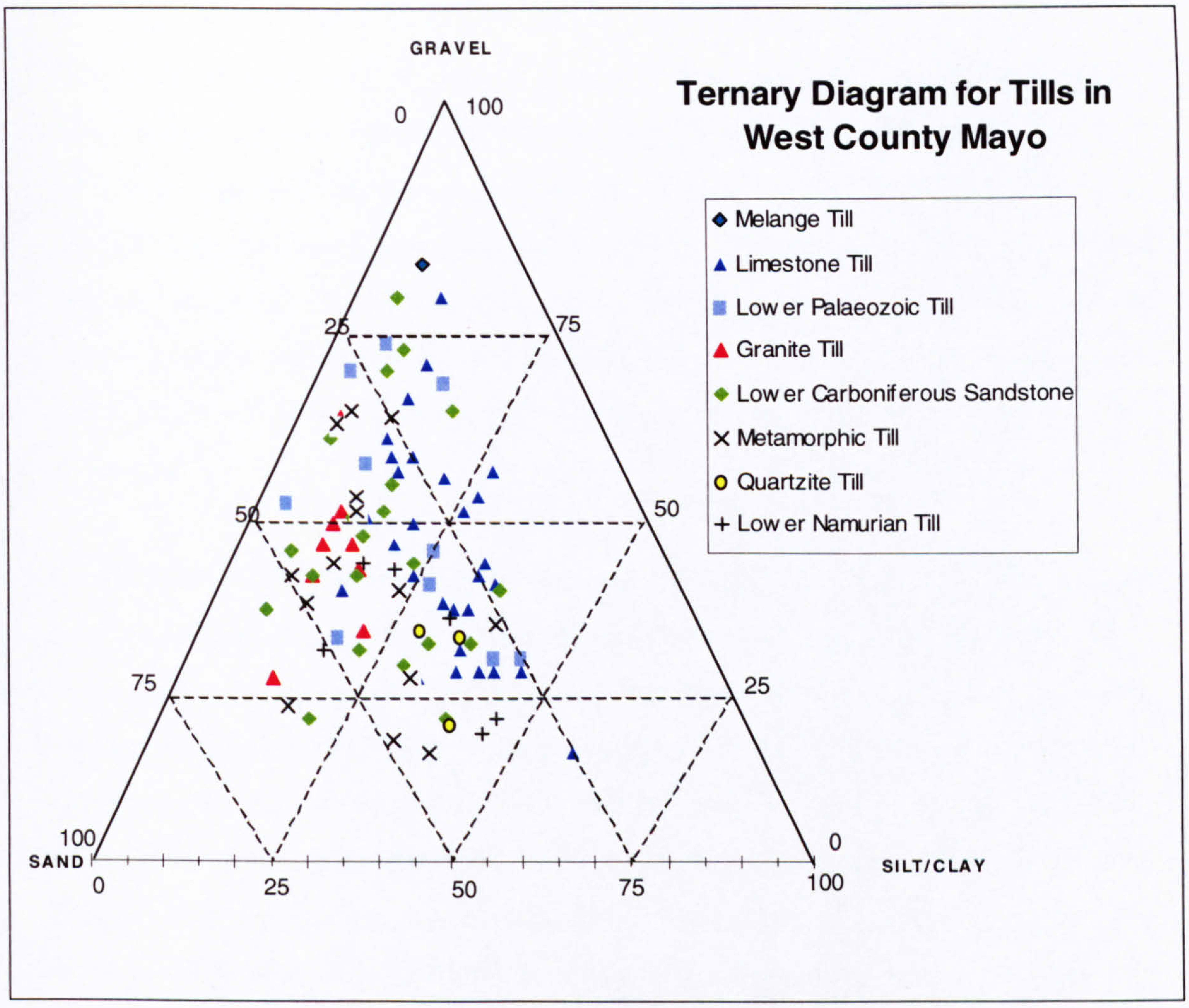

Figure 4.2 Ternary diagram of component with respect to dominant phenoclast petrography for tills in Clew Bay.

In Clew Bay the distribution of the tills, as defined by their phenoclast petrography, is closely related to the bedrock geology from which the tills are derived, *i.e.* the tills are not far travelled. There are two notable exceptions however. These are also the only two localities in the study area where there are double or multiple till sequences.

i. Where sandstone till overlies limestone till in the drumlins in the bay. This will be dealt with in detail in the following chapter.

ii. At Old Head (a coastal section 1.4km long to the east of Louisburgh) where sandstone and schist till is overlain by sandstone till (with a low proportion of schist). Analyses during this research have been corroborated by later research (Bokhorst, 2001; Vriend, 2001) indicating that the lower till was deposited by ice flowing towards the west and the upper by ice towards the northwest.

Till fabric eigenvectors are another method used to determine the direction of ice flow. Till fabrics were recorded at 39 sites across the study area, summarised in figure 5.21. These indicate that the direction of ice flow in the southeast quadrant of the study area was generally from south to north, while in Glen Nephin and Glenhest in the northeast quadrant it was towards the northeast, following the valley axes. Data gathered along the Clew Bay coastline and from islands in the bay indicate that ice flowed towards the east in the eastern half of the bay, and towards the west in the western half of the bay, the dividing line being to the west of the 090000 meridian line (figure 5.21).

Erratics were also mapped. When displayed in relation to their provenance these provide indisputable evidence for the direction of carriage, and therefore of ice flow. Figure 4.3 summarises the location of Lower Carboniferous sandstone, Devonian sandstone, granite and silica-rich volcanic erratics in relation to their provenances. For the areas where erratic carriage data are available it indicates ice flow generally from south to north but these data will be linked to the other spatial data to provide an holistic picture of the ice flow directions. Erratics occur throughout the study area, however they were only included in figure 4.3 if they could be tied to a specific bedrock provenance. For example, limestone clasts could not be used as indicators of ice flow direction because limestone bedrock occurs through the eastern half of the study area as well as beneath the sea in Clew Bay itself.

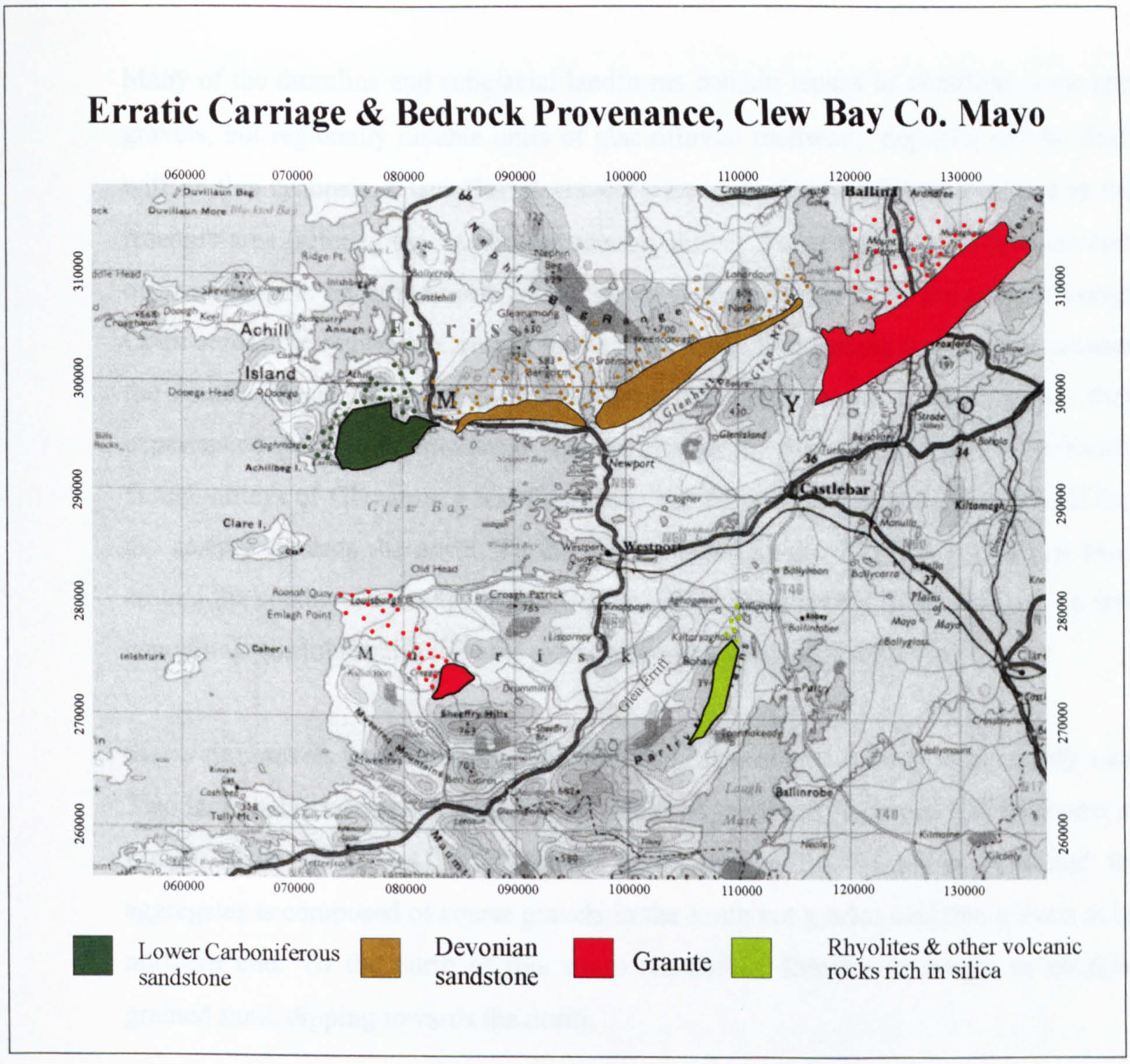

Figure 4.3. Erratic carriage with bedrock provenance

Many of the drumlins and subglacial landforms contain lenses of stratified sands and gravels, but regionally notable units of glaciofluvial meltwater deposits will be dealt with in this synopsis. Glaciofluvial gravels were recorded at various locations in the research area (refer to the Landforms section above). Large expanses of peat-covered outwash gravels lie to the north of the moraines that stretch from the west of Lough Conn across the region to Corraun in the west. Clast imbrication is generally towards the south. These gravels frequently contain ice-wedge casts, indicating that they experienced periglacial conditions. Just to the south, the gravel areas in the south-facing valleys of Glenamong and Erris have flat upper surfaces and contain beds that dip steeply towards the north. To the east of these lie the Foxford eskers that bend around the southwestern edge of the Ox Mountains terminating to the north in an area containing glaciolacustrine deltaic sediments and kame/kettleholes.

Sands and gravels were also mapped in the southern mountain range of the study area. Two large kame terraces exist along the flanks of the Erriff Valley to the northwest of Lough Mask (Plate 4.4). The eastern kame terrace that is being exploited for aggregates is composed of coarse gravels in the south but grades into fine gravels at its northern end. To the north of this again are deltaic foresets in coarse to medium grained sand, dipping towards the north.

It is important to ascertain the mode of deposition at each exposure as this provides direct evidence relating to the environment of deposition. The environment of deposition can subsequently be used to reconstruct a model of the glaciation of the research area. An interpretation of the mode of deposition was arrived at using an holistic approach involving an analysis of particle shape, particle size, particle fabric, particle packing, phenoclast petrography and structure. Table 1.2 summarises how these factors are used to categorise tills into lodgement till, subglacial melt-out till, deformation till, supraglacial melt-out till, flow till and sublimation till. The broad associations of glacial environments with Quaternary sediments, processes of deposition and features/landforms have been summarised below in Table 4.1.

Environment	Process	Feature/deposit
Subglacial	Glacial erosion Rock moulding Glaciotectonics Direct glacial deposition Glaciofluvial	Striae Roche moutonnées Tadpole rocks P-forms Tectonised bedrock Tills Eskers Stratified gravel cavity fills
Proglacial	Glaciotectonics Glaciofluvial Glaciolacustrine Outwash	Ice push ridges Ice-contact stratified ridges *e.g.* De Geer moraines Deltas and fans Sandar
Periglacial	Indirect weathering	Ice wedge casts Involutions
Ice stagnation and decay	Direct glacial deposition Glaciolacustrine Glaciofluvial	Flow tills and melt-out tills Fans and lacustrine silts/clays Kames/kettleholes
Ice readvance	Direct glacial deposition Glaciotectonic deformation	Tills Reworked sediments
Subaerial	Glaciofluvial Outwash	Kame terraces Meltwater channels Sandar
Subaqueous	Glaciolacustrine	Fans, deltas and distal sediments

Table 4.1. Relationships of glacial environments, processes and Quaternary sediments / features.

Plate 4.3 Photograph of bedrock sheared up into till in Turlin drumlin. Ice flow is from left to right.

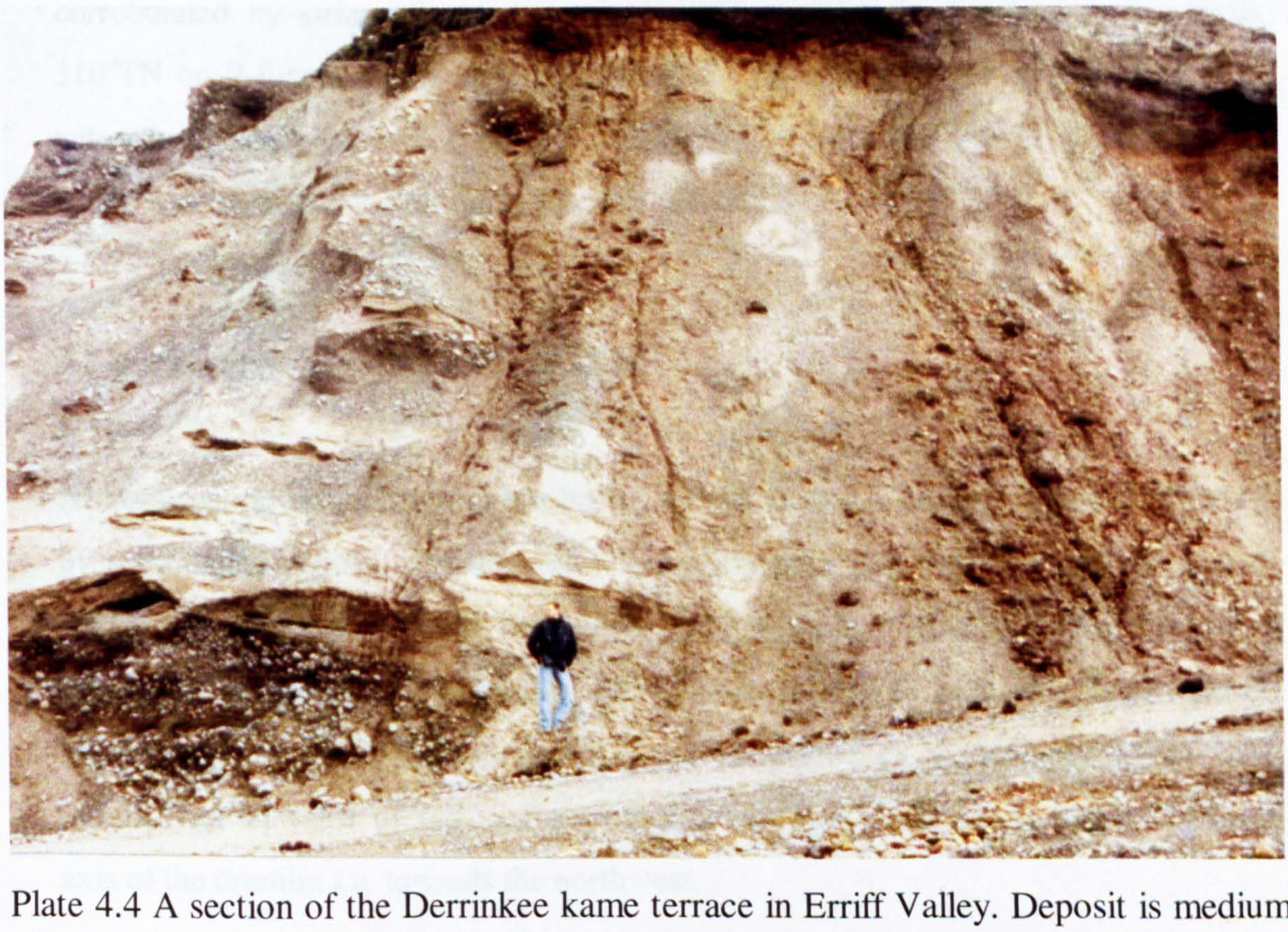

Plate 4.4 A section of the Derrinkee kame terrace in Erriff Valley. Deposit is medium-grained gravels interbedded with coarse sands.

4.2 DIRECTIONAL INDICATORS FROM OUTSIDE THE 15 1:25K MAP SHEETS

Indicators of ice flow direction including drumlin crest alignment, striae orientation and till fabric analysis were recorded on Clare Island and at Roonah Quay (NGR 07455 28096). These sites were chosen due to their situation on the western fringes of Clew Bay so that there would not be any gaps in the spatial distribution of data relating to the directions of ice flow in the last glaciation *i.e.* data would be available from the full circumference of Clew Bay.

4.2.1 Clare Island

Due to time and transport constraints, data could only be gathered along the south-facing shores of Clare Island. The axial trends of the drumlins are aligned west-southwest on the east of the island and towards the west on the west side. This is corroborated by striae aligned towards 231°TN at Glen in the east, and towards 310°TN on P-forms on the west of the island. Extensive till fabric and phenoclast petrography analyses, carried out by Coxon (1982) also indicate that ice flow on the island was towards the west during the last glaciation.

4.2.2 Roonah Quay (NGR 07455 28096)

A cross section into a drumlin has been exposed at this location. Though dominated by subrounded cobbles and boulders of conglomerate and pebbly sandstone it also contains clasts of pelite and psammite which originate from the Lough Nacorra Formation to the southwest. The till is massive and is normally consolidated, consisting of rounded cobbles and boulders supported by a medium-grained sand matrix. The V_1 value of 149° indicates that the ice flow was sub-parallel to the long axis of the drumlin *i.e.* towards the northwest.

4.3 SUMMARY

The majority of the research area is composed of drumlinised till. Over much of the research area it is over-consolidated, horizontally fissile, and contains striated clasts, which along with the eigenvalues suggest that it was deposited through the process of subglacial lodgement. Erratic carriage, till lineations (including drumlins), rock lineations (including roche moutonnées), deformation structures, and till fabric eigenvectors indicate that the ice flowed generally from south to north in the east of the area, and towards the west in the west of the area.

A summary of the stratigraphy of the study area is made straightforward by the fact that the majority of the deposits form a single sequence, and it is reasonable to assume that these date from the last glacial maximum, termed the Fenitian by Warren (1985) or the Midlandian (e.g. Coxon & Browne, 1991) corresponding to the Late Devensian in Britain. The bi-partite till sequences comprising the drumlins in the Bay and at Old Head do not require two periods of glaciation for their deposition. There is no evidence to suggest an interglacial or interstadial. The simplest explanation is simply that they were deposited towards the end of the last glaciation when ice was able to flow offshore. Some researchers (summarised in Coxon & Browne, 1991) have argued that the deposits in Erris which have been described above as gravels with periglacial modifications are in fact tills from the Munsterian (the glaciation preceding the Midlandian). However no evidence was found during this research to corroborate this suggestion whereas it seems more likely that they are simply outwash gravels from the Midlandian/Fenitian. Until dates are available this argument is really a matter of conjecture.

Evidence for the Lough Nahanagan stadial (corresponding to the Loch Lomond in Britain) occurs in the form of small moraines (usually a sequence of three) in the corries of the Nephin Beg Range. This comprised a 'cirque glaciation' nowhere as extensive as the Loch Lomond in Britain.

The area at the head of the Clew Bay, between Westport and Newport requires more detailed sedimentological descriptions, to be supplied in the following section that describes eleven exposures along the coast and on the islands. Regional interpretations and conclusions, incorporating the remote sensing data, the mapping data and the eleven sites logged in detail (and described in the following chapter) will be provided in the final chapter of this thesis.

5 SEDIMENTOLOGY OF QUATERNARY EXPOSURES IN CLEW BAY

5.1 INTRODUCTION

The area at the head of Clew Bay has been controversial from the time of Close (1867) to Knight (1999) with various researchers proposing a variety of ice flow directions including onshore, offshore, and even simultaneous flow onshore in the north of the bay and offshore in the south of the bay, refer to Section 1.3.1.2.

Luckily, marine erosion has exposed extensive sections into both the partially submerged drumlins in the bay and the mainland coastline at the very focus of the controversy. These exposures contain geological data that can be used to solve the puzzle of ice flow directions. Moreover, as well as addressing the question of ice flow directions, these exposures consisting of long-, oblique- and cross-sections (and in one instance a section extending the full perimeter) into drumlins, provide an excellent opportunity to study the genetic processes involved in drumlin formation. Eleven sites were analysed and logged to elucidate the glacial history of this most controversial area. The exposures that underwent detailed study were chosen using the following criteria, they must be:

- extensive, extending the full length of the drumlin cross- or long-section if possible;
- clean and relatively free from slumping;
- accessible either by land or by sea.

The distribution of sites is concentrated in the southern half of the bay, figure 5.1, with the exception of Inishbee and Rosbarnagh Islands that are in Newport Bay. This is due to the fact that the ocean is deeper and the currents are stronger in the south which increases the erosive power, creating the sections. Small slumped sections (less than 1m high) do exist in the north, in Newport Bay, but the shallow waters made navigation impossible even at high tide. This sample design is slightly problematic as it produced a concentration of sample locations in the south of Clew Bay, however the north of Clew Bay was represented by a number of exposures and is not devoid of data.

The bedrock geology beneath the waters of Clew Bay where these sections are located is indicated as Lower Carboniferous limestone on the regional bedrock geology map, figure 1.3.

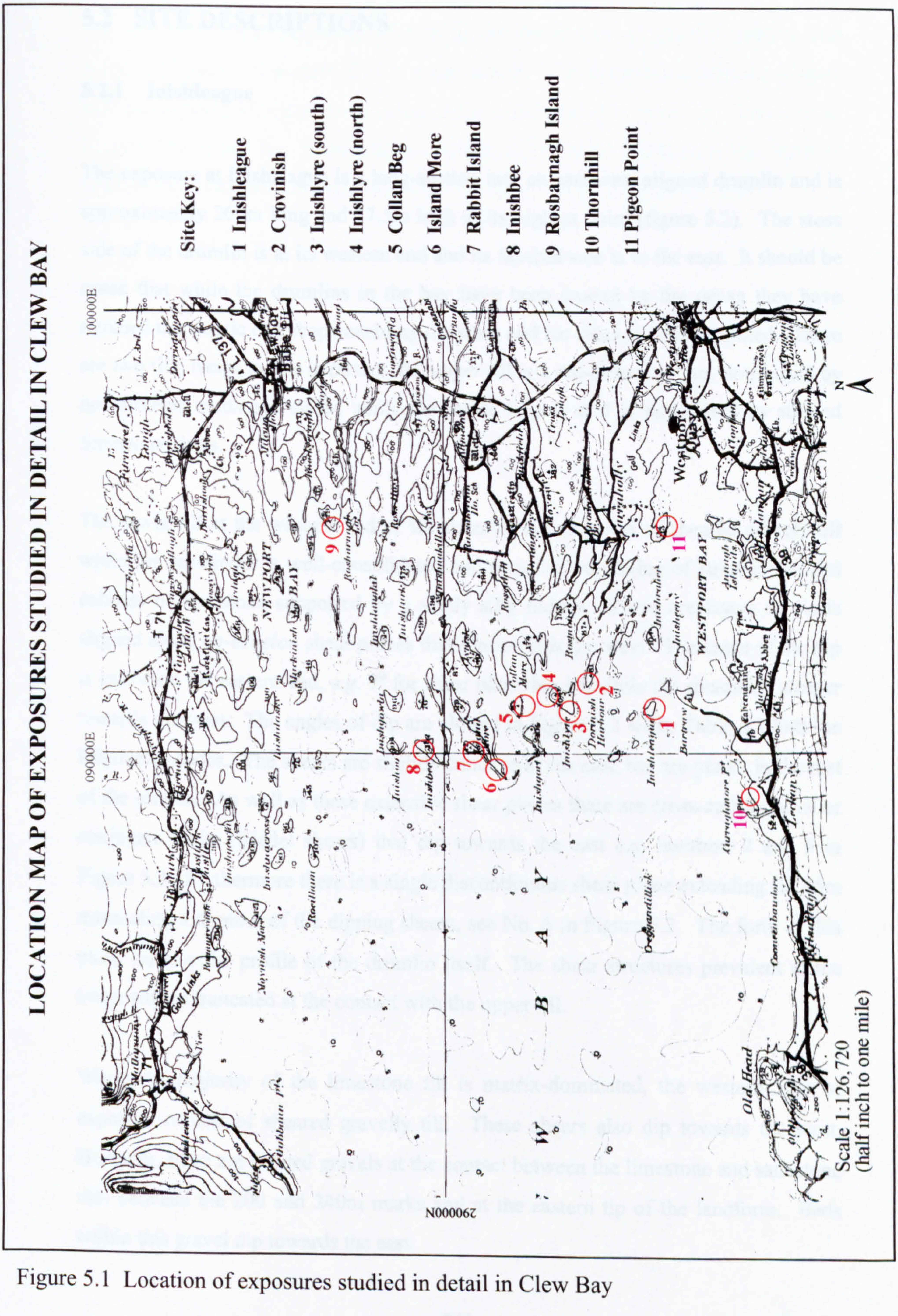

Figure 5.1 Location of exposures studied in detail in Clew Bay

5.2 SITE DESCRIPTIONS

5.2.1 Inishleague

The exposure at Inishleague is a long-section into an east-west aligned drumlin and is approximately 260m long and 17.5m high at its highest point (figure 5.2). The stoss side of the drumlin is at its western end and its tapered side is to the east. It should be noted that while the drumlins in the bay have been eroded by the ocean they have retained the classic egg shape enabling the stoss and lee sides to be determined. There are two tills facies in this exposure, the upper till is a red-brown colour, dominated by non-striated sandstone clasts, while the lower is grey and is dominated by striated limestone clasts.

The lower till at the western end of the drumlin is composed of sheared gravely till while the remainder is well-consolidated and massive, consisting of striated rounded cobbles of limestone supported by a sandy silty matrix. There are layers of clasts aligned along *en-echelon* shear planes that dip towards the west. The angle of the dip is gentle on the eastern end, *e.g.* 7° for shear plane No.10, while the shears are steeper towards the west. The angles of dip are plotted in Figure 5.2 while Table 5.1 lists the lithofacies codes. The shears are slightly concave in the east, but are planar in the rest of the section. As well as these extensive shear planes there are cross-cutting, smaller conjugate faults (Riedel shears) that dip towards the east *e.g.* numbers 2 and 5 in Figure 5.2. Furthermore there is a single discontinuous shear plane extending for 45m transecting a number of the dipping shears, see No. 6 in Figure 5.2. The form of this plane mirrors the profile of the drumlin itself. The shear structures prevalent in the lower till are truncated at the contact with the upper till.

While the majority of the limestone till is matrix-dominated, the western 50m of exposure consist of sheared gravelly till. These shears also dip towards the west. However, there are bedded gravels at the contact between the limestone and sandstone tills between the 200 and 240m marks and at the eastern tip of the landform. Beds within this gravel dip towards the east.

The upper till is approximately 2.5m thick and consists of subrounded pebbles and cobbles of sandstone supported by a sandy matrix. It is under-consolidated, massive and undeformed, although some crude horizontal bedding is apparent. The contact between the upper and lower tills is unconformable with a discontinuous layer of bedded gravels almost 1m thick in places separating the upper and lower tills.

Code	Lithofacies Description
Diamictons	
Dmm	Matrix-supported, massive
Dms	Matrix-supported, stratified
Dcm	Clast-supported, massive
Dml	Matrix-supported, laminated
Boulders	
BL	Boulder lag or pavement
Gravels	
Gms	Matrix-supported, massive
Gm	Clast-supported, massive
Gsi	Matrix-supported, imbricated
Gmi	Clast-supported, massive (imbricated)
Gh	Horizontally bedded
Gd	Deformed bedding
Sands	
Sh	Very fine to very coarse and horizontally/plane bedded or low angle cross-lamination
Sc	Steeply dipping planar cross bedding (non-deltaic foresets)
Sd	Deformed bedding
Sl	Horizontal and draped lamination
Silts & Clays	
Fl	Fine lamination
Fm	Massive
---(s)	Sheared
---(p)	Includes clast pavement(s)
---(w)	With dewatering structures
---(d)	With dropstones

Table 5.1 Lithofacies coding scheme, based on Eyles *et al.* (1983).

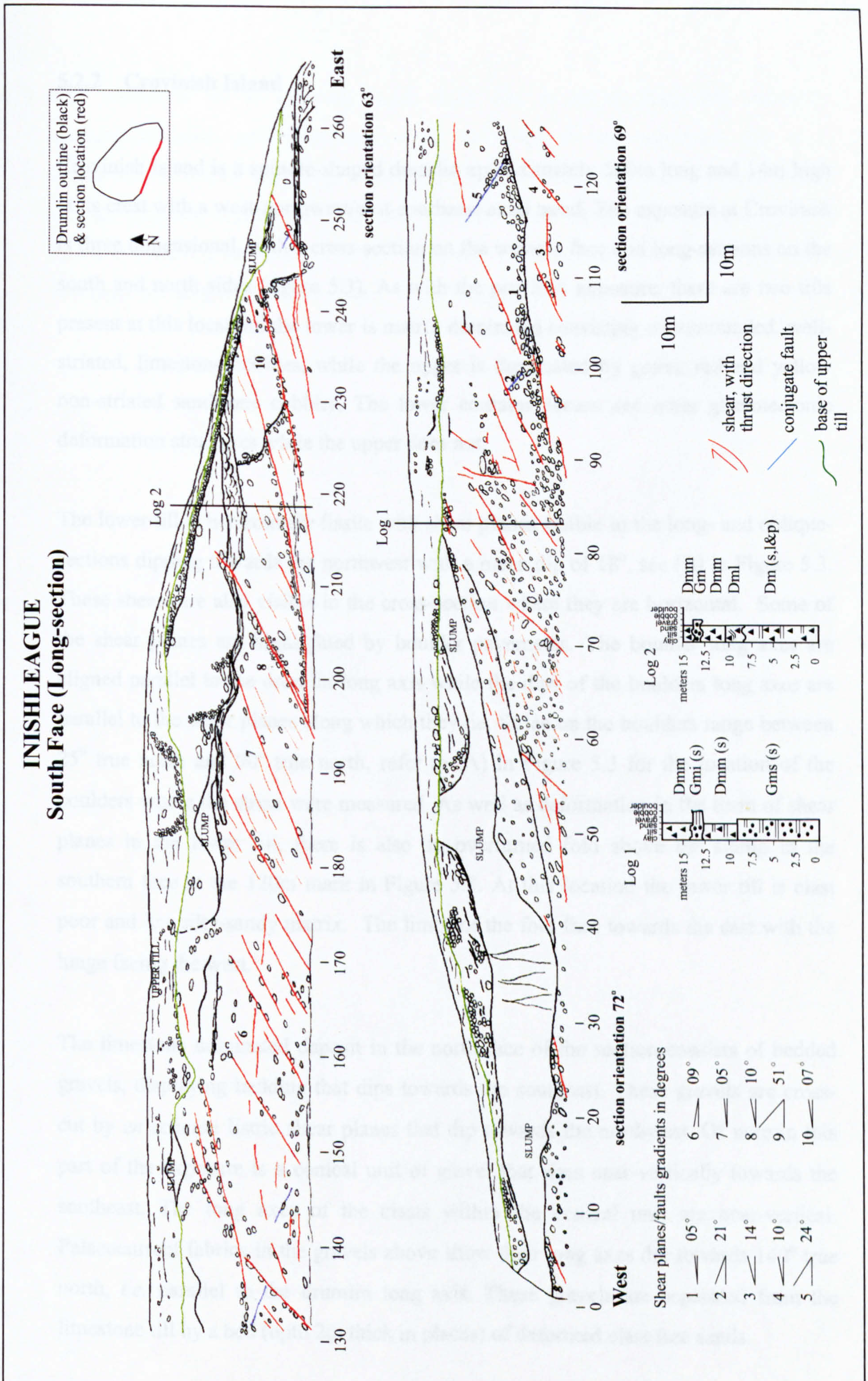

Figure 5.2 Profile drawing of Inishleague drumlin

5.2.2 Crovinish Island

Crovinish Island is a spindle-shaped drumlin approximately 500m long and 14m high at its crest with a west-northwest/east-southeast axial trend. The exposure at Crovinish is three dimensional, with a cross-section on the western face and long-sections on the south and north sides (figure 5.3). As with the previous exposure, there are two tills present at this location, the lower is matrix dominated consisting of subrounded, well-striated, limestone cobbles, while the upper is dominated by green, red and yellow non-striated sandstone cobbles. The lower contains shears and other glaciotectonic deformation structures while the upper does not.

The lower till is horizontally fissile with shear planes visible in the long- and oblique-sections dipping towards the northwest with a mean dip of 18°, see (B) in Figure 5.3. These shears are also visible in the cross-section where they are horizontal. Some of the shear planes are highlighted by boulder pavements. The boulder long axes are aligned parallel to the drumlin long axis while the dips of the boulders long axes are parallel to the shear planes along which they lie. Striae on the boulders range between 25° true north and 90° true north, refer to (A) in Figure 5.3 for the location of the boulders where the striae were measured. As well as deformation in the form of shear planes in the lower till, there is also an overturned fold above the slump in the southern face at the 120m mark in Figure 5.3. At this location the lower till is clast poor and has silty-sandy matrix. The limbs of the fold face towards the east with the hinge facing the west.

The limestone dominated deposit in the north face of the section consists of bedded gravels, displaying bedding that dips towards the southeast. These gravels are cross-cut by *en echelon* listric shear planes that dip towards the northwest. Of note in this part of the exposure is a conical unit of gravel that rises near-vertically towards the southeast. The long axes of the clasts within the conical unit are near-vertical. Palaeocurrent fabrics in the gravels above show their long axes dip towards 140° true north, *i.e.* parallel to the drumlin long axis. These gravels are separated from the limestone till by a bed (upto 2m thick in places) of deformed clast free sands.

The sandstone till is generally 1.5m thick and is matrix-supported, massive, underconsolidated and undeformed. At the base of the sandstone till is a discontinuous bed of massive gravels less than 0.5m thick. This rests unconformably on the limestone unit beneath, however, in part of the section the sandstone gravel facies at the top grades into the upper surface of the limestone till. At the 95m mark the upper till is injected into the lower till to a depth of 2.5m.

Figure 5.3 Scale drawing of section on Crovinish Island

5.2.3 Inishlyre (south)

The exposure at Inishlyre (south) is a cross-section 15m high and more than 60m long into the west end of a spindle-shaped drumlin (Figure 5.4). The long axis of the drumlin is aligned east/west. There are two tills at this section. The lower till is grey in colour and is dominated by rounded/sub-rounded, striated limestone clasts, supported by a silty sandy matrix. It contains boulder pavements that dip towards the north, and shear planes and is well-consolidated. The upper till is a red-brown colour and is composed of subrounded sandstone clasts supported by a sandy matrix. It is underconsolidated and massive. The contact between the upper and lower tills is unconformable.

The lower till consists of two facies (Figure 5.4). The basal facies, Dm(s) is a massive sheared till with two planes of shear, one dipping to the north *e.g.* plane no.1 with a dip of 2°, and the other dipping to the south *e.g.* no.2 with an average dip of 23°. Clasts in this facies have been brecciated and streaked out towards the north. Above this is the second facies that consists of massive till containing boulder beds that average 1m thick dipping towards the north at an average angle of 6°. The boulders do not have planed-off surfaces and are not bullet-shaped. The boulder layers are contained within massive, well-consolidated limestone till, with no deformation structures.

While the shear planes in the southern 35m of the section extend approximately 5m up from the base, those at the north of the section extend from the base to the top of the lower till and generally dip (with higher dip angles) towards the south. Moreover, while the shears in the south of the section are planar, those in the north are convex or listric and contain clasts pavements along their planes.

The upper till is composed of subrounded non-striated sandstone cobbles that are supported by a sandy matrix. The deposit is underconsolidated and massive with no glaciotectonisation apparent. It is approximately 1.5m thick, draping over the lower till. The contact between the upper and lower till is unconformable.

Figure 5.4 Section drawing of Inishlyre (south) exposure

5.2.4 Inishlyre (north)

The exposure at Inishlyre (north) consists of a cross-section 60m long and 16m high in the western end of an east-west aligned drumlin (Figure 5.5). There are two till units visible at this exposure. The upper till is approximately 1m thick and is dominated by sandstone clasts. 10m of the lower till, dominated by limestone clasts, is visible above a slump at the base of the section.

The lower till is grey, consolidated, fissile and contains lenses of massive gravels. The phenoclast petrography is homogeneous, consisting of striated, subrounded limestone cobbles and boulders supported by a sandy silty matrix. This sediment has undergone glaciotectonisation visible as shear planes and folding. The shear planes are generally horizontal in the cross-section with no displacement or streaked out clasts. At either end of the section the shears fold over upon themselves exposing a fold hinge in the northeast of the exposure.

Evidence for the direction of glacial transport is provided by, amongst others, bullet boulders in the lower till. The long axis of the boulder and the orientation of the striae (which are parallel to the boulder long axis) are aligned towards 123° true north. Furthermore, the rounded side of the boulder is orientated towards the northwest, and the tapered end towards the southeast. These alignments are parallel to the axial trend of the drumlin.

The upper till is a brown-red colour and is composed of subrounded/subangular cobble-sized sandstone clasts that are supported by a sandy matrix. It is underconsolidated. The deposit is massive, with no deformation structures apparent. The contact between the two tills is unconformable, and the deformation structures in the lower till are truncated at the contact.

Figure 5.5 Drawing of Inishlyre (north) cross-section

5.2.5 Collan Beg

The exposure at Collan Beg consists of a long-section approximately 11m high by over 140m long into an east-west aligned drumlin (Figure 5.6). As with the previous sections two till units have been recognised on the basis of the dominant phenoclast petrography and structures, the upper unit being dominated by sandstone clasts, and the lower by limestone clasts.

The lower till is grey and consists of massive till interbedded by dipping beds of gravelly diamict. The till is well-consolidated and is composed of subrounded striated limestone cobbles supported by a silty sandy matrix. Horizontal fissility is visible throughout. Two sets of till fabric data were taken from this till. Their locations and equal area projection contour diagrams are shown in Figure 5.6, with more complete statistical data, plots, and rose diagrams in Figure 5.7. Site 1 is approximately 3m from the west end of the section, and is 0.5m above a gravel bed. The eigenvector value is 248 while the eigenvalues S1 and S3 are 0.591 and 0.028, respectively. Site 2 is 65m from the west end of the section and is 1m from the base, situated below a gravel bed. The eigenvector value is 312 while the S_1 and S_3 values are 0.636 and 0.069 respectively.

The beds of gravelly diamict within the lower till unit (there are nine discrete beds) have a mean dip of 5° towards the west, and are slightly concave in profile. They are generally 1m thick at their upper ends and taper out to one cobble thickness at the base of the section. They are matrix supported and massive, but deformation structures are visible in the form of sand and silt stringers which have been streaked upwards towards the east. Clast imbrication is towards the west. The upper and lower contacts between the gravel and the till are unconformable with no gradational boundary or intermixing of the two deposits.

The upper till is a red-brown colour and consists of subrounded/subangular pebbles and cobbles of sandstone, supported by a sandy matrix. It is underconsolidated and massive with no deformation structures apparent. The contact with the limestone till beneath is often covered as the more easily erodable upper till has slumped downwards, but where it can be seen, it is unconformable with truncation of the structures in the lower till. The depth of the sandstone till is never greater than 1m, forming a drape over the limestone till.

Figure 5.6 Scale drawing of Collan Beg drumlin exposure

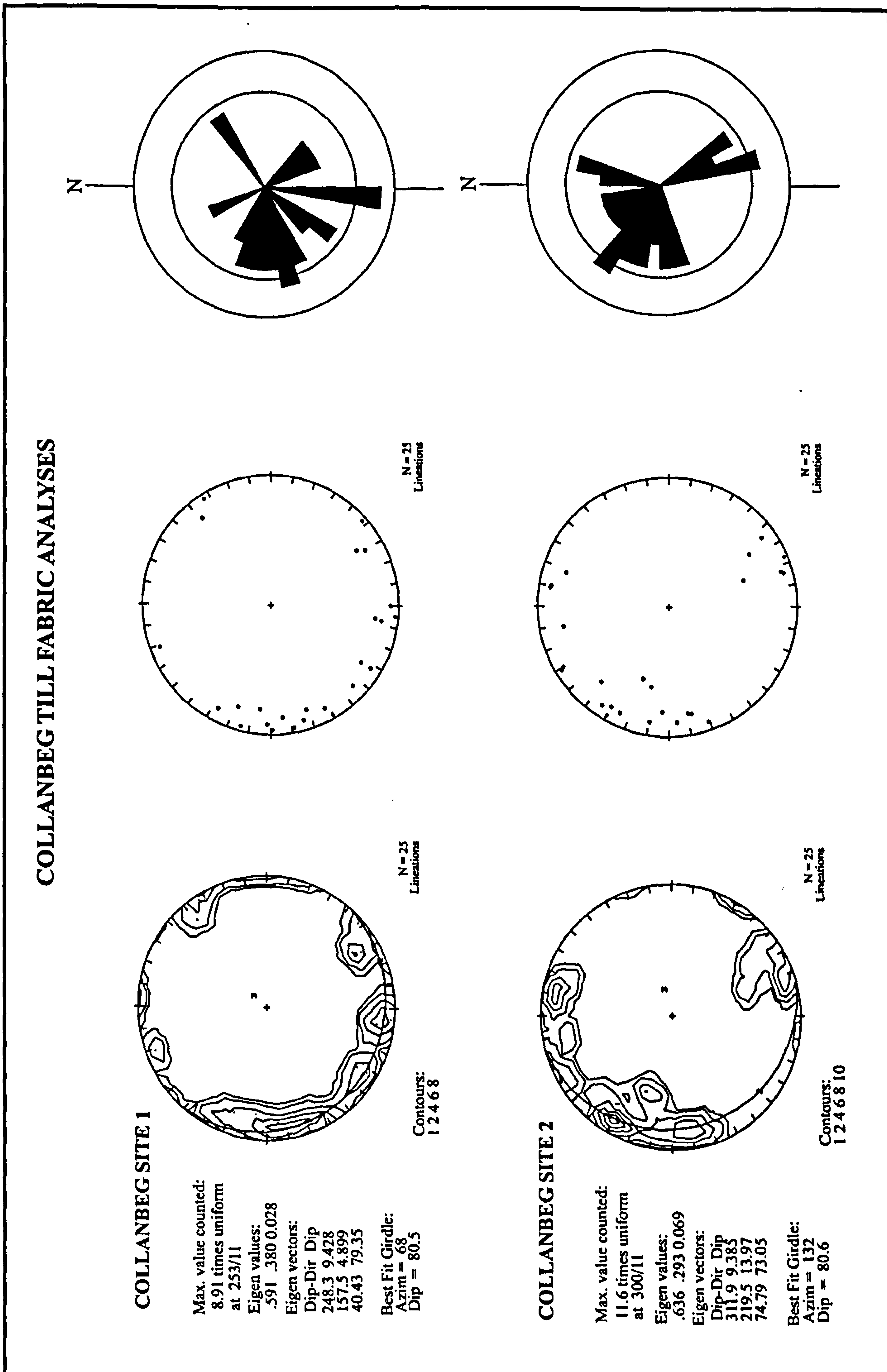

Figure 5.7 Till fabric data from Collan Beg Island

5.2.6 Island More

The exposure at Island More is a cross-section 65m long by 10m high into the western end of an east-west aligned drumlin (Figure 5.8). The total cross-section is approximately 100m long, but only the northern end was sufficiently well exposed to enable logging. Two tills have been identified on the basis of dominant phenoclast petrography, the lower being dominated by limestone clasts, and the upper by sandstone.

The lower till is grey, well-consolidated, massive, consisting of striated subrounded cobbles and boulders of limestone supported by a sandy silty matrix. Sub-horizontal boulder pavements traverse the cross-section, with a slight dip of less than 2° towards the north. The upper surfaces of many of the boulders are flat and well-striated, while their bottom sides are rounded or keel-shaped. The striae are consistently aligned towards a mean orientation of 95° true north, parallel to the drumlin long axis.

Deformation structures are common with three patterns of shear planes:

a) horizontal shear planes, located between 25 and 60m (Figure 5.8);
b) concave planes dipping towards the north, located in the north of the section, between 2 and 46m. These are cross-cut by smaller planes dipping towards the south (conjugates);
c) concave shear planes dipping towards the south, located in the south of the cross section, between 57 and 65m.

Striae on boulders in the centre of the cross section are aligned parallel to the drumlin long axis. However, the long axis of the bullet boulder, and its striae on the northerly-dipping shear plane at the 20m mark are aligned towards 128° true north, oblique to the drumlin long axis.

The upper till is approximately 1.5m thick at the crestline, generally becoming thinner towards the drumlin flanks. The phenoclast petrography is dominated by subrounded/subangular sandstone pebbles and cobbles which are supported by a sandy matrix. It is a red-brown colour, under-consolidated, massive and undeformed. The contact between this till and the limestone till beneath is unconformable, with the deformation structures and boulder pavements of the lower till truncated at the contact. There is a discontinuous bed of massive gravels less than 0.5m thick marking the base of the sandstone till.

Figure 5.8 Scale drawing of Island More drumlin exposure

5.2.7 Rabbit Island

The exposure at Rabbit Island is a north-south (oblique) section 220m long by 16m high (at the crest) into the western end of a southwest-northeast trending drumlin (Figure 5.9). Two tills have been defined on the basis of the dominant phenoclast petrography, limestone till at the base and sandstone till above.

The lower till is grey in colour and is well-consolidated. There are thirteen beds of massive gravel, each approximately 1m thick, with a mean dip of 5° towards the northeast. These beds are cross-cut by shear planes that dip towards the southwest (parallel to the drumlin long axis). Where the shears cross cut the gravels, sand lenses at the upper surfaces of the gravel beds have been sheared across and upwards towards the northeast (see shear plane no. 6).

Between the dipping gravel beds is massive well-consolidated till. This is composed of subrounded striated cobbles of limestone, supported by a silty sandy matrix. The deformation structures in this sediment have been discussed above in connection with the gravel beds, but generally the thrust shears dip towards the southwest, cross-cut by Riedel shears at the southern end of the section.

There is a unit of gravel at the northern side of the exposure, extending 60m along the northern end of the exposure. It consists of imbricate gravels that dip at a mean angle of 6° towards the northeast, indicating palaeocurrent flow from the southwest. These gravels are separated from the adjacent limestone till by a lens of bedded sand that is clast poor. These sands contain beds dipping towards the northeast. There are two shears within the gravel unit, dipping towards the southwest.

The upper till is composed of less than 1m of subrounded sandstone pebbles and cobbles supported by a medium-grained sand matrix. This deposit is underconsolidated with crude horizontal bedding, and a notable absence of glaciotectonic structures. The contact between this and the limestone till beneath is unconformable, and it is also notable that the gravel beds and shear structures present in the lower till are truncated at this contact.

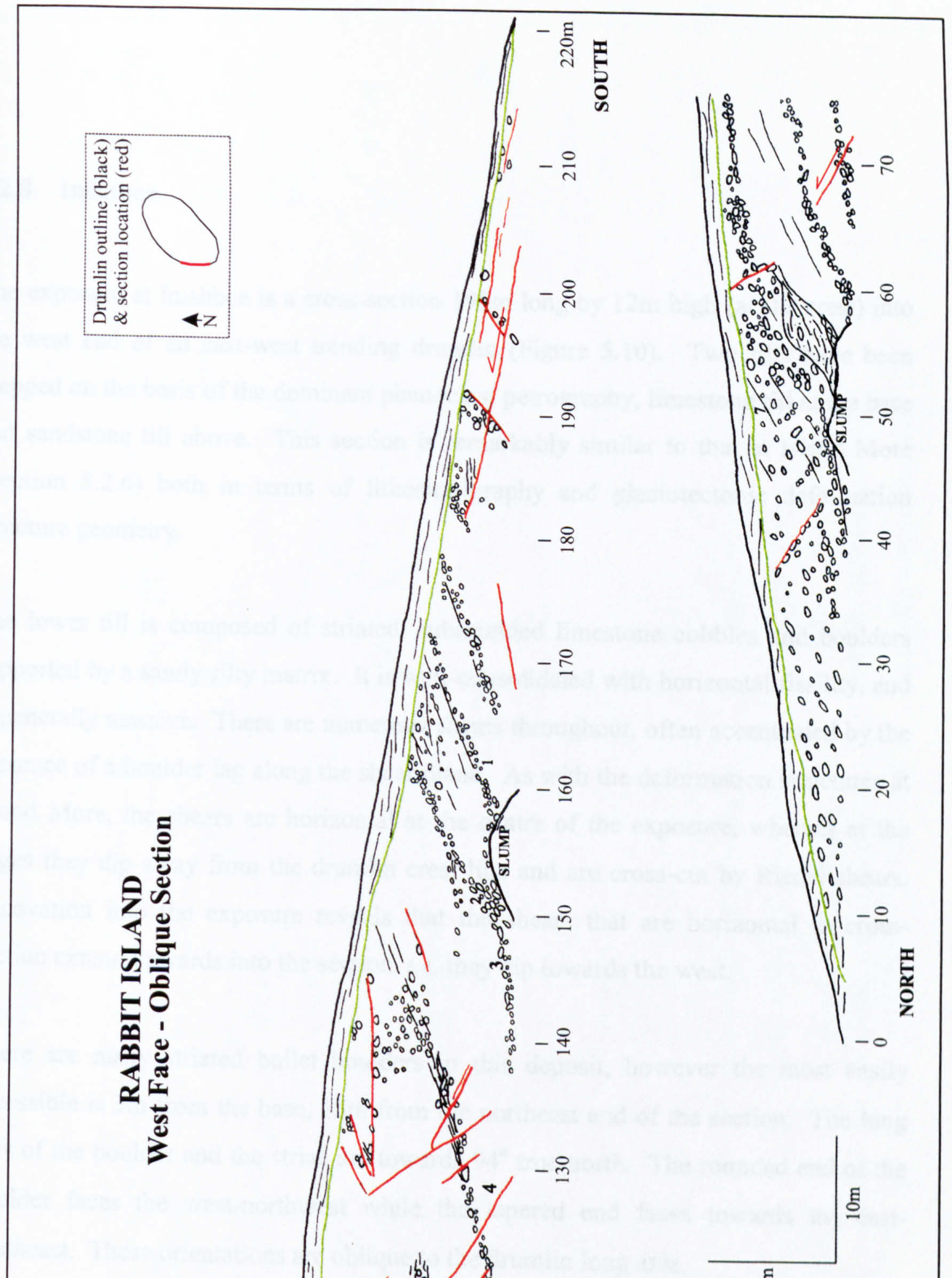

Figure 5.9 Scaledrawing of oblique section at Rabbit Island

5.2.8 Inishbee

The exposure at Inishbee is a cross-section 195m long by 12m high (at the crest) into the west end of an east-west trending drumlin (Figure 5.10). Two tills have been mapped on the basis of the dominant phenoclast petrography, limestone till at the base and sandstone till above. This section is remarkably similar to that at Island More (Section 5.2.6) both in terms of lithostratigraphy and glaciotectonic deformation structure geometry.

The lower till is composed of striated, subrounded limestone cobbles and boulders supported by a sandy silty matrix. It is well-consolidated with horizontal fissility, and is generally massive. There are numerous shears throughout, often accentuated by the presence of a boulder lag along the shear plane. As with the deformation structures at Island More, the shears are horizontal at the centre of the exposure, whereas at the edges they dip away from the drumlin crest line and are cross-cut by Riedel shears. Excavation into the exposure reveals that the shears that are horizontal in cross-section extend upwards into the section, *i.e.* they dip towards the west.

There are many striated bullet boulders in this deposit, however the most easily accessible is 3m from the base, 65m from the northeast end of the section. The long axis of the boulder and the striae are towards 94° true north. The rounded end of the boulder faces the west-northwest while the tapered end faces towards the east-southeast. These orientations are oblique to the drumlin long axis.

The upper till is never thicker than 1m and is composed of subrounded/subangular sandstone cobbles and pebbles. The clasts are supported by a silty sandy matrix. The till is poorly consolidated and displays crude horizontal bedding, but there is a notable absence of any deformation structures. The contact with the limestone till beneath is unconformable, truncating the structures visible in the lower till.

Figure 5.10 Scale drawing of the cross-section at Inishbee

5.2.9 Rosbarnagh Island

The exposure at Rosbarnagh Island is three-dimensional, consisting of a cross-section (west face), an oblique section (southwest face) and a long-section (southern face) which combine to produce a section 140m long by 9m high into the western end of an east-west trending drumlin (Figure 5.11). Two tills have been defined on the basis of the dominant phenoclast petrography, limestone till at the base and sandstone till at the top.

The lower till is composed of striated, subrounded cobbles and boulders of limestone, supported by a sandy silty matrix. It is over-consolidated, horizontally fissile and traversed by numerous shears. The shears are horizontal and planar in the cross-section, but are concave and dip towards the west in the oblique and long sections, cross-cut by Riedel shears from the 40m mark onwards. Boulder pavements are common along the shear planes. The upper surfaces of the boulders are flat and striated while their bases are rounded and keel-shaped. One set of till fabrics was taken from the lower till. A contoured plot and summary statistics are shown in Figure 5.11. The first eigenvector (V_1) is 268.5 while the S_1 and S_3 eigenvalues are 0.634 and 0.065 respectively.

There is a unit of gravels at the oblique section and the western end of the long-section. These gravels are massive and contain shear planes that dip towards the west.

The upper till is less than 1m thick and is composed of subangular/subrounded pebbles and cobbles of sandstone supported by a sandy matrix. The deposit is underconsolidated, has crude horizontal bedding, and has a notable absence of glaciotectonic deformation structures. The contact with the limestone dominated till beneath is unconformable with the structures in the lower till truncated at the contact.

Figure 5.11 Scale drawing of Rosbarnagh Island esposure

5.2.10 Thornhill

The exposure at Thornhill strand is an oblique long-section 335m long by 10m high (at the crest line) into a northwest-southeast aligned drumlin (Figure 5.12). Four main facies associations have been recognised at this section: i) limestone dominated till; ii) laminated sands and silts which are clast poor; iii) sandstone dominated till; and iv) dipping planar bedded sands.

i) As with the other sections described in this chapter, the limestone till is overlain by sandstone till. Between 0 and 210m the limestone till forms a low dome-shaped unit with a maximum thickness of 6m (at the 95m mark). This unit is composed of well-striated rounded cobbles and boulders of limestone, supported by a matrix of silt and sand. It is over-consolidated, horizontally fissile, and highly deformed by glaciotectonics as indicated by the presence of shears and conjugates. It also contains boulder pavements, clastic dykes and water escape structures. There are two patterns of shear planes within the sediment.

a) Shears that dip towards the northwest occur the full length of this unit. The strike and dip directions of forty-two of the thrust shears were recorded in the field and plotted on a rose diagram in Figure 5.12. This diagram clearly shows that the prevailing pattern of dip is towards the northwest. Displacement along the shears (*e.g.* of gravel lenses) is uniformly towards the southeast. At the southwestern end of the section between the 60 and 90m marks, they are cross-cut by Riedel shears
b) Sub-horizontal shears that undulate along the base of the section, mirroring the surface morphology of the limestone till. These are also cross-cut by the thrust shears discussed in (a) above, also see Plate 5.1.

The dipping shears are frequently up to 2cm wide and consist of silt bands within the till with brecciated, streaked-out clasts and sand stringers. They are also often characterised by the presence of a clast lag, generally one clast thick, along the lower boundary of the shear plane. The upper surfaces of the clasts are flat and striated. Although the shears are generally either concave or convex in profile, there is one which has a listric shape, starting at the 100m mark. This shear is the upper contact of a lens of deformed bedded gravels at this location in the exposure.

There are eight clastic dykes, aligned parallel to the thrust shears, between 165 and 220m. These are composed of pebble-sized clasts with their a-axes aligned near-vertically, located in steeply dipping joints in the till. The joints are an inverted V shape, pointed at the upper ends, and are up to 30cm wide at the base (Plate 5.2). There is also an intermediate set of sediments between the silty shears and the clastic dykes. These are morphologically similar to the dykes but are composed of both silt and vertically aligned pebbles. Smaller scale water escape structures (besides the clastic dykes) were also recorded at four locations in the exposure, see Figure 5.12. These are composed of cuspate sequences of laminated silts and sands which project at an angle from the upper surfaces of shear planes. They are associated with shear planes that contain clast lags.

Four till fabric analyses were carried out in the limestone till. The first two were taken at the 130m mark, and the results have been summarised in Figure 5.12 and plotted in full in Figure 5.13. Fabric 1_1 was taken from an area of massive till where no deformation structures are apparent. The V_1 eigenvector value is 312.4 while the S_1 and S_3 eigenvalues are 0.767 and 0.096 respectively. Fabric 1_2 was taken 1m away, but on a shear plane. The V_1 value is 307.8 while the S_1 and S_3 eigenvalues are 0.613 and 0.052 respectively.

The third and fourth till fabric measurements from the limestone till were taken at site two, located at 190 and 195m. Summary data are shown in Figure 5.12, with full data in Figure 5.14. Both of these sets of measurements were taken on one of the pseudo horizontal undulating shear planes, which at this location is dipping slightly to the east. At site 2_1 the V_1 value is 94.54 while the S_1 and S_3 values are 0.549 and 0.1511 respectively. Site 2_2, is on the 195m mark and located on the same shear plane, but where it is horizontal, resulting in a V_1 value of 156.7, and S_1 and S_3 values of 0.594 and 0.054 respectively.

The sedimentology of the deposit changes east of the 255m mark on the section. It alters from an over-consolidated, massive till with shear planes, clast pavements and dewatering structures *i.e.* lithofacies code Dmm (s,p,w) to a well-consolidated, massive till with pseudo-continuous dipping boulder pavements *i.e.* lithofacies code Dmm (p). The sediment is composed of well-striated cobbles and boulders supported by a sandy silty matrix with boulder pavements one clast thick which dip in a planar fashion towards the northwest. This part of the section also differs from the Dmm(s,p,w) area as it reaches a thickness of at least 9m at the 300m mark, rising sharply at the point where the sheared till terminates.

ii) Laminated sands and silts, Fl(s), which are clast poor are found above the limestone till between 30 and 40m and within it between 210 and 255m. The sand and silts between 210 and 255m have undergone the same glaciotectonics as the till in which they lie. This is clearly seen at 213m where the southwestern end of the sand/silt unit has been displaced upwards and towards the southwest along a shear.

iii) The third lithofacies association is sandstone dominated till *i.e.* Dms (sst) which is found at the top of the sequence. It is composed of subrounded/subangular clasts of Silurian sandstone supported by a silty sandy matrix. There is crude horizontal stratification with no deformation structures apparent, and it is underconsolidated. It is less than 1m thick where it covers the thick massive limestone till, but is up to 6m thick where it overlies the sheared limestone till at the west-southwest side of the section. This change in thickness maintains the regular and smooth drumlin morphology of the landform. The contact between this deposit and the limestone till beneath is unconformable, with the truncation of the deformation structures in the lower till.

Two sets of till fabric data were recorded in this deposit, at 65m and 92m, Upper Till Sites 1 and 2 respectively, summarised in Figure 5.12 and shown in full in Figure 5.15. Site 1 statistics show a V_1 of 299.2, and S_1 and S_3 eigenvalues of 0.645 and 0.035 respectively. At site 2 the V_1 value is 309.8 while the S_1 and S_3 values are 0.671 and 0.1149 respectively.

iv) The fourth and final lithofacies association at this exposure consists of steeply dipping planar bedded sands with subangular sandstone boulders *i.e.* lithofacies code Sc. This sediment is located at the west-southwestern end of the section between 0 and 32m.

Figure 5.12 Scale drawing of Thornhill drumlin exposure. Full till fabric data are shown in Figures 5.13, 5.14 and 5.15.

Figure 5.13 Till fabric analysis results from Thornhill drumlin, site 1.

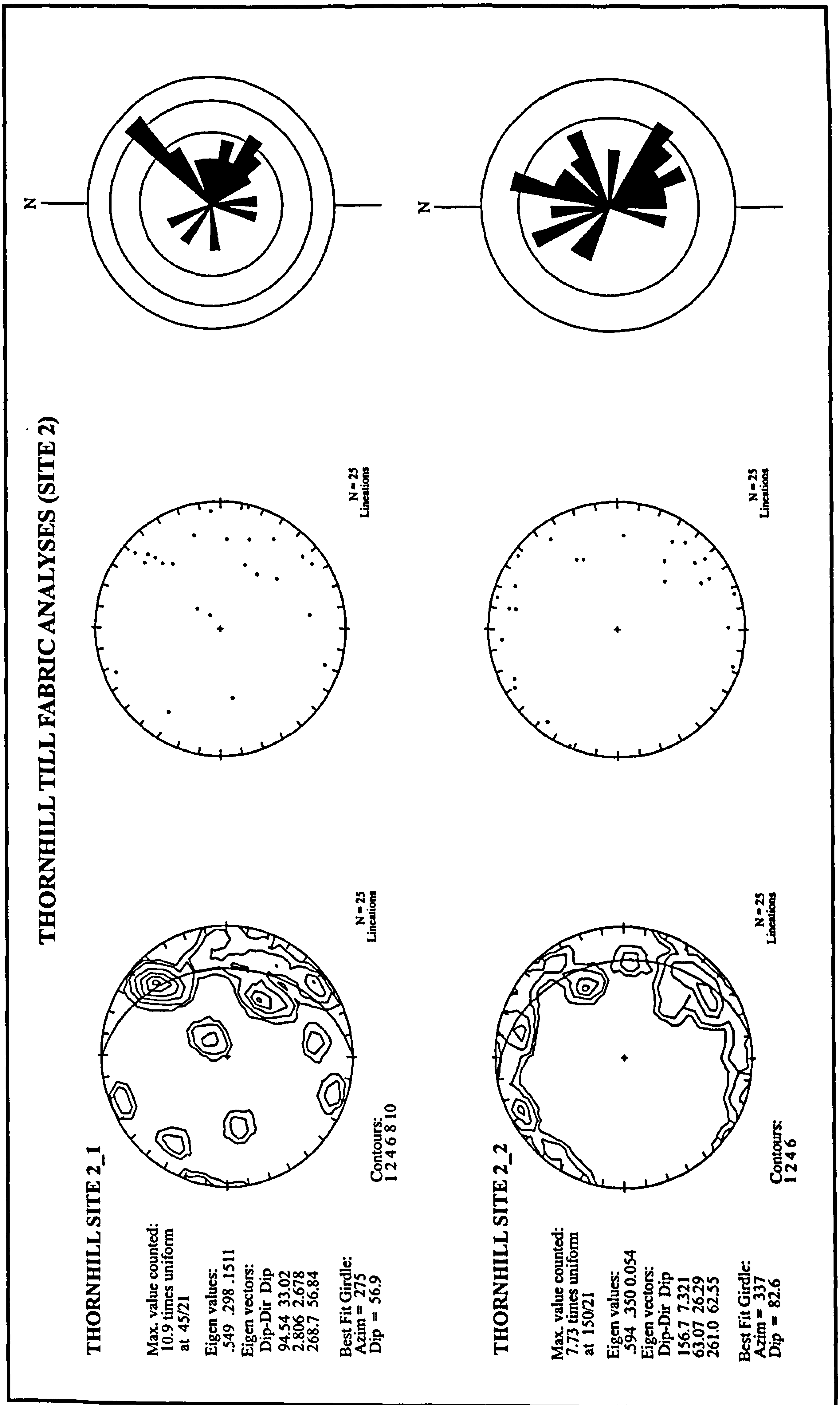

Figure 5.14 Till fabric analysis results from Thornhill drumlin, site 2.

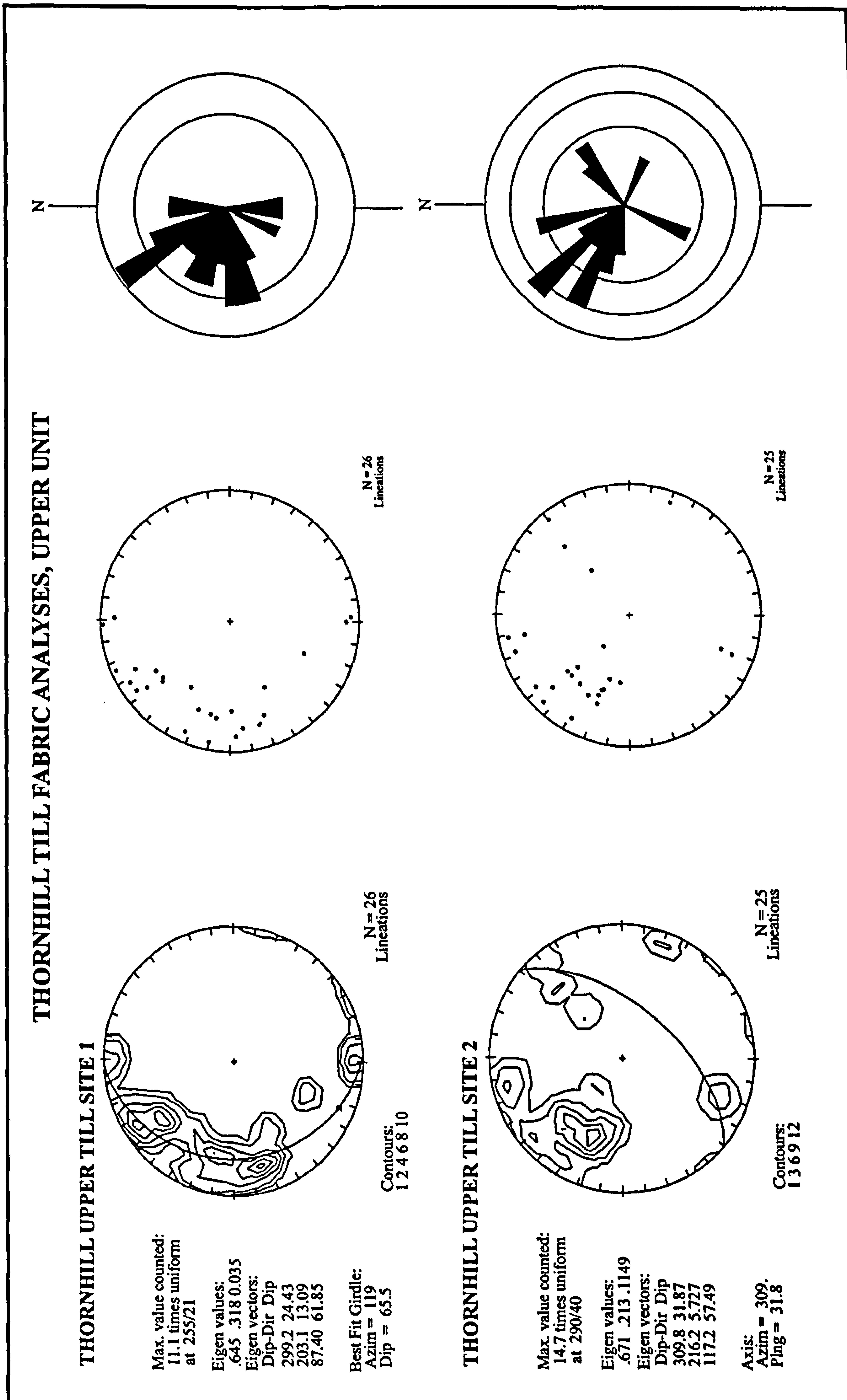

Figure 5.15 Till fabric analysis results from the upper till unit a Thornhill drumlin..

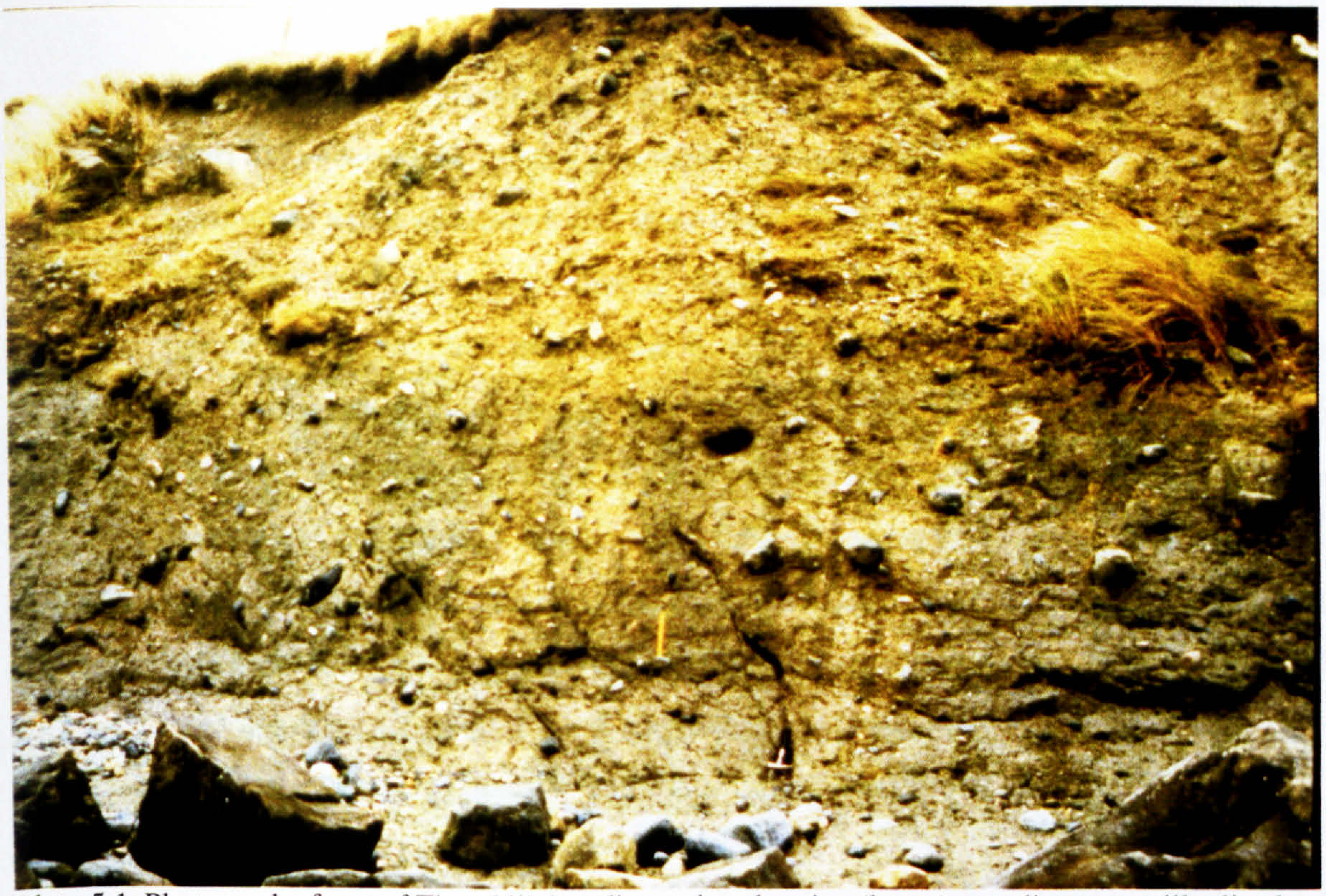

Plate 5.1 Photograph of part of Thornhill drumlin section showing (lower) grey limestone till, olive brown (upper) sandstone till, and horizontal and dipping shear structures. Scale is 30cm long

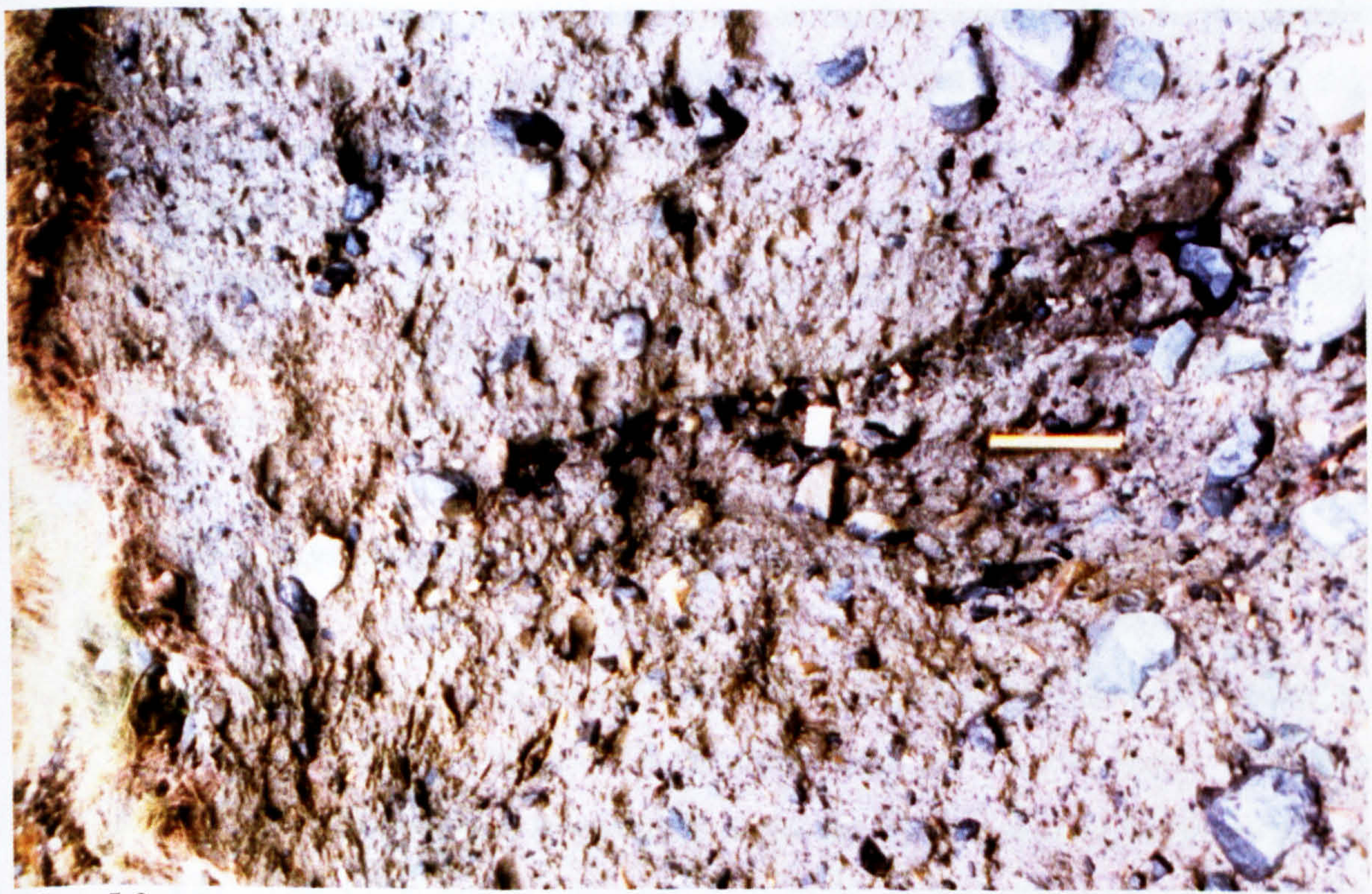

Plate 5.2 Detail of a clastic dyke in Thornhill drumlin. Note the vertical alignment of the clasts in the dyke, and the cross-cutting of the horizontal shear planes. Scale is 30cm long. Photo is portrait layout

5.2.11 Pigeon Point

Pigeon Point is a drumlin with an 803m long axis bearing 113° true north, a 299m short axis bearing 22°, and a perimeter 1794m long. Its rounded (stoss) end faces the northwest, while its tapered end faces the southeast. This drumlin is of special interest because it has a nearly-continuous marine-eroded exposure running the length of its perimeter, but still has easy access by road. This was taken advantage of by several previous researchers including Hanvey (1988), Hart (1997) and Hiemstra (1995) each of whom approached the landform from different perspectives and methodologies. Hanvey (1988) relied solely on lithofacies analysis, while Hart (1997) relied completely on glaciotectonic deformation structures, and Hiemstra (1995) focussed on evidence from till fabric data. This study incorporates all of these approaches, in combination with phenoclast petrography, striae data and detailed regional mapping of the Quaternary sedimentology and morphology.

The same lithofacies associations described at the previous exposures, consisting of a lower limestone dominated till and an upper sandstone dominated till are present here, with the addition of a gravel association along the southern flank of the drumlin. The limestone till has two component lithofacies, a massive matrix-supported till, Dms, and a clast rich deformed till, Dcm(s) (Figure 5.16). The matrix-supported till occurs in the western 740m of the drumlin. It is composed of striated subrounded/rounded cobbles and boulders of limestone, supported by a sandy silty matrix. The sediment is over-consolidated and massive with no apparent glaciotectonic deformation structures apart from horizontal fissility.

The southeastern 60m of the drumlin consists of clast supported till. The contact between the matrix and clast supported tills is concealed behind a slump. This till is composed of subangular/angular limestone boulders and cobbles with a small silt/sand matrix component. Many of the boulders have been brecciated by glacial pressure with clear displacement towards the southeast, parallel to the drumlin long axis (Plate 5.4). This till is highly deformed with folds, shears and rotational structures. The main body of folding in this site is a normal fold with the hinge lines on the southeastern end and the limbs closing towards the northwest. The nose of this fold is at the 23m mark in Figure 5.16, with the 'slump zone' (Mulugeta & Koyi, 1987) extending as far as 48m where the section becomes overgrown. There is a rotational deformation structure, 15cm in diameter, within this fold at the 8m mark. The rotation is clockwise. Bedrock outcrops at the base of the section where the clast supported till occurs.

Hiemstra (1995) obtained till fabric data from nine sites in the limestone till around the perimeter of Pigeon Point for a project run in combination with this research by the Geological Survey of Ireland and the University of Amsterdam. Till fabric data from the northwestern (stoss) end of the drumlin indicated that the clast a-axes lay transverse to the long axis of the drumlin, while the alignment of the clasts were parallel with the drumlin axial trend in the southeastern (tapered) end of the landform.

The upper till occurs the length of the drumlin as far as the 9m mark, where in thins out and disappears. It is composed of subangular pebbles and cobbles of sandstone, limestone and metamorphics, supported by a silty sandy matrix. It is under-consolidated with crude sub-horizontal bedding apparent in places. The contact between the sandstone till and the limestone till beneath is unconformable. The thickness of this sediment varies and at times is injected as wedge-shaped features into the subjacent limestone till. These injection structures are generally 2m wide at the top, but reduce in a 'V' shape to 50cm at the base. These units do not contain horizontal bedding and the long axes of the component clasts are arranged vertically. Similar but smaller of these features are located between the 40 and 44m marks at the southeastern end of the drumlin. These are up to 50cm deep, and 25cm wide at the top, extending down in a 'V' shape.

One set of till fabric data was taken from the upper till unit. The location is shown in Figure 5.16 along with summary data, while full data and plots are shown in Figure 5.17. The S_1 and S_3 eigenvalues are 0.56 and 0.06 respectively and the V_1 eigenvector value is 352°.

There is also a stratified gravel assemblage that runs along the southern flank of the drumlin. It occurs as lithified beds which are horizontally arranged at their outer edges, but which rise to meet the limestone till where they adjoin the drumlin (Plate 4.1). The gravels are composed entirely of limestone clasts, varying in size from pebble to boulder. Although complete palaeocurrent fabric data could not be obtained because of the lithified nature of the deposit *i.e.* the clasts could not be removed and examined, the clasts are imbricated towards the northwest and downstream lee-side infilling takes place southeast of larger boulders. This is parallel to the drumlin long axis.

Figure 5.16 Scale drawing of the eastern end of the Pigeon Point drumlin, south face. Lithofacies codes explained in the main text..

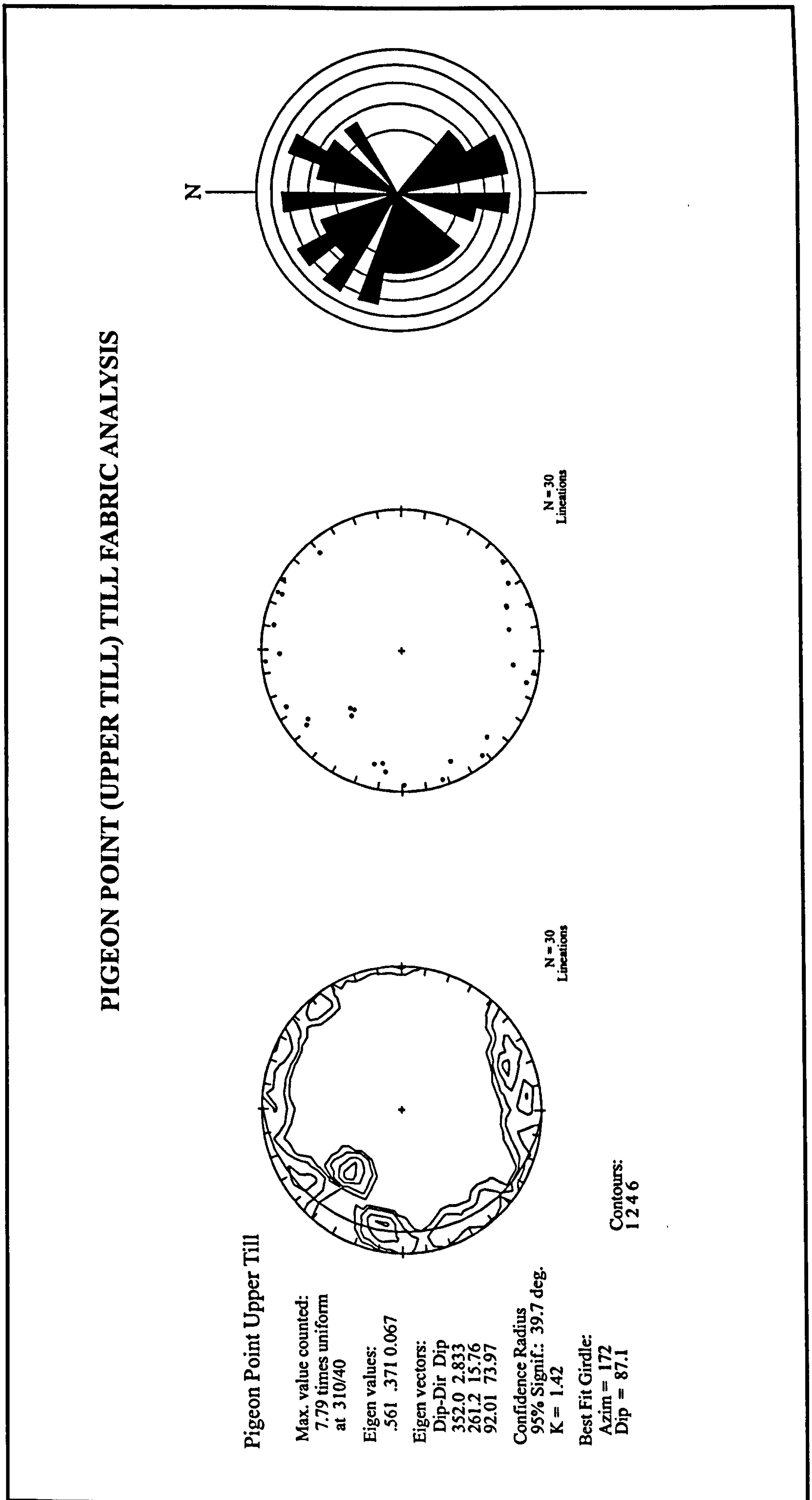

Figure 5.17 Till fabric results from Pigeon Point upper till

Plate 5.3. Photograph of Pigeon Point long-section exposure, southeastern end, between 0 and 21m. Ice flow was from left to right. Hard hat in centre for scale.

Plate 5.4. Detail view of brecciated clast in Pigeon Point drumlin. Ice flow from left to right. Photograph is in portrait layout. Hammer for scale

5.3 INTERPRETATION

Studies of drumlin research *e.g.* Hart (1997) have shown that many researchers have concentrated on the morphology and distribution of drumlins rather than on their internal structure and Patterson & Hooke (1995) attributed this to the lack of good drumlin exposures. However, where sedimentary evidence has been recorded, it has shown a complex array of sediments and stratigraphies (*e.g.* Whittecar & Mickelson, 1979; Dardis *et al.*, 1984; Dardis & McCabe, 1987; Shaw & Sharpe, 1987; Hanvey, 1988; and Boyce & Eyles, 1991; and Meehan *et al.*, 1997) which have still left the genesis of the drumlin as a matter of some debate *e.g.* (Menzies, 1979; Smalley, 1981; Shaw, 1983; and Rose, 1987). Although this thesis has not focused on finding an answer to the enigma of drumlin formation, the exceptional exposures in Clew Bay could not be ignored, nor could their repercussions in the field of drumlin research. Therefore, these landforms and their genetic processes have been studied in the dual contexts of glacier reconstruction and drumlin formation.

Two tills were recorded at each of the eleven sites, limestone dominated till at the base and sandstone dominated till above. The limestone till will be dealt with first. The limestone clasts are not a useful indicator of ice flow direction as limestone probably forms the bedrock geology beneath all of the bay as well as the low-lying mainland east of both Westport and Newport. This means that this if phenoclast petrography was the sole line of evidence, the ice could have flowed into the bay from the east or the west. It is therefore necessary to focus on other lines of evidence such as deformation structures, till fabrics, bullet boulders and striae. From the summary descriptions above of the eleven sections it is clear that the lower (limestone) unit in the drumlins is composed of a range of deposits and sedimentological structures. The glaciological proceses that produced these will be elucidated in this section.

Seven of the sections have similar sedimentological and glaciotectonic structures; these are **Inishbee, Island More, Crovinish Island, Inishleague, Rosbarnagh Island, Thornhill, and Pigeon Point**. The limestone till is over-consolidated, consisting of subrounded/rounded striated limestone clasts supported by a silty sandy matrix. The deposit is horizontally fissile with shear planes that dip gently towards the west, often extending the full thickness of the unit. Due to the massive nature of the till, displacement is difficult to identify, however it can be seen in the form of streaked out clasts and silt stringers with displacement generally towards the east. The extensive planes are interpreted as thrust shears. The shorter and steeper shears cross-cutting them are interpreted as Riedel shears. Using the model of the strain ellipse (Brodzikowski & van Loon, 1985; Park, 1986; Hanmer & Passchier, 1991; and van der Wateren, 1995) discussed in section 2.3.3.3, the dip of the *en-echelon* thrusts (towards the west) indicates that the strain forces applied by the ice were from the west, while the conjugate fault planes indicate that tensile forces were acting towards the east, both parallel to the long axes of the drumlins. This conclusion has been corroborated by recent work at Thornhill (Kramer & Snabilié, 2000). It should be noted however that the deformation need not be syndepositional but could have occurred when ice overrode and resedimented existing deposits.

Direction of ice flow can also be determined from boulder pavements that occur along many of the thrust shears. The boulders commonly have keel-shaped bottoms with flat striated upper surfaces. The striae are aligned generally towards the east, parallel to the long axes of the drumlins. If the till was emplaced through lodgement and accretion, the pavements suggest that the sediments were still weak when further deposition occurred on top of them leading to winnowing of fines by the newer deforming layer above resulting in the boulder pavement lag (Boulton, 1996; Hindmarsh, 1997). Alternatively the boulder pavements could have formed at the base of former subglacial deforming layers as noted elsewhere by Clark, 1991; and Hicock, 1991.

Care should be taken when interpreting boulder pavements and clast lags, and they should not be used as a sole criterion for lodgement or deformation tills. They have also been attributed to currents flowing in marine or lacustrine environments which rework bottom material by transporting away fine-grained material to leave a boulder lag, with subsequent glacier readvances producing a striated clast pavement similar to those produced in subglacial situations (Powell, 1984) although these generally have no clear dominant striae direction (McCabe & Haynes, 1996) unlike the striae in these drumlins. Either way, the glacier advance that produced the pavements was from west to east.

Stoss-lee boulders are also common within the limestone till. The rounded ends of bullet boulders face west while their tapered ends face towards the east. This also indicates ice flow towards the east.

Till fabric analyses were carried out both on clasts within the thrust shears and on clasts in the intervening massive till. Fabrics from both show that the dominant dip of the clasts is towards the west. Previous research by Holmes (1941), Glen *et al.* (1957), Lindsay (1970) and Benn (1995) has shown that a-axes of clasts within shears lie parallel with the direction of shear indicating, in this case, ice flow from the west. However, the fabrics from the thrust shears also show a secondary pattern of clasts that are aligned transverse to the dip of the shears. While the majority of clasts in the shears are imbricated up-ice, this secondary pattern shows that some clasts roll along their b-axes, following a model of least resistance. This indicates the importance of noting sedimentological and deformation structures when taking and interpreting till fabric measurements and highlights the statement by Dowdeswell *et al.* (1985) that "*although shearing influences the geotechnical properties of lodgement till, its effects on pebble fabric is not well known*" (p.703).

The directional indicators of ice flow above are all parallel to the drumlin long axes however this is not the case at the drumlin flanks. For example, at the flanks the shears dip away from the drumlin crestline and the striae and bullet boulders are aligned oblique to the drumlin long axes. Hiemstra (1995) noted the same pattern in till fabrics taken at Pigeon Point. These data indicate that while the forces that formed these drumlins were parallel to the axial trends near the crestlines they were oblique to the long axes at the flanks (figure 5.18).

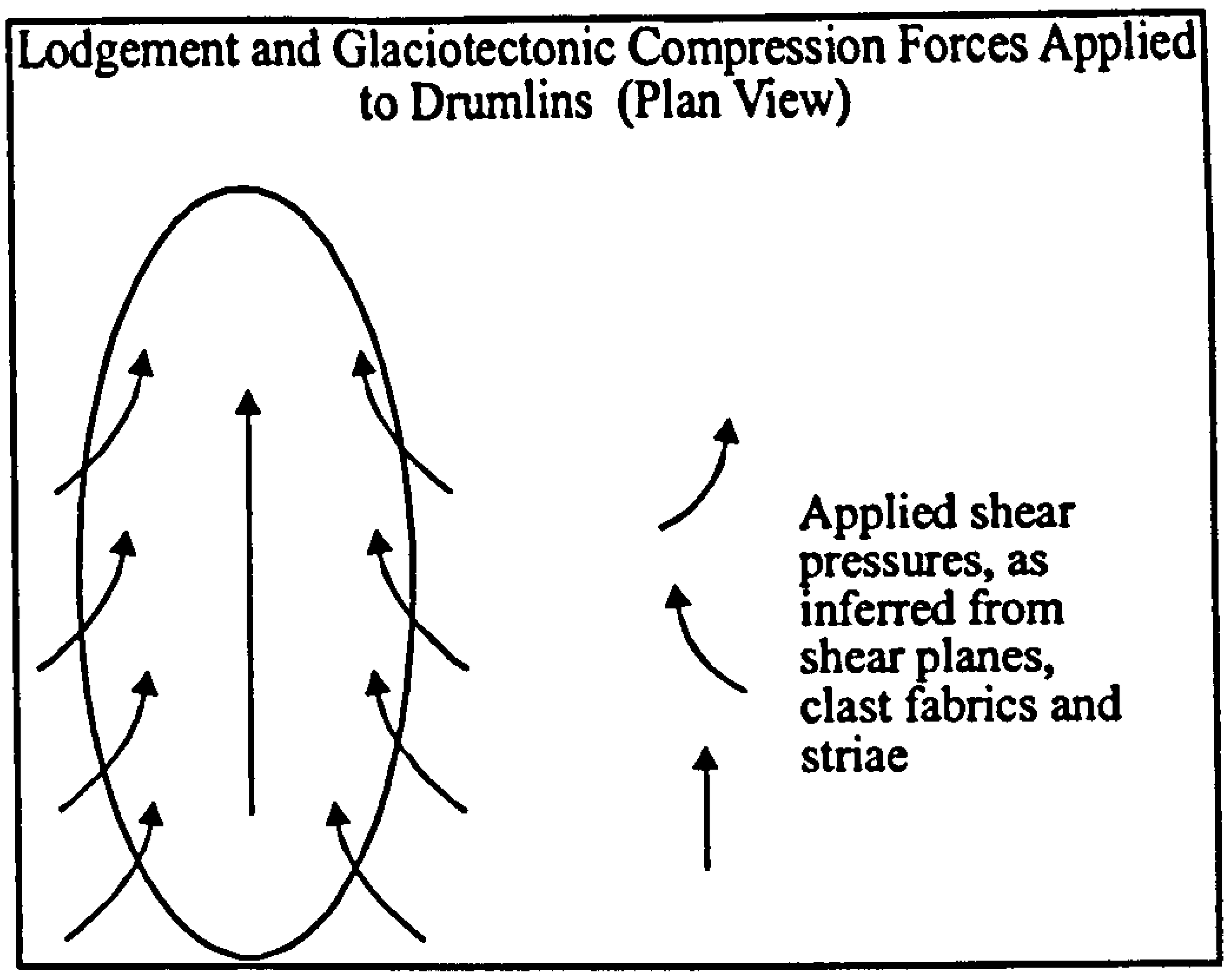

Figure 5.18 Plan view of proposed glaciotectonic forces applied to drumlins

The massive and dilated nature of the till indicates that it was emplaced under high porewater pressures as a slurry flow at the ice/bed interface or squeezed into a subglacial cavity, as proposed at other locations (*e.g.* Dyson, 1952; Hoppe & Schytt, 1953; Vernon, 1966; Boulton 1982; Lundqvist, 1997; and Meehan *et al.* 1997). It is known that dilation occurs in response to shear deformation thereby increasing the porosity (Reynolds, 1986). Water escape was facilitated through the shear planes where fines were eroded leaving a further emphasised boulder lag (Arch *et al.*, 1986).

The question as to what caused the deformation to occur is most likely answered by the presence of the deformed gravel units at the west ends of some of the drumlins. These may have been deposited initially in a low-pressure subglacial cavity where subglacial meltwater flows would converge and deposit their bedload into the lower energy environment (Hooke, 1998) or possibly in the proglacial environment as coarse gravel bars preceding ice overriding and deforming around these cores (Boulton, 1987). This heterogeneity could have been the impetus for subglacial deformation to begin and the obstacle around which drumlinisation could occur as postulated elsewhere by Menzies (1979, 1982) Boulton (1975, 1987) Hart (1995) and Moran *et al.* (1980). This proposed sequence of events is corroborated by the multi-phase drumlin formation and deformation characteristics noted elsewhere by Knight & McCabe (1997) and Zelcs & Dreimanis (1997).

The higher strain pressures experienced at the western end of the landforms are in contrast to the lower cryostatic pressure in the east of the exposures, as seen by the presence of stratified gravels which indicate the presence of subglacial meltwater, possibly in a cavity. The gravels are superimposed onto the till indicating later deposition. These may have been deposited in a low pressure 'lee side' subglacial environment as the ice flowed from west to east around and over the growing landform, parallel to the axial trend of the drumlin as seen elsewhere by Dardis *et al.* (1984). This process is depicted in Figure 5.19.

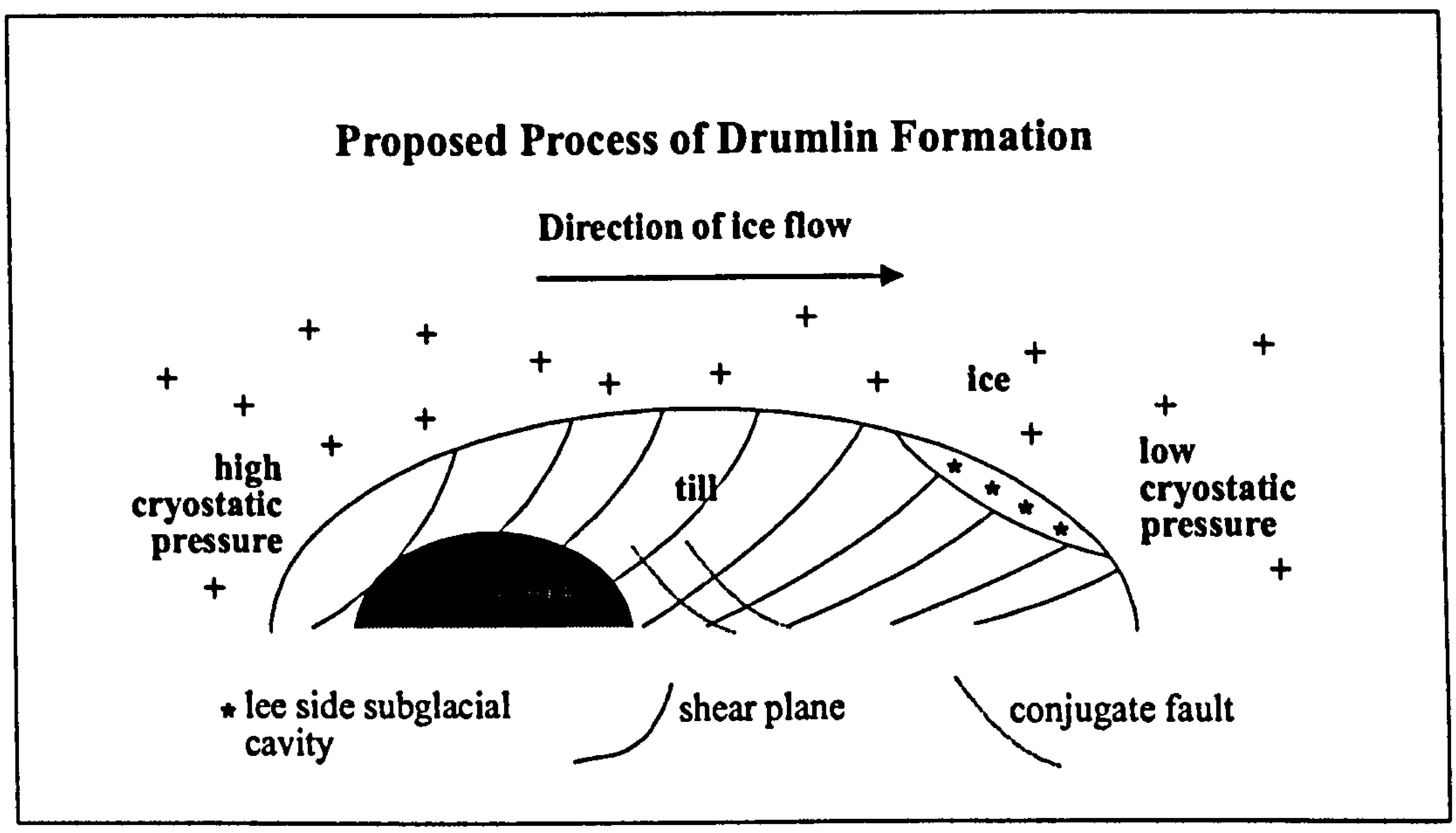

Figure 5.19 Proposed process of drumlin formation, inferred from lithofacies, deformation structure geometry, striae, bullet boulders and till fabrics.

It is proposed that where deformed gravels are absent there is another explanation for drumlinisation. It is recognised that sediments, are transported in a deforming subglacial layer (Boulton, 1979; Boulton & Jones, 1979; Alley, 1991; Johnson *et al.*, 1991; Jenson *et al.*, 1995; and Hooke & Elverhoi, 1996) but after dewatering, through the shears and clastic dykes (Rijsdijk *et al.* 1999) it gained shear strength and became a competent obstacle around which the ice was forced to flow. Dewatering occurs when the hydraulic pressure within the sediments is greater than the cryostatic pressure (Arch *et al.*, 1986). Hydraulic pressure subsequently built up in the bed/ice interface and caused uncoupling of the ice from the bed which produced a lower cryostatic pressure zone (possibly even a cavity) in the lee of the obstacle (Hooke, 1998). While the ice was still overriding the bedform (as seen from the fabrics, striae and deformation structure geometry) bedded gravels were deposited in the lee-side.

An explanation such as that above is not required when a drumlin is rock-cored as that is the obstacle around which sediment is lodged. Limestone bedrock is just beneath ground surface at the eastern end of Pigeon Point and at the surface it has been folded up through glaciotectonisation into a core that may have initiated drumlinisation. The limestone beds were incorporated into the glacier sole and folded as shown in figure 5.20 below. This process of folding has been reconstructed in a squeeze box by Mulugeta and Koyi (1987) and in this situation clearly indicates ice flow from the northwest. The surrounding till is clast supported consisting of angular limestone blocks. Clearly the sediment has not been transported far, and as such has been termed 'immature till' (Lliboutry, 1993; and Alley *et al.*, 1997). This direction of folding is corroborated by the large number of brecciated clasts in this till which have clearly been displaced towards the southeast, parallel to the drumlin long axis. The shear strength of this till is a result of the reduction in void space and a corresponding increase in frictional strength as the bedrock is crushed and abraded in the subglacial deforming layer as a comminution till (Elson, 1989), which eventually exceeds the driving stress and gives the sediment the competency to act as an obstacle around which the ice is forced to flow.

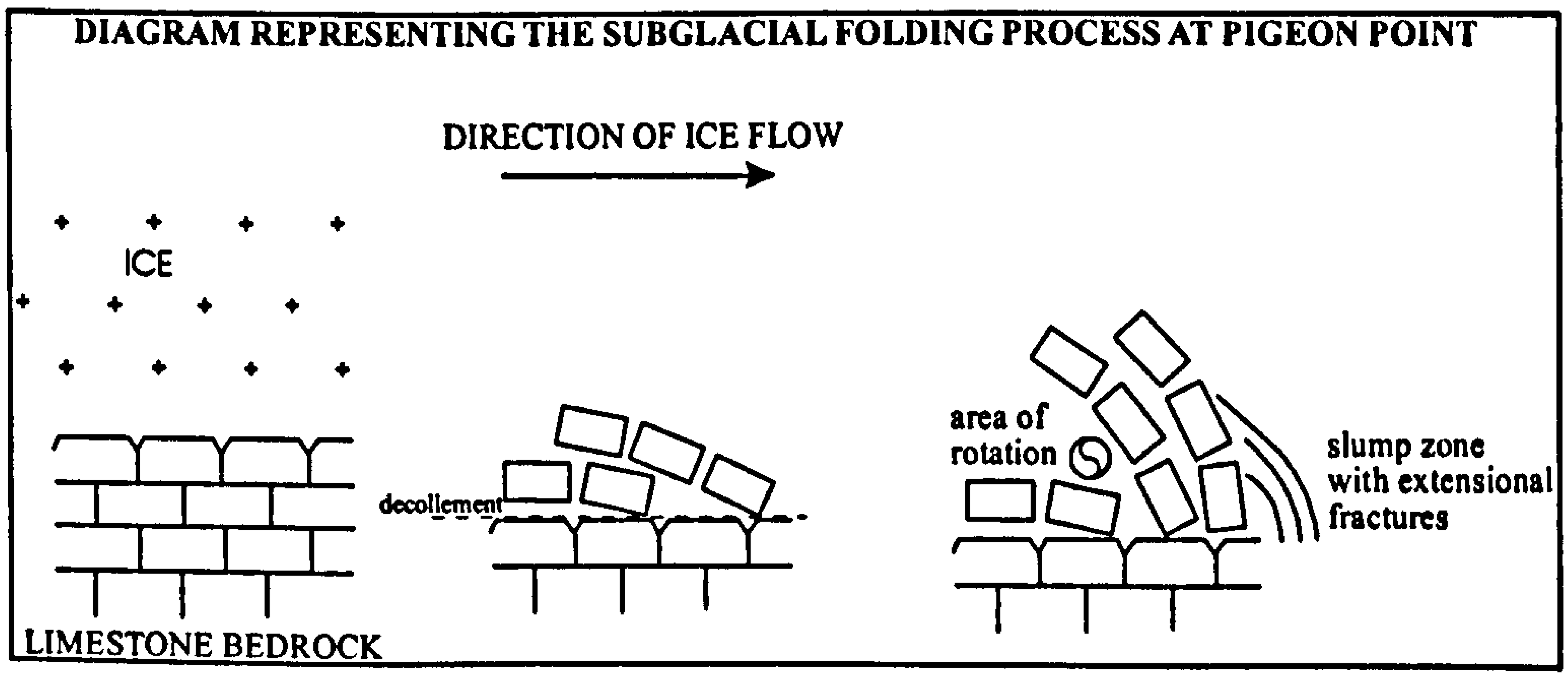

Figure 5.20 Illustration of subglacial folding process of the disaggregated bedrock at Pigeon Point

The stratified gravels that occur along the southern flank of the drumlin are unique in Clew Bay. They were most probably deposited subglacially in a channel along the drumlin flank. Ice must have been in position over the channel because the profile of the beds shows the effects of hydrostatic pressure in the conduit, and of streamlining by the overriding ice. Clast imbrication indicates that the palaeocurrent direction was from northwest to southeast, parallel to the drumlin long axis. The clast sizes, concave-shaped beds and conical lateral contact with the limestone till indicate that the gravels were deposited in a high-energy flow. The conical pattern of incision of the gravels into the till was most likely produced by variations in flow velocity which would have been affected by the thermal regime of the system which would control the amount of meltwater, the amount of sediment input, the hydrostatic pressure in the cavity and the degree of coupling between the ice and the bed (*i.e.* the drumlin/gravels). This glaciofluvial deposit may be evidence of arterial channel flow within subglacial hydraulic systems, proposed elsewhere by Lliboutry (1983) and Dardis *et al.* (1984) especially in systems with high porewater pressures and unconsolidated substrates (Boulton & Hindmarsh, 1987).

It has become clear through an analysis of this site, and the previous research undertaken here, that the methodology undertaken will affect the results obtained. Hanvey (1988) approached the site with the preconception that the ice flowed from southeast to northwest and was therefore forced to explain factors such as why the stoss side was down-ice and the tapered side was up-ice. More importantly however, the author gave no palaeocurrent direction for the glaciofluvial gravels and no explanation of the deformation structures in the clast rich till, but focused on lithofacies analyses to corroborate her theory on ice flow directions.

Subsequently, Hart (1997) focused on the deformation structures at the site and relied on Hanvey (1988) for the remainder of the data. However, Hart makes some fundamental errors when she discusses this site (*e.g.* she states that the drumlin is only 200m long, in contrast to its actual length of over 800m) and the fold structures in particular when she interprets them as having been '*stacked onto the core of the drumlin*' (p.99) by ice flowing from the southeast. This does not account for the brecciated clasts and suffers from an approach which does not incorporate till fabric analyses. Hiemstra (1995) demonstrated that detailed analyses and unbiased interpretation (albeit solely of till fabric data) can provide meaningful information, in this case regarding both the direction of ice flow (from the northwest) and the flow regime. He concluded that Pigeon Point was formed through compressive flow at the northwestern end (*i.e.* up-ice) with a gradual change to an extensional regime towards the tail. This corroborates the direction of flow interpreted from the deformation structures described above. It is abundantly clear however that the best methodology involves an holistic approach to each site, where a combination of sedimentological techniques are used to ascertain as much data as possible before interpretation begins.

Thornhill has also been interpreted by Hanvey and Hart. Hanvey (1988) approached the site with the preconception that the ice 'debouched' into Clew Bay *i.e.* flowing from the Midlands towards the west, and offshore through Clew Bay. Although Hanvey mentions that there are eighteen '*wavy deformation structures*' (p.162) she makes no effort to determine the direction from which the stresses were applied and focuses on glaciomarine processes such as a fluctuating grounding zone and tidal pumping to postulate a subaquatic environment of deposition for the accretion of the drumlin in the grounding zone of the ice sheet. The lack of data such as till fabrics or deformation structure geometry along with the preconception of ice flow towards the west lead to a misinterpretation of the sediments at this location. Furthermore, no foraminifera were found in samples taken by this researcher despite Hanvey's glaciomarine model.

Hart (1997) included Thornhill in her paper on the relationship between drumlins and other forms of subglacial glaciotectonic deformation at 33 sites in Europe and North America. She states that the drumlin formed by compressive deformation around a deformed sediment core, citing open folding and backthrusting, yet includes no lithofacies analysis, no till fabric data, no section log/drawing, and, in effect, no data whatsoever to corroborate her interpretation. Hart does state that Thornhill is an example of lee side deformation which suggests that she proposes that ice flowed offshore at this location, *i.e.* towards the west. Nevertheless, with no data to back up her claim, her hypothesis cannot be further entertained.

Inishlyre North is a cross section into the west end of an west-east orientated drumlin and has been interpreted differently to the seven above. Bullet boulders with their rounded ends facing west and tapered ends facing east indicate ice flow towards the east. This is corroborated by striae. The horizontal shears in the centre of the section, along with the fold hinges on either side of the section are indicative of a sheath fold as recognised elsewhere by Boulton (1987), Mulugeta & Koyi (1987), and Owen (1988). These authors associated this fold type with compressive forces applied by a glacier flowing over a deforming bed. The upper extents of the sheath fold are no longer present, most likely having been eroded by the overriding ice. Although a definitive direction for the folding of the sheath fold could not be determined (simply that it was parallel to the drumlin long axis) it is logical to assume that it was parallel to the other directional indicators, *i.e.* towards the southeast.

The sedimentology of **Inishlyre South** is different to the sections above. The lower 5m of the deposit have been highly deformed with planar low-gradient shears and conjugate faults. The gradients of the shears are steeper towards the north of the section where they are convex in profile. There is no clear evidence such as displacement to denote what direction the forces that formed the planar shears were applied from but the convex ones were formed by ice flowing from south to north.

Apart from horizontal fissility, there are no shears associated with the boulder pavements above the shears and the clasts do not have flat striated upper surfaces. It is therefore likely that they were deposited through the process of gravity flow onto a subglacial slope, from south to north. However, the landform is orientated west-east so it could be a Rogen moraine (or a De Geer moraine) streamlined after it was deposited. The streamlining would have been an erosive process with no remobilisation of the subglacial till as noted in other drumlins by Colgan & Mickelson (1997). There is not sufficient evidence to say either way.

Collan Beg and **Rabbit Island** look very similar with their planar dipping gravel beds, however, they may have formed through different glacial processes, demonstrating clearly the concept of convergence (sometimes also referred to as equifinality). In Collan Beg the gravel beds dip towards the west, as do the thrust shears within the gravel beds and the intervening limestone till, indicating that displacement was towards the east, parallel to the drumlin long axis. Boulder pavements within the till also dip towards the west, indicating the same direction of ice flow. These data are corroborated by striae and two sets of till fabric data. The deposit has been interpreted as a lodgement till as the clasts are subrounded and striated, it is well-consolidated, the phenoclast petrography is dominated by local rock types and there is horizontal fissility.

While the sedimentology and till fabric eigenvalues indicate that the till is a subglacial lodgement till, the gravel beds indicate that there may have been sequences involving lodgement, melt-out, and deformation as recognised elsewhere by Dreimanis *et al.* (1986) Hicock (1990) and Benn (1994). The sequence of dipping beds could have formed in the following ways:

i. the gravel beds are subaqueous Gilbertian-type deposits, while the tills are gravity flow tills. This would necessitate deposition from east to west, contrary to the till fabrics and the shear structures;
ii. the sediments are englacial and were deposited through the melting of debris-rich ice where the internal foliation was retained;
iii. proglacial seasonal meltwater deposited the gravels in an outwash sequence which was sequentially covered by subglacial till when readvances occurred. The dipping is due to deformation of the beds by the overriding glacier in the form of thrust shears that dip up-ice;
iv. the stratigraphy was formed by subglacial deposition through sequences of melt-out (gravels) and the subsequent lodgement of till through accretion that deformed the gravels;
v. tectonics, as a stacked sequence.

The first scenario is unlikely as the gravels are not bedded, and it does not account for the till fabric orientations. Also, it would require deposition to have taken place in the opposite direction to that of the deposits in the surrounding drumlins, although modelling by Hindmarsh (1997) suggests that sediment deposition can occur in the opposite direction to the direction of ice flow. The second possibility is also unlikely because of the regular and near-planar bed profiles. Englacial thrusting would produce more contorted foliations, and faulting due to settling as the ice melted (Brodzikowski & van Loon, 1985). The third theory has been ruled out because it is very doubtful that there could have been nine sequences of proglacial outwash followed by ice readvances which would have left such a regular stratigraphical pattern. Also, if the gravels were deposited through proglacial outwash, how did all the beds remain fully intact after readvance without large scale ductile or brittle deformation?

The fourth option, that of subglacial deposition through cycles of lodgement, melt-out and deformation, has been recognised in Ontario by Dreimanis *et al.* (1986) and Hicock (1990) and in Norway by Benn (1994). It is proposed that subglacial lodgement took place, periodically interrupted by melt-out and the deposition of gravels. This increased hydraulic activity could be annual or a cyclic event as hydraulic pressure built up in ice-base contact forcing period uncoupling and enabling throughflow of meltwater. This process of formation would account of the till fabric eigenvalues and eigenvectors, the dipping gravel beds with their interval deformation, the overall stratigraphical sequence and the landform morphology. Nevertheless, the final option, that of tectonic stacking is the simplest. The concept has been noted in ice-pushed ridges (Croot, 1988) and drumlins (Hart, 1997) and would account for the sedimentology of Collan Beg.

The section at Rabbit Island is visually similar but detailed analyses show that it could have formed through different subglacial processes. Due to the high level of consolidation, rounded, well striated clasts and shear structures it has been interpreted as originating from a subglacial environment. The gravel beds dip towards the northeast (parallel to the drumlin long axis) forming as either melt-out or flow till deposits in gravity slurry flows under high pore water pressures as the sediment was deposited into a subglacial cavity. The dilated nature of the till indicates that flow till is the more likely depositional process. This till was subsequently covered by gravels during episodic periods of melt-out. This has been documented at other locations (Boulton, 1982; Lundqvist, 1997). As the overriding ice flowed towards the northeast, these were deformed and cross-cut by thrust shears which dip towards the southwest. The increasing dip of the thrust shears in a southwesterly direction is further evidence of ice flow towards the northeast, as is the presence of Riedel shears which dip towards the northeast. As with Collan Beg, however, the simpler process of tectonic stacking is also a possibility for the formation however neither process can be definitively ruled out.

In contrast to the lower (limestone) till which is heterogeneous and highly glaciotectonised, the upper sandstone-dominated till is homogeneous, undeformed and massive, although crude horizontal bedding is apparent in some places. It is notable that the deformation structures in the lower till are always truncated at the unconformable boundary with the sandstone deposit. Moreover, the upper unit is underconsolidated and contains far-travelled subangular sandstone clasts. It has weak preferential fabric orientation that indicates ice flow generally from the south or southeast. The exact provenance of the clasts cannot be defined as the eastern side of the bay is ringed by sandstone. However, at Thornhill, the phenoclast petrography includes metamorphics which originate from the southeast. The consolidation of the till cannot be used as a sole factor for interpreting the origin of the sediment as supraglacial because the matrix consists of coarse sand which will inevitably be underconsolidated.

This till occurs as a thin drape/carapace, never more than 2.5m thick, on the surface of the drumlins. The 'V' shape features with vertical clast fabric seen a Pigeon Point developed when the till filled gaps in the limestone till which may well have initially been tension cracks. The presence of a discontinuous layer of limestone gravels between the two tills and the bedded gravels in the lee of the drumlins indicates that glaciofluvial meltwater was present prior to deposition of the sandstone till. These facts point to an active erosion (streamlining) period which moulded the drumlin forms from the west before the sandstone till was deposited from the east/southeast. It cannot be definitively ascertained whether the sandstone till was sub-, en-, pro-, or supra-glacial, however the fact that it occurs as a consistently thick drape from crest to base of the drumlins suggests that it was deposited subglacially. If it was deposited from any other environment one would expect slumping to have occurred with much thinner sandstone till on the crestlines than at the base. Also one would expect the cover to be more inconsistent across the area. Moreover, one has to question how the sandstone till could have been transported (if not subglacially) because there are no high relief areas of sandstone bedrock to act as sources for a supraglacial deposit.

5.4 SUMMARY

The striated, rounded cobbles and boulders, along with the high level of compaction, fissility, and shear structures indicates that lodgement and deformation were the processes by which deposition of the limestone till took place. Moreover, the dilated nature of the sediments suggest that high pore water pressures were present and that the deposit moved as an over-saturated fluid in a slurry flow prior to dewatering. This would have occurred in a subglacial deforming layer, and deposition could have been directly from that layer, or possibly into a subglacial cavity. Once a critical level of compaction was attained, the sediment acted as an obstacle around which the ice was forced to flow, and streamlining occurred to preserve the ice flow momentum while the drumlin was maintained as part of the subglacial bedform continuum.

The sandstone till was draped over the drumlin in later glacial times during a period of active retreat or downwasting. There is no evidence to suggest that the sediment was deposited from a separate ice mass during a later glaciation. In some sites the depth of the sandstone till is slightly thicker where it infills depressions in the underlying limestone deposit, but it always appears as a consistent carapace. Despite its secondary role in the drumlin-forming scenario, the upper till elucidates the multi-phase deposition sequence that is required to explain drumlin formation, comprising processes from lodgement, deformation, melt-out and flow till deposition, to subglacial glaciofluvial deposition in a variety of combinations. The complex nature of the depositional and erosive processes which act in the subglacial environment where a combination of several processes determined by factors such as climate and rheology combine to produce the drumlin form is well known (Piotrowski, 1997).

The directions of ice flow were determined from phenoclast petrography, till fabric analyses, striae, glacigenic deformation structure geometry, brecciated clast displacement, bullet boulders and drumlin morphology. These data have shown that the limestone till was deposited by ice flowing generally towards the east while the sandstone till is derived from the east. All data on ice flow direction have been complied onto figure 5.21.

The final question to be answered in this section is where do these eleven sites fit into the six models for drumlin formation, see Section 1.3.2.2.7? The spacing and pattern of the drumlins do not correlate with Baranowski's (1969) theory incorporating a 'frost heave' where there is a progression of a thermal front down through the ice, thereby ruling this model out immediately. The Shaw (1983) theory which drew an analogy between drumlin morphology and the bedforms produced by marine turbidity currents must also be ruled out as no evidence of extensive subglacial flooding was found. However, the glaciofluvial deposits within the drumlins and on their lee sides depressions does lend credence to the theory of subglacial meltwater deposition into cavities assuming that the gravels were laid down subglacially (Dardis & McCabe, 1983; Dardis *et al.* 1984). This may not necessarily be the case as it is also possible that the gravels (except those in the lee sides) could have been preglacial or proglacial and subsequently overridden by the ice (Boulton, 1987).

The remaining four models entail direct till emplacement in the subglacial environment. The dilatency model proposes that the till is transported in a subglacial deforming layer of dilatent material (Smalley, 1966; Smalley & Unwin, 1968). If the strength of the material increases, relative to the shear strength of the ice, then the competency of the sediments will result in the formation of smooth hills (Hart, 1995). This theory has been enhanced by work carried out by Boulton (1987) and Aario & Peuraniemi (1992) who proposed two layers of deforming material, the lower horizon which is jointed and relatively well consolidated and shows an elastic-plastic strain response to stresses, while the upper horizon is dilatent with a high void ratio and responds to stresses in a non-linear viscous manner. This would account for the horizontal shear planes at the base of the sections with the dipping shear planes above, which are seen in many of the exposures.

The difference between this, and the glacial kinematic fluting model is that Shaw & Freschauf (1973) and Rose (1989) propose that the deforming layer of basal till is concentrated in linear belts, characterised by helicoidal flow patterns (Folk, 1971). Although the scepticism held by Sugden & John (1976), Paterson (1981), Drewry (1987) and Hooke (1998) regarding the existence of helicoidal flow patterns in active ice sheets is acknowledged and accepted, the pattern of applied shear strain obliquely towards the crest lines seen in the thrust shears, striae and clast pavements in many of the drumlins does indicate that cryostatic pressures do exist. This simply means however that glacial stresses are applied both parallel and oblique to the direction of flow, but there is no need to postulate full helicoidal flow patterns or concentrations of linear belts of subglacial deforming tills.

Subglacial construction of drumlins through accretion of till layers over time (Alden, 1918; Goldwaith, 1924; Fairchild, 1929; Flint, 1948; Hill, 1968; and Hanvey 1992) is linked to the deforming bed theory where the sediments are accreted onto obstacles in the ice-bed interface (Boulton, 1987). Because of this cross-over of processes in the dynamic subglacial environment, it is difficult to distinguish and separate sediments which may have been produced through a combination of lodgement, accretion and deformation. It has been shown however that these processes were responsible for the sedimentology recorded in many of the exposures.

The final model for drumlin formation involves till being squeezed into hollows in the glacier sole (Dyson, 1952; Hoppe & Schytt, 1953; Vernon, 1966). Dilated sediments with accompanying high porewater pressures which enabled the saturated tills to flow as slurry flows to be squeezed into subglacial cavities have been logged throughout the eleven sites in Clew Bay. This clearly shows that the process of squeeze-in was part of the drumlin forming process. Moreover, it highlights the fact that no single process was responsible for the formation of the eleven drumlins logged in detail in Clew Bay, but that a combination of the genetic process proposed in the various theories of drumlin formation led to the development of the drumlins. It also supports the concept of convergence whereby several different glaciological processes may have produced the same morphological bedform.

Ice movement direction derived from striae, moulded bedrock forms, deformation structure geometry & till fabrics
Clew Bay, County Mayo

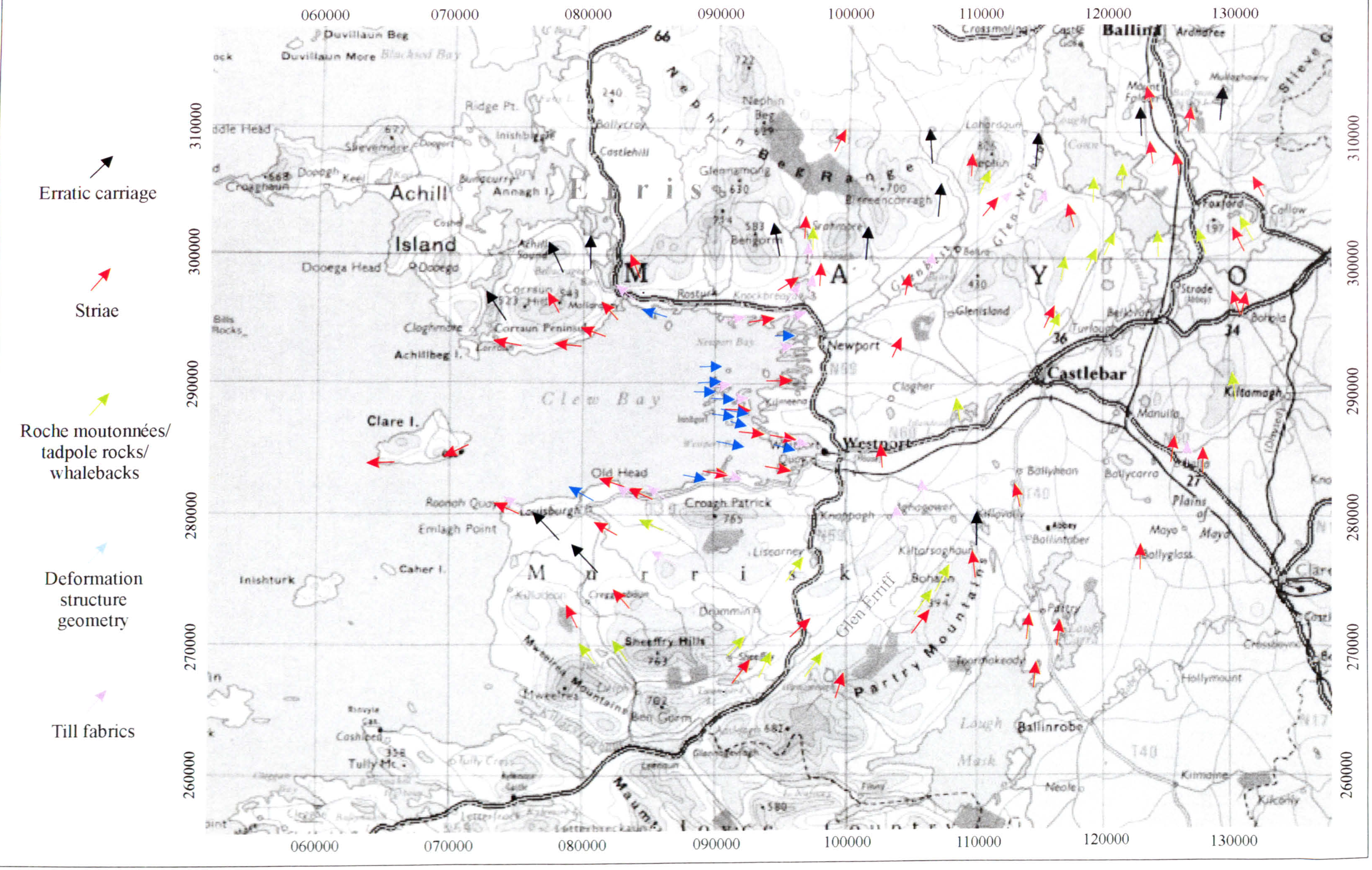

Figure 5.21 Ice flow direction derived from bedrock lineation, deformation structure geometry and till fabric analyses

6 DISCUSSION & CONCLUSIONS

6.1 FOREWORD

The aims of this thesis were twofold. The first was to map the Quaternary geology of west County Mayo, Ireland, using the established/conventional methodology adopted by the Quaternary and Geotechnical Section of the Geological Survey of Ireland as outlined in Warren & Horton (1991). Of importance in the methodology is that the area was mapped objectively with no preconceptions regarding ice flow directions or glacial depositional environments. Secondly, the sediments and morphology maps that were produced were enhanced by integrating the techniques of satellite remote sensing and digital image processing with the conventional mapping methodology to produce a multidisciplinary yet holistic model to reconstruct the glaciation of the research area.

The objective of the thesis was to test the ice sheet reconstruction produced from field mapping and remote sensing against the four current conflicting hypotheses (refer to Section 1.3 of this thesis for details of these hypotheses) which have been summarised as follows:

1. there was a single ice mass that flowed from the Midlands of Ireland in a westerly direction and exited offshore through Clew Bay;
2. there was a single ice mass in west Mayo that flowed towards the northwest from the Midlands, therefore the landforms at the head of Clew Bay are Rogen moraines (aligned transverse to flow) and not drumlins, which are aligned parallel to flow, and that ice flowed into the bay towards the southwest from Lough Conn;
3. there were multiple synchronous ice domes in the research area consisting of a northern dome that fed ice into the area from the east, and a central dome over Connemara, which extended over Clew Bay;
4. the landforms and sediments are the cumulative results of several, non-contemporaneous glaciations.

The contribution made by the satellite imagery will be summarised here, followed by the method of glaciological reconstruction, with the hypothesis testing concluding this chapter. The conventional mapping techniques will not be reviewed here as this has been done numerous times and their perceived advantages and limitations are well catalogued (*e.g.* Lowe & Walker, 1987; Warren & Horton, 1991).

6.2 REMOTE SENSING

Digital satellite imagery was chosen over hardcopy data for several reasons:

i. it is more flexible than hardcopy imagery, giving the user more scope for scene-dependant image processing and image enhancement;

ii. digital imagery can be interpreted on-screen at a variety of scales;

iii. once rectified to the Irish National Grid, maps produced in AutoCAD or purchased from other agencies such as the Ordnance Survey can be overlaid or underlain as required;

iv. images and maps can be plotted at a variety of scales for hardcopy interpretation or publication.

Three satellite image datasets were evaluated for their Quaternary geology information content, ERS-1 RADAR, Summer Landsat-5 Thematic Mapper (TM), and Winter Landsat-5 TM.

1. The first, and most complex sensor was ERS-1 RADAR image data which operates by sending out microwave pulses which detect and analyse the dielectric properties and texture of surface objects. In theory this should be the optimum sensor as the microwaves can penetrate cloud and rain to provide information about the moisture content of the land surface as well as the texture/morphology. Unfortunately these data were degraded by the geocoding algorithm used at the ground receiving station, making the imagery virtually unusable and certainly inferior to the other two datasets. The data degradation was made yet worse by the high amount of surface water on the terrain which overwhelmed the sensor readings.

2. The second dataset evaluated was Summer Landsat-5 TM multispectral data. This is a passive sensor using the 0.4 to 12.5μm range of the electromagnetic spectrum. The blanket of H_2O-rich vegetation in Ireland, especially agricultural crops, during

the summer months appears on the imagery as a patchwork quilt which camouflages the data of interest to the geologist. This can be circumvented in a minor way by using infrared bands that are used to accentuate any heterogeneity in the vegetation which may be attributable to subsurface conditions. Limited success was achieved using this sensor, because although regional drainage patterns could be discerned, it was not sufficiently discriminative to determine subsurface sediments in the detail required. Moreover, due to the high solar elevation at the time of imaging only large morphological features, or those aligned transverse to the direction of illumination, could be discerned. Therefore the drumlins and other landforms with north-south axial trends were not visible on the imagery despite all image processing efforts.

3. The third and final image was Winter Landsat-5 TM image data. This was evaluated for two main reasons: a) the Winter data has a low solar elevation that highlights morphological data; and b) the absorptive area of H_2O molecules in both soil and plants lies between 1.55 and 1.75μm (band 5 of the TM sensor). During Irish winters all green vegetation, except coniferous forestry, has a similar water content when soil moisture is constant, therefore, any pixel variations within this portion of the spectrum are attributable to morphology and soil moisture. This imagery was extremely successful and was adopted for mapping Quaternary geology at every scale from synoptic regional information down to individual drumlins and kames. Grey-scale imagery was used to map high-frequency data while multispectral pseudo-colour band combinations were used to map regional patterns due to the modulation transfer function of the human retina (Section 3.3.3, Figure 3.1). Winter Landsat TM imagery is therefore recommended for mapping Quaternary geology in northern Latitude temperate climates over the other two listed above. If cloud free imagery is unavailable then RADAR can supply some information.

The information obtained from the satellite imagery was only part of that used in the glaciological reconstruction. Conventional techniques consisting of aerial photograph interpretation, and field mapping of sediments and sedimentology (including analyses of clast fabrics, phenoclast petrography, strain histories and lineation alignments) were also employed and integrated with the image-derived information in a digital environment to provide an holistic approach to the data interpretation. The glaciological reconstruction was carried out based on the 'inversion model' (Kleman & Borgström, 1996) that operates by delineating assemblages of glacial and deglacial landforms of known depositional environments and dating them relatively using cross-cutting landforms at the margins of the assemblages.

6.3 RECONSTRUCTION OF THE GLACIATION

The first priority is to establish flow assemblages (or fans) of ice flow on the basis of spatial continuity and/or the resemblance to a glaciologically plausible pattern (Boulton & Clark, 1990; Kleman & Borgström, 1996). The data are displayed in Figure 6.1. Three main flow patterns were distinguished from the data.

1. The first assemblage that one sees in Figure 6.1 is the generally south-to-north flow pattern which extends from Ballinrobe and Lough Mask in the south towards the north, past Foxford. This flow is in the shape of an extended 'S' where the ice in the western extents of this assemblage attempted to exit offshore through Clew Bay but was forced to flow in a northerly direction. In the east of the research area, from Ballinrobe to beyond Claremorris, this flow spreads out in a northeasterly direction where the frequency of lineations (drumlins in particular) diminishes and terminates at a series of east-west end moraines. At Foxford the drumlins terminate at an esker complex. (Although drumlins exist, and were mapped, in the Foxford area, they are not shown in Figure 6.1 because satellite imagery could not be acquired).

2. The second flow assemblage occurs in the west of the research area, centred on Clew Bay and the mountains of Connemara. The pattern of flow illustrates a north-south divide, centred in Clew Bay. The flow pattern is generally towards the east at the eastern margins, towards the west at the western margins, and towards the north at the northern margins. Looking in more detail, the pattern of flow in the east of this assemblage is fan-shaped with ice flow towards the east-southeast at Westport,

towards the northeast at Newport. Also, the ice exited towards the northeast and northwest at Furnace Lough and Bellacragher Bay respectively, on either side of the Nephin Beg Range. The lineation data also suggests that while earlier flow was towards the northeast at Lough Furnace (north of Newport) there was a later ice flow event towards the east. More detail can also be seen at Corraun where the ice flowed in a curved pattern around the hill in a generally westerly direction. These data show that much of the ice flow was constrained by the mountainous topography and that preferential flow occurred along the valleys. It should also be noted in this context that although the ice followed these pathways, the higher levels of ice in the sheet might have flowed independently of these restraints.

3. The third flow pattern exists in the southeast of the research area and consists of ice flow towards the northwest. Unlike the other two ice flow patterns that were determined using a combination of till and bedrock lineations, this was resolved primarily using elongate erosional scour lineaments (shown in blue in Figure 6.1).

An interpretation of the interplay between these three flow assemblages was used to produce a relative chronology of the flow events. Beginning with the central and western assemblages, there is evidence that there was interaction between the ice margins in the zone between Westport, and Newport. Firstly amongst this is the existence of the glaciotectonised bedrock ridges which are aligned southwest-northeast where the two ice masses met. Their presence indicates that there was cryostatic pressure generally from the west and the east at this location. This conclusion was reached using a combination of ice flow direction data from till fabrics, striae, erratic carriage, deformation structure geometry and morphology which shows ice flow converging in this area

It should be clarified that although Punkari (1985) proved from work in Soviet Karelia that such ridges were produced at a confluence zone between two distinct ice masses, this is not necessary the case here.

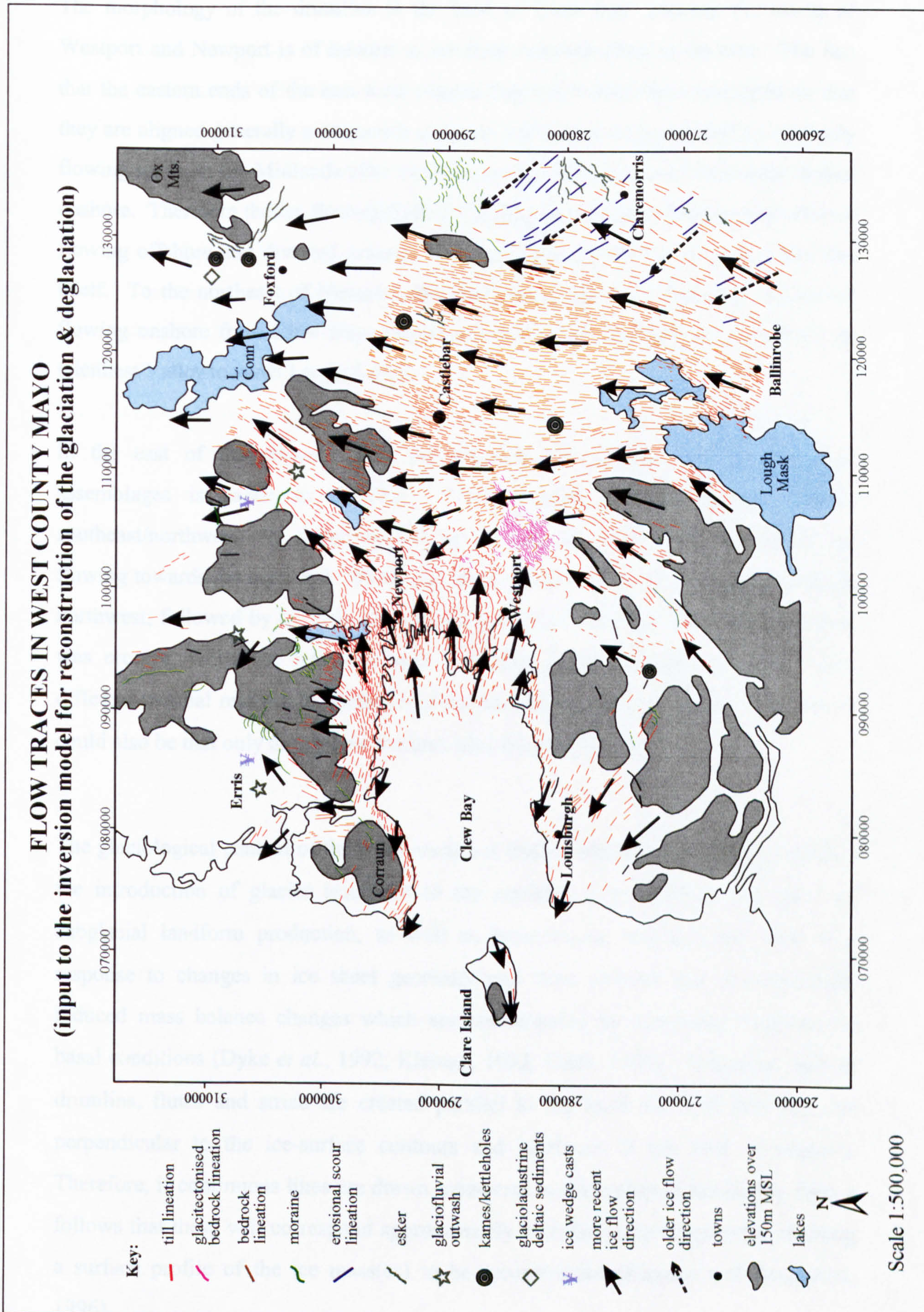

Figure 6.1. Flow traces in west County Mayo, used in the inversion model for the reconstruction of the glaciation and deglaciation of the area.

The morphology of the drumlins at the head of Clew Bay, between the towns of Westport and Newport is of interest to ice sheet reconstruction in the area. The fact that the eastern ends of the east-west aligned landforms have been reoriented so that they are aligned generally south-north suggests that they were remoulded by northerly flowing ice from the Midlands after initially having been formed by ice which flowed onshore. Therefore the ice flowing from the Midlands must have been prevented from flowing offshore and diverted towards the north by the presence of ice in Clew Bay itself. To the northeast of Newport, the ice flowing from the Midlands and the ice flowing onshore from Clew Bay merged and flowed in a northeasterly direction up Glenhest Valley towards Lough Conn.

In the east of the research area the temporal relationships between the flow assemblages is easier to decipher. The elongate erosional scours, aligned southeast/northwest, are superimposed by the drumlins that were formed by ice flowing towards the northeast. Therefore, there was an earlier flow of ice towards the northwest, followed by ice flow towards the northeast. The fact that the earlier flow was erosive, while the later one was depositional may indicate that there were different thermal regimes in operation at the base of the two ice masses. However it could also be that only the erosive features have been preserved.

The glaciological context of these ice masses is further defined in Figure 6.2, through the introduction of glacier isochrons to the model. It is accepted that zones of subglacial landform production, as well as preservation, migrate over time as a response to changes in ice sheet geometry and flow patterns due to climatically induced mass balance changes which are compounded by non-linear responses to basal conditions (Dyke *et al.*, 1992; Kleman, 1992; Clark, 1993). Lineations such as drumlins, flutes and striae are created parallel to the local ice flow direction and perpendicular to the ice-surface contours and isochrons at the time of creation. Therefore, if continuous lines are drawn transverse to these aligned landforms, then it follows that these will correspond approximately with the glacier isochrons, enabling a surface profile of the ice mass(es) to be reconstructed (Kleman and Borgström, 1996).

The isochrons in Figure 6.2 clarify the pattern of glacial geology in the research area. It is most plausible that the area was covered by a single large ice mass over the Midlands and Connemara which was generally moving in a north/northwesterly direction. The isochrons indicate that there was a north-south ice divide in Clew Bay and that this 'dome' was the barrier that stopped the Midlands ice flowing offshore during the glacial maximum. This ice was of sufficient thickness to do this because, while it may have been relatively thin over the mountains of Connemara, it was sitting within the topographic basin that is Clew Bay giving it sufficient thickness to be stable. Also, as the sea level would have been substantially lower, it is most likely that the ice existed for 10s of kilometres to the west, sitting on the Continental Shelf, adding to its stability.

The isochrons also highlight the zone of confluence at the head of the bay where they depict ice flowing from Westport, from the Sheeffry Hills and from the Erriff Valley converging in the area where the glaciotectonised bedrock ridges are located.

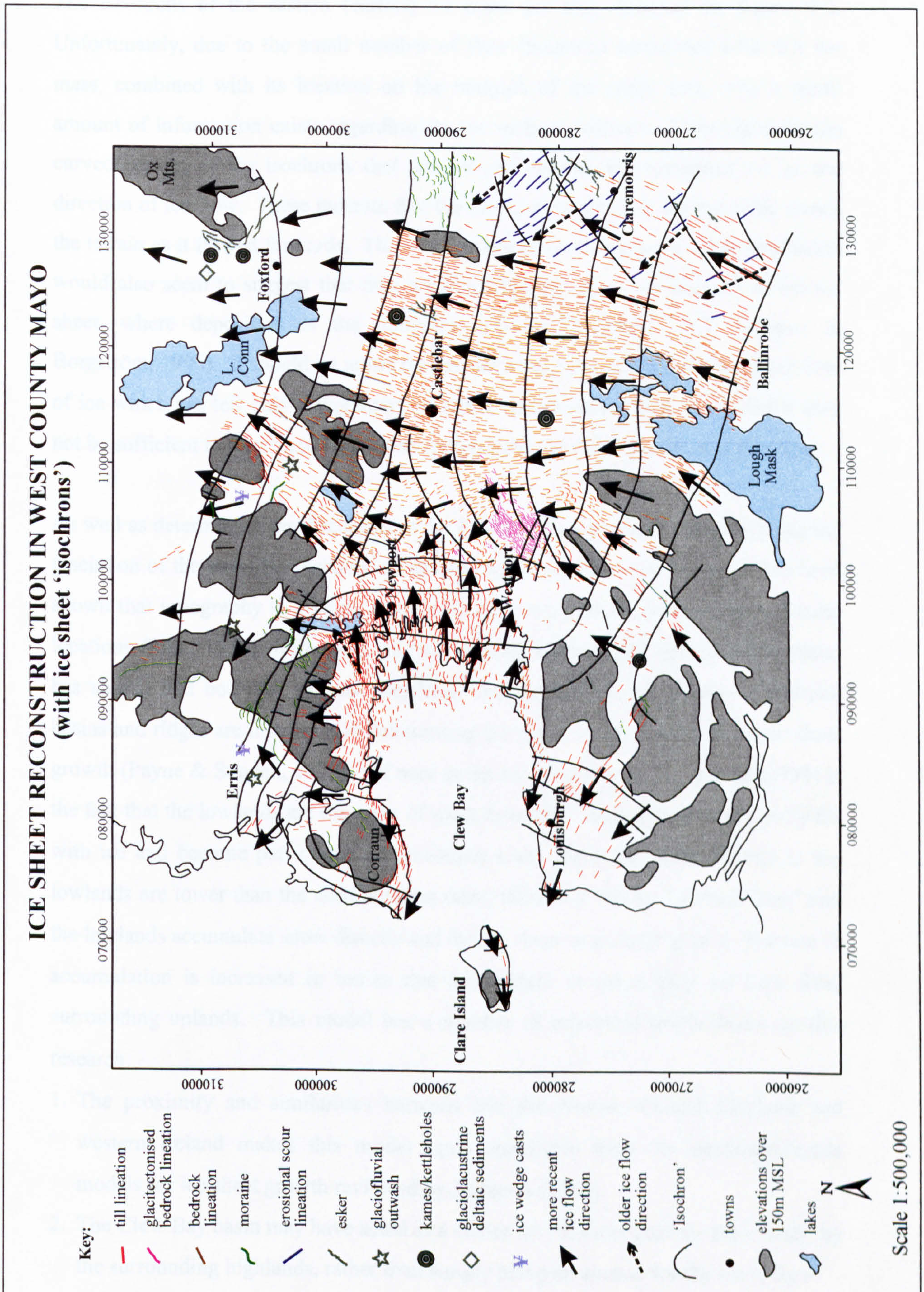

Figure 6.2. Inversion ice sheet reconstrucion in west County Mayo,with ice sheet isochrons..

The isochrons of the eastern (earlier) ice mass are also depicted on Figure 6.2. Unfortunately, due to the small number of flow lineations associated with this ice mass, combined with its location on the margins of the study area, only a small amount of information exists regarding the ice surface contours. They highlight the curved pattern of the isochrons that are convex towards the northwest *i.e.* in the direction of ice flow. These indicate that the ice mass fanned out and extended across the terrain as it flowed forwards. The erosional process of formation of the landforms would also seem to suggest that they were not formed along the margins of the ice sheet, where deposition is the dominant process (Boulton, 1987; Kleman & Borgström, 1996). It should be noted that the area has been overridden by a later flow of ice which has left only fragmentary evidence of the earlier flow event which may not be sufficient to formulate a complete reconstruction of the glaciation at that time.

As well as determining the directions of ice flow in space and time, reconstructing the glaciation of the area also includes modelling the growth of the ice sheet. It has been shown that topography is a major control on the snow and ice build up in particular locations (Flint, 1971) while work on the maritime mid-latitude uplands of Scotland has shown that both the vertical amplitude and the spatial distribution of bedrock basins and ridges are important in determining the pattern, rate and extent of ice sheet growth (Payne & Sugden, 1990). Of note in the work by Payne and Sugden (1990) is the fact that the lowlands are the areas of most dynamic change where they rapidly fill with ice and become part of the accumulation area. Once the ablation rates in the lowlands are lower than the accumulation rates, there is a 'strong feedback loop' and the lowlands accumulate snow directly and the ice sheet as a whole grows. The rate of accumulation is increased in basins that are subject to converging ice flow from surrounding uplands. This model has a number of important implications for this research.

1. The proximity and similarities between late Pleistocene western Scotland and western Ireland makes this model more applicable than the continental-scale models for ice sheet growth reviewed by Andrews (1982).
2. The Clew Bay basin may have acted as a centre for ice sheet growth, fed initially by the surrounding highlands, rather than simply being an avenue for the ice to flow.

Using Payne & Sugden's (1990) findings as the foundation of glaciological plausibility, a model for the ice sheet growth in west Mayo was constructed where the growth pattern would, by definition, culminate in the ice sheet pattern and ice surface profiles determined in the inversion model above. It is probable that ice flowed under its own weight from the highland plateaux in Connemara along the valleys into the Clew Bay basin, which was most likely a dry land basin at that time. This ice may have been joined by ice from the Nephin Beg Range in the north. The ice in the Clew Bay basin subsequently became a zone of accumulation in its own right and merged with the Connemara ice sheet so that they grew together.

The question may be asked, however, where is the evidence for this ice influx in the glacial sedimentary record in the bay? It was noted in the preceding chapter that the limestone till in some of the drumlins in the bay was deposited by ice from the south while streamlining and deformation was by ice flowing towards the east. This suggests that ice initially filled the bay from the south but as an ice 'dome' built up in the Clew Bay basin a north-south ice divide in the bay forced the ice to flow to the east and to the west (depending on which side of the divide it lay). This ice would have been supplemented by a northerly flow of ice from Connemara throughout the last glaciation.

Roughly synchronous with the ice accumulation in Clew Bay, ice was also building up in the east of the research area as part of the Midlands dome described by Warren & Ashley (1994). As this ice mass grew and attempted to flow with the topographic gradient towards the west, offshore through Clew Bay, its path was blocked by the ice already in place in the Clew Bay basin. The Midlands ice was deflected in a northerly direction until it merged with the onshore flow of ice from Clew Bay and flowed towards the northeast to Lough Conn. The growth of the Midlands ice sheet may have been slower than that in the bay however because there were no high altitude mountain ranges providing an ice source to initiate the process of ice accumulation and feed into the lowlands.

6.4 RECONSTRUCTION OF THE DEGLACIATION

The Quaternary sedimentary record in the research area is dominated by glacial sediments, with a noticeably smaller distribution of deglacial sediments and landforms (Figures 6.1 and 6.2). Deglacial meltwater sediments are distributed around the eastern and northern margins of the study area, with the exception of two isolated kame deposits (Figure 6.1). The largest area of meltwater sediments are the outwash deposits in the Erris lowlands to the northwest of the Nephin Beg Range of mountains. The presence of widespread subaqueous sediments indicates that there was an ice-dammed lake situated to the northwest of the Nephin Beg Range in late glacial times that consisted of trapped meltwater from both the corrie glaciers and the ice that flowed northwards through Bellacragher Bay from Clew Bay. At Bellacragher Bay itself, glaciolacustrine sediments are overlain by coarser subaqueous sediments suggesting that there may have been either a minor readvance of the ice, or that the speed of melting increased.

The glaciofluvial, subaerial outwash in Glenhest, southwest of Lough Conn contains imbricate clasts dipping towards the southwest indicating that the palaeocurrent flow was towards the northeast, along the valley axis, and parallel to the direction of ice flow in the valley. A recessional moraine that runs perpendicular to the axial trend of the valley delineates their southwestern boundary. A similar sequence, located along the same Northing and the same elevation exists in the next valley to the west, where there are outwash sediments delineated on their southern margins by a recessional moraine. These sequences have therefore been interpreted as part of the same stagnation event that occurred while the ice was retreating towards the southwest.

Furthermore, the pattern of recessional moraines and proglacial outwash in the valleys discussed above is part of a two-step sequence with a second (earlier) recessional moraine and associated outwash deposits further to the north in both valleys. In the western valley they consist of coarse, proximal gravels which were deposited directly from the ice margin into a subaqueous environment. The foreset dips and clast imbrications indicate that palaeocurrent direction was towards the north. The lake into which the sediments were deposited was retained on three sides by the valley walls and head wall, and on the fourth (southern) side by the ice mass from which the meltwater and sediments were being deposited. There is a recessional moraine at approximately the same Northing in the eastern valley that still dams a Lough on its southern shores. The slopes of the moraine are steeper on the south side, indicating that this was the ice-contact side. The patterns of meltwater and recessional moraine deposition in these valleys indicate that there was a two-step sequence of stagnation and melt-out as the ice margin retreated in a southerly direction (along a line from Lough Conn to Erris) towards Clew Bay.

The meltwater traces in the eastern half of the study area are dominated by eskers. The most southerly complex of eskers is located to the north of Claremorris. The morphology and sedimentology of the eskers show that palaeocurrent direction was towards the northwest, parallel to the direction of ice flow in that area. As with the drumlins in this area, the eskers are superimposed upon the elongate scours, providing a relative chronology of glacial deposition. The location of these eskers also coincides with the zone where the frequency of drumlins decreases dramatically, suggesting that this was an area of thinner ice, in a wet-bed system at the margins of an ice sheet (Kleman and Borgström, 1996). North of these eskers, and transverse to the drumlins, are a series of moraines that denote the former location of the ice margin.

An esker complex also exists to the northeast of Foxford, along the southwestern and northwestern flanks of the Ox Mountains. Palaeocurrent directions obtained from within the eskers are initially towards the northwest, but alter towards the northeast when they round the southwestern limits of the Ox Mountains. There is a large assemblage of glaciolacustrine sediments at the northern boundary of these eskers. These were deposited into a lake that was dammed by ice to the north and the south, and by topographic highs to the east and west. Large scale ductile folding in the glaciolacustrine sediments indicates that there must have been a readvance of ice from the south during the late glacial/early deglacial period.

The final set of deglacial sediments are the recessional moraines associated with the corrie glaciers in the Nephin Beg Range (also mapped by Kenyon, 1986). The northwest-facing corries have five arcuate moraines associated with them, where their concave sides face the corries. The outer moraines have been reoriented by the lowland ice, showing that the corrie glaciation and the main Fenitian/Midlandian glaciations were synchronous. The inner recessional moraines show a staged retreat of ice back into the corries, although lack of absolute dates also leaves the possibility that they are the result of advances during the final stadial, the Nahanagan, the effect of which was only felt in Ireland at higher altitudes (Kenyon, 1986).

In short, it is suggested that the system of moraines in the north of the study area denote the limit of the ice. To the south of this limit the landforms are subglacial and outwash is rare, whereas glacial outwash dominates the sedimentological record to the north. This indicates that the ice retreated actively in a southerly direction. The upper till in the drumlins in the bay is sandstone dominated and of subglacial origin. This indicates that at late glacial times the ice exited offshore through Clew Bay, having flowed onshore during the glacial maximum. The discontinuous thin gravel layer between the sandstone and limestone tills indicates that meltwater was present in the subglacial system prior to expulsion of the ice offshore.

6.5 COMPARISON WITH EXISTING MODELS OF ICE SHEET RECONSTRUCTIONS

The first realisation that can be drawn from the multiplicity of models and research methodologies that have been carried out on the Quaternary geology of west Mayo is that the morphology and sedimentology of the area are complex, which in itself has resulted in the formulation of numerous interpretations. It has also shown that once an accepted theory has permeated through the literature, such as Hulls 1878 model, it gains credence with each reference in future works until it becomes the pervasive model.

The range of both currently proposed and historical models for the glaciation of west Mayo have already been described and discussed in Section 1.3.1 (Figures 1.5, 1.6, 1.7, 1.8 & 1.9), but they will be briefly summarised here to provide a context for the comparison with the model constructed during this research. Between 1867 and 1999 the ice sheet dynamics in west Mayo have appeared in the literature twenty-nine times. Some of these publications are summaries and reinterpretations of previous research with little or no new research carried out by the respective author(s). These twenty-nine have been grouped into four categories.

1. Those who believe that there were several synchronous ice domes in west Mayo (Close, 1867; Kinahan & Close, 1872; Charlesworth, 1929; Warren 1991, 1992; and Warren & Ashley, 1994).
2. Those who support the 'Great Central Snowfield Theory' which proposes that a single ice sheet spread across Mayo from the east and exited offshore through Clew Bay (Hull, 1878; Cole *et al.*, 1914; Mitchell, 1957, 1960; Synge & Stephens, 1960; Synge, 1963; Farrington & Stephens, 1964; Sissons, 1964; Orme, 1967; Bowen, 1977; Coudé, 1977; McCabe *et al.*, 1986; McCabe, 1987; Hanvey, 1988; Coxon & Browne, 1991; Eyles & McCabe, 1991; McCabe, 1993; Dardis, 1995; Hart, 1997; Knight & McCabe, 1997; McCabe & Clark, 1998; Benn & Evans, 1998; and McCabe *et al.*, 1998).
3. Those who believe that the landforms and sediments were the result of metachronous ice masses (Synge, 1968; Synge, 1979).
4. Kenyon (1986) who concentrated on the corrie glaciations in the Nephin Beg Range with no account of the regional glaciation.

It should be noted that the recent research carried out by Dardis (1995), Hanvey (1988) and McCabe (1993) focused on the location and description of 'glaciomarine' sequences along the coastal zones of western Ireland. These sequences were used to further develop the model of ice flowing offshore into a glaciomarine environment with little note taken of glaciotectonic structures or till fabric analyses. In the glaciomarine model, marine muds were deposited after the ice uncoupled from the bed due to eustatic rise, enabling the sediments to be deposited through the following mechanisms; deposition from meltwater flows or plumes, direct deposition from the glacier margin, the 'rain-out' of debris from icebergs, settling of particles from suspension, resedimentation of sediment gravity flows, resedimentation by current reworking, and shoreline sedimentation.

The disparity between the interpretion of certain deposits as glaciomarine by Hanvey

(1988) and McCabe (1993) and interpreted as glacioterrestrial and glaciotectonised throughout this thesis will be addressed using the criteria that determine the glaciological genesis of sediments, as defined by Powell (1984 & 1990), Eyles, Eyles & McCabe (1991), Hart & Boulton (1991), Hart & Roberts (1994), Bennett & Glasser (1996), and Menzies (1996) refer to Table 6.1.

	Glaciomarine	**Glacioterrestrial /Glaciotectonic**
Sedimentary units	Laterally continuous, onlapping relationship	Laterally discontinuous, tectonic boundaries
Basal boundary	Sedimentary	Décollement surface
Laminations	Graded	Non-graded
Shells	Common, in situ	Rare, not in-situ
Folds	Gravitational flow folds, restricted to local areas, orientated downslope	Tectonic folds, deformation throughout, orientated in the direction of flow
Boudins	Rare	Common
Lonestones	Dropstones	Sinking clasts
Fabric	Variable, if present will reflect local slopes or flow directions	Variable, but may be well developed in the direction of shear

Table 6.1 Table of criteria used to distinguish subglacial from glaciomarine sediments.

A look at any of the section descriptions in Chapter Five will immediately show that the sediments described in the mapping area are characteristic of subglacial / glaciotectonic deformation while no exposures had glaciomarine traits. Furthermore samples of clay from the '*muds of glaciomarine origin*' (Hanvey, 1988; McCabe *et al.*, 1998) from four locations around Clew Bay were sent for analysis to the Institute of Quaternary Studies, Maine and were found to contain no marine macrofossils or foraminifera of any kind. Hanvey (1988) and McCabe (1998) used a one-dimensional research approach, focusing on the apparent location of glaciomarine sediments. The deformation structures such as the 42 thrust shear planes logged at Thornhill were interpreted by Hanvey (1988) as being the result of water escape in listric intrusive sheets brought about by hydraulic tidal pumping at the base of fluctuating grounded ice. The simpler option of subglacial lodgement / deformation till thrust planes was not entertained.

The model of ice flow towards the west, offshore through Clew Bay, corroborated by the supposed glaciomarine sedimentation processes is at odds with the interpretation made in this thesis using the inversion model that has located an ice dome in Clew Bay with ice flow towards the east in the eastern half of the bay and towards the west in the western half of the bay, similar to the models proposed by Warren (1992) and Warren & Ashley (1994).

There are two schools of thought regarding the glaciation of Murrisk and Erris. The first is that the subdued geomorphology at these locations is the direct result of having been formed in a previous glaciation (the Munsterian, or Connachtian) and subject to subsequent periglacial weathering (Synge & Stephens, 1960; Farrington & Stephens, 1964; Sissons, 1964; Orme, 1967). This theory uses the same morphostratigraphic approach that was used to propose that the subdued terrain south of the South Irish End Moraine must be of an earlier glaciation, the Munsterian, and in fact Sissons (1964) equates this glacial limit in Mayo directly with the SIEM. The second school of thought regarding the glaciological genesis of these regions is that they were part of the subglacial environment during the last glaciation (Coudé, 1977) and that some of the moraines which skirt part of the Nephin Beg Range were formed by synchronous corrie and lowland ice (Kenyon, 1986).

The proposal that the regions of Erris and Murrisk belong to a previous glaciation (the Munsterian/Connachtian) purely on the basis that the landforms are relatively subdued is founded on weak evidence. Research by Synge (1963) and Kenyon (1986) clearly showed that the corrie moraines at Erris on the northwestern flanks of the Nephin Beg Range are synchronous with the adjoining lowland moraines. This alone indicates that Erris was under an ice mass during the last glacial maximum. Furthermore, detailed mapping in Erris during this study has shown that the area is composed of glaciolacustrine sediments and glaciofluvial outwash, which are characteristically subdued morphologically, and that these sediments are covered by extensive blanket bog that has filled in hollows further levelling the terrain. Meanwhile, satellite image and aerial photograph interpretation has provided evidence that drumlins do exist in Murrisk, even in the Dardis (1995) '*numlin zone*'. These drumlins are aligned parallel to, and with the same elongation ratios, as those outside this so-called area of older deposits, indicating that this area was under ice during the last glacial maximum.

Debate also exists regarding the form of glaciation that occurred in the Connemara Highlands. It has been generally accepted that an ice cap did exist over the area during the last glacial maximum and that this merged with the lowland ice, flowed anticlockwise around the Partry Mountains and Croagh Patrick and flowed towards the west, offshore through Clew Bay (*e.g.* Mitchell, 1957, 1960; Synge & Stephens, 1960; Orme, 1967). Although Warren (1992) and Warren & Ashley (1994) agree with the existence of an ice cap in Connemara, they do not support the argument that it flowed offshore through Clew Bay but believe that it extended as a single dome over Clew Bay. The notable exceptions to the proposal of an ice cap over Connemara are the publications by Farrington & Stephens (1964) and Sissons (1964) who believed that Connemara remained unglaciated, and in fact, acted as a barrier to ice which flowed in a westerly direction from the Great Central Snowfield.

The radial flow patterns derived from drumlins, till fabrics, striae *etc.* extending from Connemara and merging with those in the lowlands are irrefutable evidence that an ice cap did exist in that area during the last glacial maximum. The results of the inversion model also partially corroborate the model proposed by Warren (1992) and Warren & Ashley (1994) for several synchronous domes in the area during the last glaciation, one over Clew Bay/Connemara, and the other further inland. It is suggested that the 'dome' in Clew Bay had a north-south ice divide approximately half distance across the bay and that ice flowed towards the east in the east half of the bay, and towards the west in the west half of the bay. These interpretations lend credence to the argument put forward by Close (1867) that ice flowed onshore at Newport to merge with ice flowing towards the north from the east of Westport.

The multiple dome model also supports part of the interpretation by McCabe *et al.*, (1998) where they state that '*the northwest pointing horns* (on the eastern sides of the drumlins in the area around Newport) *record the latest phase of ice overprinting'*. It is proposed in this thesis that the 'overprinting' *i.e.* resedimentation and streamlining was indeed the last phase of overprinting but that it was carried out by the western margins of the Midlands ice. However, McCabe *et al., (1998)* propose that there was a single ice mass from the Midlands (in continuing support of Hull's (1878) model) and that it flowed offshore through Clew Bay. In fact, their interpretation in this case may be the fault of their sampling system, where only two sites on the western end of Clew Bay were analysed. Understandably, these showed ice flowing offshore, but it is unreasonable to extend this interpretation inland to the head of the bay with no data sites to support their argument. This highlights the importance of a good distribution and a large number of data sites across a complicated research area.

With regard to integrating the model of glaciation proposed in this thesis with the two existing models for regional ice flow on the island of Ireland (Figure 1.5), there is a clear correlation with the model comprising of several synchronous ice domes (Warren & Ashley, 1994). The Clew Bay dome with its north-south divide, extending from the Connemara ice cap, correlates with the Central Dome in Warren & Ashley (1994). The one criticism of Warren & Ashley's (1994) model is that their shape of the Central Dome is too elongate and should be more rounded to account for the south-north orientation of the drumlins in the Plains of Mayo. The older flow pattern from the southeast that was determined from the elongate erosional scours at the eastern margins of the research area correlates with the flow depicted from the Northern Dome. These ice flow patterns contrast starkly with the east-to-west ice flow pattern shown in part A of Figure 1.5 (the Great Central Snowfield Model) that is clearly at odds with the reconstruction obtained using the inversion model in this research.

No previous research has been carried out on the deglaciation of the research area, and therefore there is no work with which to compare the interpretations made in this research. Nevertheless, it can be discussed in terms of the publications that deal with the deglaciation of Ireland as a whole. For example, some researchers have proposed that there was a general retreat of ice from south to north across the country, back to the source of the Great Central Snowfield (Charlesworth, 1963 and Synge, 1970, 1977, 1979) while others postulate that the ice sheet broke-up into its constituent domes with discharge outlets between the domes (Warren, 1992; Warren & Ashley, 1994). The pattern of retreat in this area is generally from north to south (determined from the sequence of recessional moraines and outwash between Lough Conn and Erris) directly opposite to the direction proposed by the proponents of the Great Central Snowfield model. The data indicates that the ice retreated back towards Clew Bay.

Meltwater deposits were mapped in the northern and eastern margins of the research area, however there is a noticeably small volume of outwash deposits in the remainder of the research area. This suggests that the glacier consisted of clean ice and that there was little or no reworking of till by meltwater during deglaciation. It is also possible that the meltwater dissipated into the groundwater through the karstic limestone bedrock that underlies most of the research area. This would account for the complete lack of glaciofluvial meltwater deposits on the Plains of Mayo. However, evidence for the existence of glaciofluvial meltwater does exist in Clew Bay. The lower till has an upper till drape, but a discontinuous layer of gravels has been recorded at the contact between the two tills. It is suggested here that as the dome retreated, meltwater reworked and deposited materials derived from the lower till before the upper till was deposited.

Eskers occur in the east of the research area in a line between Claremorris and Foxford where the frequency of drumlins decreases, indicating the margins of a temperate wet-based glacial system (Kleman and Borgström, 1996). This is also the location where the drumlins superimpose erosional scours that have been attributed to ice from the east, delineating the former margins of two ice masses. This appears to support the Warren & Ashley (1994) model of ice disintegration into domes with meltwater drainage concentrated along the disintegrating margins. In fact, the discharge outlet proposed in Warren & Ashley (1994) (Figure 1.2) is located along the line of esker distribution.

6.6 THEORIES OF DRUMLIN FORMATION

The objectives of this thesis did not include attempting to find a solution to the question of how drumlins form, however, as drumlin exposures dominate the sedimentological record in the research area, the question must be summarily addressed. A literature review has revealed that there are six main models postulated for drumlin formation: 1) the subglacial lodgement model (Alden, 1918; Goldwaith, 1924; Fairchild, 1929; Flint, 1948; Hill, 1968; Hanvey 1992); 2) the squeeze-in model (Dyson, 1952; Hoppe & Schytt, 1953; Vernon, 1966); 3) the frost heave model (Baranowski, 1969); 4) glacial kinematic fluting model (Shaw & Freschauf, 1973; Rose, 1989); 5) Shaw wash model (Shaw, 1983; Sharpe, 1987); 6) dilatency model (Smalley 1966; Smalley & Unwin, 1968; *Smalley & Piotrowski, 1987*). These models have been reviewed in detail in Section 1.3.2.2.7.

One point seems clear, any successful model will have to account for drumlin morphology, drumlin sedimentology, spatial distribution, local topographic factors and not be at odds with glaciological theory. None of the models appears universal in answering the problem of how drumlins form, *i.e.* no single model can explain all the sedimentological or morphological features of the drumlin swarms in the research area. Likewise, the models are not mutually exclusive, but a degree of transition is seen between them. For example, sediment could be either squeezed or deposited by meltwater into cavities and subsequently deformed by the overriding ice into sediiments that approximate those of lodgement tills or dilatent sediments. Furthermore, the meltwater present towards the end of the glaciation could remobilise sediments, lending support to the Shaw wash theory. The answer may lie in the concept of equifinality where different processes can produce the same landform.

Direct evidence to support each of the six models of drumlin formation except frost heave has been recorded and described from various exposures in the Clew Bay area (Chapter 5). The sediments at Thornhill appear to have been deposited through subglacial lodgement as the drumlin built up through accretion on the up-ice side of a competent mass of pre-existing till (Section 5.2.10). The model of squeeze-in is supported by the sediments at exposures that consist of till that may have been saturated during deposition as it was extruded into longitudinal cracks in the glacier sole, followed by streamlining and deformation by overriding ice. These deposits are difficult to differentiate from sediments that have been deposited through the dilatency model where stress in the glacier/bed interface keeps a layer of dilatent deforming till in motion but where the dynamic stresses are not sufficiently high to reinitiate movement once the material has come to rest. These sediments are also overridden by the glacier and undergo deformation. Examples of this were described in Chapter 5 relating to, amongst others, Rosbarnagh, Inisgleague and Inishlyre North. Boulton (1987) pointed out that for hummocks to develop in the subglacial deforming layer, leading to drumlinisation, heterogeneous sediments are required to initiate 'jamming'. The deformed gravel units in the stoss ends of the drumlins at Inishleague and Rosbarnagh may have acted as heterogeneous units capable of initiating drumlinisation. This gravel may have been deposited proglacially or subglacially.

The model of glacial kinematic fluting requires the formation of subglacial flutings within helicoidal flow cells (Figure 1.14). Although the till fabrics and deformation structure geometry from Pigeon Point and Island More show that applied stresses were pseudo-parallel to the drumlin long axis with a secondary orientation towards the axis *i.e.* a herring bone pattern (Figure 5.10), which may be due to helicoidal flow patterns, they are more likely to be the result of cryostatic pressure applied obliquely onto the drumlin flanks by the overriding ice. This is clearest at Pigeon Point where the till fabrics show compressive flow at the stoss end grading into extensional flow at the lee side with the applied stresses oblique to the drumlin long axis along its flanks. Doubt regarding the existence of helicoidal flow patterns is strengthened by the fact that they have not been observed beneath active ice sheets and there is no mention of their existence by workers involved in glacier mechanics (Drewry, 1987; Hooke, 1998; Paterson, 1981; Sugden & John, 1976).

The model of drumlins as erosional remnants of subglacial flooding relies on the perception that there is a lack of observed internal glaciotectonic deformation structures (Sharpe, 1987) while stratified sediments are common (Krüger & Thomsen, 1984) therefore the only remaining process for sediment emplacement is deposition by subglacial meltwater in turbulent flows (Shaw, 1983) or in subglacial water-filled cavities (Dardis & McCabe, 1983; Dardis *et al.*, 1984; Muller, 1974). Evidence for lee-side glaciofluvial deposition is seen at Inishleague, Rabbit Island and Collan More (South) while the gravels along the southern flank of Pigeon Point are indicative of glaciofluvial deposition in a channel. The deposits at the lee sides of Inishleague, Rabbit Island and Collan More (South) indicate deposition in subglacial water-filled cavities while those at Pigeon Point show glaciofluvial erosion into the flank of the drumlin followed by deposition. This shows that while subglacial meltwater does play a part, it is not the sole process for drumlin formation in Clew Bay.

While many of the drumlins in Clew Bay contain glaciotectonic deformation structures (refer to Chapter 5) no structures are visible in the drumlin exposures inland. It could be assumed that deformation structures do exist within the sediments inland but that they are not visible; that the structures are visible at the coastal sections as a result of marine erosion processes. This cannot be proven however.

The width/length ratios of the drumlins were easily calculated in the digital image processing system where a clear pattern emerged. The width/length ratios were consistent in the low-lying and flat regions of the research area where spindle-shaped drumlins were prevalent, but the landforms became shorter and more rounded at the up-ice sides of hills and mountains. This pattern is most likely due to the velocity and relative thickness of the ice decreasing on the up-ice side of the obstacles (Mills, 1987; Rose, 1987). Furthermore, in the Sheeffry Mountain valleys, the drumlins at the heads of the valleys are rounded and short but they change gradationally into longer drumlins with a more spindle-shape with distance down-valley. Another example of the information interpreted from morphology is in the area around Furnace Lough, to the northwest of Newport, where 'megadrumlins' (Embleton & Liedtke, 1990) with west-east trending long axes are superimposed by drumlins with southwest-northeast trending long axes showing changing ice flow patterns over time.

6.7 SYNOPSIS

The objective of this thesis, as outlined in Sections 1.1 and 6.1, was to test the four existing hypotheses of ice sheet flow in west Mayo. In order to test objectively the current models of ice sheet dynamics, it was necessary to map the sediments and morphology of over 2000km^2 using a *tabula rasa* approach which, by definition, would not contaminate any of the maps with theory-laden data obtained by previous researchers. The conventional Quaternary geology mapping methodology was adopted, which involved recording lithofacies, till fabrics, phenoclast petrography, glaciotectonic deformation structure geometry, erratic carriage, striae alignment, roche moutonnées, crag and tails, whalebacks, tadpole rocks, drumlin morphology, moraine morphology, clast imbrication in glaciofluvial deposits, kame/kettle hole locations, eskers and periglacial features. Moreover, the technique of digital satellite remote sensing was evaluated and integrated with the conventional Quaternary geology mapping techniques in an effort to improve the glaciological reconstruction. The data obtained from both the conventional mapping techniques and digital remote sensing were integrated and interpreted using an 'inversion model' (Klemen & Borgström, 1996).

The glacial and deglacial reconstruction enabled the four hypotheses to be tested as follows.

- ***There was a single ice mass in the research area that flowed from the Midlands of Ireland towards the west and exited offshore through Clew Bay.***

It has been concluded that this model is incorrect because it does not account for the evidence of ice flowing onshore, towards the east, at the head of Clew Bay. Moreover, the ice flow direction in the east of the research area, between Ballinrobe and Foxford is from south to north, and not towards the west.

- ***There was a single ice mass in west Mayo that flowed towards the northwest from the Midlands, therefore the landforms at the head of Clew Bay are Rogen***

moraines (aligned transverse to flow) and not drumlins, which are aligned parallel to flow, and that ice flowed into the bay towards the southwest from Lough Conn.

This hypothesis is also rejected as it has been shown that ice flowed onshore at the head of Clew Bay and towards the northeast in Glenhest in the direction of Lough Conn. The western margins of the northerly-flowing ice mass did re-align the eastern ends of the drumlins at the head of Clew Bay between Newport and Westport but the landforms are not Rogen moraines and do not signify ice flow towards the northwest.

- ***There were multiple synchronous ice domes in the research area consisting of a northern dome that fed ice into the area from the east, and a central dome over Connemara, which extended over Clew Bay.***

The Quaternary geological information obtained during this research corresponds closely to this model. The inversion model (Figures 6.1 & 6.2) indicates that there was an eastern and a western 'dome' that coalesced as a single ice sheet. The western dome was situated in Clew Bay and had a north-south ice divide which ran approximately half way along the bay (although it should be stressed that the ice divide would have been dynamic as dome sizes oscillated). Ice flowed towards the west in the western half of the bay, and onshore towards the east in the eastern half. The western extents of this dome are located somewhere in the Atlantic Ocean. The furthest west that they have been traced in the research are the sediments and landforms on Clare Island that were formed by ice that flowed towards the west. This dome was the northerly extension of a larger ice mass that existed over Connemara at the time.

The eastern half of the research area was under an ice mass that flowed generally from south to north. At its western margins it attempted to fan out and flow towards the northwest but the dome that was resident in Clew Bay blocked its progress. The convergence zone between the eastern and western domes is located in a line from Westport to Newport. The region of maximum convergence is to the east of Westport town where the glaciotectonic ridges are located. To the north of these the morphology consists of drumlins that were formed by ice that flowed onshore. The eastern extremities of these drumlins were reshaped by northwesterly flowing ice. While it is possible that the drumlins were produced by metachronous ice masses, the glaciotectonic ridges could only have formed by converging flow thereby determining that the ice domes must have been synchronous, part of a single ice mass.

There are superimposed landforms in the far eastern margins of the research that may support the final hypothesis which states that

- ***The landforms and sediments are the cumulative results of several, non-contemporaneous glaciations.***

Southeast-northwest trending erosional scours are cross-cut by drumlins and eskers that were formed by the eastern of the two domes discussed above. The inversion model states that relative dating is determined from cross-cutting landforms at the margins of assemblage fans. In this situation it is clear that the drumlins and eskers are associated with a later period of ice flow than the scour marks. Without absolute dates, there is no possibility of determining the time gap between the formation of the superimposed landforms in the context of this research.

No models for the deglaciation of the research area have been published to this authors knowledge. Glaciofluvial meltwater assemblages, indicative of deglaciation, have been mapped in the eastern and northern extents of the research area. Both instances show retreat from north to south. In the north the retreat is staged. There are two sets of recessional moraines with associated subaerial and subaqueous outwash to the north. Erris is one such area of outwash. In the east there is an assemblage of eskers to the south of recessional moraines. Periglacial landforms are found in the areas of outwash and also on hilltops. Both of these sets of locations would have been exposed to periglacial conditions during deglacial times.

A discontinuous bed of gravels is commonly recorded between the upper limestone and lower sandstone tills mapped in Clew Bay. Both tills have been interpreted here as subglacial lodgement/deformation. It is proposed that the ice in the bay receded in late glacial times, enabling the Midland ice to flow offshore, thereby depositing the sandstone till.

One of the major conclusions drawn from this research is that the methodologies adopted during Quaternary geology mapping and glaciological reconstruction affect the outcome. Researchers who approached this region with preconceptions seem to have worked to vindicate their preconceived ideas/theories. Furthermore, it was found that if a one-dimensional approach was adopted, for example, focussing on morphology to the detriment of sedimentology, or on small numbers of sample sites rather than a well-distributed number, the glaciological model would inevitably be flawed. The optimum approach, adopted in this thesis, is to take account of existing research and models, but not to let them taint the mapping process.

Mapping entailed objectively recording morphological and sedimentological data using both conventional techniques and digital image analysis and integrating them holistically in an inversion model to reconstruct the glaciation. Satellite imagery (notably Band 5 of Winter Landsat TM data) provided both a synoptic view of the geology and detailed information on single landforms. Moreover, its digital format enabled on-screen digitising, easy measurement of landform dimensions, and direct comparison and integration with the digitised morphology and sediments maps produced from field mapping and stereoscopic aerial photographic interpretation. The transparency and inherent objectivity of the inversion model reduced the possibility of adopting a theory-laden approach and increases the interpretability of the model for future researchers.

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