A palaeo-glaciological reconstruction of the last Irish Ice Sheet.

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CONTAINS PULLOUTS

Abstract.

An inversion of the glacial geomorphological record provides an effective means to reconstruct former ice sheets at ice sheet-scale. The last Irish Ice Sheet has a long history of investigation, but its most basic properties are debated. Much previous research, based on an incremental development of knowledge through field observation of glacigenic landforms and deposits, has locally yielded high levels of detail but this detail is spatially fragmented across the former ice sheet bed. The evidence-base for ice sheet reconstruction is therefore patchy and incomplete, and its internal inconsistencies make an ice sheet reconstruction, via this approach, problematic.

This thesis explores new opportunities for palaeo-glaciological reconstruction offered by remotely sensed data. Systematic glacial landform mapping has been conducted throughout Ireland from a variety of satellite imagery and digital elevation models, and yields new Glacial Maps for Ireland comprising >39,000 landforms. These landform maps are the building blocks for a palaeo-glaciological reconstruction of the ice sheet. Adopting a 'flowset' approach, the full population of landform data is summarised as discrete cartographic units – flowsets – and their spatial, temporal and glaciodynamic information is extracted. The flowset record, integrated with the wealth of evidence and dating constraints in the literature, stimulates a reconstruction describing seven broad stages of ice sheet history. These provide a framework for the evolution of the last Irish Ice Sheet.

Key elements of the reconstruction confirm and extend an early advance from a British ice source, a maximum period likely dominated by large ice streams, fragmentation of the ice sheet into separate ice bodies during retreat, and final decay in western mountain groups. The pattern of ice sheet evolution is both asymmetric and asynchronous. A range of scales of ice sheet behaviour are observed, from first-order, fundamental changes in ice sheet geometry (centres of mass and ice flow structure) to more local-scale high-frequency fluctuations of ice flow patterns. This new model acts as a framework for continued investigation of the evolution of the Irish Ice Sheet, and the observed ice sheet behaviour demands further exploration of the sensitivities and role of ice sheets in the wider ice – climate system.

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SECTION A:

Introduction and Background

Colour relief shaded image of SRTM DEM. Image from NASA.

Chapter 1. Introduction

1.1 Ice sheets and the Earth system

Ice sheets are spectacular phenomena. The Earth's polar regions have drawn explorers and scientists to them for over 100 years, and their landscapes and wildlife continue to capture the imagination of the wider public. Continental-scale ice sheets represent a final frontier of exploration: vast, inaccessible and inhospitable wildernesses, which experience extremes of climate and can possess treacherous terrain. Present-day ice sheets remain some of the least mapped and, scientifically, some of the least understood parts of the world.

Ice sheets are more than simply frozen continents, but rather are flowing bodies, driven by their own weight under gravity. At their peripheries, ice interacts with the bounding medium – the bed, the atmosphere, the ocean – and as such ice sheets are an integral component of a complex and coupled Land-Ocean-Atmosphere system. In order that we understand this system as a whole, it is important that we understand the role and behaviour of each component. Our understanding of the mechanics of ice flow has developed massively in the past few decades but the sensitivities of ice sheets to forcing are still poorly understood and we are only now realising the potential for extremely dynamic and abrupt behaviour. Understanding of the processes of interaction between the ice sheet and its bounding Earth system components, and the potential for dynamic ice flow behaviour which may arise from these processes, remains limited and is a key uncertainty in efforts to make future climate system projections (IPCC, 2007).

A fundamental problem in understanding contemporary ice sheet dynamics is the slow evolution of an ice sheet. We can only observe a short snapshot of activity in a much longer cycle of evolution. However, continental-scale ice sheets have waxed and waned throughout the Quaternary period, particularly across the northern hemisphere mid-latitudes, leaving a record of their evolution in the landscape. Reconstruction of these former ice masses has fascinated geologists since the glacial theory was first advocated by Agassiz (1838, 1840), as an exercise in satisfying academic inquisitiveness, to address questions of large-scale landscape evolution, as a tool for mineral exploration, for land-use, construction and engineering purposes. However, of perhaps greatest value for Earth system science, Quaternary ice sheet reconstruction provides an opportunity to understand ice sheet behaviour through a full glacial cycle. We can begin to consider its responses to and effects on atmospheric circulation and climate patterns, ocean circulation, crustal depression and rebound, and sea level change. It allows ice sheet models, based on physical laws and a quantitative description of ice flow dynamics, to be refined and tested, and so addresses wider Earth system science objectives.

1.2 The significance of the Irish Ice Sheet

The motivation for a palaeo-glaciological reconstruction of the Irish Ice Sheet is twofold. Firstly, despite almost 150 years of investigation, several basic properties of the Irish Ice Sheet are still unknown or contested. A new paradigm of mobile and dynamic ice sheets requires us to either modify or discard earlier reconstructions of the ice sheet which draw on only a single ice sheet configuration, fixed in time, to explain the glacial record. We require a more comprehensive palaeo-glaciological model which yields the position of ice divides, ice sheet extent, ice flow patterns, dynamics, ice retreat patterns and, most importantly, documents and attempts to explain the changes in each of these elements through the ice sheet's evolution. Until this is achieved, the Irish Ice Sheet presents itself as an academically appealing, unresolved problem.

Importantly, the Irish Ice Sheet holds particular potential for addressing wider Earth system science objectives. Given its maritime location on the fringes of the North Atlantic, one would expect a sensitive relationship between the terrestrial ice mass, the ocean properties and climate forcing. Coupled with its small size and consequent ability to respond to forcing on short timescales, it is a logical assumption that the ice sheet may have displayed highly dynamic behaviour. A reconstruction of the evolution of the ice sheet, documenting such behaviour, would present a key test for ice sheet modellers, for whom capture of rapid behaviour in ice sheet models remains a challenge. If a model can successfully capture the dynamics revealed by the physical legacy of glaciation, this would enable a comprehensive exploration of the drivers of ice sheet dynamics and consequently advance our ability to model the wider Earth system.

1.3 Approaches to ice sheet reconstruction

Ultimately any ice sheet reconstruction must be both physically sound and account for the direct evidence of glaciation. Approaches to reconstruct former ice sheets begin either with the physical principles of how an ice sheet operates and work towards matching the evidence, or make a more direct interpretation of the observational record with checks to ensure the interpretation is glaciologically plausible.

Numerical approaches to the problem implement either ice physics or Earth physics (and coupling the two is an ongoing field of work). Ice sheet models typically calculate the evolution of ice thickness as a function of ice flow mechanics and mass balance. The model is forced by tuned climate parameters and constrained by upper and lower surface boundary conditions. The output is tested against geological evidence (e.g. Payne, 1999; Hubbard, 1999; Marshall *et al.*, 2000; Hagdorn, 2003). An alternative approach invokes Earth physics, and calculates the Earth's isostatic response to changing surface loading as the global distribution of water varies between ice sheet and ocean storage. Glacio-isostatic response is manifested as relative sea level (RSL) change. Predicted RSL curves are compared to the geological evidence of sea level change at spatially distributed sites around the margins of the palaeo-ice mass (e.g. Lambeck, 1993a,b; Peltier, 1994; Peltier *et al.*, 2002; Shennan *et al.*, 2002, 2006).

Observation of the geological legacy of glaciation has driven reconstructions of former ice masses for over 150 years (Agassiz, 1842; Geikie, 1894; Flint, 1943; Charlesworth, 1957; Denton and Hughes, 1981; Dyke and Prest, 1987; Boulton and Clark, 1990a,b; De Angelis, 2007). It is assumed that the character and distribution of glacial deposits and landforms can inform us of the nature of the ice sheet which led to their creation, i.e. we can 'invert' the geological and geomorphological record to yield palaeo-glaciological information. The solution of an 'inversion problem' requires certain knowledge and/or assumptions of the 'genetic problem', the processes responsible for deposit and landform genesis (Figure 1.1). Given such assumptions we can infer the geographic and glaciological properties of the ice sheet responsible for evidence observed in the landscape today. This logic has underpinned evidence-based ice sheet reconstruction since its inception as a science; an increasingly formalised framework for the inversion of the geomorphological record has been developed over recent years (Boulton and Clark, 1990a,b; Clark, 1997, 1999; Kleman and Borgström, 1996; Kleman *et al.*, 1997, 2006).

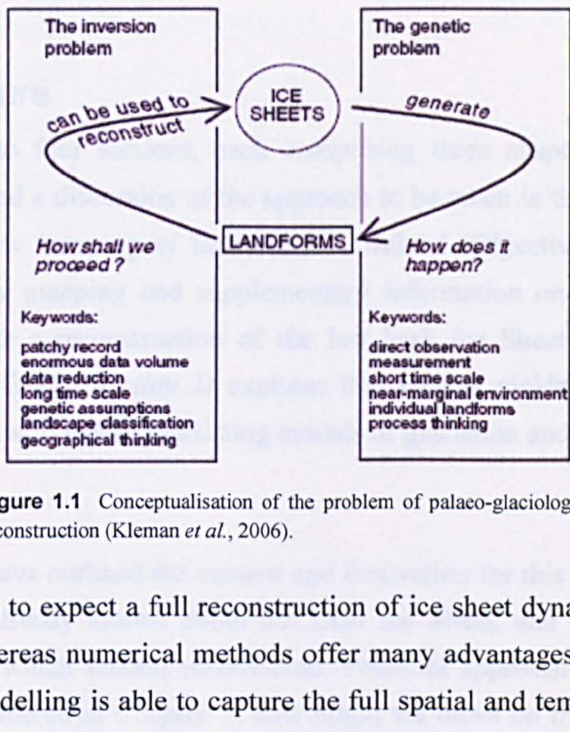


Figure 1.1 Conceptualisation of the problem of palaeo-glaciological reconstruction (Kleman *et al.*, 2006).

It is perhaps unrealistic to expect a full reconstruction of ice sheet dynamics based solely upon its physical legacy, whereas numerical methods offer many advantages for solving Quaternary ice sheet problems. Modelling is able to capture the full spatial and temporal domain of the ice sheet. Furthermore, the ice sheet configuration and dynamics inferred from a numerical model are, with some caveats, assured to be a glaciologically plausible reconstruction since the model is based upon physical principles and laws. Finally, numerical modelling presents a powerful tool to examine ice-ocean-atmosphere interactions and the forcing/response relationships between the different components of this system. For such an approach to fulfil its potential it is imperative that models are substantiated by the best available evidence. For a glaciologically sound reconstruction there must be a convergence of approach which ensures models can account for the evidence, and/or observational-based reconstructions are physically plausible.

Reconstruction of the British-Irish Ice Sheet via numerical methods is in its infancy, but demands a comprehensive reconstruction of the ice sheet from the direct geological and geomorphological evidence of its activity, to serve as a rigorous test of modelled ice sheets. This thesis seeks to address the unresolved problem of the Irish Ice Sheet with a geomorphological-based inversion approach to ice sheet reconstruction. It is hoped that such a reconstruction will serve as a framework for and a test for numerical modelling initiatives exploring the whole of the British-Irish Ice Sheet and its role in the wider Earth system.

1.4 Specific aims of the research

There are four specific aims of this research:

1. To systematically map the glacial geomorphology of Ireland.
2. To assimilate the relevant published evidence pertaining to the last Irish Ice Sheet, and ancillary information to assist a reconstruction, into a GIS database.
3. To produce, given the above, a palaeo-glaciological reconstruction of the ice sheet that best fits the evidence.
4. To explore potential drivers of ice sheet behaviour and configuration changes captured by the reconstruction.

1.5 Thesis structure

This thesis is split into four sections, each comprising three chapters. *Section A* contains introductory material and a discussion of the approach to be taken in this research; *Section B* is concerned with the new mapping of landforms in Ireland (Objective 1, above); *Section C* considers how the new mapping and supplementary information on glacial history may be integrated, and presents a reconstruction of the last Irish Ice Sheet based upon these data (Objectives 2 and 3); finally *Section D* explores the insights yielded by the reconstruction scenarios (Objective 4) with regard to existing models of glaciation and to the wider ice-climate system.

Section A. Above, I have outlined the context and motivation for this research. In *Chapter 2* I shall review what is already known about the Irish Ice Sheet, and discuss the outstanding questions and debates which remain unanswered. Potential approaches to tackling ice sheet reconstruction are considered in *Chapter 3*: how might we move on from some of the debates outlined in Chapter 2, and what can we learn from the approaches which have been undertaken in reconstructing other palaeo-ice sheets?

Section B. This section is concerned with the collection of new landform data, the primary data for ice sheet reconstruction. Remotely sensed data offer the geomorphological mapper an opportunity to conduct rapid, systematic and countrywide landform mapping, and *Chapter 4* outlines the methods employed to achieve this task. *Chapters 5 and 6* present the results of this mapping programme as two new glacial maps, a subglacial bedform map (Chapter 5), and a moraine and meltwater landform map (Chapter 6). Both chapters comment on the physical character of the landforms mapped, their distribution, spatial relationships, and I consider how the newly mapped features relate to the Irish literature describing the landform record: what is new information, what is replicated, what is challenged?

Section C. Three stages of interpretation of the glacial record are presented and discussed in Chapters 7-9. Each chapter outlines the logic and assumptions for each interpretative stage. *Chapter 7* considers the spatial significance of landforms, presents bedform 'flowsets', and compiles all necessary information which may assist the reconstruction. In *Chapter 8* the glaciological and chronological interpretation of that information is discussed. Finally, *Chapter 9* presents potential scenarios of the Irish Ice Sheet's history, reconstructed from the mapped and compiled data.

Section D. Finally, the implications of the reconstructed scenarios are explored. *Chapter 10* discusses the ice sheet scenarios, and considers their plausibility and consistency with existing literature models. In *Chapter 11*, a range of insights and ideas which are stimulated by the reconstruction are explored. The potential drivers of the behaviour and evolution of the reconstructed ice sheet are considered. *Chapter 12* concludes the thesis and summarises the major findings of this research.

Chapter 2. Status of knowledge of the last Irish Ice Sheet: a critical review

2.1 Introduction

Before embarking on a new reconstruction of the Irish Ice Sheet it is necessary to consider and evaluate the current status of knowledge of the subject. I have suggested in Section 1.2 that existing conceptual models of the ice sheet must be modified or discarded in light of a new paradigm of mobile and dynamic ice sheets. This chapter reviews the development of and current understanding of the palaeo-geography and palaeo-glaciology of the last Irish Ice Sheet, the ice sheet models which underpin the literature, the key debates, and recent developments in thinking. This should serve to support the above statement.

A palaeo-glaciological reconstruction should ideally provide us with knowledge of the positions of main ice divides, the lateral and vertical extent of the ice sheet, ice flow patterns and the dynamic role of ice streams, the pattern of ice margin retreat, and a chronology for the attainment of and changes in each of these elements. The wealth of evidence that has been gathered to date goes some way to informing us of these ice sheet characteristics. However, interpretation of the Irish evidence of glaciation seems to be invariably associated with debate and controversy. This review asks why agreement has been so difficult to reach and seeks to be as critical as possible in an attempt to reconcile the disparate views of the Irish Ice Sheet. Rather than attempting an exhaustive review of all and every individual study, salient palaeo-glaciological themes are drawn out and the key controversies, unknowns and wider paradigm debates are discussed. In this chapter, and throughout the thesis, the reader is referred to Map 1 for the location of key places and topographic features referred to in the text.

2.2 Evidence-based palaeo-glaciology

The Irish landscape is rich with evidence of former glaciation, and has been extensively studied for well over 100 years (e.g. from Close, 1867; to Ballantyne *et al.*, 2008). The earliest observational data were collected at a time when theories of a past glaciation were still in development and an understanding of the relative roles of different agents of landscape modification was vague. Close (1867) was among the first to comment on the ubiquity of rock striations and 'elongate drift ridges' (which he termed 'drumlins', meaning a ridge-shaped hill) at a countrywide scale. Drawing on his own observations, together with those of Geological Survey officers, he summarised the then known distribution of features and attempted to address their origin. He asserted that they must have a common origin due to their parallel nature over large distances and, having considered four possible scenarios, Close concluded that glacier ice was the most likely candidate to explain the variety of erosional and constructional landforms. However, on the basis of differences in form and composition, he suggested Ireland's extensive esker networks and associated stratified deposits were water-lain under a sea which rose above present levels following the hypothesised period of countrywide ice cover.

Close's paper moved ideas on from localised feature mapping to consideration of their greater significance with regard to ice sheet geography and behaviour, and with regard to the environments and processes effecting landform genesis. Whilst many process theories of the time have been superseded, the individual feature mapping still provides some of the most detailed knowledge of landform or feature distribution (e.g. Kinahan and Close's (1872) drumlin and striae map for parts of Counties Galway and Mayo). Many elements of the glacial record in Ireland have since been reported, although consensus of interpretation has been difficult to achieve. Not only do scientific paradigms inevitably shift through time, but debates of genetic process and palaeo-glaciological meaning have arisen between separate contemporary schools of thought. As a result, there is presently little consensus regarding many characteristics of the last (and previous) ice sheet(s) to engulf Ireland (McCabe, 1987; Knight *et al.*, 2004).

2.2.1 Traditional ice sheet models

Since the 1860s, a model of the last ice sheet has always underpinned any interpretation of the Irish glacial record. In drawing together existing knowledge of glacial landform distribution, Close (1867; Figure 2.1a) was the first to invoke a countrywide ice sheet nourished by local (as opposed to polar) snowfall and glacier expansion, and described in detail a model of how he interpreted the ice sheet to have been configured. From the distribution and directions of striations, drumlins and drift carriage Close envisaged a single ice mass, but one which comprised several sectors, sourced from the western mountains, which connected and interacted with each other.

Shortly following Close's seminal work, Hull (1878) undertook a similar task, asserting his interpretation closely followed the work of Close and the Geological Survey. However, his schematic conceptual model of the ice sheet contains striking differences with that which Close described (Figure 2.1b). In Hull's model ice emanated from a single, central, lowland axis, the 'Great Central Snowfield'. The main mountain masses nourished independent ice caps which served only to deflect ice stemming from the lowland axis, rather than contributing the main ice flow paths as under Close's model. It is Hull's ice sheet configuration which has dominated subsequent literature and it has formed the framework for research throughout much of the 20th century (e.g. Wright, 1914; Synge and Stephens, 1960; Synge, 1969a; Stephens *et al.*, 1975; Mitchell, 1976; McCabe, 1985; Knight *et al.*, 2004). With little exception (Charlesworth, 1924, 1928b, 1939) the 'Great Central Snowfield' model was largely unquestioned until Warren proposed a large-scale overhaul of 'accepted' ideas of Irish Quaternary glaciation (1985, 1991a, 1992). Debate arose once more between two contrasting models of the last Irish Ice Sheet (Figures 2.1c-d).

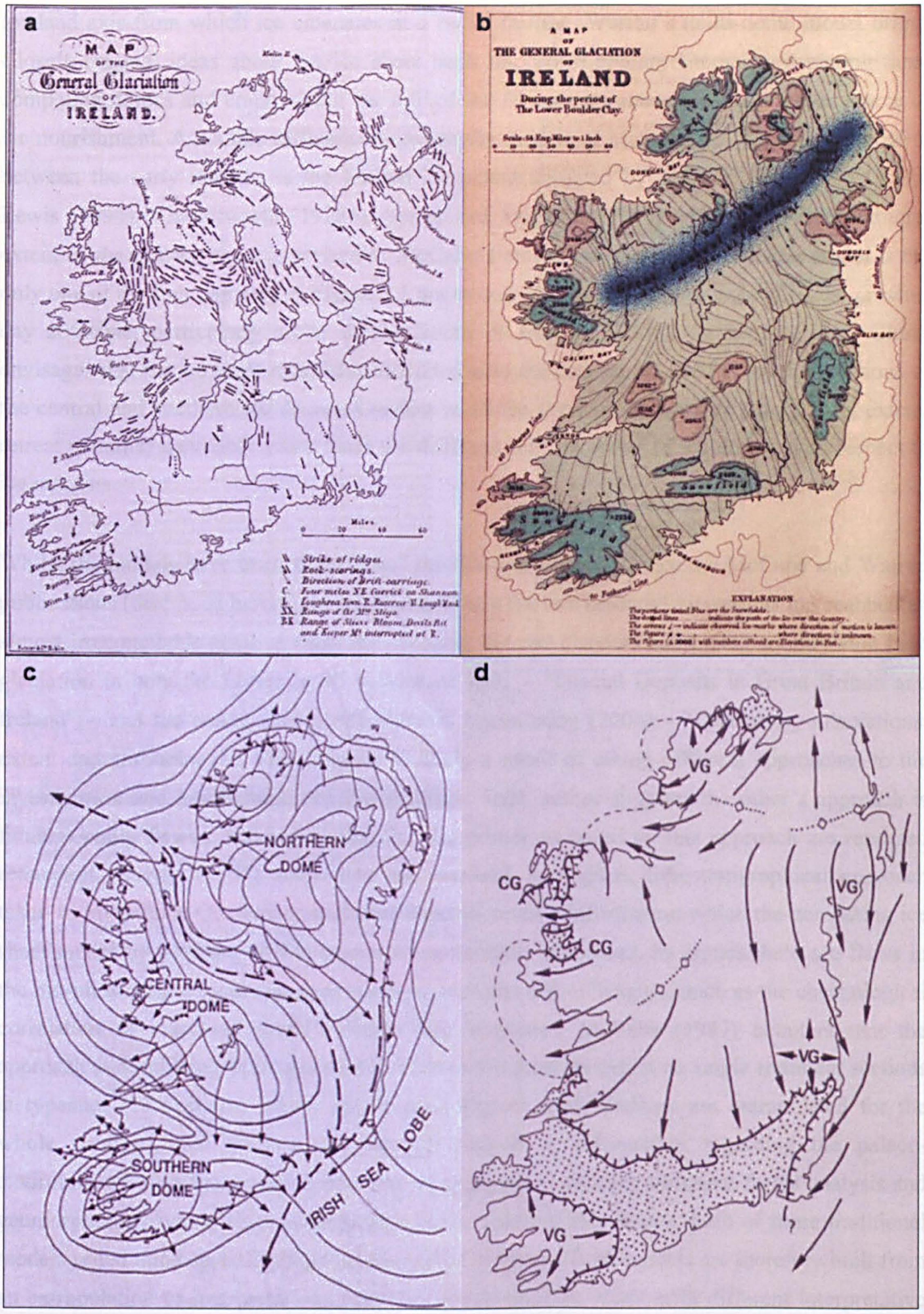


Figure 2.1 Models of the last Irish Ice Sheet have underpinned the literature for 140 years. The model of Hull (1878) **(b)** apparently followed that of Close (1867) **(a)** but the descriptions revealed striking differences. Over a century later, the competing models of Warren and Ashley (1994) **(c)** and McCabe (1985) **(d)** echo the former debate.

The similarities and contrasts between the conceptual models of Warren (1992; Warren and Ashley, 1994) and McCabe (1985) echo the comparison between the models of Close (1867) and Hull (1878) over a century previously. The model McCabe described in 1985 exemplifies the long-standing framework that has followed Hull's depiction of the ice sheet, with a central lowland axis from which ice emanates in a radial fashion. Warren's multi-dome model brings Close's original ideas about the ice sheet back into contemporary literature, depicting three competing domes and emphasising the role of the Connemara mountains as a major source of ice nourishment. A notable difference between the models of McCabe and Warren, not present between the early models, is the limited ice extent depicted by McCabe. Following Carvill Lewis (1894), Charlesworth (1928b), Synge and Stephens (1960) and others, the maximum extent of the last ice sheet is revised in McCabe's model (see Section 2.2.3). His model is the only one of the four depicted in Figure 2.1 not to describe ice reaching or exceeding the present-day coastline, particularly so in the far south of Ireland. Warren, in keeping with Close, envisages that the ice sheet must have extended onto the continental shelf given the positions of the central and southern ice domes. Conflict in all ice sheet properties (ice flow routes, extent, retreat patterns) inevitably arises from the different configurations of ice domes with respect to ice margins.

Whilst the models have been adapted and modified in the years since the McCabe and Warren publications (discussed herein) the conflict between the two essential viewpoints has reached an almost irreconcilable position (note the necessity for two chapters addressing countrywide Irish glaciation in both the Ehlers *et al.* volume of 1991 – "Glacial Deposits in Great Britain and Ireland" – and the recent Ehlers and Gibbard compilation (2004) – "Quaternary Glaciations: extent and chronology"). This impasse is likely a result of taking different approaches to the investigation and interpretation of the evidence. Each author suggests the other's approach is fundamentally flawed, and argues that the interpretations based on that approach are rendered redundant. Warren (1985) states that the standard, geological, lithostratigraphical approach taken to investigate Quaternary sediment deposits reveals information which the competing ice sheet model by McCabe (1985) cannot accommodate. Moreover, he argues there are flaws in the morphostratigraphical approach taken by McCabe and colleagues, such as the chronological correlation of extensive drumlin fields with moraines. McCabe (1987) counters that the approach underpinning Warren's model relies to too great an extent on single sediment sections at typesites (12 sections, whose palaeo-glaciological interpretations are extrapolated for the whole country), and doesn't use the full degree of information regarding the palaeo-environments of sediment deposition that an approach combining sediment facies analysis and geomorphology would reveal. Regardless of the value of this debate, both of these traditional models relied upon spatially fragmented lines of evidence. Both models are therefore built from an extrapolation of interpretations from one site to another, albeit with different interpretative schemes.

Conflicts between these models mean that many elements of the ice sheet remain contested or unknown, in particular the position of ice sources and all but the major flow routes. Continued observation, documentation and interpretation of the glacial record *should* provide critical tests of opposing models. However, the degree to which the deep entrenchment of these models in the Irish literature has impacted upon the objectivity of interpretation is unclear. For example, patterns of ice flow should be invaluable as objective lines of evidence pointing us to sources of ice dispersal. However, given such strongly argued and persistent frameworks for ice dome or divide positions, interpretation of new flow routing evidence may be guided by how the configuration of ice domes is conceptualised. This can make it hard to separate observation of evidence from theory-laden interpretation. Evidence for *elements* of both models is compelling, which accounts for the longevity of both in the literature and the ongoing conflicts regarding the basic properties of the ice sheet.

The following sections will consider how the glacial record underpins conceptual models of the ice sheet, discussing key palaeo-glaciological properties in turn: ice sources, extent, flow and retreat patterns and a chronology for ice sheet behaviour. Within this framework for discussion, the key debates will be outlined: the significance of the Southern Ireland End Moraine (SIEM), the role of 'Scottish ice', the Drumlin Readvance, the glaciomarine model for deglaciation, and participation in North Atlantic Heinrich Events.

2.2.2 Ice sources

Traditional models have established a (still unresolved) debate in the Irish glacial literature as to the location of centres of ice nourishment: a single ice axis lying across the central lowlands from Co. Galway to Lough Neagh (Hull, 1878; McCabe, 1985), versus a multi-domed ice sheet nourished from mountain sources, predominantly the western coastal massifs (Close, 1867; Warren, 1992). The glacial record has provided support for elements of both of these models, hence the conflict continues.

2.2.2.1 Central lowlands axis

The single axis of ice outflow is a model reinforced by many workers since the late 19th century (Wright, 1914; Synge and Stephens, 1960; Stephens *et al.*, 1975; McCabe, 1985; Knight *et al.*, 2004; see Figure 2.1b,d). It comprises two elements: a main axis lying across the central lowlands, with minor northern 'branch' axes positioned between Lough Neagh and Omagh Basin.

This model finds support from the disposition of major ice flow paths and erratic transport patterns, recorded since the early work of Close (1867) and Hull (1878), which appear to diverge from the hypothesised axis positions. In the central lowlands basin, two striking and well-mapped patterns of parallel glacial lineations (drumlins etc., see Chapter 3) diverge from an apparent axis, south-eastwards across Counties Monaghan, Cavan, Longford, Meath, Westmeath and Louth (Close, 1867; Hull, 1878; Synge, 1970; McCabe, 1972; Knight *et al.*, 1999; McCabe *et al.*, 1999; Meehan, 1999; Clark and Meehan, 2001), and north-westwards from the Shannon river in Co. Roscommon over/through the Ox Mountains to Killala Bay, Co. Mayo (Close, 1867; Hull, 1878; Synge, 1970; Coxon and Browne, 1991; Hoare, 1991a). The line of their divergence has been interpreted as the position of the main ice divide. A northern branch axis (Synge and Stephens, 1960; Colhoun, 1970, 1971; Stephens *et al.*, 1975; Knight and

McCabe, 1997b; Knight, 2003b) would account for the carriage and dispersal of sediments and genesis of ice-directional landforms in NNE to NNW directions over Cos. Donegal, Londonderry and Antrim. The axis is positioned south of the Sperrin Mountains, across south-central Tyrone, on the basis of till clast provenance (Colhoun, 1970, 1971; Colhoun *et al.*, 1972; McCabe *et al.*, 1978) and the breaching of cols and saddles of the Sperrins range which suggests the mountains did not nourish the main ice sheet but rather were overwhelmed by ice flowing northwards over them (Colhoun, 1970, 1971; Colhoun *et al.*, 1972).

The positioning of an ice divide on the basis of major ice flow indicators is a logical interpretation. However, both axes within this model remain poorly constrained and their relationship ill-defined. Key proponents of the lowlands axis model have drawn their divide in varying positions though they are argued to be based upon the same line of evidence (Hull, 1878; Kilroe, 1888; McCabe, 1985; Figure 2.2). In the north, the configuration and extent of a west-east axis beyond 'south-central Tyrone' is poorly known, particularly with regard to the role of Donegal ice: a primary ice centre (Charlesworth, 1924), part of the axis (Colhoun, 1970) or an independent ice cap with little influence on the main ice sheet (McCabe *et al.*, 1999)? There is a stronger body of thought that Lough Neagh represents the eastern extent of both the main and the northern axis, accounting for divergent flow patterns from the region of the lake basin (e.g. Hill and Prior, 1968; Stephens *et al.*, 1975; Dardis *et al.*, 1984; Knight *et al.*, 2004). Charlesworth (1924) suggests that since the field evidence for the location of these proposed lowlands axes is scant, the model cannot be supported; this evidence deficit has not been well-addressed in the years since Charlesworth's observation.

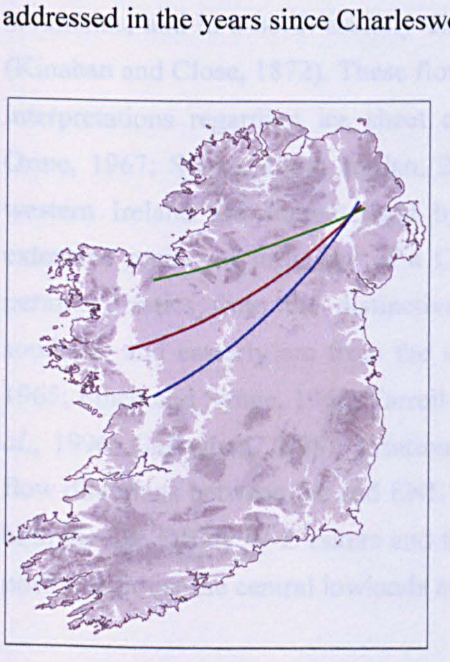


Figure 2.2 Curiously, different proponents of the central axis model locate their main ice divide in different positions across Ireland, supposedly based upon the same lines of evidence: red – Hull (1878); green – Kilroe (1888); blue – McCabe (1985). Charlesworth (1924) argued that this inconsistency undermines the model.

2.2.2.2 Mountain ice centres

Under palaeo-ice sheets such as the British and Fennoscandian, mountains occupy the central spine of the ice sheet, and thus it is logical that ice emanated radially from upland regions. Ireland's broad morphology is that of a basin, with mountains located around the rim. Over many years workers in Ireland have struggled to reconcile ice growth from points of nucleation in the mountains, with their peripheral location. The role of different mountain masses envisaged in the literature ranges from blocking and funnelling the offshore escape of lowland ice (e.g. Synge, 1963, 1968), to supporting independent ice caps (e.g. Hull, 1878; McCabe, 1985), to being integral to the nourishment of the main ice sheet (e.g. Charlesworth, 1924, 1939, 1953).

Charlesworth (1924, 1928a,b, 1929, 1939, 1953) was the main opponent of a single axis ice sheet until Warren (1992) reprised Close's original (1867) concepts. Charlesworth had trouble reconciling a central ice dispersion area with a lowland region, proposing instead that ice must emanate from mountain groups which are more conducive to ice accumulation and glacier inception. Charlesworth advocated main ice sources over the mountains of Co. Donegal and Connemara, based on the distribution and orientation of striations, and his detailed mapping of moraines and morainic sediments indicates successive ice retreat positions towards these mountain masses. However, many of Charlesworth's moraines, particularly in Co. Donegal, have since been re-interpreted as subglacial bedforms (Knight and McCabe, 1997b; Knight, 2003b) casting some doubt on his deglacial pattern.

Many lines of argument do, however, support a substantial ice centre situated over the Connemara mountains. In the immediate surrounds, drumlin and striae distributions indicate divergent ice flow paths, towards the west on the coastal periphery of the Connemara mountains, and in a north-easterly direction from Lough Mask towards Castlebar and Foxford (Kinahan and Close, 1872). These flow patterns have been replicated by many authors, although interpretations regarding ice sheet configuration vary (Hallissy, 1914; Charlesworth, 1929; Orme, 1967; Synge, 1968; Jordan, 2002). Ice flow indicators in the wider region of central-western Ireland are characterised by a strong west-to-east component, suggesting a more extensive region of influence of a Connemara ice source than a central lowland axis would permit. Erratics from the distinctive Galway granite outcrops are widely distributed in a southerly and easterly arc from the source area (Figure 2.3), whilst in Co. Clare (Farrington, 1965; Finch and Synge, 1966; Farrell *et al.*, 2005) and in Cos. Galway and Offaly (Gallagher *et al.*, 1996; Gallagher, 1998), striations, sediment fabrics and clast provenance analysis reveal flow directions between SE and ENE sourced from Connemara. Furthermore, the disposition of both the Co. Offaly W-E eskers and the Co. Mayo SW-NE eskers is at odds with an ice source positioned over the central lowlands as suggested under the single axis model.

It could be argued that an ice source over Connemara merely represents a southern 'branch' of the central ice axis, as a Tyrone source represents a northern 'branch'. However, at two opposite extremes of viewpoint, neither Warren (1992) nor Synge (1968, 1969) concur with this model. Warren's reprisal (1992; Warren and Ashley, 1994) of Close's ice sheet model (Figure 2.1c) goes further than simply suggesting Connemara was a primary ice centre, but rather depicts an extensive Connemara ice divide stretching from the Slieve Aughtys, across Connemara, Clew

Bay and into the Nephin Beg range in North Mayo. *Under this model, Warren describes onshore* ice movement through Clew Bay, an idea which has received some limited support from Jordan (2002). Warren's configuration of northern and central ice domes results in a saddle positioned perpendicular to where the central axis would lie, and through which ice is evacuated in major streams; this configuration of ice over Connemara and a central lowland axis are therefore mutually exclusive.

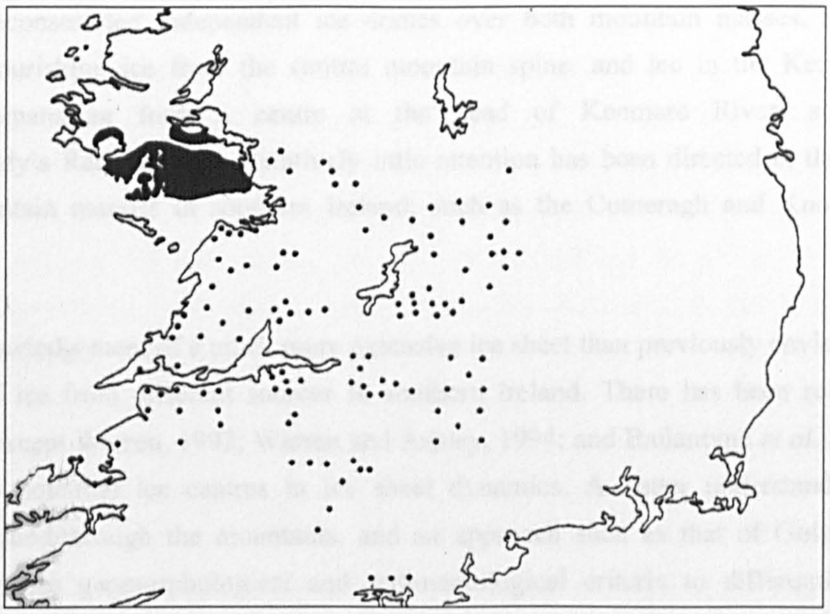


Figure 2.3 The distribution of Galway granite (modified from Warren, 1991a) is used by several workers as support for a more substantial Connemara ice source (Warren, 1992; Warren and Ashley, 1994; Gallagher *et al.*, 1996; Gallagher, 1998; Hegarty, 2002a) than encapsulated in the central axis model.

On the other hand, Synge reconstructs almost no ice over Connemara and west Mayo. The region may have supported some local ice, but is argued to have presented a barrier to a lowlands ice sheet which could only penetrate beyond via the coastal lowland bays. There remains little support for an ice sheet of such limited extent on the west coast during the last glaciation, and there is a general acceptance that Connemara supplied ice to the Irish Ice Sheet (Farrell *et al.*, 2005). However, whether the configuration of a western ice centre was such that flow was directed onshore through Clew Bay, as advocated by Warren, is still contested. The role of a Connemara ice source in controlling wider ice sheet dynamics is also unresolved.

2.2.2.3 Southern ice masses

Following Carvill Lewis (1894) and Charlesworth (1928b) the regions of Leinster and Munster were for many years considered to be beyond the limits of the main ice sheet (Section 2.2.3, below). Ice centres in these regions were thus discussed as local ice caps, spatially and temporally separate from the lowlands ice sheet. In Kerry/Cork and the Wicklows, early workers interpreted the glacial record in terms of a phasing of 'general' and 'local' glaciation related to different climatic periods (e.g. Charlesworth, 1928b; Farrington, 1934, 1947, 1954). However, it is now recognised (e.g. McCabe, 1987; Ballantyne *et al.*, 2006) that this 'phasing' likely reflects fluctuations in the boundaries between local and external ice rather than distinct glacial advances followed by retreats.

The degree of glaciation over the southern hills is, however, still unresolved. Were southern mountain masses completely subsumed by ice from the lowlands, did they nourish ice caps which were driven by the main ice sheet, or did these centres actively *source* the main ice sheet? Recent work in both the Wicklows (Ballantyne *et al.*, 2006) and in the south-west (Rae *et al.*, 2004) has reconstructed independent ice domes over both mountain masses, the Wicklow mountains nourishing ice from the central mountain spine, and ice in the Kerry and Cork mountains emanating from a centre at the head of Kenmare River, south of the MacGillycuddy's Reeks massif. *Relatively little attention has been directed at the role of the* smaller mountain massifs in southern Ireland, such as the Comeragh and Knockmealdown mountains.

Recent acknowledgement of a much more extensive ice sheet than previously envisaged implies contiguity of ice from different sources in southern Ireland. There has been relatively little suggestion (except Warren, 1992; Warren and Ashley, 1994; and Ballantyne *et al.*, 2006) of the role of such potential ice centres in ice sheet dynamics. A better understanding of flow dynamics around/through the mountains, and an approach such as that of Golledge (2007), which establishes geomorphological and sedimentological criteria to differentiate between different styles of glaciation in mountain environments, could usefully inform this debate.

2.2.2.4 Ice sources: summary

Two opposing models of glaciation in Ireland underpin ideas of ice centre locations. A single axis model has dominated the literature and received some support from field investigation of the glacial record, particularly in the north of Ireland. However, the model cannot incorporate evidence which suggests a substantial ice mass over the Connemara mountains. Neither model considers satisfactorily the role of potential ice sources in the southern mountains of Ireland; this partly relates to a long-standing debate over ice sheet extent (Section 2.2.3, below). Recent recognition of a more extensive ice sheet, perhaps laterally and vertically, demands a re-examination of the role of southern ice masses in nourishing the ice sheet.

Much discussion of ice sources of the last Irish Ice Sheet has taken place under a paradigm of slowly evolving ice sheets which reached and maintained steady state configurations. Current recognition of more dynamic ice sheets driven by abrupt atmospheric, oceanic and internal glaciological process feedbacks, suggests that ice divides may migrate throughout the evolution of an ice sheet. Consequently, the traditionally conceived ice centres should be considered from a new perspective. Several identified centres may not have operated concurrently, and the position of a single ice divide may have fluctuated throughout time. Local- to regional-scale migrations in Irish ice centre locations have recently been identified (e.g. Knight, 2003b; Clark and Meehan, 2001) but using ice sheet-wide evidence we have yet to identify the evolving positions of ice sources. Furthermore, we should ultimately strive not only to identify regions of ice nourishment and their migration, but also to determine the causes underlying such ice divide movements.

2.2.3 Ice extent

2.2.3.1 Spatial extent: the onshore record

Early conceptual models of the Irish Ice Sheet depicted ice extending off the present-day shores of Ireland (Close, 1867; Hull, 1878). Carvill Lewis (1894) was the first to suggest a more limited glaciation. He identified features in central-southern Ireland which he believed represented the maximum extent of an ice sheet, and drew a glacial limit across the country from the Shannon estuary on the west coast to south of Dublin Bay in the east, circumventing the Wicklow mountains. In 1928, Charlesworth described his own observations of this limit, documenting in detail the path of the apparent end moraine and the retreat of ice from this position. Charlesworth's paper proved influential and his Southern Irish End Moraine (SIEM) became the standard view of the maximum southerly extent of the last Irish Ice Sheet (Farrington, 1954; Synge and Stephens, 1960; Stephens *et al.*, 1975; Hoare, 1991; Mitchell and Ryan, 1998). The SIEM model has been used in most, if not all global summaries of Quaternary ice sheet limits (e.g. Denton and Hughes, 1981; Ehlers and Gibbard, 2004).

Beyond the limits of the SIEM, glacial 'drift' was attributed to a prior, more extensive ice sheet (e.g. Farrington, 1947, 1954). The subdued surface morphology and weathered sediments across southern Ireland were interpreted as an 'Older Drift', distinct from the fresh appearance of the 'Younger Drift' north of the SIEM (e.g. Wright, 1914; Synge and Stephens, 1960). Similar differences in drift characteristics and landscape appearance were used to define limits of the more recent glaciation elsewhere: the Erris and Killadoon drifts in Co. Mayo (Synge, 1968, 1969b), the weathered and 'fresh drift' in Co. Donegal (Stephens and Synge, 1965). A counterpart of the interpretation of drift boundaries as glacial limits was the view that an absence of drift recorded an absence of glaciation. Under such a paradigm, entirely unglaciated enclaves in southern Ireland, Donegal and Connemara were identified (Farrington, 1947; Synge, 1968, 1969). Based on such glacial limits an extensive penultimate ice sheet (during the Munsterian period), followed by a more limited last glaciation (the Midlandian) became an established model of Irish glacial history (Synge and Stephens, 1960; Synge, 1970; Stephens *et al.*, 1975; Bowen *et al.*, 1986).

Under this model of a limited last Irish Ice Sheet, independent ice masses were proposed in southern mountain ranges. These ice bodies were generally confined within the mountains although in the south-west a more substantial ice mass was envisaged, extending from the south Kerry mountains to the Kilcummin and Killumney end moraines (e.g. Farrington, 1954; see Warren, 1991b). Farrington (1954) suggested the Killumney limit could be correlated with the SIEM on a morphological basis and thus envisaged a main ice sheet terminating at the SIEM, contemporaneous with a smaller ice cap over the south-west mountains.

The interpretation of the SIEM and the correlated moraines and drift limits was largely unquestioned until the late 1970s-1980s; these limits have appeared in numerous revisions to Synge and Stephens' (1960) schematic 'glacial map' (Synge, 1970, 1979; McCabe, 1985; Coxon and Browne, 1991; Knight *et al.*, 2004). Challenges arose from Charlesworth (1953, 1973) regarding the correlation between drift presence/absence and ice limits; Sissons (1964) briefly queried the division of evidence into 2 separate glacial periods; and Colhoun (1970) argued for the extension of ice onto the continental shelf in the north of Ireland, beyond the Lough Foyle – Bloody *Foreland limit of Stephens and Synge (1965). However, in proposing an* entirely alternative model of Irish glaciation, Warren argued strongly against the established ice limits (Warren, 1985, 1991a,b, 1992). In these and in subsequent papers by a range of authors, a more extensive last Irish Ice Sheet is proposed, supported on two fronts: arguments against the existence of a continuous Southern Irish end moraine and arguments supporting the extension of inland ice over the south coast.

Arguments against the SIEM. In parts, there is consensus on the presence of morainic sediments or landforms, for example the Ballylanders section of the proposed SIEM (Finch and Ryan, 1966; Synge, 1977; Warren, 1991a). However, in Cos. Laois and Kilkenny, through which the SIEM supposedly runs, Kilfeather (2004) and Hegarty (2002a, 2004) respectively have systematically tested the basis for the moraine and find little support for it. They find no morphological expression of a major moraine. Lodgement tills are described from both north and south of the proposed line, with no marked differences in sedimentological characteristics which would suggest they belong to a different glacial period, or that the southern tills are any more 'mature' than those further north. Jordan (2002) likewise suggests the 'Older' Erris till described by Synge (1968) in north-west Mayo does not display any characteristics which suggest an ice limit exists in this region; rather, tills are overlain by outwash (glaciofluvial) sediments such that the surface morphology appears relatively subdued. This latter point likely explains the reason for the observed differences in landscape freshness.

Warren (1991a,b) suggests that smaller moraines positioned across the country are likely diachronous features, erroneously grouped together to describe a synchronously formed ice limit. He also notes that it is yet to be shown that these moraines, regardless of their continuity, mark a maximum ice extent; they may merely represent periods of ice standstill during retreat rather than the maximum ice limit. It is increasingly recognised that where evidence for moraines exists, they likely represent a halt in deglaciation, rather than a maximum extent end moraine, and that the maximum limit of the last Irish Ice Sheet was located offshore (McCabe, 1987, 1998; McCabe and Ó Cofaigh, 1996; Bowen *et al.*, 2002; Farrell *et al.*, 2005).

Offshore passage of ice. Along much of the south coast of Ireland is a raised rock platform with an overlying sediment sequence of peats, sands and diamictons. Each element of this succession has been variably interpreted and the controversies regarding the stratigraphy underpin several wider conflicts regarding Irish glacial history. The marine platform can be interpreted as either a product of high interglacial sea levels (Warren, 1985, 1991a,b), or high *relative* sea level during late Midlandian deglaciation, arising from isostatic depression of the coast (McCabe, 1987; McCabe and Ó Cofaigh, 1996). If the former stance is taken, as is the case for similar sections elsewhere in the British Isles (Sissons, 1964), the tills lying near the top of the sequence must have been deposited during the last glaciation. In contrast, McCabe and Ó Cofaigh (1996) invoke a subaqueous (likely glaciomarine) depositional environment for sediments in south coast sections, laid down under high relative sea levels immediately following ice retreat onshore from the continental shelf. Under either of these scenarios coastal ice cover during the last glacial is invoked; this interpretation is supported by the emerging chronological constraints upon the south coast stratigraphy (Heijnis *et al.*, 1993; Gallagher and Thorp, 1997; Bowen *et al.*, 2002; Ó Cofaigh and Evans, 2007).

2.2.3.2 Spatial extent: the offshore record

Whilst the chronological framework is still debated and 'traditional' (SIEM) limits are often replicated (see Knight *et al.*, 2004; Knight, 2006a,b), continental shelf glaciation around the entire Irish coast during the Midlandian is generally advocated (e.g. McCabe, 1998; Knutz *et al.*, 2001; Bowen *et al.*, 2002; Sejrup *et al.*, 2005; Hiemstra *et al.*, 2006; Ó Cofaigh and Evans, 2007; Ballantyne *et al.*, 2007, 2008). However, the question of a maximum limit still remains: how far offshore did ice extend? A combination of approaches including offshore coring, seismic stratigraphy and imaging of seabed morphology is providing evidence in support of ice extent into the present-day Celtic Sea, towards the Porcupine Bank, and across the Malin and Hebrides shelves to the Rockall Trough margin west and north of Ireland (Sejrup *et al.*, 2005).

Emerging evidence suggests that not only was the Celtic Sea glaciated, but potentially experienced multiple phases of ice cover from different sources of the British-Irish Ice Sheet. The controversial south coast stratigraphy has recently been reinterpreted, with an absolute chronology, by Ó Cofaigh and Evans (2007) who conceptualise first the *onshore* movement of ice from the Irish and Celtic Seas at ~20 ^{14}C ka (~23 cal ka), followed by an *offshore* advance of inland ice into the Celtic Sea (Figure 2.4). On the northern Scilly Isles, a moraine limit and subglacially deposited material attest to a similar event and timing, documenting a short-lived advance of Irish Sea ice close to the LGM (Scourse, 1991; Scourse and Furze, 2001; Hiemstra *et al.*, 2006). Furthermore, cores on the continental slopes beyond the Celtic Sea identify ice rafted material which can be attributed to a Celtic shelf origin (Hall and McCave, 1998; Scourse *et al.*, 2000; Peck *et al.*, 2006) suggesting Celtic Sea ice cover must be grounded. Scourse and colleagues (1991, 2000; Scourse and Furze, 2001) propose the grounding line (and thus maximum extent of grounded ice) lies at approximately -127 to -145m depth, where there is a sediment transition from subglacial tills to laminated (glaciomarine) clays.

Off the north and west coasts of Ireland, where coastal fringes were once thought to be ice free during the last glaciation (e.g. Synge, 1968, 1969) evidence is now pointing to continental shelf glaciation. West of Cos. Galway, Mayo and Donegal a sequence of moraines was identified on shallow seismic profiles (Figure 2.5) by Haflidason *et al.* (1997), reported by Sejrup *et al.* (2005), whilst iceberg ploughmarks along the outer shelf and upper slope north from Clew Bay indicate calving margins were likely positioned in these areas (Belderson *et al.*, 1973). Further north, on the Hebrides and Shetland shelves, there is emerging evidence of ice stream activity feeding glacial trough mouth fans, overlain by the moraine record of ice sheet retreat (Stoker and Bradwell, 2005; Stoker *et al.*, 2006; Bradwell *et al.*, 2007).

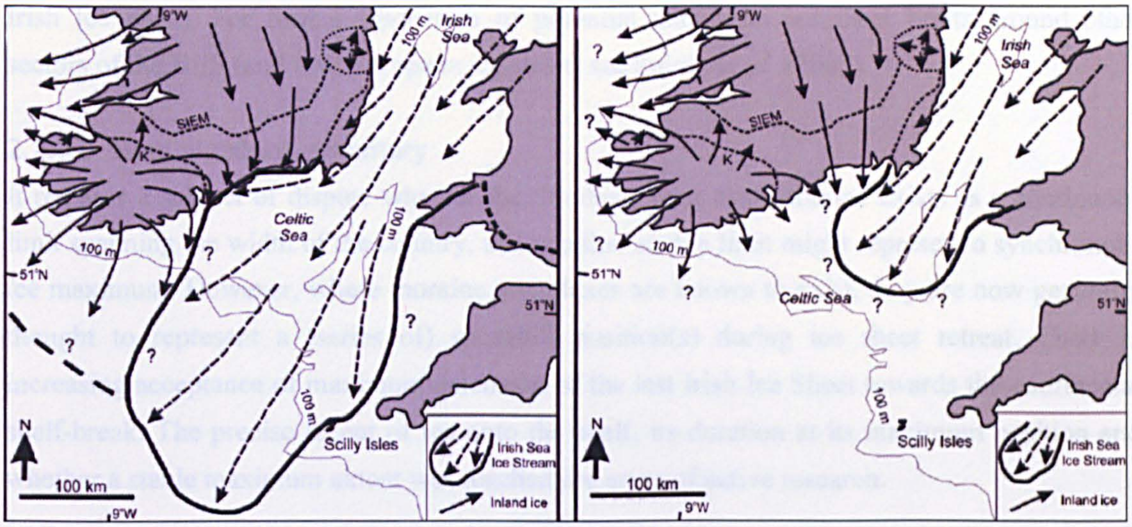


Figure 2.4 Model for Celtic Shelf glaciation proposed by Ó Cofaigh and Evans (2007), in which the Celtic Sea undergoes extensive glaciation during the maximum period of the BIIS, followed by a stage of Irish Ice Sheet advance into the Celtic Sea once earlier ice withdraws towards the Irish Sea Basin. This clearly exceeds the position of the SIEM and Killumney moraines. The maximum stage is proposed to occur at a maximum age of ~20 ^{14}C ka; the timing of the following stage is relative only.

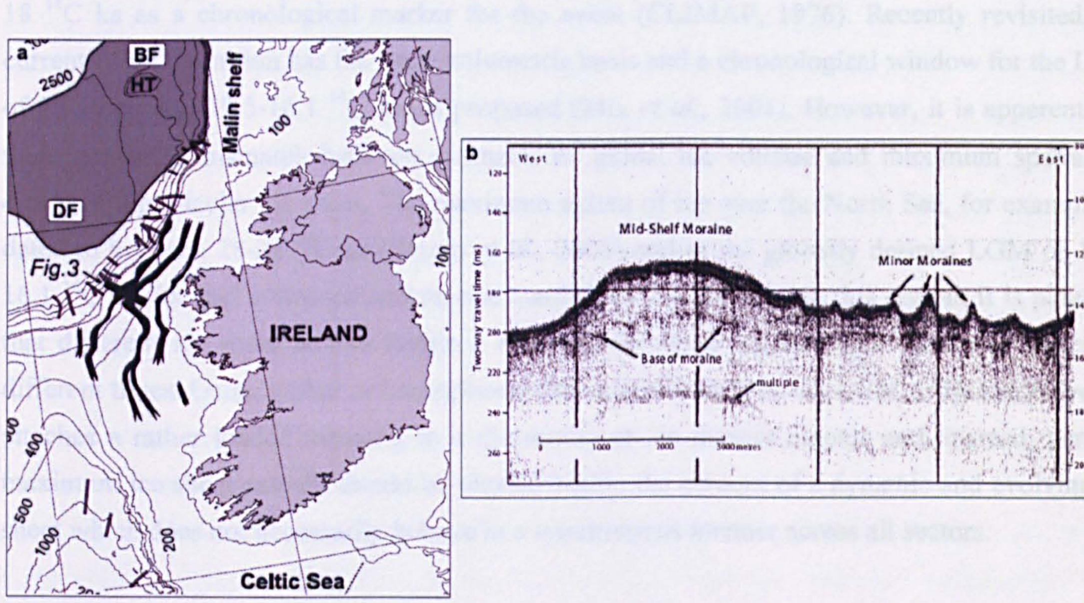


Figure 2.5 Moraines on the Porcupine Shelf identified by Haflidason *et al.* (1997), reported in Sejrup *et al.* (2005). **a)** location of end moraines; black band across moraines, labelled their Fig. 3, gives location of airgun profile **(b)**; DF and BF are Donegal and Barra Fans, bathymetry contours given in metres. The large outer moraine is interpreted as a maximum ice sheet limit, with smaller recessional moraines located inside it towards the present-day. This sequence of moraines is interpreted as last glaciation in age, although there is no direct dating support for this as yet.

Finally, the stratigraphic records of trough mouth fans along the north-west European margin reveal glaciation close to or at the shelf-edge at stages within the last glaciation (see Sejrup *et* *al.*, 2005). Several high-resolution and well-dated core analyses from the Barra/Donegal Fan, located north-west of Co. Donegal, suggest that ice reached a 'maximum' position at the shelf on numerous occasions during the last glaciation. Ice originated from sources in the Tertiary provinces of west Scotland and Northern Ireland, and this sector of the BIIS was characterised by abrupt margin oscillations (Kroon *et al.*, 2000; Knutz *et al.*, 2001, 2002b). This has implications for understanding dynamic behaviour of the ice sheet, but in the context of the present discussion adds to the growing body of evidence for a laterally extensive last (British)-Irish Ice Sheet. For further discussion of potential maximum ice sheet limits around other sectors of the BIIS (and NW European ice sheet) see Sejrup *et al.* (2005).

2.2.3.3 Spatial extent: summary

It remains a subject of dispute whether the Southern Irish End Moraine exists as a continuous limit spanning the width of the country, and whether such a limit might represent a synchronous ice maximum. However, where moraine complexes are known to exist, they are now generally thought to represent a (series of) standstill position(s) during ice sheet retreat. There is increasing acceptance of maximum extension of the last Irish Ice Sheet towards the continental shelf-break. The precise extent of ice onto the shelf, its duration at its maximum position and whether a stable maximum extent was reached are areas of active research.

A note of caution should be added to a discussion of maximum extents of palaeo-ice sheets, which are often referred to in terms of the 'LGM limit'. The CLIMAP project defined the term 'Last Glacial Maximum' specifically as the time of maximum global ice sheet volume, and took 18 ^{14}C ka as a chronological marker for the event (CLIMAP, 1976). Recently revisited, the current LGM definition has the same volumetric basis and a chronological window for the LGM of 23-19 cal ka (19.5-16.1 ^{14}C ka) is proposed (Mix *et al.*, 2001). However, it is apparent that there can be a mismatch between estimates of global ice volume and maximum spatial ice extent of a particular ice sheet. The maximum extent of ice over the North Sea, for example, is dated to between 28-22 ^{14}C ka (Sejrup *et al.*, 2005) and at the globally defined LGM of 19.5-16.1 ^{14}C ka, ice had collapsed and marine conditions had resumed in this region. It is plausible that different ice sheet sectors within a dynamic ice sheet attained their maximum extent at different times. Using global or hemispheric time-markers such as the LGM or Heinrich event 1 attaches a rather loaded meaning to a discussion of ice margin extents and, instead, perhaps maximum ice sheet extents should be viewed within the context of a dynamic and evolving ice sheet which does not necessarily behave in a synchronous manner across all sectors.

2.2.3.4 Vertical extent

The question of the vertical extent of past ice sheets is perhaps considered with less frequency than discussion of two-dimensional spatial extent, but ice thickness is an essential boundary condition for ice sheet, climate, ocean and solid earth modellers (e.g. Peltier *et al.*, 2002; Shennan *et al.*, 2002, 2006).

As schools of thought regarding lateral extent have varied, so have models of ice sheet thickness. The long-standing limited ice model conceptualised not only an ice sheet terminating at the SIEM, but a thin ice mass of insufficient power to penetrate or override coastal mountains, leaving nunataks and unglaciated regions (Synge, 1968, 1970). Under this model, ice thickness has often been discussed in rather qualitative terms: nunataks protruded in Cos. Mayo and Antrim (Synge, 1968, 1970; elevations of ~700 m and ~500 m respectively), the Castlecomer Plateau was not overtopped (Synge and Stephens, 1960) and the Mourne mountains were viewed as a barrier to ice despite their proximity to the proposed Lough Neagh ice centre (Hill and Prior, 1968; Stephens *et al.*, 1975). However, both Kilfeather (2004) and Hegarty (2002a,b) reconstruct ice over the Castlecomer Plateau and Colhoun (1971) suggested the Sperrin Mountains (maximum elevation of 678 m) were completely engulfed by ice derived from the central Tyrone ice source. Arguments for both a 'thick ice' and a 'thin ice' model have been put forward.

A more rigorous examination of evidence for ice sheet thickness has been slow in forthcoming, in contrast to a wealth of studies concerned with trimline mapping and ice surface reconstruction in Britain over the last decade (e.g. Ballantyne *et al.*, 1998; McCarroll and Ballantyne, 2000; Lamb and Ballantyne, 1998; Stone and Ballantyne, 2006). However, a relevant body of work is now emerging from Ireland. Four recent studies consider this problem in the Kerry/Cork mountains (Rae *et al.*, 2004), in the Wicklows (Ballantyne *et al.*, 2006), in Co. Donegal (Ballantyne *et al.*, 2007) and in western Ireland (Ballantyne *et al.*, 2008). Trimline investigation in these regions yields an ice surface altitude in the south-west of approximately 600 m, in the Wicklows an altitude of ~725 m, in Donegal an ice divide height of ~700 m and an ice surface altitude potentially in excess of ~740 m in Connemara, western Ireland. In response to ongoing debate over the significance of a trimline (Ballantyne *et al.*, 1998; Kleman, 1994; Hättestrand and Stroeven, 2002), Ballantyne and colleagues more recently acknowledge a thin carapace of cold ice could have lain over warm, erosive ice and suggest their reconstructions represent a minimum vertical extent of the ice mass. These studies are contributing a reasonably consistent picture of ice thickness in Ireland. Their locations are, however, peripheral to the ice mass centre and these studies cannot yet offer an insight as to the connection between locally reconstructed domes and the ice sheet interior.

The only other estimates of the thickness of the last Irish Ice Sheet are derived from glacio-isostatic modelling (see below, Section 2.3.2), but no such model for the British Isles has yet provided a good match with the whole available dataset of RSL markers (Shennan *et al.*, 2006). Furthermore, as yet, no model run for the whole British-Irish Ice Sheet has included any Irish RSL markers for model-observation comparison. Ballpark estimates for Irish Ice Sheet thickness at its maximum (spatially and chronologically) are currently ~600-800 m (Lambeck, 1996), 500-750 m (Shennan *et al.*, 2002), 750-875 m (Shennan *et al.*, 2006) and 750 m (Brooks *et al.*, 2008). Of interest, Shennan *et al.* (2006) find that the fit achieved for the BIIS under their 'thick ice' model does not differ greatly from that under a 'thin ice' scenario. In response to such estimates, McCabe (1997) has argued for a much thicker ice sheet (though does not express how thick) to sufficiently depress the land to match markers of high RSL on the east Irish coast. However, some of these apparent markers of high RSL have come under heavy criticism and been reinterpreted as lake, rather than sea level indicators (McCarroll, 2001). The future for this avenue of research lies in incorporating a more spatially complete evidence-base for model testing.

2.2.4 Ice flow patterns

The key questions in reconstructing ice flow are concerned with its spatial pattern and, increasingly, we wish to understand the behaviour of ice flow: did ice move at sheet or at ice stream velocity? The main patterns of ice flow in Ireland are well-known, but the traditional models of the ice sheet typically mask considerable complexity. Key debates relate to untangling such complexity where multiple flow patterns exist (such as the relative influences of Scottish versus Irish ice, where evidence for both exists in the record), and relate to ice stream identification. These issues are considered below.

2.2.4.1 General patterns of ice flow

It is often patterns of ice flow that inform us of the sources of ice dispersal and, given this association, the key patterns of ice flow have long been known. It is therefore best to refer back to the summary figures of the traditional models of the ice sheet and its flow paths (Figure 2.1a-d). It is clear that the main flow routes which characterise more recent thinking feature in the earliest models, for example the north-westerly flow over Cos. Roscommon and Mayo, and the south-easterly flow over the east midlands for which there is striking evidence in the landform record. All models invoke funnelling of ice through western embayments, though in Clew Bay there is a direct conflict in the proposed directions of ice flow. All models depict ice flow divergence from Lough Neagh and central Tyrone and these flow paths are clearly revealed by striae, erratics and drumlins. However, the dominance of models in the literature creates the risk that observation of evidence is not rigorously separated from theory-laden interpretation. It is certainly the case that these models mask considerable complexity of the glacial record, and have been highly influential with regard to providing a framework for the interpretation of newly discovered evidence.

Conflict over initial landform identification inevitably leads to controversial palaeo-glaciological interpretations. At its most extreme, disagreement in Clew Bay (Figure 2.6) over the identification of a complex suite of subglacial bedforms has led to the proposal and debate of almost every conceivable ice flow pattern. Traditionally, ice was seen as flowing westwards through the bay in a lobate form (Synge and Stephens, 1960; Orme, 1967; McCabe, 1985). Warren's ice sheet model (1992) opposed this view, postulating an ice divide across the mouth of the bay inducing onshore ice movement (eastwards); this model has received some support from Jordan (2002). In contrast, a ribbed moraine interpretation of the bedforms would imply north-westwards ice flow (Smith *et al.*, 2006), whilst Knight (2006b) adopts a two-stage model: firstly westwards flow funnelled through the bay, and subsequently a northwards ice flow partially remoulding the primary bedforms (drumlins). Ongoing investigation of the landforms and setting (Carolan, 2006) reverts to a ribbed moraine interpretation.

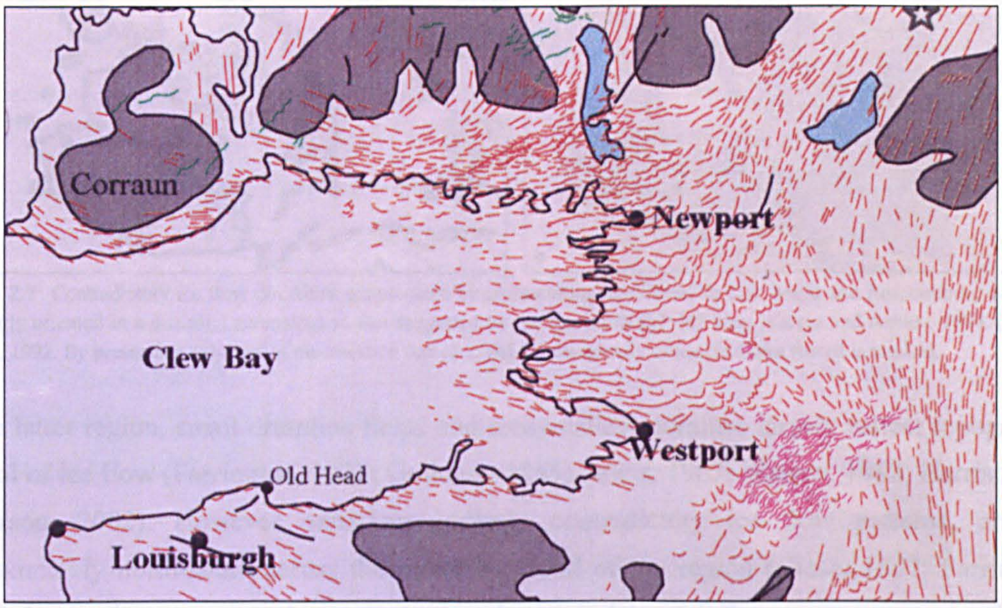


Figure 2.6 Subglacial bedforms in Clew Bay mapped (in red) along their crestlines (Jordan, 2002). Four different models of ice flow patterns arise from different interpretations of these landforms by different authors: westwards ice flow, eastwards, northwestwards, and a two-stage model of west followed by northerly ice movement.

At Clew Bay it is the interpretation of one set of bedforms which stirs debate. At many other sites, multiple ice flow indicators are recognised, such as cross-cutting striae, cross-cutting landforms, or multiple tills in a stratigraphic sequence. Cross-cutting striae have been well-known since the work of Close (1867; Kinahan and Close, 1872) and whilst attention has only recently turned to cross-cutting landforms, there is a clear contradiction between the directions of lineations and that of the Co. Mayo eskers captured in the long-standing glacial maps (Figure 2.7). In Co. Clare, the lineations reveal south-westerly flow whilst erratic distributions indicate a south-easterly movement (Farrell *et al.*, 2005). The multiple tills in stratigraphic sequence in Cos. Down and Antrim reveal two conflicting flow directions but whilst Hill and Prior (1968) assign these to the same glacial period others adhere to a two glaciations model, attributing earlier tills to the Munsterian and upper tills to the most recent ice sheet (Synge and Stephens, 1960; Stephens *et al.*, 1975). The key issue for sites of multiple flow indicators is the chronology attached to the flow patterns inferred. Such complexity of ice flow history is often disguised by the generalised flowlines which characterise the conceptual models. Regionally generalised ice flowlines have likely hampered recognition of an evolving ice sheet.

In the south of Ireland, the conceptual models do not depict any major ice flow paths and flow directional information is notably sparse. There may be a real dearth of ice directed features here, or the apparently empty record may result from a lack of study given the long-held view that southern Ireland was not recently glaciated. Close's original map of ice directed features (1867) indicates offshore flowing ice in Cos. Waterford and Wexford but this area has received little subsequent attention, most research efforts focussing instead on the Kerry/Cork mountains.

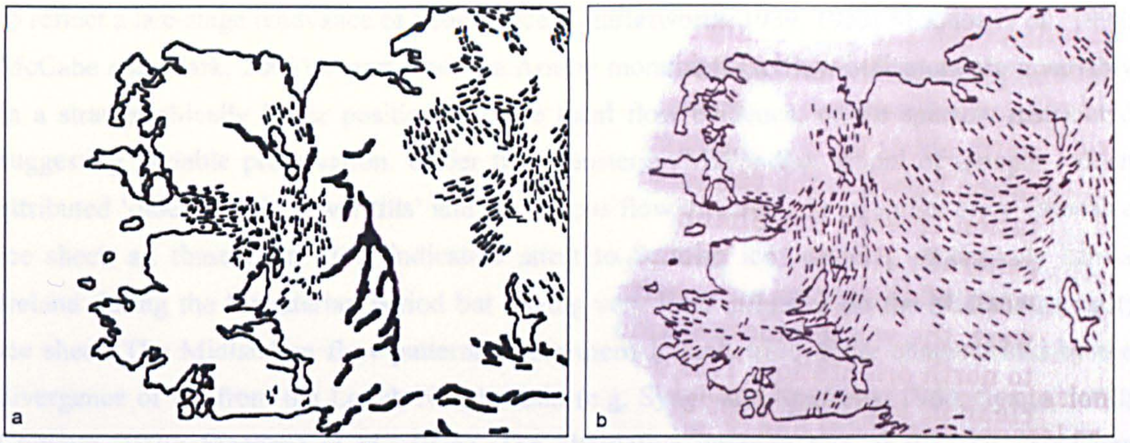


Figure 2.7 Contradictory ice flow directions are revealed by cross-cutting landforms. In Cos. Mayo and Roscommon, eskers **(a)** are clearly oriented in a direction anomalous to that suggested by the lineations **(b)**. **(a)** from Warren and Ashley, 1994. **(b)** from Warren, 1992. By presenting only part of the lineation record in **(a)** the complexity of the landform record is masked.

In the latter region, small drumlins fields and cross-valley moraines largely reflect topographic control of ice flow (Farrington, 1936; Guilcher, 1965; Lewis, 1967; Warren, 1988; Harrison and Anderson, 2002). However, striations indicate contradictory ice flow patterns, oriented approximately north-south across the structural trend of the region (Close, 1867; Farrington, 1936). Again, there appear to be contradictions between data of different sources.

A plethora of sites in Ireland indicate changing ice flow patterns. Determining the timescale of changing flow is the main barrier to a consistent interpretation. Traditionally, anomalous evidence, or that which does not 'fit' an accepted model, has been smoothed over by a regionally generalised ice flowline, or assigned to an earlier ice sheet (Close, 1867; Synge and Stephens, 1960). However, unless independent chronological information suggests it is valid to do so, important information may be lost. It is perhaps likely that where there is apparent evidence for multiple ice flow directions this is indeed the correct interpretation: multiple snapshots of ice activity may be recognised in the glacial record.

2.2.4.2 'Scottish ice'

The debate surrounding the influence of Scottish-sourced ice on the Irish landscape during the last glacial period is a classic example of the issue raised above, of the differing interpretations which may arise from conflicting suites of information in the same location. The key issue in the Scottish ice debate is not whether Scottish ice has had any influence upon the Irish landscape, for this is generally accepted, but whether evidence for this ice flow pattern is attributed to the *last* ice sheet or the *previous*.

There is an abundance of field evidence in Ireland testament to ice flow paths sourced in Scotland: Scottish erratics such as the distinctive Ailsa Craig microgranite (widespread across Northern Ireland, Charlesworth, 1939; Cos. Londonderry and Donegal, Colhoun, 1970; Co. Wexford, Culleton, 1978), 'shelly' tills deposited on land from the Irish Sea basin (Colhoun, 1970; McCabe, 1972; Ó Cofaigh and Evans, 2001b, 2007), south-westerly ice directional indicators in Co. Down (Hill and Prior, 1968), and the Armoy moraine in Co. Antrim, thought to reflect a late-stage readvance of Scottish ice (Charlesworth, 1939, 1953; McCabe *et al.*, 1998; McCabe and Clark, 2003). Apart from the Armoy moraine these flow indicators are invariably in a stratigraphically lower position to more local flow evidence, or are sparsely distributed suggesting variable preservation. Under the Munsterian/Midlandian school of thought, which attributed 'older drifts', 'lower tills' and anomalous flow directions to an earlier more extensive ice sheet, all these relict flow indicators attest to Scottish ice sweeping extensively across Ireland during the Munsterian period but having very little influence on the Midlandian (last) ice sheet. The Midlandian flow patterns in Northern Ireland were rather characterised by the divergence of ice from the Lough Neagh basin (e.g. Synge and Stephens, 1960; Synge, 1970; Colhoun, 1970; Stephens *et al.*, 1975). The alternative interpretation of the same evidence groups the two lines of evidence into the same glaciation. Rather than a *pre*-Midlandian timing, Scottish ice is attributed to the *early* Midlandian, prior to the expansion of 'local' Irish-sourced ice (Charlesworth, 1924, 1939, 1953; Hill and Prior, 1968; McCabe, 1972; McCabe *et al.*, 1999; Clark and Meehan, 2001).

Without strong absolute dating control all of these arguments, be they stratigraphical (Hill and Prior, 1968; Stephens *et al.*, 1975) or geomorphological (McCabe *et al.*, 1999; Clark and Meehan, 2001), cannot be firmly evaluated. Whether the lowest unit was laid down during an *early stage* of the *last* glacial or during the *previous* glacial cannot be determined. However, the basis for a Munsterian/Midlandian subdivision is essentially a 'count from the top' stratigraphic approach, assigning each till unit to a separate glaciation. Under modern paradigms of dynamic ice sheets capable of inscribing multiple imprints in a single glacial cycle this approach might be viewed untenable. Furthermore, one should *expect* British sectors of the ice sheet to influence Irish sector dynamics purely on the mutual proximity of the two ice masses. All numerical ice sheet modelling reconstructions to date, whilst preliminary in many ways (Section 2.3, below), are characterised by ice inception and flow from Scotland in the initial phases of ice sheet development (Boulton and Hagdorn, 2006; Hubbard *et al.*, 2007; Vieli *et al.*, 2007). Given the proximity of the two landmasses and the greater elevations of ice-nourishing mountains in Scotland it is hard to envisage how Scottish sourced ice would not have had any influence upon the Irish sector's flow dynamics.

2.2.4.3 Ice Streams

Ice 'streams' have been described in Ireland since the earliest writings on Irish glacial history. However, the significance of the term has evolved. 'Streams of ice' were often described in older literature in an almost poetic, literary style, to describe a major ice flow route (Close, 1867; Hull, 1878; Charlesworth, 1928b; Synge and Stephens, 1960). However, in modern scientific literature the term 'ice stream' has a much greater implication for ice sheet dynamics; rather, it denotes a trunk of ice in a grounded ice sheet which flows much faster (~10^2-10^3 m/yr) than the surrounding, more sluggish ice (~10^1 m/yr) (Paterson, 1994). The potential effect of ice streaming on ice sheet dynamics is considerable, discharging substantial proportions of the total ice sheet drainage which would likely have a profound effect on ice divide locations and overall ice sheet flow geometry and topography. Given the glaciological importance of ice streams, these are a key ice sheet property for which evidence should be sought and carefully evaluated in the palaeo-record (e.g. Stokes and Clark, 1999; Clark and Stokes, 2003).

Terrestrial record. Few ice streams have been identified to date in the onshore Irish glacial record; only flow patterns in eastern sectors of the Irish Ice Sheet have been assigned specifically as such (McCabe *et al.*, 1998, 1999; Knight *et al.*, 1999; Figure 2.8). However, ice stream locations cited by Knight, McCabe and colleagues appear to be based mostly upon an association of drumlin occurrence with streaming ice velocities; lateral ice stream margins are delineated according to transitions in the degree of the underlying ribbed moraine modification. If this were the case any location in which drumlins are found, in Ireland or other previously glaciated landscapes, should be interpreted as the bed of a former ice stream. Given the considerable flux of ice discharged through these arteries, and the considerable distribution of drumlins (in Ireland and elsewhere), the interpretation of drumlins as signatures of ice streams is clearly implausible: an ice sheet could not have sustained such fluxes.

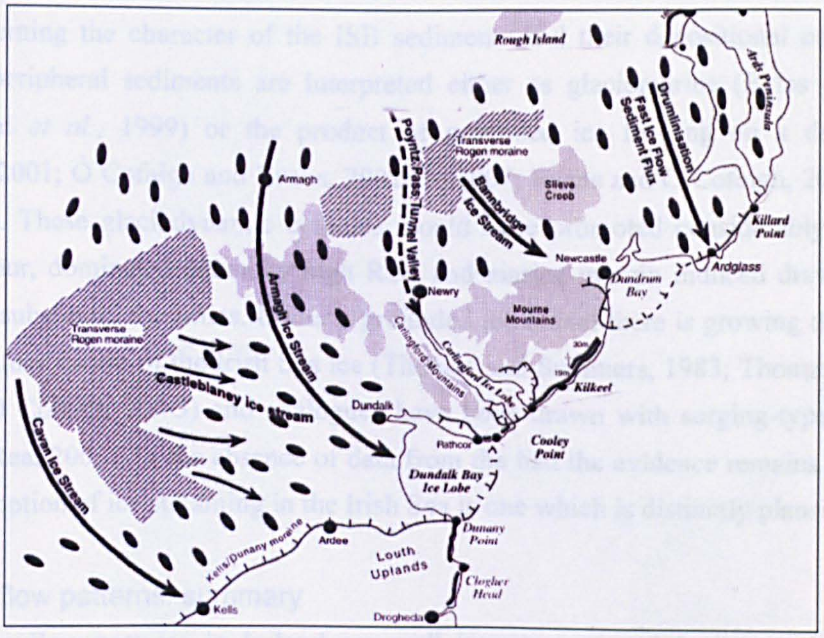


Figure 2.8 Palaeo-ice stream tracks identified by McCabe *et al.* (1998) and Knight *et al.* (1999) in the eastern Ireland bedform record. The basis for their classification as such is not clear and few of the criteria suggested by Stokes and Clark (1999) for palaeo-ice stream identification are met. Figure adapted from McCabe *et al.* (1998) and Knight *et al.* (1999).

Offshore record: Irish Sea ice stream. The Irish Sea Basin (ISB) undoubtedly formed a major drainage route of the last British-Irish Ice Sheet. However, the proposed dynamics of this flow route remain uncertain. The terms Irish Sea Glacier (Eyles and McCabe, 1989; Ó Cofaigh and Evans, 2001b; Hiemstra *et al.*, 2006) and Irish Sea Ice Stream (Eyles and McCabe, 1989; Ó Cofaigh and Evans, 2001a; Everest *et al.*, 2005) appear to be used interchangeably despite the glaciological implications of invoking streaming velocities.

Arguments supporting ice streaming in the ISB are fourfold: convergence of ice flow into the northern ISB is revealed by drumlin fields in eastern Ireland, western Britain and the Isle of

Man (Eyles and McCabe, 1989; McCabe *et al.*, 1998; Knight *et al.*, 1999; Roberts *et al.*, 2007); the basin is a likely location for an ice stream, since ice will be topographically funnelled over soft, deformable marine sediments; there is evidence of pulsed IRD deposition on the continental slope beyond the Celtic Sea (Scourse *et al.*, 2000; Peck *et al.*, 2006); and, finally, the geometry of the ice limit which protrudes into the Celtic Sea (Scourse *et al.*, 1991; Sejrup *et al.*, 2005; Hiemstra *et al.*, 2006; Ó Cofaigh and Evans, 2001b, 2007) seems to require a surge or ice stream to deliver ice to this advanced position. However, direct evidence of ice streaming velocities has not been forthcoming. Existing diagnostic criteria for palaeo-ice streams hinge largely on access to the bed (Stokes and Clark, 1999) in order to scrutinise the geomorphological imprint of the overriding ice flow. In the ISB the lack of access to and the dearth of data visualising the bed considerably hinder determination of the dynamics of Irish Sea ice. The available data is limited to the onshore regions feeding the Irish Sea and the typical geomorphological signatures of ice streaming have not yet been sought on the seabed.

Given the unsuitability of a geomorphological approach to reconstructing ISB ice dynamics, the sediments peripheral to the basin have received much attention. However, a long-standing debate concerning the character of the ISB sediments and their depositional context hinders consensus: peripheral sediments are interpreted either as glaciomarine (Eyles and McCabe, 1989; Knight *et al.*, 1999) or the product of grounded ice flowing on a deforming bed (McCarroll, 2001; Ó Cofaigh and Evans, 2001a,b, 2007; Evans and Ó Cofaigh, 2003; Hiemstra *et al.*, 2006). These glaciodynamic contexts would have promoted considerably different ice flow behaviour, dominated either by high RSL and marine margin induced drawdown, or by independent subglacial dynamics. Under a grounded ice model there is growing documentation of the oscillatory nature of the Irish Sea ice (Thomas and Summers, 1983; Thomas *et al.*, 2004; Evans and Ó Cofaigh, 2003) and analogues have been drawn with surging-type landsystems (Evans and Rea, 2003). In the absence of data from the bed the evidence remains inconclusive, but the assumption of ice streaming in the Irish Sea is one which is distinctly plausible.

2.2.4.4 Ice flow patterns: summary

The main ice flow patterns in Ireland are well known, captured in the earliest maps and conceptual models of the ice sheet. However, it is often the case that these patterns are oversimplifications of the true geometry of ice flow revealed by a more detailed analysis of the evidence. Patterns more complex than the models suggest arise at sites where there is a single flow indicator but multiple interpretations are possible, and at sites where there are several flow indicators, when the question becomes what are the spatial and/or chronological relationships between them? Working under the framework of a specific conceptual model may increase the tendency to ignore or assimilate complexity into the model. In fact the complexity may reveal important new information about the patterns of ice flow which challenges the existing model.

Specific debates in the literature regarding ice flow patterns often relate to the latter problem, such as the role of the Scottish ice. A key focus of current research is constraining not only the pattern but the behaviour of ice flow routes, in particular the location and dynamics of ice streams; evidence for ice streams is limited in both the on and offshore records, but the most favoured location is in the Irish Sea Basin.

2.2.5 Retreat patterns

One can distinguish two elements of reconstructing ice sheet retreat: the pattern of margin retreat, and the environmental context under which the ice decayed (e.g. terrestrial, glaciolacustrine or glaciomarine contexts, ice stagnation, or oscillating or readvancing margins etc.). Charlesworth contributed a large body of work (Charlesworth, 1924, 1928a,b, 1929, 1939, 1973) describing patterns of ice margin retreat at a regional scale and his concept of an orderly withdrawal of ice from the SIEM northwards has been much supported (e.g. Synge and Stephens, 1960; McCabe, 1985; Hoare, 1991). However, most of the focus of research has been concerned with building frameworks for retreat, rather than mapping out actual margin retreat patterns. Local retreat reconstructions exist (e.g. Colhoun, 1970; Glanville, 1997; Meehan, 1999; Delaney, 2002; Knight, 2003a,b; Lafferty *et al.*, 2006), but ice sheet-wide retreat maps for the Irish Ice Sheet are only found as a small part of a British Isles or European glacial map (e.g. Andersen, 1981; Boulton *et al.*, 1985; Figure 2.9). This is in stark contrast to most other Quaternary ice sheets for which retreat patterns have been more clearly outlined (e.g. Prest, 1969; Denton and Hughes, 1981; Dyke and Prest, 1987; Kleman *et al.*, 1997; Boulton *et al.*, 2001). Attention in Ireland has rather been turned towards examining the environmental contexts of deglaciation (Eyles and McCabe, 1989; McCabe, 1996; McCabe and Ó Cofaigh, 1996; Warren and Ashley, 1994; van der Meer and Warren, 1997).

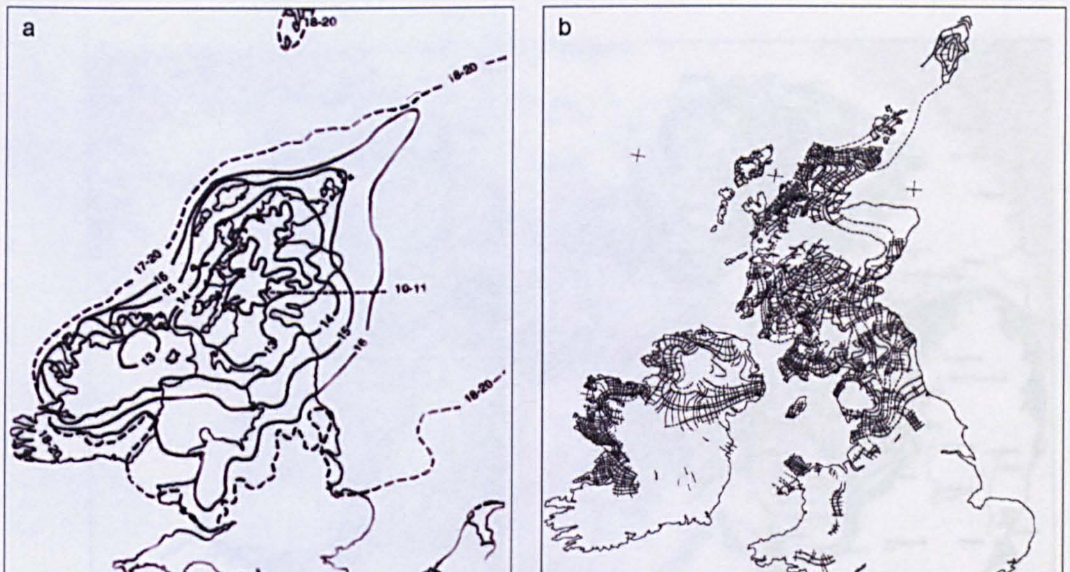


Figure 2.9 Retreat patterns for the Irish Ice Sheet are only to be found as a part of larger compilations: **a)** Andersen (1981) in Denton and Hughes; **b)** Boulton *et al.*(1985). There is no more detailed map of ice sheet retreat across Ireland.

The combined investigation of margin retreat patterns and context of deglaciation has led to three overriding frameworks for ice sheet decay. The concept of the 'Drumlin Readvance' pervades literature from the 1960s onwards, under which model the ice sheet withdraws smoothly towards the north before a margin readvance during deglaciation inscribes the main drumlin populations on the landscape. Over the last ~20 years McCabe and colleagues (Eyles and McCabe, 1989; Haynes *et al.*, 1995; McCabe, 1996, 1997; McCabe *et al.*, 1986, 1998, 2005; McCabe and PU Clark, 1998, 2003; PU Clark *et al.*, 2004; Knight *et al.*, 2004) have developed the readvance concept within a glaciomarine framework for deglaciation. Finally, Warren's model of the ice sheet configuration (1992) captures the central Irish eskers, whose orientation and relationship to ice flow patterns had hitherto not been well explained. Deglaciation is characterised by fragmentation of the ice sheet as margins withdrew towards its component ice centres. Each of these three frameworks for deglaciation is built on a different line of evidence; none as yet incorporates all elements of the deglacial record.

2.2.5.1 Steady margin retreat and the Drumlin Readvance: *moraines and bedforms*

Charlesworth's regional models of ice sheet retreat were based upon highly detailed maps of morainic and glaciofluvial sediments and landforms over Ireland. He, and subsequent workers, reconstructed an orderly south-north pattern of retreat disturbed only by retreat into the major western mountain masses of Donegal, Connemara and Kerry/Cork (Figure 2.10; Charlesworth, 1924, 1928a,b, 1929; Synge and Stephens, 1960; Synge, 1969, 1970; McCabe, 1972, 1985, 1993; Hoare, 1991). Broad belts of hummocky topography were connected across the country and interpreted as major stillstand or readvance moraines: the SIEM, the Galtrim Moraine, the Fedamore/Kells/Dunany/Dunleer/Drumlin Readvance Moraine and finally, on the east coast, retreat into lobes in Dundalk Bay, Carlingford Lough and across SE Down.

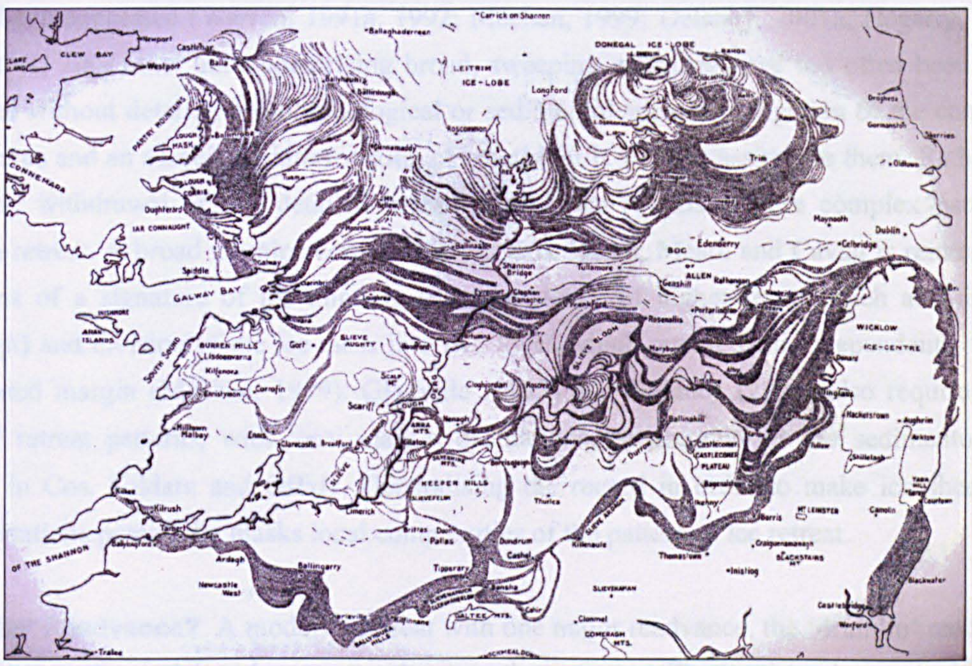


Figure 2.10 Charlesworth's seminal paper in 1928 established a model of steady retreat from moraine to moraine. However, his liberal depiction of moraines across the whole country has not been well-supported.

Orderly withdrawal was interrupted by the 'Drumlin' Readvance (Synge, 1970, 1979), an inferred margin readvance to the moraine of this name (and its aliases). Given that this apparent moraine is purported to bound the main drumlin fields in Ireland, it was inferred that the drumlins and the moraine are genetically linked. Implicit in this model are the assumptions that drumlinisation delivers material to the margin to be deposited as a moraine, and that drumlinisation occurs during margin advance. This model of steady retreat punctuated by a major readvance represented a framework of Irish Ice Sheet deglaciation for decades and, to a certain extent, underpins an existing framework for ice sheet decay (McCabe *et al.*, 1998; Knight *et al.*, 2004). However, both elements of the model have been questioned: the validity of a simple steady pattern of retreat, and the existence of a major margin readvance.

Steady retreat? Given the apparent detail of moraines and marginal landforms presented in Charlesworth's maps one would perhaps expect his retreat patterns to have withstood subsequent appraisal. However, in many places the details of his mapping has been invalidated. The presence of the SIEM is now under doubt (Warren, 1991a; Hegarty, 2002a,b; Kilfeather, 2004) (certainly its significance as an end moraine, see Section 2.2.3). In various places along its path Charlesworth's glaciofluvial hummocky spreads have been found to be proglacial outwash (sandur) sediments (Hegarty, 2002a) or bedrock knolls thinly draped with sediments (Hegarty, 2004). In the north, Charlesworth's arcuate moraines in Omagh Basin have been re-interpreted by Knight (2003b, 2006a; Knight and McCabe, 1997b) as ribbed moraine, whilst many of Charlesworth's 'overflow channels' and resultant retreat patterns in this region have been reinterpreted (e.g. Colhoun, 1970) in light of the paradigm shift to subglacial, rather than subaerial hydrology (Mannerfelt, 1949; Sissons, 1958, 1960, 1961).

It has been suggested (Warren, 1991a, 1992; Meehan, 1999; Delaney, 2001a; Hegarty, 2002a; Kilfeather, 2004) that units comprising broad, sweeping moraines have too often been drawn together without detailed geomorphological or sedimentological investigation of the contiguity of features and an associated interrogation of whether it is valid to assimilate them. Rather than a steady withdrawal of ice, detailed investigation often reveals a more complex pattern of margin retreat. A broad moraine complex across Cos. Louth, Meath and Cavan is reinterpreted in terms of a signature of ice thinning (the emergence of higher terrain such as Slieve na Calliagh) and division of the ice mass into two lobes which retreat semi-independently from a crenulated margin (Meehan, 1999). Glanville (1997) and Delaney (2002) also require multi-phased retreat patterns, with local margin oscillations, to account for the sedimentological record in Cos. Kildare and Offaly. Generalising the record in order to make ice sheet-wide interpretations potentially masks local complexities of the pattern of ice retreat.

'Drumlin' Readvance? A model of retreat with one major readvance, the 'drumlin' readvance, has been heavily criticised by some authors on three counts. Firstly, there is no glaciological basis for equating a moraine with margin (re)advance; indeed, most moraines are stillstand accumulations deposited during ice sheet recession rather than a 'bulldozed' advance feature

(Meehan, 2006). Secondly, and a corollary of the first point, there is no basis for equating *drumlinisation* genetically with margin advance or moraine building (Knight, 1999; Meehan, 2004, 2006). Finally, as with the SIEM, the basis for a continuous moraine bounding the drumlin fields has been questioned. Warren (1992) argues that the position of the Drumlin Readvance Moraine (DRM) has never been clearly established, and neither has the hummocky ground it comprises been examined geomorphologically or sedimentologically (Delaney, 2001a). Meehan (2006) convincingly demonstrates that this apparent moraine has been at least inconsistently, if not erroneously, located over the years by a number of authors (Figure 2.11).

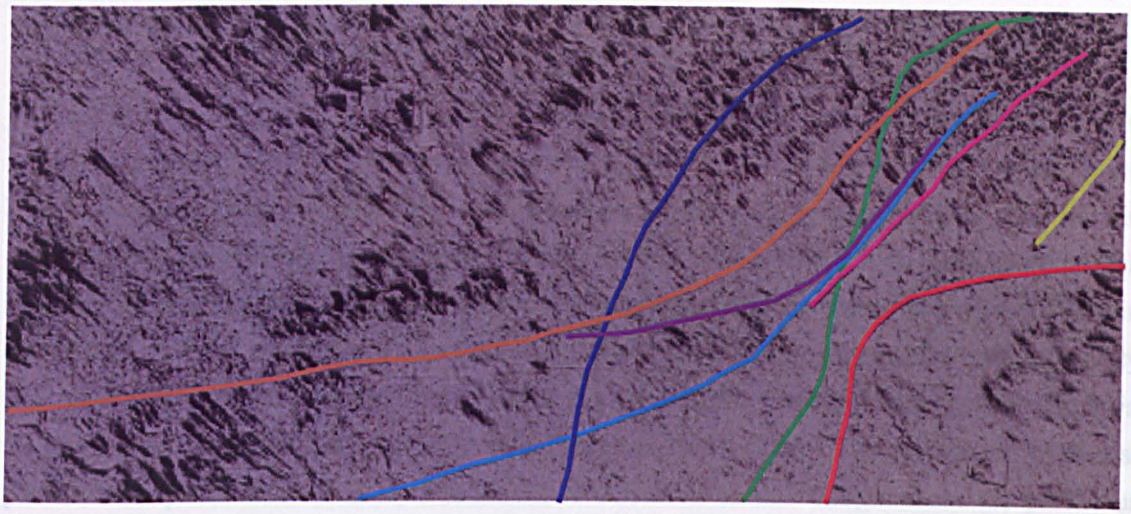


Figure 2.11 Meehan (2006) demonstrates eight proposed DRM positions in the region of the typesite, Kells, superimposed upon a high-resolution Digital Elevation Model visualised to enhance the appearance of slope changes. No morphological expression of a moraine is apparent in the image, nor is there any noticeable textural difference in the land surface appearance, and intact subglacial bedforms are apparent both in front and behind the supposed limits. Figure modified from Meehan (2006).

2.2.5.2 Glaciomarine framework: *readvances & glaciomarine sedimentation*

The glaciomarine framework for deglaciation of the Irish Ice Sheet incorporates and is partly built from a 'drumlin' readvance model. It adds an environmental context not only for the readvance, but for the deglacial sequence in which the readvance occurs: a context of high relative sea level and glaciomarine conditions in the Irish Sea Basin. A number of drumlin-fronting moraines of the east coast of Ireland, such as at Dunany Point, Kilkeel and Killard Point, were proposed by Synge (1970) to have been deposited in a glaciomarine environment. A large body of work has followed which identifies and discusses ice marginal sedimentation in a glaciomarine setting around the Irish coast (e.g. McCabe and Hoare, 1978; McCabe *et al.*, 1984; Eyles and McCabe, 1989; Haynes *et al.*, 1995; McCabe, 1996, 1997; McCabe and PU Clark, 1998, 2003; PU Clark *et al.*, 2004; Knight *et al.*, 2004; McCabe and Dunlop, 2006; McCabe *et al.*, 1998, 2005, 2007b).

Exposed in coastal sections, particularly around the Cos. Down and Louth coasts, are sequences of alternating glaciomarine muds and terrigenous sediments. These sequences are interpreted as recording the oscillation of the ice margin over the present-day coastline. Phases of high RSL, during which sedimentation is glaciomarine in nature, are argued to be associated with a time of ice margin withdrawal. These phases alternate with one or more periods in which the ice margin is at or very close to the present-day coast where the section is now exposed. The material delivered during these latter periods is interpreted as morainic (although not explicitly ice-contact for all sites). The stratigraphic sequences are interpreted as the record of marine transgression and margin retreat, alternating with readvance phases delivering morainic material to the present-day coastal regions. Given the long-standing ideas from the onshore record of a major ice margin readvance during overall retreat, it has been suggested that the readvance(s) interpreted from the exposures equate to the 'drumlin' readvance. This framework for ice sheet retreat hinges on two discussion points: the evidence for retreat and readvance of the ice margin, and the context of high relative sea level.

Retreat and readvance? Accepting the sedimentological interpretations in the above body of work, the stratigraphy of the key exposures (e.g. Killard Point, Cranfield Point, Cooley Point, Linns, Dunany Port; see McCabe and Dunlop, 2006) clearly demonstrates ice margin oscillations. However, the spatial scale of these oscillations is difficult to deduce from such point data. McCabe and colleagues associate the coastal stratigraphy with onshore drumlin patterns to infer the spatial scale of a readvance. However, this association is subject to exactly the same arguments which have challenged the relationship between the onshore Drumlin Readvance Moraine and the drumlins within (Meehan, 2004, 2006). The association of spatial pattern with point data assumes i) sediment is delivered to this margin from the particular drumlinising phase recorded onshore, and ii) the drumlins are formed during ice margin advance. Since ice flows forward (and is therefore capable of streamlining its bedforms) irrespective of margin movement, the latter assumption in particular is nonsensical. Furthermore, the most recent reconstruction presented from this coastal stratigraphy data (McCabe *et al.*, 2007b) interprets two readvances of the margin; it is not clear to which readvance the onshore ice flow patterns are presumed to relate.

The scatter of sites around the Irish coast which record a similar oscillation of the ice margin is argued by McCabe and colleagues (McCabe *et al.*, 1998; McCabe and PU Clark, 2003; McCabe, 2005) to support their interpretation of an ice sheet-wide readvance. Undoubtedly, these sites record dynamic margin movements. However, more conclusive support for the model of a large readvance into glaciomarine environments would reveal the *longitudinal* element of a readvance, not simply the *radial*. Coastal sections provide no more information than an inferred presence or absence of an ice margin; they are less able to reveal whether oscillations are minor, or represent a considerable retreat of ice followed by a large-scale readvance. The spatial and ice dynamical significance of the ice margin oscillations recorded in the coastal stratigraphies remains to be resolved.

High Relative Sea Level? The identification and interpretation of glaciomarine beds underpins the retreat-readvance model of decay, but is subject to fierce debate (e.g. Eyles and McCabe, 1989; Knight, 2001; McCarroll, 2001; Ó Cofaigh and Evans, 2001b; Scourse and Furze, 2001).

The original model of decay of ISB ice under glaciomarine conditions suggested that glaciomarine sedimentation was recorded at up to 140 metres above present-day sea level (Eyles and McCabe, 1989; see Knight, 2001). This interpretation has been firmly rejected by a number of authors, including an entire issue of Journal of Quaternary Science in 2001 (McCarroll *et al.*, 2001), preferring a model of glacio*lacustrine* delta formation at the (terrestrial) margin of Irish Sea ice. Furthermore, at a number of sites around the ISB glaciotectonic structures indicate a grounded ice mass on a deforming bed which, in places, cannibalised rafts of sediment from the Irish Sea floor (McCarroll, 2001; Ó Cofaigh and Evans, 2001a,b; Hiemstra *et al.*, 2006). Notwithstanding these well-supported arguments against glaciomarine sedimentation in the southern ISB, there is general acceptance of a higher than present RSL (+20 – +30m) around the north-east coast (McCarroll, 2001; Roberts *et al.*, 2006), at the sites critical to the readvancing margin model.

As a body of work the glaciomarine framework has propelled ideas forward in terms of conceptualising the Irish Ice Sheet as a dynamic ice mass which experienced a dynamic mode of retreat, and is the only body of research in Ireland currently attempting to tie together the onshore and offshore records (e.g. Knutz *et al.*, 2001, 2002a; Peck *et al.*, 2006) on a large scale. There are some key remaining questions which the model does not yet explain. What was the manner of ice recession once onshore? Does it thin and fragment, or behave as a coherent ice mass? In which directions do ice margins retreat, prior to and following any readvances? The drivers of retreat and readvance sequences have been considered but remain unknown. Are the margin oscillations purely a response to climate forcing, or are they dynamic responses to the high RSL and tidewater conditions, which may induce rapid drawdown of ice from the ice sheet interior? These are outstanding questions for which the glaciomarine framework of deglaciation may provide a context but does not yet explain.

2.2.5.3 Fragmentation: *eskers & glacial lakes*

Mapping and investigation of the striking central Irish eskers is long-standing (Sollas, 1896; Gregory, 1920; Charlesworth, 1928b; Flint, 1930; Synge, 1979; Warren and Ashley, 1994; Delaney, 2002; Figure 2.12). Modern models for esker development interpret these ridges as ice directed features formed in subglacial and/or ice marginal settings, and they therefore hold great potential for unravelling both the geometry and the environmental context of ice sheet retreat patterns. Eskers hold particular significance in the Irish glacial record since their disposition is quite anomalous to ice flow patterns revealed by subglacial bedforms (Delaney, 2002; Knight, 2003a,b). However, the two models for deglaciation outlined above (the Drumlin Readvance, and the glaciomarine framework) fail to fully address the palaeo-glaciological significance of glaciofluvial landforms and deposits in the Irish glacial record.

In outlining a genetic model for the formation (and therefore palaeo-glaciological interpretation of eskers) Warren and Ashley (1994) propose a framework of Irish Ice Sheet deglaciation characterised by the fragmentation of a coherent ice mass into its component domes.

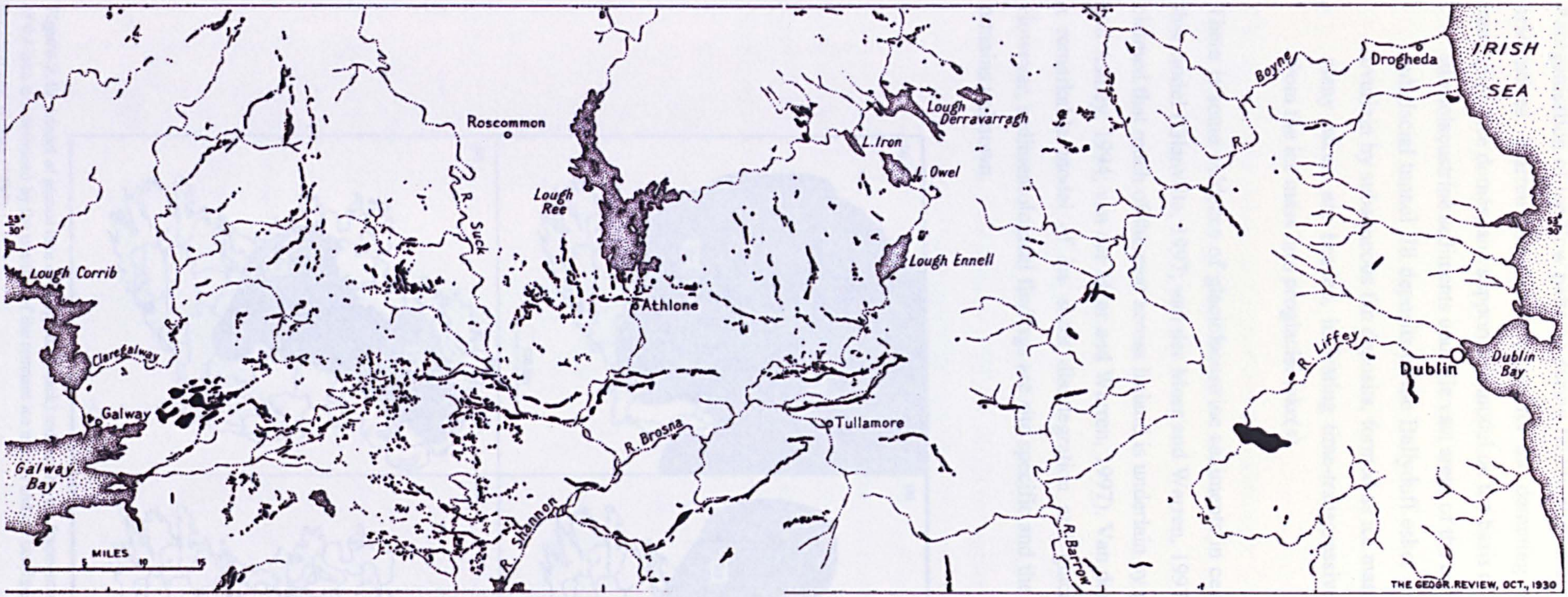


Figure 2.12 Esker distribution in central Ireland (Flint, 1930).

Reorganisation of ice flow patterns during fragmentation accounts for the anomalous landform orientations. Warren and Ashley argue for the damming of a large proglacial lake between uncoupling ice domes, and support this model on the basis of three lines of argument:

- glaciolacustrine sediments underlie vast areas of the central Irish bogs.
- subglacial tunnel fill deposits of the Ballyduff esker (part of the central W-E system) are overlain by subaqueous fan deposits, formed as ice masses uncoupled.
- many eskers are beaded, indicating time-transgressive genesis as sediments discharged from the ice mass into proglacial lake(s).

There is some evidence of glaciolacustrine sediments in central Ireland which lend support to this model (Glanville, 1997; van der Meer and Warren, 1997; Kilfeather, 2004) and it has been claimed that much of the peat across Ireland is underlain by glaciolacustrine sediments (Warren and Ashley, 1994; van der Meer and Warren, 1997). Van der Meer and Warren (1997) develop a remarkable model of ice sheet disintegration and glacial lake expansion (Figure 2.13). However, sedimentological findings are site specific and the true extent of buried lake deposits remains unknown.

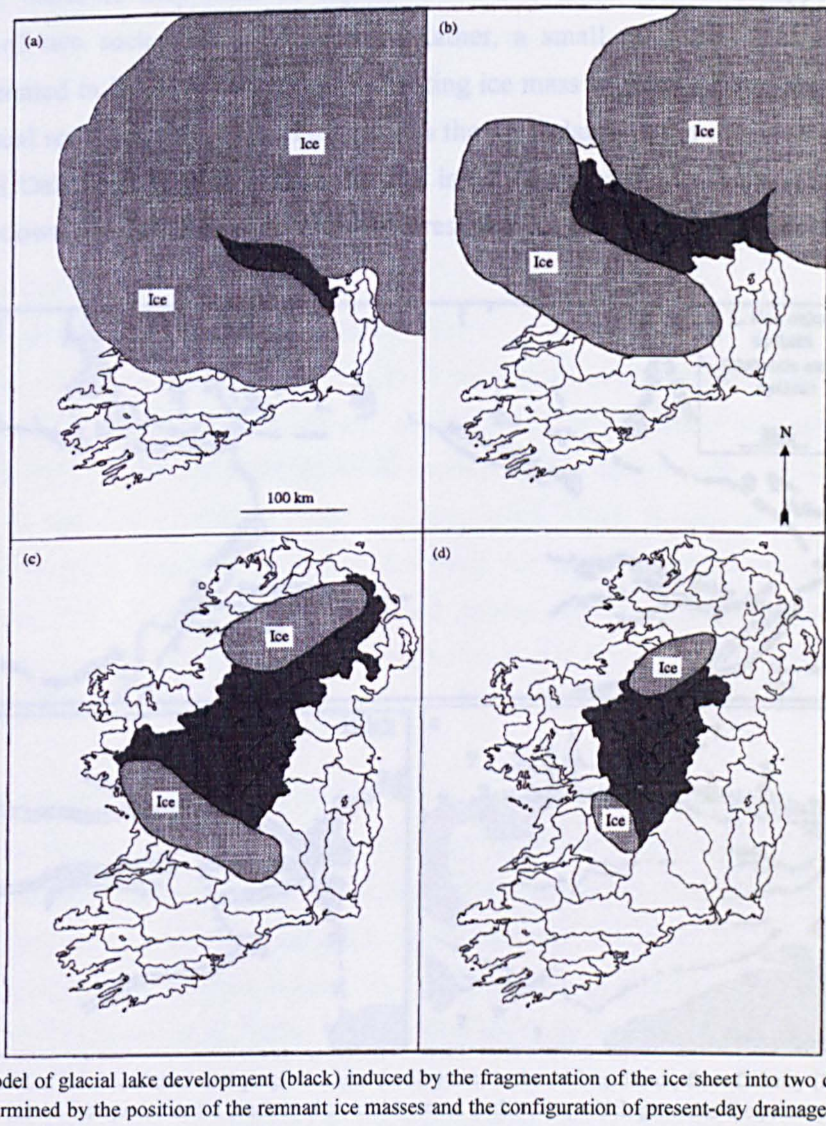


Figure 2.13 Model of glacial lake development (black) induced by the fragmentation of the ice sheet into two domes. The extent of the lake is determined by the position of the remnant ice masses and the configuration of present-day drainage basins. From van der Meer and Warren (1997).

Until extensive evidence is produced of such a glacial lake it remains only an interesting hypothesis. A fragmenting ice sheet resonates with local retreat patterns. There is complexity and cross-cutting in the glaciofluvial landform record and both Glanville (1997) and Meehan (1999) reconstruct thinning and uncoupling of lobes of ice which withdraw in contrasting directions. The scale of fragmentation is not as large as that envisaged by Warren and Ashley (1994); however, such reconstructed patterns contradict models which depict steady recession of a coherent ice mass and, notably, have no need to invoke major margin readvances.

2.2.5.4 Fragmentation vs glaciomarine/readvances

The fragmentation and readvance models of retreat are formulated largely on different lines of evidence and little attempt has been made to force the models to engage. However, Delaney (2002; Mitchell and Delaney, 1997) proposes a local model of retreat for the Lough Ree area which goes some way to suggesting how the two frameworks could be reconciled. Whilst Warren and Ashley (1994) attribute the two main esker systems (W-E and NW-SE) to a single phase of uncoupling ice domes, detailed sedimentological analyses of the eskers and kames around Lough Ree lead Delaney (2001a,b, 2002) to suggest there is *superimposition* of the two landsystems, therefore they must be separated in time. This would not support large-scale uncoupling of two sectors of the ice sheet. Rather, a small proglacial lake is invoked by Delaney, dammed in front of a westwards retreating ice mass by local topography, into which a small and local readvance from the NW deposits the secondary system of eskers (Figure 2.14). Mitchell and Delaney (1997) speculate that the initial westwards retreat could be induced by marine drawdown into the ISB; however, they stress that the Lough Ree evidence suggests only

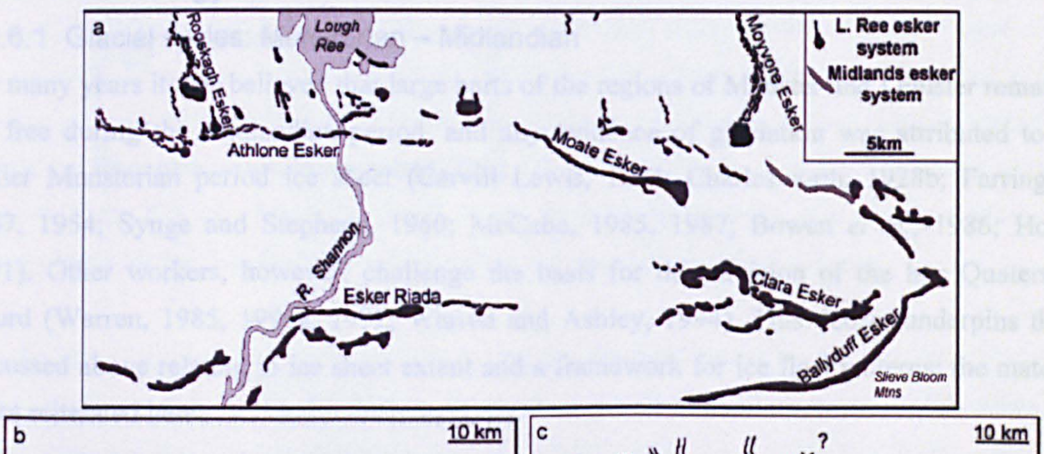


Figure 2.14 Model of local readvance and proglacial lake development in the Irish midlands, from Delaney (2002). The central systems of eskers **(a)** are interpreted as the product of an initial retreat to the west, which generates the primary esker system **(b)** followed by readvance into a proglacial lake (light grey) which deposits a secondary esker system **(c)**.

a local readvance, and should not be correlated with a larger-scale margin readvance over the east midlands without further investigation.

2.2.5.5 Retreat patterns: summary

Early ideas of a steadily retreating ice sheet punctuated by stillstands and a main readvance were built largely on moraine evidence. However, recent geomorphological and sedimentological analyses reveal that the regional or countrywide moraines such as the SIEM, Galtrim Moraine or DRM are diachronous features exhibiting a greater complexity of ice margin retreat than presented under earlier models (see Warren, 1991a, 1992; Meehan, 1999, 2004; Delaney, 2001a). Furthermore, the implicit assumption that the drumlins and moraine building occur during a margin advance is questioned.

The glaciomarine model and the fragmentation model represent two opposing frameworks for deglaciation of the Irish Ice Sheet. However, neither is comprehensive in describing the manner or pattern of margin retreat and giving a climatic or dynamic context for deglaciation, and neither really engages with or challenges the fundamental evidence on which the other is based. Recent work (e.g. Delaney, 2002) represents an important step in critically examining frameworks for ice sheet deglaciation although its findings are local in scale. The deglacial record must be considered in such a critical manner at ice sheet-scale, and future work must aim to link the onshore, coastal and offshore records of ice sheet decay in order to resolve the existing dichotomy of deglacial models.

2.2.6 Chronology

2.2.6.1 Glacial cycles: Munsterian – Midlandian

For many years it was believed that large parts of the regions of Munster and Leinster remained ice free during the Midlandian period, and any evidence of glaciation was attributed to the earlier Munsterian period ice sheet (Carvill Lewis, 1894; Charlesworth, 1928b; Farrington, 1947, 1954; Synge and Stephens, 1960; McCabe, 1985, 1987; Bowen *et al.*, 1986; Hoare, 1991). Other workers, however, challenge the basis for this division of the late Quaternary record (Warren, 1985, 1991a, 1992; Warren and Ashley, 1994). This debate underpins those discussed above relating to ice sheet extent and a framework for ice flow patterns; the material is not reiterated here.

Part of the reason this conflict remained unresolved for so long lies in the ambiguous evidence for interglacial periods in Ireland. A key type-site for interglacial sediments is at Gort, Co. Galway, but its floral assemblage is not typical of the Ipswichian (MIS5e). On the basis of different assumptions, competing stratigraphical frameworks for the Irish Quaternary can both be argued: the Gortian as the penultimate interglacial i.e. pre-Munsterian (Hoxnian) on palaeo-ecological grounds (Jessen *et al.*, 1959; Watts, 1985; McCabe, 1985, 1987; Coxon, 1993), or on a purely stratigraphical basis the Gortian as the last interglacial (Warren, 1985). Unfortunately, discovery of an unambiguous Ipswichian age interglacial site in Ireland, which would clearly demarcate Munsterian from Midlandian deposits, has not been forthcoming. It remains to be seen how Irish stratigraphic models shall be reinterpreted in light of the new consensus opinion of an extensive (offshore) Midlandian Irish Ice Sheet (Heijnis *et al.*, 1993; McCabe and Ó Cofaigh, 1996; Gallagher and Thorp, 1997; McCabe *et al.*, 2005; Farrell *et al.*, 2005; Sejrup *et al.*, 2005; Ó Cofaigh and Evans, 2001a,b, 2007).

2.2.6.2 Early-Middle Midlandian

Little is known about possible ice cover during the earlier stages of the Midlandian (MIS4-3). One school of thought suggests an ice sheet of fairly limited extent overrode parts of Ulster, based on the identification of tripartite sequences (till – organic horizons – till) in Cos. Fermanagh and Down (e.g. Colhoun *et al.*, 1972; McCabe *et al.*, 1978). The organic silts at three sites have been dated by conventional radiocarbon methods but unfortunately only one provides a finite date of 30.5 ^{14}C ka (Derryvree - Colhoun *et al.*, 1972). The underlying till must therefore be older than this age, and McCabe suggests an early Midlandian ice sheet potentially sourced from Scotland (in Bowen *et al.*, 1986; McCabe, 1987). However, a pre-Midlandian interpretation cannot be ruled out.

There are a few interesting contributions to this debate from further afield. In Cos. Clare and Galway, two ice flow directions are known (e.g. Farrington, 1965) but are poorly constrained in time. Recent dating of a site on the west coast of the Burren may inform this question. Two distinct diamicts, interpreted as tills, are separated by and underlain by flowstone deposits. Uncorrected U-Th dates for the flowstones suggest the lower till was emplaced between 53ka and 38ka; the upper till was emplaced after 38ka (Simms, 2005). It is tentatively suggested by Simms (2005) that these dates constrain an ice movement from Connemara, north-west of the site, over the Burren during the early-middle Midlandian. In the North Sea, Carr *et al.* (2006) propose a model of grounded ice coverage in the early Midlandian (Weichselian), potentially correlating with MIS4 at approximately 70ka. Given a British Ice Sheet of sufficient scale to merge with the FIS over the North Sea it would be likely Ireland was also glaciated. However, the suggested timing places this ice sheet before the dated diamict in Co. Clare.

Independent of these observations, two preliminary numerical modelling experiments (Hagdorn, 2003; Vieli *et al.*, 2007) produce a large BIIS in the early Devensian/Midlandian, at approximately 60ka. Caution should be exerted in interpreting these modelling results since they are preliminary experiments with limited tuning to the geological record and model behaviour is reported to be very sensitive to the climate forcing. However, this approach, combined with a much improved geochronology throughout the Midlandian, may help to resolve the question of ice coverage in the early-middle Midlandian.

2.2.6.3 Timing of maximum extent

There is compelling evidence for ice attaining its maximum position near the shelf break and remaining there for several thousand years, although the estimated time periods differ for different sectors. In the North Sea sector, grounded glaciation has been reconstructed from ~29-22 ^{14}C ka on the basis of dated core stratigraphies (Sejrup *et al.*, 1994; Carr *et al.*, 2006; Graham *et al.*, 2007), followed swiftly by deglaciation, whilst a prolonged maximum extent of ice on the western UK continental shelf is dated to a slightly later time interval. From the Barra Fan, Knutz *et al.* (2001, 2002b) reconstruct shelf edge glaciation from ~26-19 ^{14}C ka (30-22 cal ka), whilst at the SW margin of the BIIS there is a steady discharge of ice rafted material to the Porcupine Seabight from 26.5-17 cal ka (Peck *et al.*, 2006). Again, there is interpreted to have been an abrupt withdrawal from the shelf edge back to a grounded terrestrial margin. In southern sectors advance to the maximum is thought to be more short-lived. Scourse invokes a relatively brief advance of ice from the Irish Sea to its Celtic Shelf maximum shortly after ~21.5 ^{14}C ka (~26 cal ka) (Scourse *et al.*, 1991; Hiemstra *et al.*, 2006), which fits with a suite of dates from the Irish south coast (Ó Cofaigh and Evans, 2007). Here, an advance of inland Irish ice is reconstructed following the withdrawal of ice from the Celtic Sea margins, another example of the asynchronous behaviour of different ice sheet sectors. Note that all of these proposed time intervals for the last spatial extent of the BIIS (Figure 2.15) are earlier than the globally defined (volumetric) LGM chronozone of 23-19 cal ka (Mix *et al.*, 2001).

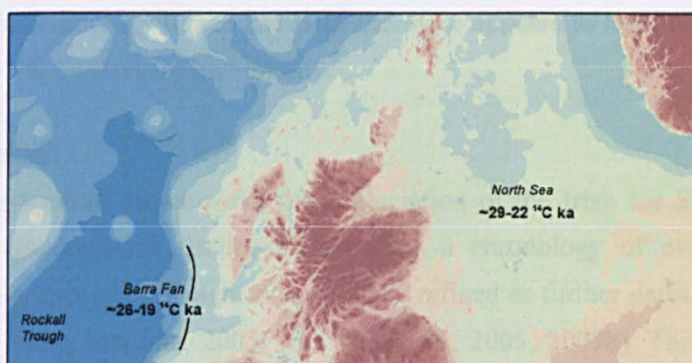


Figure 2.15 Proposed timings of maximum extent in different sectors of the BIIS, with corresponding margin positions (from literature cited above). Bowen and colleagues' model (2002) (grey limits) has found little support; ice does *not* reach the Scilly Isles during the last glaciation, and its 'LGM' position lies at the SIEM.

Whilst there appears to be convergence of opinion regarding the timing and extent of the last BIIS maximum, particularly from marine geologists, Bowen advocates an altogether different model (Bowen *et al.*, 2002). On the basis of his amino-acid geochronology for the British Isles and cosmogenic exposure dates from Ireland, Bowen's maximum Devensian/Midlandian BIIS occurs at approximately 40 cal ka. This ice sheet reaches offshore positions around western Ireland, and the BIIS and FIS are confluent; however, the Celtic Shelf is not extensively glaciated and ice does not reach the Scilly Isles. Bowen's ice sheet fluctuates/withdraws between 37.5-25.1 cal ka before advancing again at the 'LGM' but only reaches the SIEM in Ireland and the ice limits originally proposed by Synge (Synge and Stephens, 1960; Synge, 1969, 1970) on the basis of young and old drifts. This ice sheet begins receding at 21.8 cal ka.

This model has been challenged on many fronts. Bowen's amino-acid chronology (Bowen and Sykes, 1988; Bowen, 1999; Bowen *et al.*, 2002) has been strongly contested by McCarroll (2001, 2002) on grounds of circular reasoning. The 'LGM' ice limits are challenged in many sectors (and are inconsistent with the interpretations of the offshore record discussed above): the North Sea (Sejrup *et al.*, 2005; Carr *et al.*, 2006; Graham *et al.*, 2007); northern Scotland (Hall *et al.*, 2003); north and west Ireland (Ballantyne *et al.*, 2007, 2008); southern Ireland (Ó Cofaigh and Evans, 2001a,b, 2007); and the Scilly Isles and Celtic Shelf (Scourse *et al.*, 2000; Hiemstra *et al.*, 2006). Ó Cofaigh and Evans (2007) suggest that Bowen's cosmogenic exposure ages are not sound evidence of an LGM limit at the SIEM: only two samples from the dating programme are from the area of 'older drift' and little information is provided on their nature or their stratigraphic context. Ó Cofaigh and Evans suggest the older ages of these samples reflect inheritance of cosmogenic nuclides, a conclusion also drawn by Ballantyne *et al.* (2007) in Co. Donegal. Bowen's chronology of the last BIIS therefore appears to have received little support from many of the UK Quaternary community.

2.2.6.4 Deglaciation

Of the existing conceptual frameworks for deglaciation of the Irish Ice Sheet (Section 2.2.5, above) only the glaciomarine framework provides a chronology of events. Six stages of deglaciation were proposed by Knight *et al.* (2004), refined as further dates have been obtained (PU Clark *et al.*, 2004; McCabe, 2005; McCabe *et al.*, 2005, 2007b). This dated sequence of events is described in Table 2.1. Certain elements of the glaciomarine framework for deglaciation have been challenged (discussed above, Section 2.2.5.2). The ice sheet-wide *chronology* for this model hinges on two factors: i) the in situ character of marine fauna in glaciomarine sediments, and ii) the validity of site-to-site correlation across the ice sheet.

In situ fauna? Haynes *et al.* (1995) support an in situ interpretation of 75 foraminiferal samples from 26 sites around the Irish Sea basin. However, McCarroll (2001) contests this conclusion on grounds of circular reasoning: the authors have first removed the pre-Quaternary fauna from the sample, and then removed the temperate individuals since these cannot have survived contemporaneously with the cold-loving individuals. The remainder of the sample is then interpreted as glaciomarine since it is comprised of cold water species. McCarroll (2001) argues that the assemblages indicate mixed populations and in many locations are more likely derived from reworking of sea floor sediments. However, McCarroll acknowledges that the sites on the coast of Co. Down, critical to the model of deglaciation, display plausible sequences of dates with in situ faunal assemblages unlike those found elsewhere around the Irish Sea Basin.

Table 2.1 Chronology of deglaciation defined by the glaciomarine framework of retreat (after Knight *et al.*, 2004; McCabe, 2005; McCabe *et al.*, 2007b).

Stage	Approximate timing (^{14}C ka)	Event	Evidence
6: Nahanagan Stadial (YD)	11-10.5	Corrie glaciation	Morphological - corrie glaciation (Colhoun and Synge, 1980) Palaeo-ecology (Gray and Coxon, 1991)
5: Rough Island (Woodgrange) Interstadial	13-11	Climate warming, marine transgression	Stratigraphy: marine mud drapes drumlins at Rough Island – high RSL (McCabe and Clark, 1998) Palaeo-ecology: e.g. organic sequences from bogs (e.g. Watts, 1985; Smith and Goddard, 1991; Lowe *et al.*, 2004)
4a: Killard Point Stadial	13.8 (14.2-13.0)	Ice readvance	Stratigraphy: readvance moraine exposed in section (outwash deposits interbedded with marine muds) (McCabe and Clark, 1998) Geomorphology: drumlinisation (McCabe *et al.*, 1998)
4b: Linns Interstadial	14.2	Ice retreat, marine transgression	Stratigraphy: marine mud underlies diamict (moraine) and outwash sediments (dated McCabe *et al.*, 2007b)
4c: Clogher Head Stadial	15-14.2	Ice readvance	Stratigraphy: deformed & sheared marine mud (dated McCabe *et al.*, 2007b) Correlated with Corvish readvance (McCabe and Clark, 2003)
3: Cooley Point Interstadial	16.7-15	Ice retreat	Stratigraphy: marine muds underlie intertidal boulder pavement, RSL similar to present (McCabe and Haynes, 1996)
2	18.3 -16 (?)	Early deglaciation	Stratigraphy: marine muds overlie diamicts at Corvish & S. Donegal Bay (McCabe *et al.*, 1986; McCabe and Clark, 2003; McCabe, 2005; McCabe *et al.*, 2007a) Stratigraphy: marine muds infill incised channels (Clark *et al.*, 2004) Geomorphology: ribbed moraine form during withdrawal to minimum ice sheet extent (McCabe and Clark, 1998; McCabe, 2005)
1b	>/~23.5 (?)	Maximum	Stratigraphy: marine muds overlying diamict interpreted as ~contemporaneous (McCabe, 2005)
1a	~40 (?)	Maximum / deep isostatic depression	Stratigraphy/sedimentology: derived shells date marine transgression after early ice sheet (McCabe, 2005).

Validity of correlation? 13 sites around the Irish coast have a stratigraphy dated and interpreted under the glaciomarine model (McCabe and Haynes, 1996; McCabe and PU Clark, 1998, 2003; PU Clark *et al.*, 2004; McCabe *et al.*, 1986, 2005, 2007a,b). These cluster in three regions: north Mayo, north Donegal, and the Cos. Down and Louth coasts (Figure 2.16). There are philosophical concerns with the correlation of such spatially fragmented point data. Is it valid to build an ice sheet-wide chronology when individual events yield only 1 or 2 dates from each site? Given the potential for different sectors of the ice sheet to display different behaviour, is it appropriate to correlate and group events across sectors in the context of ice sheet-wide synchronous events? Is it valid to group dates from different sites which are not exactly coincident but fall roughly in the same timeframe? Units yielding dates 1000 years apart have been grouped together to describe the same, single event (McCabe *et al.*, 2005) but it may be possible that such differences between sites represent real, dynamic behaviour asynchronous across the ice sheet (McCabe *et al.*, 2007b). Until there is a more spatially and temporally complete geochronology of the Irish glacial record it is difficult to resolve these questions. Only one group of proponents – McCabe and colleagues – has thus far attempted the challenge.

Intricately connected to the glaciomarine framework chronology is a proposal that these ice sheet-wide oscillations can be tied to the sequence of millennial-scale climate events in the

North Atlantic (McCabe and PU Clark, 1998). There is no doubt that the ice sheet displayed dynamic behaviour and margin oscillations, and evidence records this behaviour in both the on and offshore records (e.g. McCabe and PU Clark, 1998; CD Clark and Meehan, 2001; Evans and Ó Cofaigh, 2003; Thomas *et al.*, 2004; Knutz *et al.*, 2001; Peck *et al.*, 2006). Tying the terrestrial and the marine records of millennial-scale behaviour is a considerable challenge.

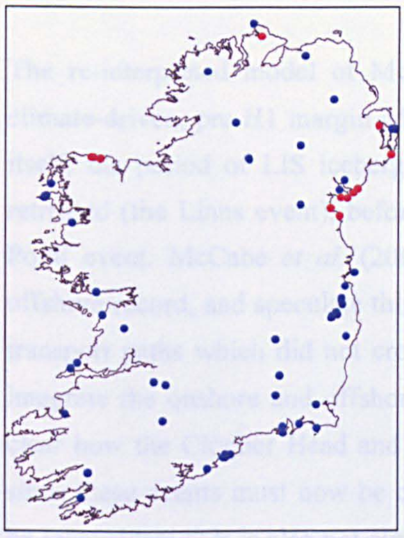


Figure 2.16 Distribution of sites which underpin the glaciomarine-based chronology (red) in context of the total distribution of dated sites in Ireland.

Heinrich 1? A readvance of the Irish Ice Sheet margin is recorded at Killard Point, Co. Down, dated initially to 14.7-13.8 ^{14}C ka (McCabe and PU Clark, 1998) and now refined to 14.2-13.8 ^{14}C ka (McCabe *et al.*, 2007b; Table 2.1). Via an association of the Killard Point moraine with the drumlin fields it bounds, this margin readvance is proposed to characterise the large eastern sector of the ice sheet and, given approximately coincident timings and flow patterns, this readvance is correlated with similar behaviour in other sectors:

- at Corvish, Co. Donegal, (15-14 ^{14}C ka, McCabe and PU Clark, 2003)
- the northern ISB: drumlin patterns in the Solway Firth and Dumfries and Galloway are correlated with the St Bees and Bride moraines in Cumbria and the Isle of Man, and interpreted as the same event (McCabe *et al.*, 1998)
- moraine bank on St. Kilda (15.2 ^{14}C ka, McCabe *et al.*, 1998)
- advance of ice in the Moray Firth (15.3 ^{14}C ka, McCabe *et al.*, 1998).

This model of ice sheet-wide readvance has found recent support from Everest *et al.* (2006) in NW Scotland, where the Wester Ross moraine has been cosmogenically dated to 17-15 cal ka.

It has been suggested that these readvances are indicative of a BIIS response to the Heinrich 1 cooling event (H1) recorded by IRD in the North Atlantic at approximately the same time (McCabe and PU Clark, 1998; McCabe *et al.*, 1998). However, this initial interpretation has been recently modified in light of new dating constraints (McCabe *et al.*, 2007b). Firstly, new dates from coastal sections around Dundalk Bay reveal not one, but two margin readvances in this area: the Clogher Head advance, which precedes the Killard Point advance. The Corvish event in Co. Donegal is now correlated with Clogher Head, rather than Killard Point. Secondly, cores from the continental margin of increasingly high resolution enable the provenance of IRD to be determined (Scourse *et al.*, 2000; Kroon *et al.*, 2000; Knutz *et al.*, 2001, 2002a; Peck *et al.*, 2006). These analyses reveal that at the time of LIS-sourced IRD deposition at both H2 and H1, i.e. Heinrich events *sensu strictu*, there is no significant change in BIIS-sourced influx at the core locations. BIIS IRD is delivered both prior to and following H2, but only pre-H1; there is no BIIS response to H1 in the IRD record (Peck *et al.*, 2006). This may be a 'real' finding or may be a false product of core location with respect to the routes of iceberg rafting.

The re-interpreted model of McCabe and others (2007b) based on new dates envisages a climate-driven, pre-H1 margin advance, the Clogher Head advance. During the Heinrich event itself, the period of LIS iceberg discharge, the ice margin on the east coast of Ireland has retreated (the Linns event), before a renewed advance immediately following H1, the Killard Point event. McCabe *et al.* (2007b) acknowledge the absence of Killard Point IRD in the offshore record, and speculate this may be due to a lower debris content of basal ice, or iceberg transport paths which did not cross the core sites. This new model is an important attempt to integrate the onshore and offshore chronologies although some uncertainties remain. It is not clear how the Clogher Head and Killard Point events relate to other BIIS margin readvances; since these events must now be considered separate in time, perhaps other correlations should be reconsidered? It is also not clear how the Linns and Killard Point events are related, if at all, to Heinrich 1. McCabe *et al.* (2007b) speculate they are events *either* driven by ocean and climate system responses to H1, such as dramatic MOC reduction, *or* independent isostatic/dynamic responses to RSL changes. The latter would seem rather coincidental given a similar pattern of events around previous Heinrich events (Scourse *et al.*, 2000; Peck *et al.*, 2006). This model and its chronology is subject to the same concerns as already discussed with regard to the glaciomarine framework for deglaciation: the validity of readvance interpretations, ice sheet-wide correlations and dating of sufficient precision to make such correlations.

Millennial-scale behaviour? An additional level of complexity to the question of BIIS dynamics in the wider North Atlantic climate system is the observation of an IRD signal derived from the BIIS with a frequency comparable to that of D-O cycles (Knutz *et al.*, 2001; Peck *et al.*, 2006). Between H2 and H1 for example, there are a potential 2-4 other IRD events. Clearly the BIIS possessed a marine margin with a variable, pulsing debris output. From the emerging chronological record it is clear the history of deglacial dynamics is more complex than a simple retreat – readvance – retreat model. However, a critical 'unknown' in interpreting the record is the palaeo-glaciological significance of IRD deposition: ice sheet advance, which enhances calving, or ice decay and flushing of icebergs (McCabe and PU Clark, 1998; Marshall and Koutnik, 2006)? A better understanding of this outstanding issue is required to make better use of the offshore sedimentological record in reconstructing the pattern and chronology of BIIS dynamics.

2.2.6.5 Chronology: summary

It is now widely accepted that the majority of land surface evidence of glaciation dates to the

Midlandian period (MIS4-2). The sequence of glaciation is, however, still unresolved. The existence of a large ice sheet in MIS4 has been little considered but recent studies suggest this may have been the case (Hagdorn, 2003; Simms, 2005; Carr *et al.*, 2006). A chronology for the extent, configuration and dynamics of the Late Midlandian Irish Ice Sheet remains piecemeal and is open to debate. A key challenge is to tie coastal and ice distal chronologies to the onshore patterns of ice dynamics. An enhanced dating programme for exposure or burial of sediments (^{14}C dating of organic horizons, OSL, cosmogenic dating) would undoubtedly constrain retreat dynamics. However, until a technique emerges which is capable of directly dating subglacial activity such as genesis of bedforms, dating internal ice flow events is limited to deriving relative chronologies (e.g. McCabe *et al.*, 1999; CD Clark and Meehan, 2001).

2.2.7 Recent advances in evidence-based palaeo-glaciology

The complexities and controversies regarding the last Irish Ice Sheet suggest that an overhaul of the traditional conceptual models of McCabe (1985) and Warren (1992) is required. Such complexities and anomalies which these models fail to capture are revealed in site-specific records of glaciation (Kinahan and Close, 1872; Meehan, 1999; Delaney, 2002; Knight and McCabe, 1997a; Knight, 2006a), regional attempts at reconstruction (McCabe *et al.*, 1999; CD Clark and Meehan, 2001) and offshore sedimentary records (Knutz *et al.*, 2001, 2002a; Peck *et al.*, 2006). Over the last decade, two models have emerged which recognise a dynamic ice sheet history and attempt to encompass complexity in the landform and sedimentary records. Whilst neither can provide a full explanation of the Irish glacial record, both are important advances in thinking from the earlier models of McCabe (1985), Warren (1992) and all the concepts which underpin them.

2.2.7.1 McCabe and colleagues: *bedforms and distal chronologies*

Two strands of work by McCabe and colleagues recognise the dynamic behaviour of the last Irish Ice Sheet and attempt to untangle a multi-temporal record. Their coastal sedimentology and dating programme aims to refine a chronological framework for deglaciation of the ice sheet (Knight *et al.*, 2004; McCabe *et al.*, 2005, 2007b; Sections 2.2.5 - 2.2.6). Through an association of margin dynamics revealed at the present-day coast with onshore bedform patterns, McCabe and colleagues attempt to tie the interior flow geometry of the ice sheet to their marginal chronology. Some limited attempt has been made to characterise the onshore sequence of flow events from subglacial bedform evidence (Knight and McCabe, 1997a; Knight, 1997, 2003b; McCabe *et al.*, 1999). The whole bedform record is captured in four phases, characterised by i) early phase of Scottish ice penetration; ii) ribbed moraine formation; iii) two phases of drumlinisation, first the generation of western drumlin fields, followed by the Killard Point Stadial (eastern drumlinisation of pre-existing ribbed moraine by ice streaming) and, finally; iv) a late south-westerly ice movement from Lough Neagh (Figure 2.17).

This model is underpinned by the bedform relative chronology. Attempts have been made to link this information to the coastal absolute chronology in order to yield an age-constrained

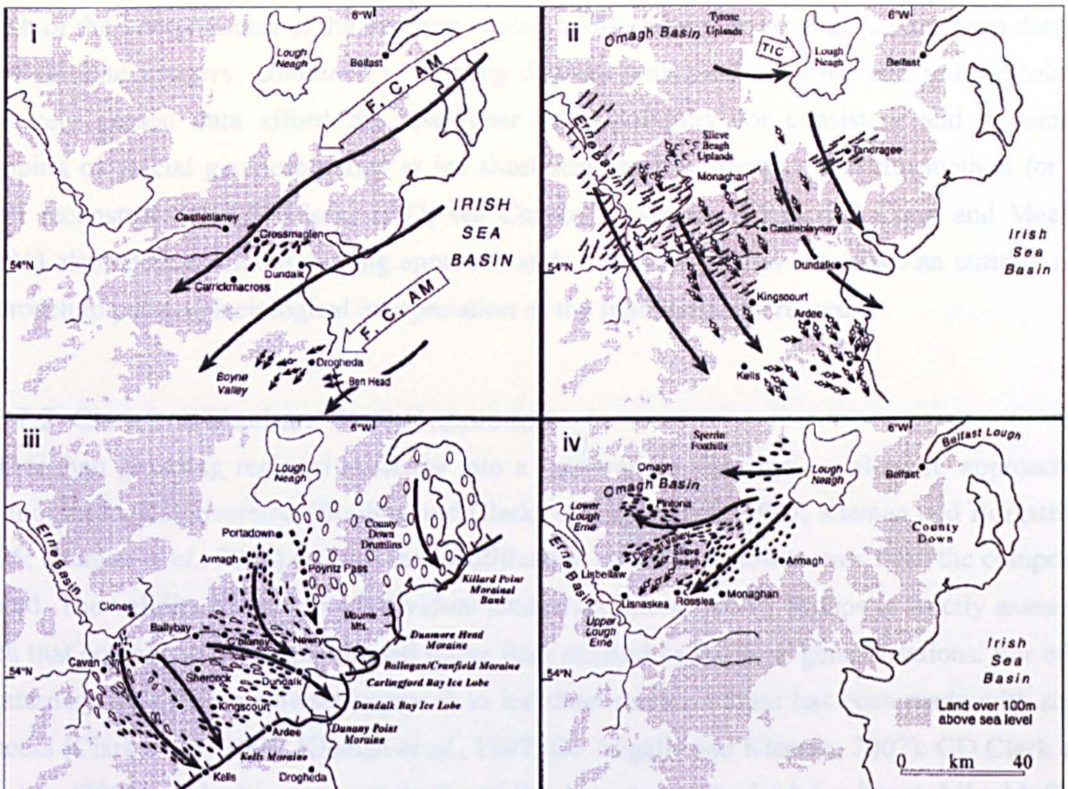


Figure 2.18 Reconstructed stages of Irish Ice Sheet flow history, based on bedform properties in north and eastern Ireland. From McCabe *et al.* (1999).

model of ice flow geometry and ice sheet evolution. Whilst the temporal framework for coastal sections is detailed (discussed above) such an attempt rests on the security with which marginal chronologies can be tied to the intricacies of interior flow patterns. Which flow patterns specifically relate to which marginal event? It is not clear how such proposed links should be interpreted or modified in light of new evidence of multiple margin readvances over the same ground (McCabe *et al.*, 2007b). At ice sheet-scale schematic models continue to use regionally generalising ice flowlines and these questions remain unsatisfactorily answered (Figure 2.18).

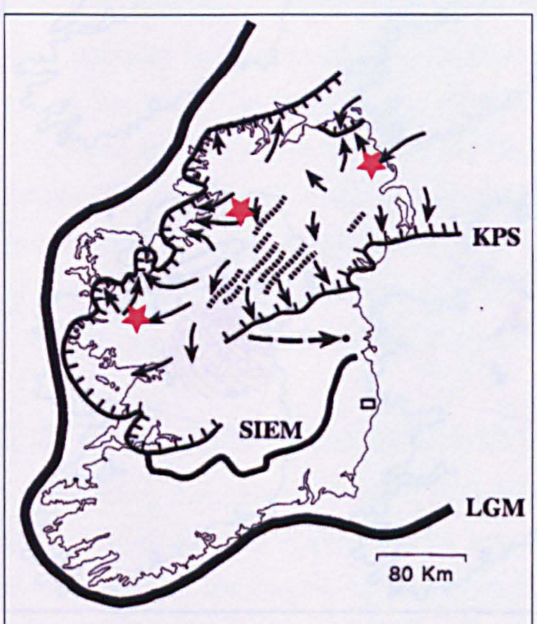


Figure 2.19 Ice flow patterns according to McCabe and PU Clark (2003) (from Farrell *et al.*, 2005). There is an attempt to recognise different stages of ice flow: three independent margins are drawn and a different ice sheet configuration is inferred for each stage. However, within a single stage implausible flow geometries remain: note several flow arrows, starred, which are not compatible with their neighbours. The generalised flow arrows mask the complexity which McCabe *et al.* (1999) revealed earlier.

Much of the interpretation of the bedform record by McCabe's research group has been derived from satellite imagery, combined to varying degrees with field mapping and sedimentology. Remotely sensed data afford the researcher an opportunity for consistent and systematic mapping of glacial geomorphology at ice sheet-scale and is therefore a useful method for ice sheet reconstruction (CD Clark, 1997; see Chapter 3, section 3.3.2). CD Clark and Meehan (2001) also adopt a remote sensing approach and, furthermore, they introduce an entirely new approach to palaeo-glaciological interpretation of the Irish landform record.

2.2.7.2 Clark and Meehan: *flowset approach*

Rather than grouping regional evidence into a 'generalised flowline', a 'flowset' approach to geomorphological inversion (Boulton and Clark, 1990a,b; Clark, 1997; Kleman and Borgström, 1996; Kleman *et al.*, 2006) enables the identification of discrete flow events from the composite record. The validity of grouping individual landforms into summary groups is strictly assessed, such that complexities are highlighted rather than masked by regional generalisations. For other Quaternary ice sheets a flowset approach to ice sheet reconstruction has been made with some success (Clark *et al.*, 2000; Kleman *et al.*, 1997; De Angelis and Kleman, 2007); CD Clark and Meehan (2001) apply this approach to the midlands sector of the Irish Ice Sheet. Like McCabe *et al.* (1999), they also identify four main stages (Figure 2.19). However, their model differs dramatically in ice sheet configuration and flow geometry. After the same early Scottish advance of ice, Clark and Meehan (2001) reconstruct a major phase of bedforming which

Figure 2.19 Model of ice sheet history derived from a flowset approach to ice sheet reconstruction in which the multi-temporal nature of the onshore flow pattern record is recognised. CD Clark and Meehan (2001) reconstruct four phases characterised by ice divide migration and configuration change. Changes are thought to be steady responses to forcing, without invoking readvances to explain the landform record. This reconstruction is based solely upon the bedform record in central Ireland; a reconstruction from the countrywide record has hitherto not been attempted.

requires an ice divide over eastern counties and westerly ice flow towards the present-day west coast. This phase precedes the formation of ribbed moraine in the east which McCabe *et al.* (1999) propose as their second phase. In Clark and Meehan's model, a close genetic relationship between ribbed moraine and drumlinisation is interpreted, and occur under the same overall ice flow geometry, their phase C. A late north-eastwards flow of ice is associated with final deglaciation. Clark and Meehan's flowset model yields an ice sheet that undergoes a regionally significant ice divide migration, and does not require readvances to explain the bedform record.

Both these new models present evolving ice sheet geometries and capture the interior ice flow dynamics more securely than preceding models which have focussed more on moraines and marginal sites. However, the chronology of events described by Clark and Meehan is only relative and that of McCabe and colleagues rests on the security of bedform – marginal sequence correlations. Neither model well-addresses the pattern or mode of retreat, and their focus remains spatially limited to the north midlands. Neither the model put forward by the McCabe group nor the model of Clark and Meehan captures both the interior *and* marginal patterns and chronology of ice sheet evolution at ice sheet-scale.

2.2.8 Key unknowns from evidence-based palaeo-glaciology

Despite recent attempts to address the complexities of the Irish glacial record, and their poor capture in conceptual models of the ice sheet, certain basic properties of the last Irish Ice Sheet remain poorly constrained. The major flow patterns of the ice sheet have long been recognised, but remaining key unknowns include:

- Position and configuration of ice divides and centres
- Spatial ice sheet extent: offshore? To what limit?
- Vertical ice sheet extent: significance of trimlines?
- Geometry and behaviour of flow patterns
- Pattern of margin retreat and framework of deglaciation
- Evolution of each of the above properties
- Interplay between ice sheet dynamics and potential drivers of change
- Correlation of events with the wider climate system.

Any reconstruction of the last Irish Ice Sheet, using any approach, must seek to address these outstanding questions. Ice sheet reconstructions, which confidently capture the key geometric properties of an ice sheet, and provide a chronology for their evolution, serve as an essential test of numerical ice sheet modelling experiments. These are the most powerful tools for exploring the latter 'unknowns' – the interplay between the ice sheet and the wider Earth system.

2.3 Theoretical approaches to palaeo-glaciology

In reviewing our current status of knowledge of the last Irish Ice Sheet, I treat the insights arising from different approaches to ice sheet reconstruction (numerical approaches versus evidence-based; see Section 1.3 and Chapter 3) separately for two reasons. Firstly, applications of modelling techniques to the BIIS are limited in number and it is not appropriate to judge what contributions have been made, or areas in which it has not been successful, until this field of research is at a more mature stage. To date, there is only one forward modelling study from the modern generation of three-dimensional, thermomechanical ice sheet models which focuses at full ice sheet-scale on the last BIIS (Boulton and Hagdorn, 2006; see also Hagdorn, 2003), although there have been recently reported attempts using independent models to address this task (Hubbard *et al.*, 2007; Vieli *et al.*, 2007). Secondly, notwithstanding the infancy of BIIS modelling, numerical and geological approaches have largely failed to engage with each other. It is likely that success may only be achieved once the approaches work in tandem, once geological reconstructions are made available for rigorous tests of modelled ice sheets. In this section, I consider the preliminary insights arising from numerical approaches to ice sheet reconstruction and highlight the potential of combined approaches to the problem.

2.3.1 Numerical ice sheet modelling

Insights from numerical modelling regarding the last Irish Ice Sheet inevitably stem from modelling efforts concerned with the whole BIIS. Although at least partly driven by independent dynamics, the last Irish Ice Sheet was but a sector of the whole. It would be inappropriate to consider it separately from the British Ice Sheet in a modelling initiative.

The earliest attempts to apply glaciological principles to reconstructions of the BIIS were semi-geological and semi-numerical in nature and cannot be considered as true numerical ice sheet simulations (Boulton *et al.*, 1977, 1985, 1991). Rather, these were a type of inverse approach in which the ice sheet extent, flowlines and retreat isochrons, reconstructed from geological evidence, were used as input to two-dimensional flowline models to explore other ice sheet variables. Surface profiles along a flowline were calculated, revealing ice thickness, ice divide locations and ice velocities (Figure 2.20). Reconstructed ice sheets vary widely, from the 1977 'maximum' model of Boulton *et al.* (maximum ice thickness contour 1800 m; max. contour over Ireland 1400 m; confluence of BIIS and FIS over North Sea) to their 1985 'minimum' model (max. contour 1000 m; max. over Ireland 750 m; no BIIS-FIS confluence).

Figure 2.20 Varying reconstructions of Boulton *et al.* (1977, 1985, 1991). Modified from Clark *et al.* (2006).

More recent numerical models aim to capture a more complete description of ice flow physics in three dimensions, driven by climate and basal boundary conditions and leaving geological data available for a critical test of the model output. Until recently, the application of more sophisticated models in the British Isles has focussed on specific sectors or regions (e.g. Payne and Sugden, 1990; Hubbard, 1999). There has been only one attempt to use a climate-driven, three-dimensional thermomechanical model to reconstruct the BIIS at full ice sheet-scale (Boulton and Hagdorn, 2006; see also Hagdorn, 2003). Boulton and Hagdorn (2006) take an exploratory approach to reveal some general glaciological characteristics and behaviour of the BIIS, rather than trying to precisely match specific geological data. Rather, they aim to broadly capture the main elements of the ice sheet. There are a number of interesting findings regarding the controls upon the behaviour and form of the last ice sheet:

- Ice streams develop dynamically ('dynamic' or 'ephemeral' streams) in addition to the 'fixed' ice streams which develop over a prescribed 'slippy' bed. The large, stable, fixed streams produce more realistic ice surface elevations than a rigid bed experiment. Ice streams, dynamic or fixed, account for 60-85% of ice discharge.
- Readvances in the Irish Sea can arise from unforced oscillations of the margin, i.e. dynamic rather than climatically forced.
- Surface elevations cannot match trimlines with justifiable ice physical parameters.
- No substantial RSL change arises, even though isostatic physics is included in the model. This result provides little support for conceptual models of deep glaciomarine margin environments (Eyles and McCabe, 1989).
- The key determinants of the overall form and behaviour of the ice sheet are the bed conditions, ice surface temperature and the ice 'softness' parameter of the flow law. Relatively soft ice (anisotropic fabrics with more impurities such as high debris content) produces a more 'realistic' BIIS when judged qualitatively against geological models.
- The BIIS is very sensitive to the climate driver, in particular the continentality gradient from W-E across the ice sheet. A small change in the position or magnitude of this gradient determines confluence of the BIIS and FIS over the North Sea. Similar findings are reported in independent preliminary attempts to model the BIIS by Hubbard *et al.* (2007) and Vieli *et al.* (2007).

With regard specifically to the Irish Ice Sheet, it is apparent that modelling initiatives to date have been largely unsuccessful at replicating either the extent or the complexity of ice flow indicated by the geological evidence. Of course it must be modelled as part of the whole BIIS, but most modelled ice sheets simply capture Ireland as an extremity to the main ice sheet, displaying little independence in terms of ice centres or dynamics. A challenge for future modelling is to better consider the geological evidence both from Ireland, and from the internal regions of the ice sheet rather than simply margins. Evidence-focussed researchers need to provide this, and a more rigorous approach to model testing than current 'eye-balling' assessments and margin matching could lead to better models and model simulations.

2.3.2 Glacio-isostatic modelling

Models of the glacio-isostatic process comprise three elements: a prescribed ice loading history, an Earth model which determines the response of the Earth to the ice loading, and a global sea level model which redistributes ocean water in response to (de)glaciation (Shennan *et al.*, 2006). The combined local effect of these three processes manifests itself as sea level change relative to the present-day, and an *observed* RSL history reconstructed from geological sea level markers can verify models of glacio-isostasy. If the Earth model parameters and global sea level history are known, by iteratively refining and matching the prescribed local ice loading to the observed RSL curves, insights may be gained into the likely configuration and evolution of the ice sheet.

As yet, no unique ice loading history has emerged from experiments applied to the British Isles (Lambeck, 1993a,b, 1995, 1996; Peltier *et al.*, 2002; Shennan *et al.*, 2002; Figure 2.21). None can successfully predict all RSL curves in the current database (Shennan *et al.*, 2006), in particular along the north-west coast of England and Wales, and in NW Scotland. Shennan and colleagues' (2006) recent effort does, however, reveal some interesting insights. They refine the ICE-4G model of Peltier *et al.* (2002; Shennan *et al.*, 2002) and obtain a 'reasonable' fit for the majority of the 59 British RSL curves under the following prescribed conditions:

- Glaciation of the North Sea and western continental shelf
- Ice surface elevation is matched approximately to Scottish trimlines, at ~1000 m.
- An advance to the Scilly Isles is prescribed at ~24 cal ka, coincident with readvance into the North Sea.
- The extent of ice over Ireland follows Warren (1992) and extends offshore
- Readvances are prescribed at 18 and 13 cal ka (Killard Point and Younger Dryas).

An ice model with these characteristics drives the glacio-isostatic model and achieves a reasonable fit with the database of RSL curves. There are a few acknowledged misfits. The NW England RSL curves are not successfully matched, and those sites with longer time records suggest there is insufficient ice in the model at 16-15 cal ka; this may reflect the early description of the Killard Point event at 18 cal ka, at least 1ka earlier than field reconstructions suggest. Interestingly, the choice of 'thick' or 'thin' ice over the North Sea has little effect on model predictions at all but two sites in NE Scotland.

The above experiment considers only the model fit against a British suite of RSL data. Remarkably, a thorough and objectively compiled RSL database has only recently been achieved and released for Ireland (Brooks and Edwards, 2006). This database is the first attempt to rigorously assess the quality and distribution of previously published Irish sea level change information. It has been found that whilst a wealth of qualitative RSL data exists there is a paucity of reliable and precise quantitative information, particularly from northern regions and from pre-10 cal ka, where data is only considered to be 'limiting data' rather than direct sea level index points. These 'limiting dates', treated with more caution, include the body of AMS dates from glaciomarine muds since these are the source of such controversy (McCabe *et al.*,

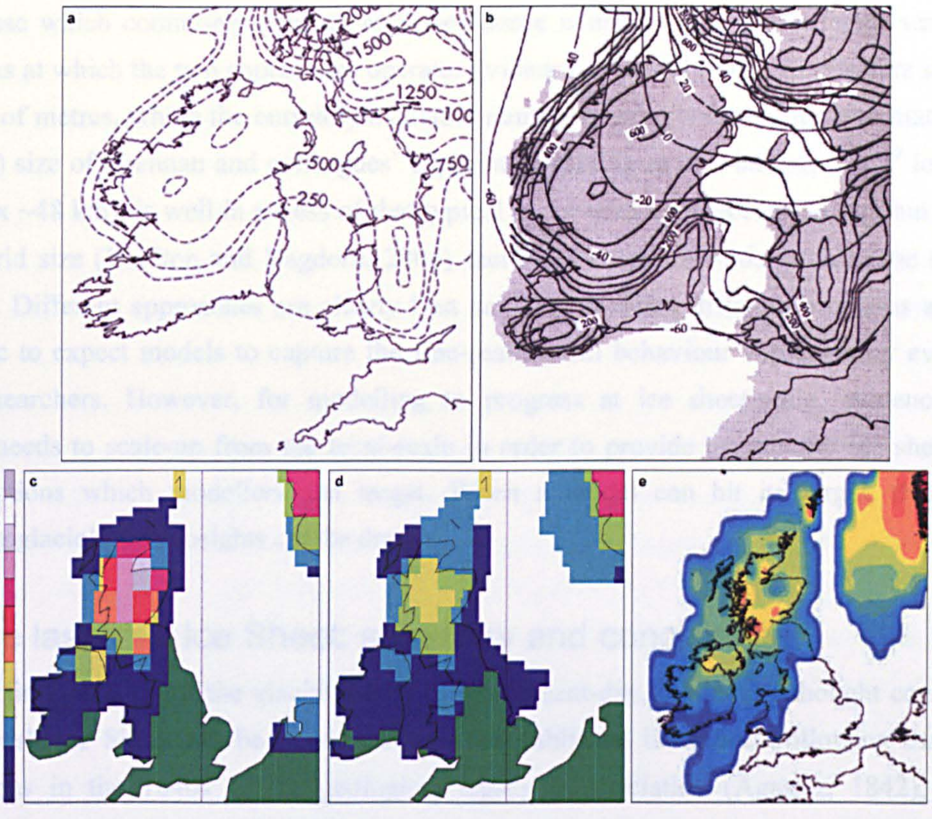


Figure 2.21 Varying LGM ice configurations determined by glacio-isostatic modelling experiments. **a)** Lambeck (1993b); **b)** Lambeck (1996), modifications over Ireland & ISB; **c)** Peltier *et al.* (2002), global ICE-4G model; **d)** Peltier *et al.* (2002), modifications to British Isles in light of trimline evidence; **e)** Shennan *et al.* (2006), 'thick ice'.

2005; McCarroll, 2001). Brooks *et al.* (2008) use this database of RSL information to guide a refinement to the ice model of Shennan and colleagues (2006) and improve the fit of predictions with RSL observations from Ireland. They find a better result is achieved if ice over the midlands of Ireland and the Irish Sea Basin is thickened during the LGM, relative to Shennan's model, and find that rapid thinning and deglaciation is required from 21 cal ka.

No single experiment has, as yet, considered the whole British-Irish Ice Sheet with respect to a full dataset of RSL information. Furthermore, glacio-isostatic models continue to be forced by ice models which, as shown throughout this chapter, are still contested heavily by those researchers who focus upon evidence-based reconstruction. A better integrated effort between the latter approach, glacio-isostatic and glaciological modelling would likely yield a more meaningful and insightful reconstruction of the last Irish Ice Sheet.

2.3.3 Modelling approaches: summary

The application of sophisticated physically-based models to the investigation of the British-Irish Ice Sheet is a powerful tool for exploring the glaciology of the ice sheet and its links to the wider Earth system. Experiments published in recent years reveal some interesting and exciting insights regarding the ice sheet's dynamics. However, accurate simulation of the ice sheet, which is ultimately required in order to make meaningful experiments, is in its infancy. Models require rigorous testing with detailed, ice sheet-wide evidence-based reconstructions.

An impasse which commonly plagues model-evidence comparison is the different scales and resolutions at which the two approaches operate. Evidence-focussed research considers scales of 10s-100s of metres, which the currently available numerical models cannot hope to match. The grid (cell) size of Shennan and colleagues' experiment (2006), at 0.7^0 latitude x 0.7^0 longitude (~77 km x ~48 km), is well in excess of that typical of forward ice sheet modelling, but even at ~10km grid size (Boulton and Hagdorn, 2006) there is a significant mismatch in the scale of approach. Different approaches are clearly best suited to tackling different problems and it is unrealistic to expect models to capture the fine-scale, local behaviour witnessed by evidence-based researchers. However, for modelling to progress at ice sheet-scale, evidence-based research needs to scale-up from the local-scale in order to provide meaningful ice sheet-wide reconstructions which modellers can target. When a model can hit its target, then some interesting glaciological insights can be drawn.

2.4 The last Irish Ice Sheet: summary and conclusions

From the first proposal of the glacial theory to the present-day, schools of thought concerning the last Irish Ice Sheet can be traced through the published literature. Following the initial observations in the 1840s of the geological legacy of glaciation (Agassiz, 1842), glacial evidence was documented throughout Ireland and brought together by Close, in 1867. Close described a model of an ice sheet covering the whole landmass, extending onto the continental shelf, and nourished from the local (i.e. Irish) mountain ranges. Hull's model (1878), presented shortly afterwards, was alleged to closely follow the work of Close, but in fact described an alternative ice sheet configuration. Two conceptual ice sheet models were thence established in Irish literature, and these models have underpinned glacial research in Ireland ever since.

For the first half of the 20th century, the focus of research remained at the ice sheet-scale, but attention turned to fleshing out the details of the overriding models. It was Hull's model, rather than Close's, which dominated thinking, though it underwent a major revision in light of a research focus on ice sheet limits. In the south of Ireland, an ice sheet terminating at the Southern Ireland End Moraine (Carvill Lewis, 1894) became the established view, following the seminal paper of Charlesworth (1928b). Not only at the SIEM, but around the western and northern coasts of Ireland, a terrestrial terminating ice sheet was proposed on the basis of an 'Older Drift' and a 'Newer Drift' and the corresponding appearance of landscape 'maturity' (Farrington, 1947, 1954; Synge and Stephens, 1960; Stephens and Synge, 1965; Synge, 1968, 1969, 1970. A 'limited' ice sheet with Hull's single axis structure became the established model of Irish glaciation, and still influences thinking today (e.g. Bowen *et al.*, 2002; Knight *et al.*, 2004).

The 1960s saw the publication of a countrywide glacial map, which provided a schematic view of the main landform and sediment relationships in Ireland (Synge and Stephens, 1960; Synge, 1970). The observed spatial relationships between drumlin fields and proposed moraine positions led to an assumption of a genetic link, which in turn stimulated the concept of the

'Drumlin Readvance' (Synge, 1970). This apparent readvance has been a lasting feature of Irish glacial research (McCabe, 1985; Bowen *et al.*, 1986; Hoare, 1991; McCabe *et al.*, 1998) but still proves contentious (Warren, 1992; CD Clark and Meehan, 2001; Meehan, 2004, 2006).

In the decades following the publication of the glacial map, the focus of research has shifted away from geomorphology. Geomorphology, stratigraphy and sedimentology became separate sub-disciplines, and the lack of agreement between overriding conceptual models is likely, in part, a product of different research approaches. The ascendancy of sedimentology was accompanied by a change in the scale of research. The last half of the last century can be seen as a time in which the research focus became ever more localised and detached from the ice sheet-wide picture, from the regional, to the local, and finally to the site-specific scale. This approach has provided high levels of information of site-specific palaeo-glaciological environments (Dardis *et al.*, 1984; Dardis, 1987; Hanvey, 1987; McCabe *et al.*, 1984; McCabe, 1987; McCabe and Dardis, 1994), but this information has often become detached from its spatial component. The last decade or so has seen an abrupt return to the broad-scale. Remotely sensed data have revolutionised Earth sciences, and the increasing recognition of the integral role of ice sheets in the wider Earth system has shifted attention back to the ice sheet-scale (McCabe and PU Clark, 1998; CD Clark and Meehan, 2001; McCabe *et al.*, 2005, 2007b).

Throughout the changing fashions – 'little ice', 'big ice', readvances, big-scale, local-scale, geomorphology, sedimentology – Irish glacial research has been dominated by overriding conceptual models of the ice sheet's configuration. The original ideas of Close (1867) and Hull (1878) manifest themselves over 100 years later through the models of Warren (1992) and McCabe (1985). The danger of ice sheet models so firmly entrenched in the scientific consciousness is that ideas propagate through subsequent literature regardless of their original founding. After ~80 years the SIEM is no longer (generally) accepted as the maximum limit of the last ice sheet. In a similar way, the basis for a large-scale 'drumlin' readvance (Synge, 1970) – the genetic association between drumlins and moraines – has been undermined by a number of workers (Warren, 1992; Knight, 1999; CD Clark and Meehan, 2001; Meehan, 2004, 2006) but the readvance concept is firmly entrenched. Recent work on the deglacial chronology support oscillating margins (McCabe *et al.*, 1998, 2005, 2007b; McCabe and PU Clark, 2003) but further efforts are required to prove a model of a spatially significant readvance. It has been argued by Meehan (2004) that the long-standing conceptual models of the last Irish Ice Sheet act as straightjackets rather than loose frameworks, into which new evidence is automatically subsumed rather than providing a critical test of an existing idea.

In recent years it has been realised that neither the traditional McCabe nor the Warren models of the 1980s-1990s are satisfactory. Marginal chronologies and landform associations have revealed the multi-temporal nature of the last glaciation, and a model is required which can capture changing ice sheet dynamics throughout its evolution. McCabe and colleagues (McCabe *et al.*, 1998, 1999, 2005, 2007b; McCabe and PU Clark, 2003; Knight *et al.*, 2004), and CD

Clark and Meehan (2001) present new models for sectors of the ice sheet but neither satisfactorily describe all the basic ice sheet properties, geometries or evolution at ice sheet-scale. A key limitation of approaches to date is their attempt to reconstruct the 'big picture' from too little data. The evidence clearly demonstrates a dynamic ice sheet, but how can we hope to fully understand its behaviour with only fragments of information? It is understandable that hard-won data is interpreted in its wider context. In this thesis, it is hoped that ice sheet-wide mapping will provide a stronger foundation for ice sheet-wide interpretation.

Numerical modelling offers an exciting opportunity to capture the big picture of former glaciation and address wider Earth system questions. However, simulation of the past Irish Ice Sheet will be hindered by inadequate evidence-based reconstructions to target. It is clear that no single approach, be it geomorphology, sedimentology, ice sheet or glacio-isostatic modelling, will be capable of solving reconstruction problems alone, and different approaches are best suited to different scales of research. To address the ice sheet-scale, observational evidence must be interpreted to match the scale of ice sheet models. To address the local-scale, the big picture must provide the contextual framework for interpretation of local dynamics. For progress in understanding palaeo-ice sheets, their geometry, their behaviour, their evolution, and their interaction with the wider Earth system, an holistic approach which combines evidence, glaciological and Earth system modelling is essential (Andrews, 1982).

Chapter 3. Observational-based palaeo-glaciology: the role of geomorphology in ice sheet reconstruction

3.1 Introduction

Two approaches can usefully be pursued to reconstruct former ice sheets: numerical methods, based upon physical laws, either of ice flow mechanics or of upper Earth physics; and observational methods based upon interpretation of the landscape legacy of glaciation. Chapter 2 discussed the roles these approaches have played in the development of knowledge and understanding of the last Irish Ice Sheet. This thesis uses an evidence-based approach, and this chapter discusses the basis and development of the approach.

The use of the geomorphological record for palaeo-glaciological reconstructions has been neatly conceptualised by Kleman *et al.* (2006; Figure 3.1). It is the left-hand side of this diagram in which we are interested for the purpose of ice sheet reconstruction. For this purpose, we would ideally have a full understanding of the right-hand side, the landform genesis problem. However, our understanding is far from complete, and therefore a suite of assumptions are required in order to make use of what we do know of landform genesis to inform our palaeo-glaciological reconstructions. We then need a method by which to get from our observations, with our genetic assumptions, to a reconstruction of a former ice mass.

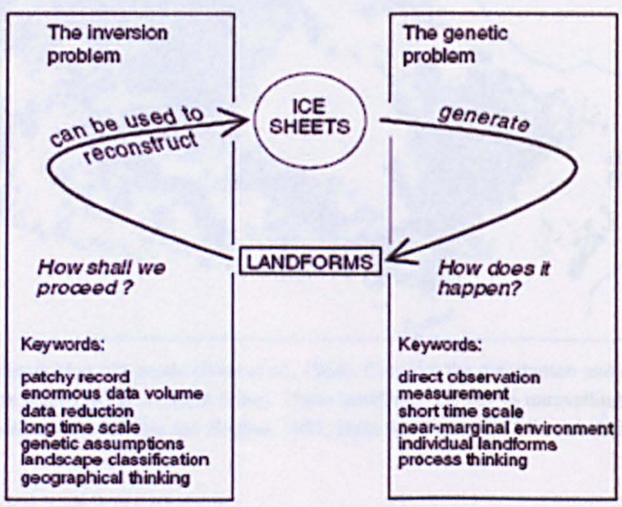


Figure 3.1 Conceptualisation of the problem of palaeo-glaciological reconstruction (Kleman *et al.* 2006).

Section 3.2 considers the elements of the geomorphological record which are employed for ice sheet reconstruction and how the 'genetic problem' is tackled. This is followed by a discussion in Section 3.3 of the potential approaches which may be undertaken to 'invert' the geomorphological record for an ice sheet history. This chapter is then summarised in Section 3.4, in a clear statement of the assumptions employed for interpreting landform patterns, and the approach followed for ice sheet reconstruction.

3.2 Glacial landforms for palaeo-glaciology

A wealth of different landforms and glacial features have been used for over a century at a variety of scales to derive palaeo-glaciological information. Key indicators of former ice flow have traditionally been striae, erratic boulders, till fabrics and carriage of clast erratics in tills (e.g. Charlesworth, 1953; Shilts, 1980; Dyke and Morris, 1988; Parent *et al.*, 1995; Kjaer *et al.*, 2003). In Ireland, where the term 'drumlin' was first introduced, these glacial lineations are widespread and early in the history of their investigation were interpreted to indicate ice flow direction (Close, 1867; Hull, 1878; see Chapter 2). However, it is only when one considers the bed of, say, the much larger Laurentide Ice Sheet (Figure 3.2; Prest *et al.*, 1968) that the ubiquitous nature of the subglacial bedform is realised. *Subglacial bedforms* are now used as a key ingredient in ice sheet reconstruction. Less attention has been paid to *meltwater traces* as a palaeo-glaciological tool (at an ice sheet-scale), but again, consider their distribution and abundance in Figure 3.2, and therefore their utility for understanding deglacial histories. Finally, *moraines* are the third landform group considered here for ice sheet reconstruction.

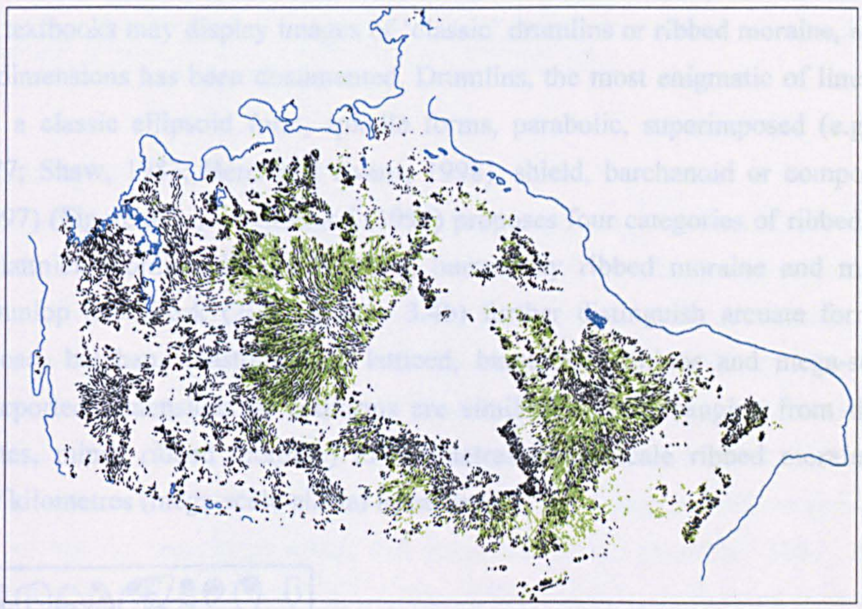


Figure 3.2 Data from the Glacial Map of Canada (Prest *et al.*, 1968). Consider the distribution and density of subglacial lineations (black) and eskers (green) with regard to the ice limit (blue). These landforms are key to unravelling a palaeo-glaciology of the ice sheet, and most LIS reconstructions (e.g. Denton and Hughes, 1981; Dyke and Prest, 1987) have relied heavily on such patterns.

3.2.1 Subglacial bedforms

3.2.1.1 Landform descriptions

Subglacial bedforms are accumulations of sediment moulded underneath the ice sheet, developed into either streamlined and elongate or ripple/wave like ridges. *Lineations* is a collective term for any bedform streamlined by ice flow: drumlins, crag and tails, flutes, mega-scale glacial lineations, and bedrock features such as roches moutonnées and whalebacks. *Ribbed* (or Rogen) *moraine* are ridges oriented perpendicular to lineations, and therefore transverse to the direction of ice flow. Subglacial bedforms tend to develop in 'fields', i.e. as a suite of landforms, rather than individual features occurring in isolation (Figure 3.3).

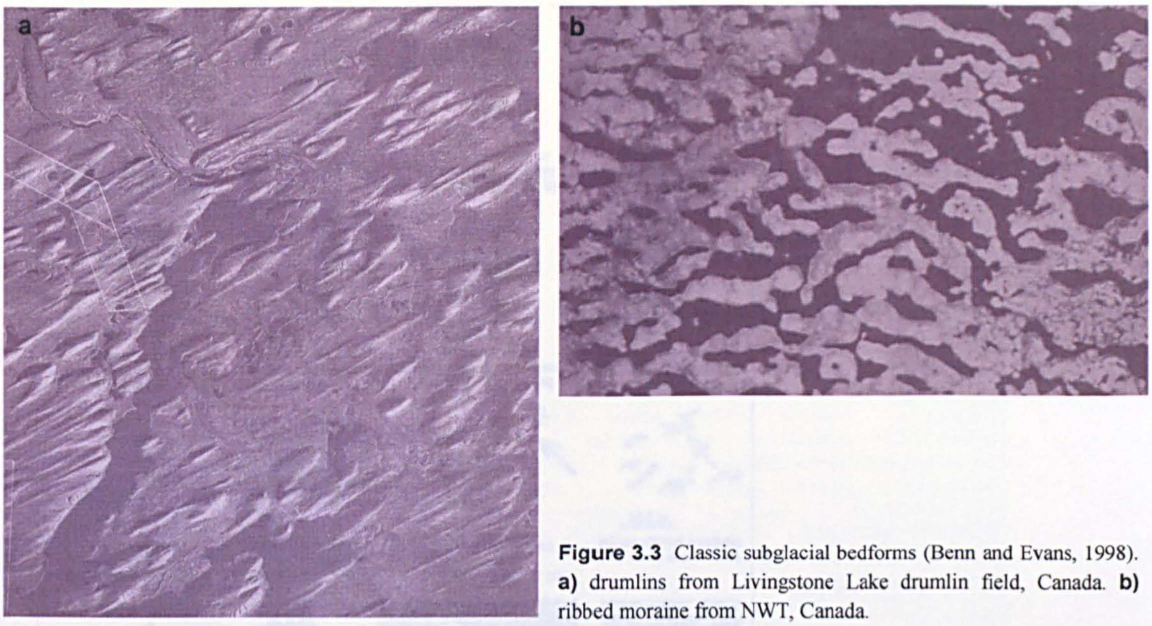


Figure 3.3 Classic subglacial bedforms (Benn and Evans, 1998). **a)** drumlins from Livingstone Lake drumlin field, Canada. **b)** ribbed moraine from NWT, Canada.

The terms 'lineations' and 'ribbed moraine' encompass a large range of landform morphologies and, whilst textbooks may display images of 'classic' drumlins or ribbed moraine, a plethora of forms and dimensions has been documented. Drumlins, the most enigmatic of lineations, may conform to a classic ellipsoid form, spindle forms, parabolic, superimposed (e.g. Rose and Letzer, 1977; Shaw, 1983; Benn and Evans, 1998), shield, barchanoid or compound shapes (Knight, 1997) (Figure 3.4a). Hättestrand (1997) proposes four categories of ribbed moraine in Sweden: Blattnick moraine, Rogen moraine, hummocky ribbed moraine and minor ribbed moraine. Dunlop and Clark (2006; Figure 3.4b) further distinguish arcuate forms, blocky, angular, broad, barchan, anastomosing, latticed, hummocky, minor and mega-scale ribbed moraine. Reported dimensions of bedforms are similarly varied, ranging from the order of metres (flutes, minor ribbed moraine) to kilometres (mega-scale ribbed moraine) to tens-hundreds of kilometres (mega-scale glacial lineations).

a

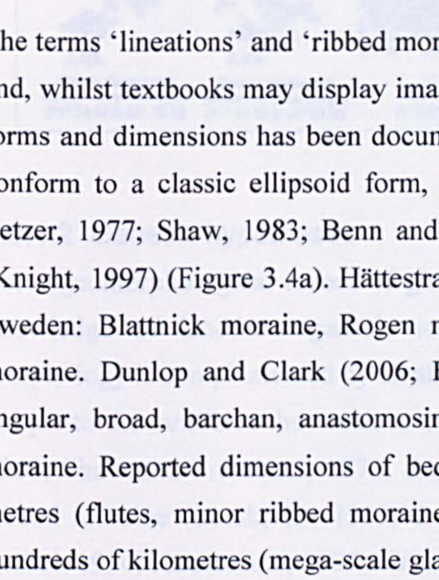
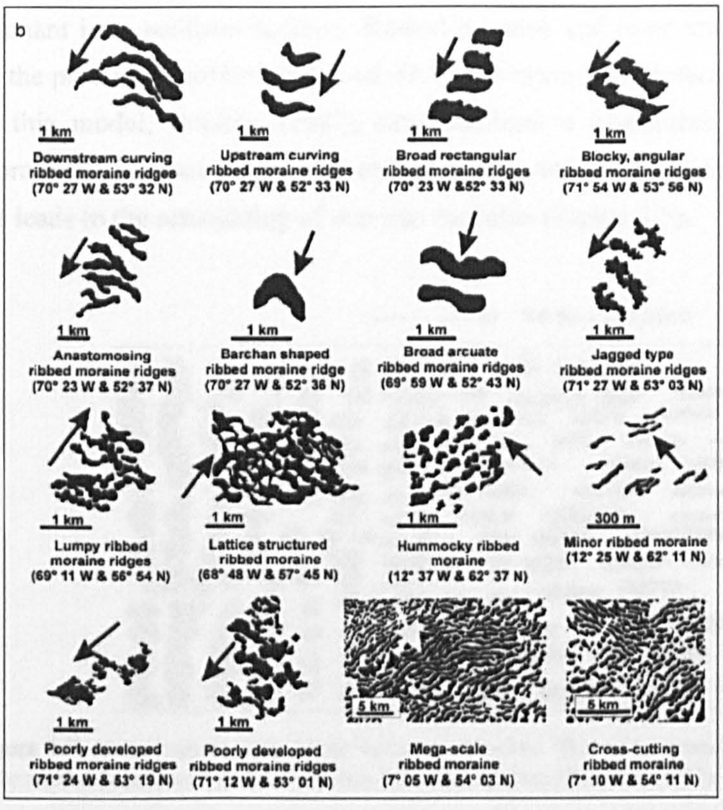


Figure 3.4 Subglacial bedforms are characterised by diverse morphologies. **a)** drumlin planforms from Finland (Gluckert, 1973; in Benn and Evans, 1998). **b)** ribbed moraine morphologies (Dunlop and Clark, 2006).



3.2.1.2 Genesis hypotheses

For a geomorphological record of glaciation to deliver palaeo-glaciological information some knowledge of landform genesis is essential. The variety which characterises bedform morphology is complemented by an abundance of formation hypotheses. Certain discussions are unique to the landform they seek to explain, either drumlins (Flint, 1947; Smalley and Unwin, 1968; Shaw and Freschauf, 1973; Rose, 1987; Menzies, 1987, 1989; McCabe and Dardis) or ribbed moraine (Lundqvist, 1969; Bouchard, 1989; Aylsworth and Shilts, 1989; Sollid and Sørbel, 1994; Hättestrand, 1997). Others propose a unifying theory of bedform genesis which is capable of explaining both longitudinal and transverse forms (Boulton, 1987; Boulton and Hindmarsh, 1987; Shaw, 1983). A full discussion of bedform genesis theories exceeds the scope of this thesis; the key theories which have a bearing on our palaeo-glaciological interpretation of a geomorphological record are commented on below.

Bed deformation model. The most widely accepted theory of bedform genesis is based on a model of sediment deformation (Boulton, 1987; Boulton and Hindmarsh, 1987). As ice rides over a bed of soft sediments (as opposed to bedrock) the sediment is redistributed by deformation; bed deformation is not just a passive response to ice movement but rather accounts for some of the forward motion of the ice (Boulton and Hindmarsh, 1987). Natural heterogeneity of the till substrate produces patches which are more prone to deformation whilst other regions are stronger or stiffer, remaining static or only slowly deforming under glacially imposed stresses. Such stiff bodies of till act as more rigid cores of bedforms, whilst more easily deformed material is readily swept downstream, flanking streamlined landforms and leaving remnant inter-bedform hollows. Ribbed moraine and more stunted bedforms are interpreted to be the product of stiffer patches of till, whilst drumlins represent the streamlining of these cores. In this model, Boulton (1987) conceptualises a continuum of bedforms, of which ribbed moraine and lineations are two end-members, and in which time and the streamlining flow of ice leads to the remoulding of one into the other (Figure 3.5).

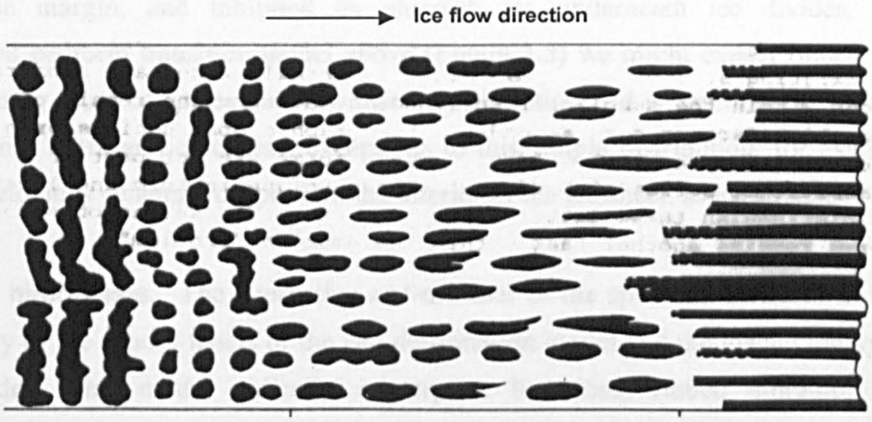


Figure 3.5 Spatial transition from ribbed moraine to lineations. The two are considered end-members of a bedform continuum under a bed deformation model (from Menzies, 1987; also Boulton, 1987; Rose, 1987).

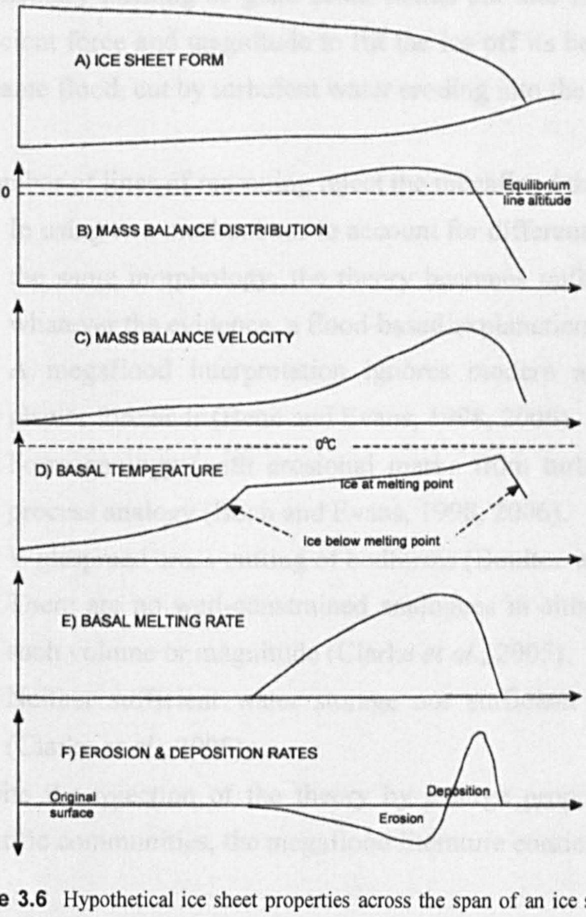


Figure 3.6 Hypothetical ice sheet properties across the span of an ice sheet (from Boulton *et al.*, 2001). Geomorphic work (F) follows velocity (C) and therefore we expect to find bedforms in the more distal zones of the ice sheet.

The bed deformation theory for genesis of a landform can be followed to some logical conclusions. Bed deformation, and therefore bedform genesis, requires a warm-based subglacial regime. Associated with this is an implication for basal ice velocity (Figure 3.6). Along an ice sheet profile (span) we expect velocity to rise to a maximum near the equilibrium line, and tail off towards the margin; it follows that the capacity of the system for geomorphic work should follow the same trend. Bedform genesis should be most prolific near the equilibrium line and towards the margin, and inhibited by sluggish ice underneath ice divides. Given the hypothesised bedform transition model above (Figure 3.5) we might expect ribbed moraine to dominate inner areas of an ice sheet, whilst drumlinisation and streamlining characterises the outer regions. There are, of course, exceptions to this simple distribution, for example where faster ice velocities penetrate deeper into the interior of the ice sheet, as ice streams.

Megaflood hypothesis. The alternative end-member of the spectrum of bedform hypotheses rejects many of the central tenets of the bed deformation model and the glacial theory on which it is founded. This model radically reinterprets lineations, ribbed moraine, and many glaciofluvial erosional forms as the product of large subglacial floods (Shaw, 1983, 1989, 2006; Shaw and Kvill, 1984; Munro and Shaw, 1997). Drumlins and ribbed moraine are accounted for under this model by either of two mechanisms. Bedforms are *either* interpreted as the sedimentary infilling of giant scour marks cut into the base of the overlying ice by floods of sufficient force and magnitude to lift the ice off its bed, *or* bedforms are erosional remnants of the same flood, cut by turbulent water eroding into the bed.

A number of lines of reasoning reject the megaflood theory for bedform genesis:

- In using two mechanisms to account for different sedimentological records in landforms of the same morphology, the theory becomes unfalsifiable (Benn and Evans, 1998, 2006): whatever the evidence, a flood-based explanation can be found.
- A megaflood interpretation ignores modern analogues of subglacial streamlining on glacier forelands (Benn and Evans, 1998, 2006).
- Form analogy (with erosional marks from turbulent flows) is an insufficient basis for process analogy (Benn and Evans, 1998, 2006).
- Widespread cross-cutting of bedforms (Boulton and Clark, 1990a,b) cannot be explained.
- There are no well-constrained analogues in either modern or palaeo-record for floods of such volume or magnitude (Clarke *et al.*, 2005).
- Neither sufficient water storage nor sufficient water production can be accounted for (Clarke *et al.*, 2005).

Despite the rejection of the theory by a large proportion of the Quaternary and Glaciology scientific communities, the megaflood literature continues to grow.

Alternative models for bedform formation. Stratified sediments in drumlins are accounted for in the Boulton model of bed deformation (1987) as more rigid material which acts as bedform cores. Sediments are typically well-drained, thereby raising effective pressure and reducing the tendency to deform. An alternative model, which finds particular favour in Ireland where there are many examples of stratified drumlins, is a model of lee-side cavity infill (Dardis *et al.*, 1984; Dardis, 1985, 1987; Hanvey, 1987; McCabe and Dardis, 1989, 1994). This model sees drumlins as analogous in process-form to crag and tails, whereby a cavity develops between the ice and the bed in the lee of an obstruction, in this case the drumlin core, and in this cavity water-lain material forms stratified sequences.

Alternative formational theories specific to ribbed moraine genesis fall broadly into two groups: those favouring compressional flow and those invoking extensional flow. The 'shear and stack' model, a compressional flow model, (Bouchard, 1989; Aylsworth and Shilts, 1989; Sollid and Sørbel, 1994) describes ribbed moraine ridges as the product of the melt-out of stacked slabs of basal ice debris. This general model has held favour for some time although the origin of the compressive flow is not agreed. The extensional flow hypothesis instead invokes fracturing of the till bed into tabular ridges (Lundqvist, 1969; Hättestrand, 1997; Kleman and Hättestrand, 1999). Kleman and Hättestrand (1999) attribute the source of the extensional flow to a thermal transition from a cold- to warm-based environment, and the associated basal velocity increase. They therefore use the distribution of ribbed moraine as a key indicator of palaeo-thermal regime zonation, in particular frozen-bed patches. Ribbed moraine are linked to the interior regions of an ice sheet both under this model and the bed deformation theory, although their formation is accounted for by different responses of the substrate to a similar zonation of ice sheet properties (Figure 3.6). Thermal characteristics of the bed are clearly an important parameter, either in inducing the necessary tensional stresses for the fracturing model, or via enhancing the susceptibility of the bed to deformation under an increasing velocity regime.

3.2.1.3 The use of subglacial bedforms for palaeo-glaciology

Ideally we would be able to derive glaciological parameters such as ice velocity, thickness, water pressure, hydrological state, thermal regime etc. from landform properties. Whilst genetic theories and hypotheses abound, none is yet mature enough to invert the geomorphological record in such a quantitative manner. The modelling and Quaternary scientific communities are in the early days of developing and testing numerical models for bedform generation. To date, a deformation model is the only such model to produce subglacial bedforms (Hindmarsh, 1998a,b, 1999), and make predictions of morphometry and distribution which can be quantitatively tested. Early tests reveal that the model predicts ribbed moraine wavelength in the correct ballpark, determined from a large dataset of ribbed moraine ridges (Dunlop, 2004).

Despite uncertainties in genetic models, there are certain conditions of formation in which we have more confidence, and therefore we can make certain assumptions which enable us to make palaeo-glaciological interpretations from the geomorphic record (Clark, 1999; Clark and Meehan, 2001; Kleman *et al.*, 2006):

- Lineations form parallel to the direction of ice flow.
- Ribbed moraine form transverse to the direction of ice flow.

- Elongation of lineations (expressed as a ratio, length:width) is thought to relate primarily to ice velocity, and mega-scale glacial lineations (MSGL) are used as an indicator of palaeo-ice streaming (Clark, 1993; Stokes and Clark, 1999; Shipp *et al.*, 1999).
- Bedforms are indicative of warm-based subglacial conditions.
- Bedforms can be preserved beneath later flows, and therefore inform us of changing flow patterns and changing subglacial regimes.
- Preservation is related to either a cold-based thermal regime or slow basal velocities which do not permit geomorphic activity.

3.2.2 Meltwater traces

3.2.2.1 Description

Glacial meltwater has both an erosional and depositional geomorphic impact and at a variety of scales, from p-forms, to meltwater channels, eskers, deltas, and tunnel valleys. Meltwater channels (including tunnel valleys, though their origin and significance is poorly understood) and eskers are the most suited landforms for integration into a large-scale ice sheet reconstruction. Meltwater channels are the remnant of where meltwater cut down into the underlying substrate whilst eskers are the sedimentary infill of a meltwater conduit.

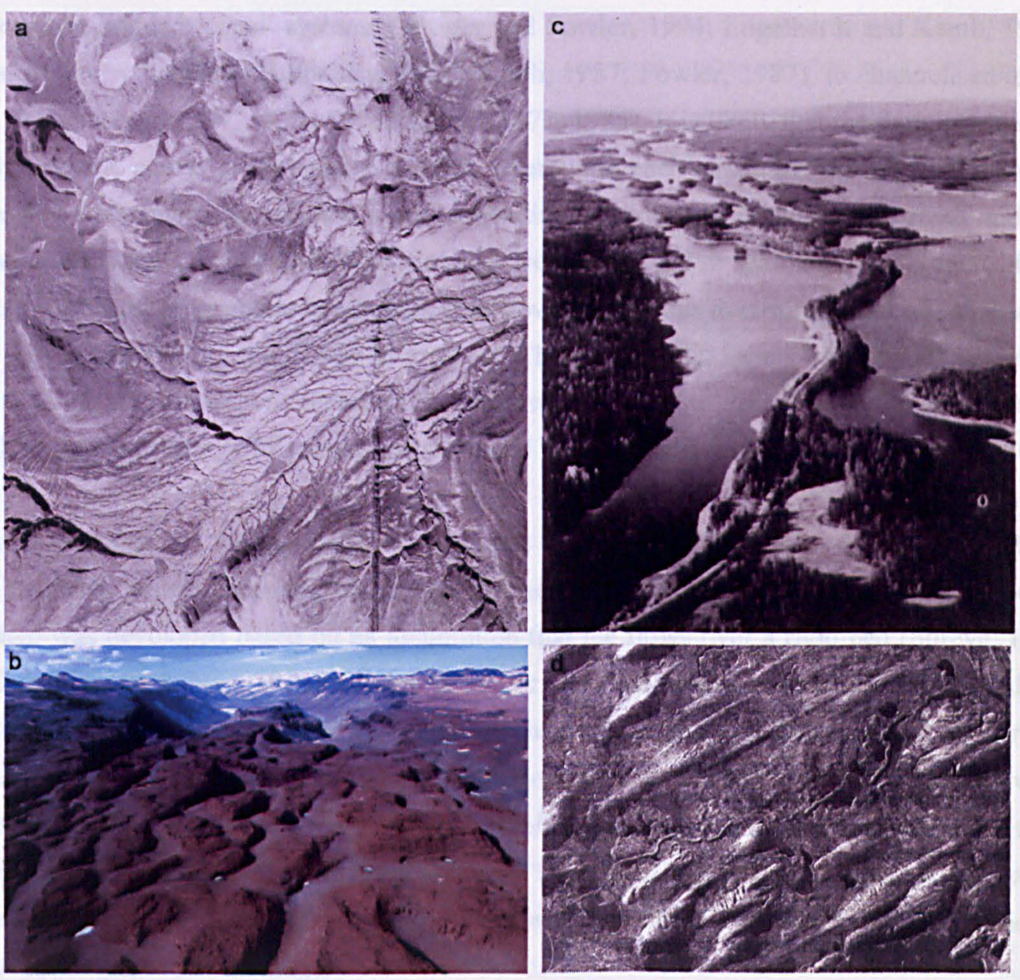


Figure 3.7 Meltwater traces in the geomorphic record. **a)** lateral meltwater channels in the Canadian Arctic (from Benn and Evans, 1998); **b)** subglacial meltwater channels in the Antarctic Dry Valleys (Lewis *et al.*, 2006); **c)** bifurcating esker in Sweden (Sugden and John, 1976); **d)** an esker drapes a drumlin field in the Canadian prairies (Benn and Evans, 1998).

Meltwater channels with greatest tendency to leave a geomorphic imprint are those which develop in either a lateral or subglacial environment (Figure 3.7a,b). Channels from different contexts within the glacial hydrological system have discernible geomorphological, size and spatial characteristics, which enables them to be distinguished from each other and the appropriate palaeo-glaciological information derived (Greenwood *et al.*, 2007). Eskers (Figure 3.7c,d) can reflect deposition into conduits from all situations within the system: supraglacial, englacial and subglacial (Warren and Ashley, 1994). In a similar sense to bedforms collecting in 'fields', all legacies of glacial meltwater flow, erosional or depositional, tend to form networks, either dendritic in arrangement or of a more chaotic, anastomosing character. Channels from a lateral position are often arranged as a series of steps on hillsides (e.g. Figure 3.7a). Across the spectrum of landforms, size may vary considerably from a few metres in width/height and a few tens of metres in length, to networks in excess of 100 km (Benn and Evans, 1998).

3.2.2.2 Genesis and significance for palaeo-glaciology

Gaining a sound understanding of the glacial hydrological system is a key research objective of glaciology, since ice flow laws require laws for basal sliding which in turn depend intrinsically upon the mode of drainage (Hooke, 2005). A suite of mechanisms have been hypothesised to discharge water from the subglacial system, from thin water films (e.g. Weertman, 1972), to shallow and braided 'canal' systems (Walder and Fowler, 1994; Engelhardt and Kamb, 1997), to linked cavity networks (Lliboutry, 1968; Kamb, 1987; Fowler, 1987), to channelised/tunnel flow (Röthlisberger, 1972; Nye, 1976; Shreve, 1972, 1985). It is likely that the drainage mode is highly variable across the subglacial system, whereupon each of the above may play a role in conveying meltwater, the selected mode depending on both glaciological properties and bed characteristics, not least whether ice is flowing over a rigid bed or sediment bed (Hooke, 2005). Whichever mode of drainage is adopted, it is governed by the overriding principle that water flow will be directed by the hydraulic gradient. The geomorphic legacy of meltwater drainage, both eskers and channels, can therefore be interpreted in terms of the palaeo-hydraulic gradient, which is guided primarily by ice surface slope and which in turn determines ice flow direction.

Meltwater channels. Palaeo-meltwater channels are usually interpreted as the legacy of Nye-type channels, where water cut down into the underlying substrate. However, this model of drainage was developed based on an assumption that ice flows over a rigid bed (Shreve, 1972; Röthlisberger, 1972; Nye, 1976). On soft sediment beds, theoretical analysis argues for shallow, broad 'canals' rather than the deeper Nye type channels or Röthlisberger tunnels (Walder and Fowler, 1994). The geomorphic and sedimentological characteristics to distinguish between modes of drainage other than the traditional Nye/Röthlisberger channelisation, such as linked cavities or shallow canal drainage, are unclear. Therefore interpretation of palaeo-meltwater channels is usually restricted to large-scale ice sheet characteristics rather than the subtleties of the modes of meltwater drainage.

Channels in the subglacial environment must be associated with a warm-based thermal regime and zones of abundant ice melting. Clark and Walder (1994) argue that channelisation (and an erosional imprint) will likely only occur in the ablation zone where sufficient melt is supplied from the both surface and the subglacial zone. However, meltwater is known to be stored subglacially throughout the ice sheet system (Siegert *et al.*, 1996, 2005; Wingham *et al.*, 2006) and has been strongly linked to ice dynamics, particularly ice stream dynamics (Joughin *et al.*, 2004; Domack *et al.*, 2006; Wellner *et al.*, 2006; Bell *et al.*, 2007; Bindschadler and Choi, 2007; Fricker *et al.*, 2007). Meltwater drainage could have a geomorphic imprint wherever it occurs in the subglacial system; it does not necessarily follow that channels in the palaeo-record can be interpreted as landsystems which developed close to the ice margin.

Lateral meltwater channels feature less frequently in process literature but are commonly interpreted in palaeo-glaciology as a deglacial signature (e.g. Dyke, 1993; Kleman *et al.*, 1997; Hättestrand and Clark, 2006a,b). Lateral channels develop where supraglacial water is deflected to the margins of predominantly cold-based ice, since the frozen structure prevents percolation through other conduits. At the margin, water collects subaerially between the ice and the bounding topography and, during ice wastage, flights of lateral channels may form as the ice surface is sequentially lowered.

The system dynamics represented by meltwater channels in the palaeo-record are not fully known, but glacial hydrology is sufficiently well-understood that the following assumptions may be employed for palaeo-glaciology:

- Meltwater flow will follow a hydraulic potential gradient, which is guided by ice surface slope, which in turn determines ice flow direction.
- Subglacial meltwater channels indicate a warm-based regime.
- Lateral channels are associated with cold-based ice and topographic constraints on flow.

Eskers. A model for esker deposition is presented by Warren and Ashley (1994), which recognises four basic types of esker: tunnel fills (from subglacial conduits), ice channel fills (from supraglacial conduits), segmented tunnel fills and beaded eskers (both from pulsed retreat of the glacier margin). Tunnel fill eskers are the geomorphological expression of former Röthlisberger channels, meltwater conduits 'eroded' via melting up into the ice rather than cutting down into the substrate. The variety of morphologies and topographic contexts displayed by such eskers has been attributed to the balance of melting and freezing of conduit walls, whether deposition occurs under hydrostatic or atmospheric pressure, or the tendency of the channel to migrate or incise (Benn and Evans, 1998). Tunnel fill eskers often represent an 'at a time' conduit system although it is unlikely that eskers extending over hundreds of kilometres, for example, were part of a single system operating synchronously. Conversely, segmented and beaded eskers are usually attributed to time-transgressive development, formed in pulses behind a retreating margin either as tunnel fill or as subaqueous/subaerial fans at the point of conduit emergence at the ice front (Warren and Ashley, 1994; Benn and Evans, 1998).

These differences are best distinguished with detailed, sedimentological analysis and, without this, there is a slight danger of over-interpreting *subglacial* conditions. However, for large-scale palaeo-glaciology we draw on some basic assumptions to interpret the significance of eskers (Kleman *et al.*, 2006):

- Eskers indicate a warm-based subglacial environment.
- Esker segments indicate the approximate ice flow direction near the margin.
- Eskers are formed in an inward-transgressive manner behind a retreating margin, therefore margin positions may be reconstructed orthogonal to the orientation of the esker.

3.2.3 Moraines

The term 'moraine' was originally applied to sheet-like spreads of till but now is generally limited to ice marginal deposits. Yet the term still encompasses a plethora of landforms and sediment accumulations from a vast array of genetic origins. Benn and Evans (1998) suggest that ice marginal moraines can be grouped into four classes, though composite moraines may be common and the classes are not exclusive: glaciotectonic (thrust) moraines, push moraines, dump moraines and fans/ramps. Additional to these groups are those moraines lowered to the surface from supra- or en-glacial positions, and those deposited subaqueously. As these categories suggest, moraines are not exclusively related to advance of ice and 'bulldozing' of sediment (push moraines), but also, perhaps more commonly (Meehan, 2006), relate to recession of ice and accumulation at standstill locations of the sediment which is constantly conveyed through the glacial system. Moraines and morainic deposits can therefore yield information regarding the mode of retreat. For a detailed understanding of the palaeo-environmental conditions of moraine deposition it is necessary to consider the entire landform-sediment association. However, if 'moraine' is treated as a generic term for any ice marginal accumulation of sediment with a geomorphological expression, the simplest information yielded is a palaeo-ice margin position. This is the approach generally deemed useful for large-scale palaeo-glaciological reconstruction (Clark *et al.*, 2004).

3.3 Inversion approaches

3.3.1 Traditional approaches

For decades, basic levels of understanding of the glaciological significance of geological and geomorphological evidence have enabled ice sheet histories to be derived. For example, even in the early days of the glacial theory, Close (1867) and Hull (1878) used aligned landforms to suggest ice flow direction in Ireland. The traditional approach to evidence-based reconstruction is one of field gathering of data, and proposition of a plausible 'glacial story' to explain the inscription of that data in the landscape. Typically, all the evidence was viewed as either a single snapshot or the latest phases of the ice sheet. A more rigorous approach to ice sheet reconstruction was adopted by Boulton *et al.* (1985) who argued that since most geomorphic work occurs close to ice sheet margins (Figure 3.6), margin positions may be reconstructed orthogonal to lineations over large areas. This logic enabled reconstructions of the maximum position and retreat phases of the ice sheet to be pieced together (Boulton *et al.*, 1985; Dyke and Prest, 1987). Whilst it is now recognised that older patterns are preserved in the landscape (e.g. Boulton and Clark, 1990a,b; Kleman, 1992) this approach had a clear logic for reconstruction, which is not always the case when glacial histories have been built.

Large area compilations of landform mapping have led to benchmark papers for ice sheet-wide geomorphological reconstructions (Prest *et al.*, 1968; Dyke and Prest, 1987; Boulton *et al.*, 1985). The availability of ice sheet-wide landform maps such as the Glacial Map of Canada (Prest *et al.*, 1968) enabled individual suites of features to be viewed as part of a whole rather than in isolation. However in the British Isles, after early consideration of the ice sheet-wide picture of glaciation, research has focussed on the details. Subsequently, ice sheet-wide reconstructions have suffered from poor synthesis of the observational record, relying on extrapolation of detailed local-scale interpretation over larger areas (Clark *et al.*, 2004).

3.3.2 'Bottom-up' vs 'top-down'

The approach described above has been termed by Clark and Meehan (2001) a 'bottom-up' approach in which the large-scale problem is tackled starting with the maximum level of detail which can be derived from physical evidence. Field work and aerial photo interpretation underpin this approach, which characterises much of the Irish research and provides a great deal of detail of specific field sites. However, synthesis of evidence collected at this scale poses numerous problems for addressing ice sheet-scale questions (Clark, 1997; Clark *et al.*, 2004, 2006). These are outlined in Table 3.1.

Table 3.1 Constraints on producing time-space ice sheet reconstructions from a bottom-up approach (from Clark, 1997; Clark *et al.*, 2004, 2006).

Constraint	Explanation
1. Fragmented evidence	The spatially separate nature of different field sites leaves gaps in the record which can only be linked by extrapolation across areas for which little is known.
2. Theory-laden interpretation	Glaciological understanding has likely changed over the time the entire body of data has been gathered. As ideas pass through the literature interpretation often becomes detached from evidence but the degree to which this is the case is not always examined.
3. Contemporaneity of evidence	The simplest interpretation of the glacial record is that it represents a single snapshot in time. However, this is known to be an over-simplification and, in fact, geological and geomorphological records of glaciation are often multi-temporal (Boulton and Clark, 1990a,b; Kleman, 1992).
4. Dating control	The availability of good chronological markers varies for different ice masses. In the British Isles, much evidence remains undated (Chapter 2; Clark *et al.*, 2004).
5. Incomplete mapping	Related to point 1, above: spatial gaps exist between the areas of known data, which likely hold valuable information.
6. Glaciological plausibility	Building a reconstruction from an incomplete dataset likely produces ice sheets which are not glaciologically plausible. Greater modelling efforts would ensure that the physical laws of ice flow allow for the dynamics reconstructed.
7. Volume of information	Synthesis of an entire body of literature can be a daunting task!

Rather than working from the field level upwards, interpretation of the glacial record from an ice sheet-wide viewpoint, a 'top-down' approach (Clark and Meehan, 2001), can provide a framework of glacial history into which details can be added. The advent of widely available satellite imagery has revolutionised landscape mapping and opened up new scales of research by allowing a single operator to conduct rapid, systematic and consistent landform mapping of large areas at ever-increasing spatial resolutions. The detail achieved may not always be as great as that realised in the field, but with satellite imagery available for large areas at a spatial resolution on the order of metres, the majority of ice sheet-scale questions may be addressed.

Furthermore, a remote mapping approach has delivered new insights into the preservation of palaeo-records of glaciation, revealing the widespread nature of old ice flow inscriptions and palimpsest landscapes underneath more recent imprints (e.g. Boulton and Clark, 1990a,b; Clark, 1993; Clark *et al.*, 2000; Kleman, 1992; Kleman *et al.*, 1994; Hättestrand, 1998; De Angelis and Kleman, 2007). Together with observations of rapid behavioural changes in modern ice sheets (Retzlaff and Bentley, 1993; Joughin *et al.*, 2002; Payne *et al.*, 2004; Wingham *et al.*, 2006) this discovery has delivered us into a new era of understanding: mobile and dynamic ice sheets. Rather than interpreting single ice sheet configurations from the glacial record, we now recognise that many snapshots in the evolution of the ice sheet may be reconstructed. We expect ice sheet reconstructions to describe the configuration and dynamics at each snapshot, and attempt to explain the changes from one state to another (Figure 3.8).

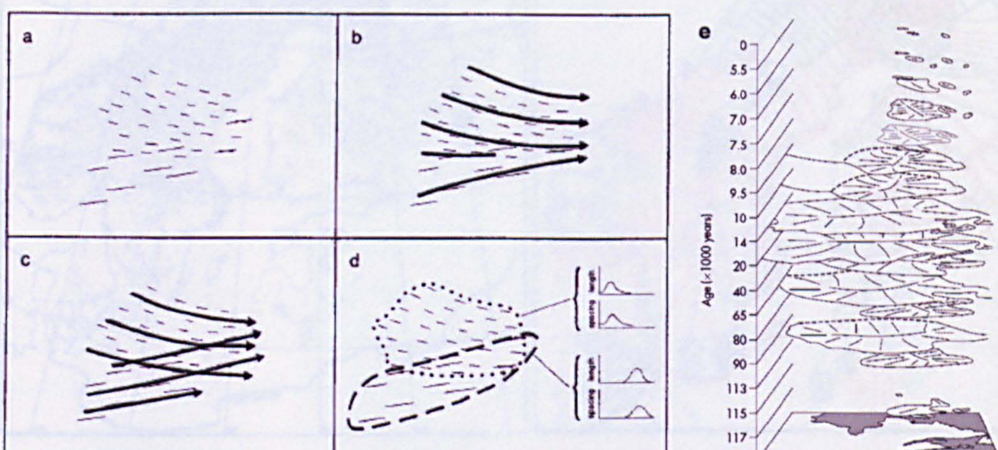


Figure 3.8 Recognition of a multi-temporal glacial record requires us to reinterpret lineation records such as the hypothetical one in **(a)**. Rather than forcing all lineations into a single flow phase **(b)**, differing morphometric properties **(d)** assist us in our recognition of two phases of ice flow in separate directions at separate time-intervals **(c)**. Defining a relative time stack of flow phases and associated ice sheet geometries is the aim of modern ice sheet reconstruction. From Clark (1997) & Clark *et al.*, (2006).

3.3.3 A semi-formalised geomorphological inversion approach

Given that reconstructions of ice dynamics in both time and space are now attainable, there is demand for more rigorous protocols for the use of geological and geomorphological evidence. Working from top-down approaches, a number of researchers over the last 10-20 years have developed a semi-formalised way to invert the glacial record and arrive at such a time-space reconstruction (Boulton and Clark, 1990a,b; Kleman and Borgström, 1996; Kleman *et al.*, 1997;

Clark, 1997, 1999; Clark and Meehan, 2001; Kleman *et al.*, 2006). Such a method allows for a more objective use of the record, and is the approach followed and developed in this thesis.

3.3.3.1 Inversion model 'building blocks'

The glacial map is the initial 'building block', or the basic unit of an inversion procedure. This represents the complete body of evidence which acts as input into the conceptual inversion model. However, the data volume contained within this basic unit (>23,000 features in the Glacial Map of Canada, Prest *et al.*, 1968; 11,000 lineations mapped for the Foxe/Baffin sector of the LIS by De Angelis and Kleman, 2007) may in fact inhibit the clarity of spatial and genetic relationships between features, and therefore data reduction is necessary (Figure 3.9). *Flowsets* (Boulton and Clark, 1990a,b; Clark, 1997), *fans* (Kleman and Borgström, 1996; Kleman *et al.*, 1997) or *swarms* (Kleman *et al.*, 2006; De Angelis and Kleman, 2007) are the main analytical units, summarised from the original glacial map. Flowsets group landforms without losing vital information on spatial relationships such as the preservation of palimpsest flow imprints. Each flowset is a cartographic representation of a larger volume of data (landforms), and representation in this form facilitates easier visualisation and interpretation of a large body of evidence.

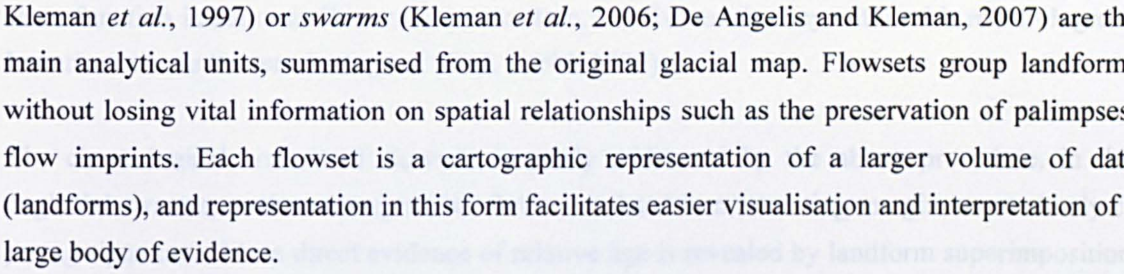


Figure 3.9 The volume of data recorded at ice sheet-scale is often such that clarity of the palaeo-glaciological information it yields is impaired (**a** – summary of glacial lineations in Fennoscandia; Kleman *et al.*, 1997). Data reduction (**b** – flowsets based on a from Kleman *et al.*, 1997, 2006) is necessary to better visualise and interpret the ice flow information represented by the landforms.

3.3.3.2 Interpretation of glaciodynamic context

In order to extract relevant palaeo-glaciological information from cartographically summarised flowsets, two further levels of interpretation are required: assessment of glaciodynamic context of the flow pattern, and consideration of the chronological context. Let us first consider interpretation of glaciodynamic context.

The Clark school and the Kleman school differ subtly in their style of interpretation of the glaciodynamic significance of flowsets. Under the Clark model (Clark, 1997, 1999) it is determined whether flowsets represent *isochronous* or *time-transgressive* imprints. Isochronous flowsets are those which formed in a snapshot, leaving a clear 'rubber-stamp' of the formative ice flow. Time-transgressive imprints develop when the ice sheet undergoes change whilst continually reworking its bed; the imprint has a 'smudged' appearance. Clark (1999) suggests that time-transgressive imprints are indicative of bedform generation behind a retreating margin where localised flow direction changes may occur. The isochronous category of Clark is conceptually similar to both the *event* and *stream* categories of the Kleman model (Kleman *et al.*, 2006), whilst Kleman's *deglacial* swarms fall within Clark's time-transgressive model. Essentially, by classifying flowsets by their glaciodynamic context, both models perform the same function in the overall inversion procedure, and for consistency within this research group I continue to use the terminology of Clark (1997, 1999).

The chronological context of flowsets is partly addressed by the above procedure, in that deglacial swarms, or time-transgressive flowsets related to a retreating margin, must clearly be young signatures. More direct evidence of relative age is revealed by landform superimposition. Further assistance in assigning relative ages to flowsets is sought from sediment stratigraphy, till fabrics and patterns of till (erratic) carriage.

These two stages of flowset interpretation enable discrete ice flow imprints to be assigned a position within a time-space reconstruction of ice sheet dynamics. The palaeo-glaciological compatibility of different flowsets, in spatial and temporal terms, must be assessed: can flowset A occur at the same time as flowset B, and what would this mean for the requisite ice sheet geometry? Flowsets which plausibly fit into similar timeslices of ice sheet history are grouped, revealing a likely ice sheet geometry for each stage, and these 'ice sheets' are arranged to yield a glaciologically plausible ice sheet evolution. Until such time as we have complete knowledge of genetic processes for our glaciological interpretations, and complete chronological control for all phases of ice flow and retreat, an assumption of minimum complexity is always invoked when arranging flowsets into a reconstructed model of ice sheet dynamics.

3.3.3.3 Application of inversion model

An inversion model as described above has been applied to a number of palaeo-ice sheets and ice sheet sectors, notably the Fennoscandian Ice Sheet (Kleman *et al.*, 1997) and sectors of the Laurentide (Kleman *et al.*, 1994; Clark *et al.*, 2000; Jansson *et al.*, 2002; De Angelis and Kleman, 2007), where the preserved glacial record is known in some detail and where the chronological constraints are abundant and well-distributed. No such top-down approach has yet been applied for the whole Irish Ice Sheet. The recorded geological evidence is patchy in detail and a synthesis of hitherto published evidence would suffer from the problems outlined in Table 3.1. New, consistent mapping of the Irish glacial landform record and inversion of this record using the model described above, is warranted.

3.4 Summary

The landforms to be mapped in this thesis and used for ice sheet reconstruction have been outlined above (subglacial bedforms, meltwater channels, eskers, and moraines). In the absence of a complete understanding of landform genesis we must employ some assumptions of these processes in order to extract palaeo-glaciological information:

- Lineations are ice flow-parallel; ribbed moraine form transverse to ice flow
- Bedforms form under warm-based conditions
- Bedforms can be preserved under later ice configurations, by cold-based ice or slow moving ice (ice divides)
- Meltwater features suggest the direction of the ice surface slope
- Subglacial channels and eskers indicate warm-based conditions
- Lateral channels form under a cold-based regime
- Eskers form behind a retreating margin, orthogonal to the margin
- Moraines indicate ice margin positions

In this thesis I shall adopt the semi-formalised approach described above to invert the landform record, using these above assumptions, for palaeo-glaciology. The framework for research is as follows:

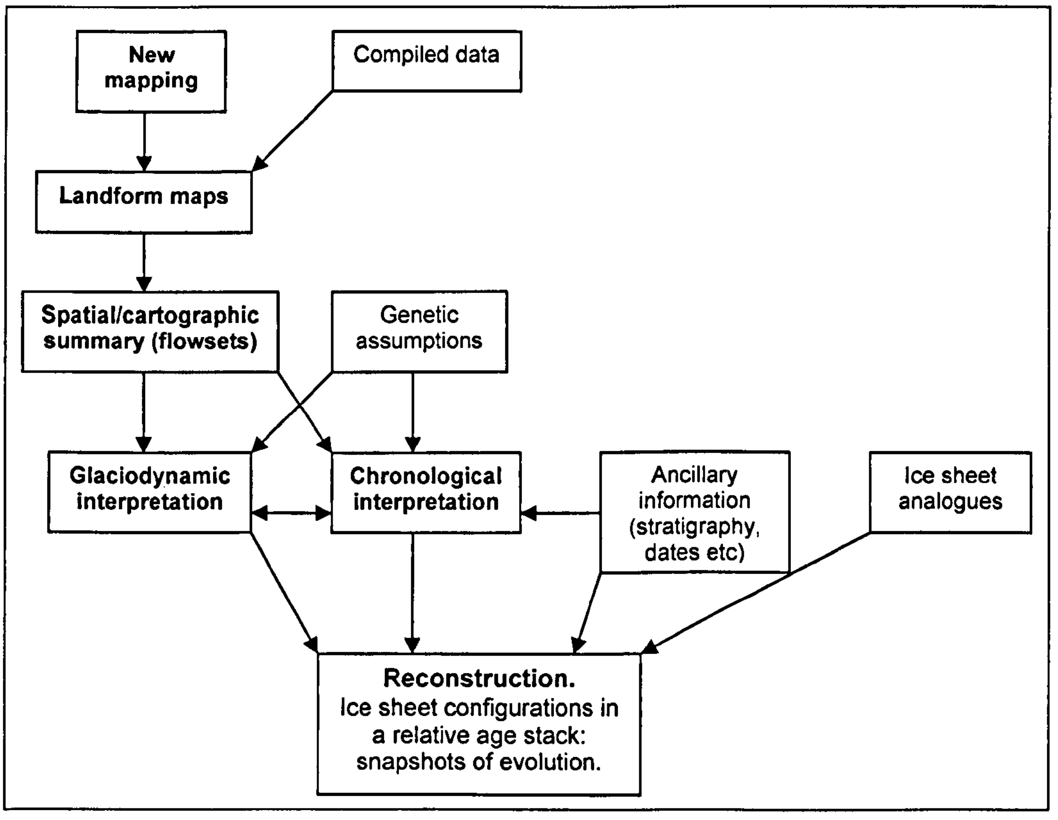
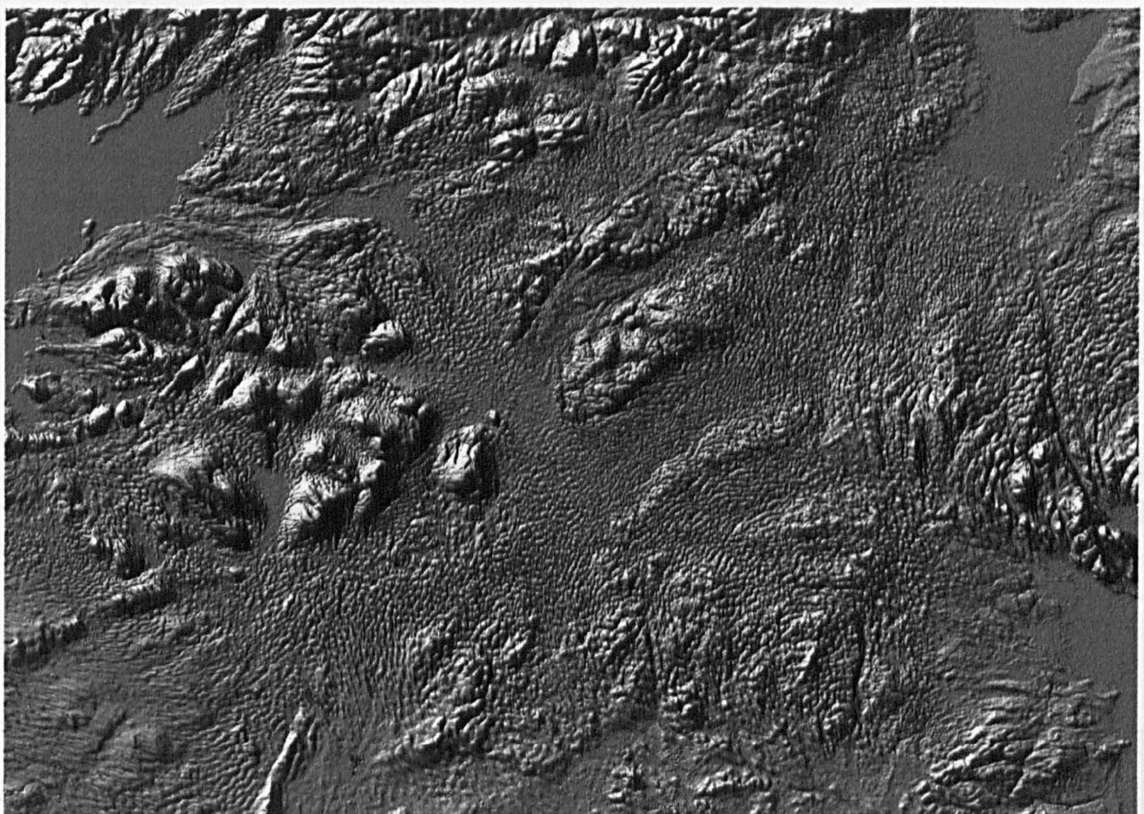


Figure 3.10 Research approach.

SECTION B:

Landform Mapping



Hillshaded SRTM image of Irish midlands.

Chapter 4. Data sources and landform mapping methods

4.1 Introduction

The relative merits of a top-down versus bottom-up approach to ice sheet-wide landform mapping were discussed in Section 3.3.2. It was suggested that a top-down approach is most likely to succeed in providing a framework for the evolution of the ice sheet. Once such a framework has been reconstructed, it stands to be challenged and constrained by the details of glacial history provided by more local, field-scale research. Such a top-down derived framework of glacial history is yet to be reconstructed for the Irish Ice Sheet, and it is the need for such a model which motivates this thesis. The initial stage for such a top-down approach is the compilation of an ice sheet-scale glacial geomorphological map (objective 1 of this thesis; Section 1.4). To this end, I appeal to a variety of remotely sensed data as the primary data source for countrywide landform mapping. This chapter outlines the data sources used, the preparation of data in order that most landform information may be extracted, then describes the procedures for landform mapping and quality control.

4.2 Primary data sources

4.2.1 Data properties and relative merits

Four primary data sources were used for landform mapping. These comprised two Digital Elevation Models (DEMs) and two suites of satellite images; their basic properties are outlined in Table 4.1. A variety of imagery was used in order that the relative merits of each data source were maximised and the limitations mitigated.

Table 4.1 Properties of data sources used for landform mapping.

Data source	Technical properties	Spatial resolution	Initial projection	Useful data coverage	Acknowledgement
Landmap DEM	DEM built from ERS-1&2 SAR images via interferometry	25m	Irish National Grid	Countrywide	MIMAS (University of Manchester & UCL)
SRTM DEM	DEM built by interferometry from shuttle mission	90m	Geographic (latitude; longitude)	Countrywide	Global Land Cover Facility (University of Maryland)
Landsat ETM+	Bands 2,3,4,5 (visible to mid-IR). Panchromatic band (visible and IR).	30m 15m in panchromatic	UTM Zones 29-30	3 images @ 185 x 185 km (see Figure 4.1)	Global Land Cover Facility (University of Maryland)
SPOT	Bands 1-4 (visible to mid-IR). Panchromatic band (visible).	10-20m 2.5m in panchromatic	UTM Zones 29-30	16 images @ 60 x 60 km (see Figure 4.1)	OASIS programme for SPOT image distribution, copyright CNES.

High resolution Digital Elevation Models (direct representations of a landscape surface) can be a superior tool for landform mapping over more traditional remote mapping methods using satellite imagery or aerial photography (Clark, 1997; Clark and Meehan, 2001). Successful landform mapping relies upon visualising the data in such a way that landforms are best highlighted. A DEM is simply a raster model of surface elevation, in which each pixel contains a value of elevation above a datum, and therefore it can be visualised according to user demands. This is in contrast with satellite imagery, where illumination and shadow effects are the sole means of providing a sense of depth, and illumination properties are fixed by the movement of the sun. The flexibility of DEMs for data visualisation and their countrywide coverage make them ideal tools for landform mapping in this study.

Whilst more 'fixed' in terms of data visualisation, satellite imagery complements DEM-based mapping in several ways. As well as natural illumination and shadow effects, the tone and textural properties of images assist landscape mapping. The familiarity of a satellite scene, which appears not unlike an aerial photograph, assists the mapper in distinguishing between bedrock and sediment surfaces, and distinguishing 'noisy' features such as forests from landforms of interest such as eskers and moraines. The imagery used has a consistently higher spatial resolution than both DEMs. This clearly offers an advantage for mapping smaller features, although the size of landforms in which we are interested for ice sheet-wide palaeo-glaciology is such that the spatial resolution of any dataset used here presents little limitation to landform detection. Bedform size is typically in the order of 100s – 1000s of metres and therefore only the smallest features should escape detection. It is argued that most important patterns for ice sheet reconstruction can be captured with confidence. Any ice flow which has left an imprint below the resolution of these datasets likely relates to very local-scale dynamics in which we are less interested at this stage.

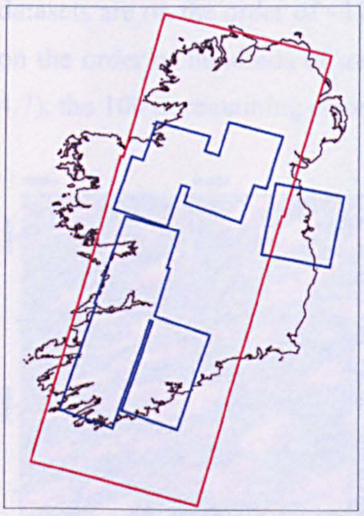


Figure 4.1 Data coverage of imagery suitable for geomorphic mapping in Ireland. Two DEMs cover the whole area; red outline = Landsat ETM+; blue outline = SPOT.

The available coverage of suitable satellite imagery for Ireland is limited, for two key reasons. Landform mapping is greatly enhanced when winter imagery is used. The distracting cover of vegetation is then at a minimum, whilst the low sun angle produces the deepest shadows, highlighting topographic variation most successfully. Secondly, visible and infrared energy cannot penetrate through cloud, therefore we also require cloud-free imagery. Although cloud-free winter days in Ireland are not in abundance, suitable images are available for a considerable area, though not countrywide (Figure 4.1). When mapping any area, all available data has been used in order to extract the maximum amount of information possible; the full (countrywide) coverage of the Digital Elevation Models ensures some level of consistency in mapping across the whole terrestrial ice sheet bed.

4.2.2 Data preparation for manual mapping

Prior to mapping, data from the various sources were geocorrected and processed to best visualise the landscape for geomorphological mapping.

4.2.2.1 Geocorrection

The four primary data types originate in different projections. Most GIS software will reproject data 'on the fly' but it is far more efficient to permanently reproject the imagery. It is a simple task to do so, and the Irish National Grid was selected as the base projection for all future work.

It is perhaps inevitable that when using data from multiple sources in combination, minor geopositional inaccuracies will be present, due to the initial accuracy of image orthorectification from the raw satellite data, and the accuracy of the transformation model used to reproject from one projection to another. Such inaccuracies exist between the four data sources used here (Figure 4.2). It is important to eliminate these as best as possible in order to preserve the spatial relationships between landforms which may be mapped from different sources. Certain Landsat and SPOT images have, where necessary, been manually re-corrected via ground control points, using Ordnance Survey map data as the target data. Manual geocorrection of DEMs is much more complicated, and it was not attempted. It is estimated that remaining errors between the datasets are on the order of ~100 m. Given that the scale of subglacial bedforms, for example, is on the order of hundreds of metres to kilometres (note the clarity of landforms in Figures 4.2–4.7), the 100 m remaining error is deemed acceptable for the scale of this research.

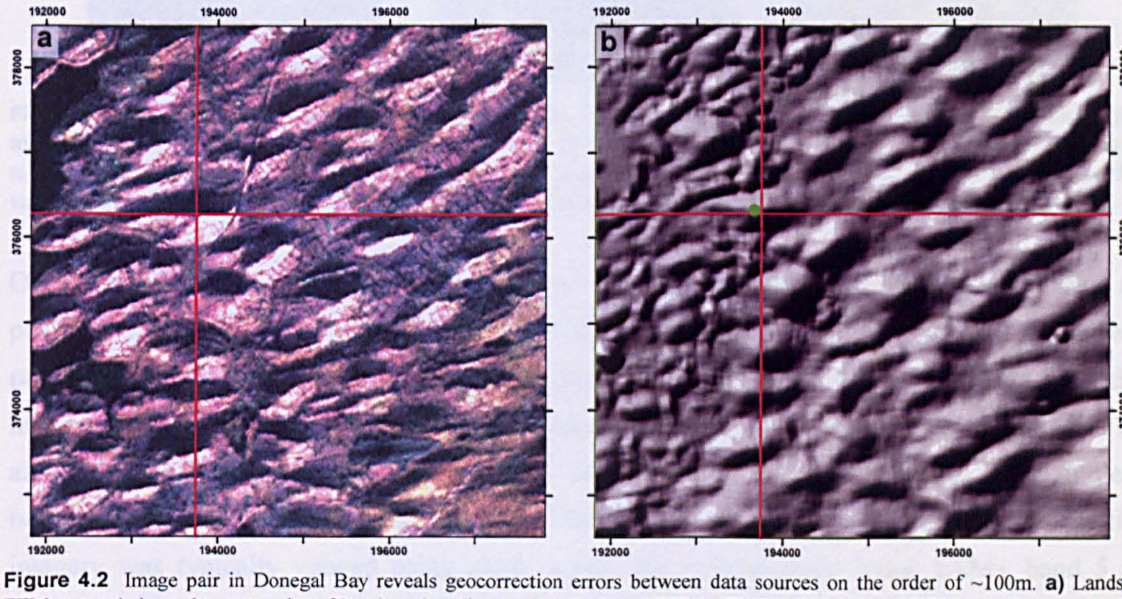


Figure 4.2 Image pair in Donegal Bay reveals geocorrection errors between data sources on the order of ~100m. **a)** Landsat ETM+; crosshair marks crest point of barchan drumlin at grid reference 193740, 376280. **b)** Landmap DEM; crosshair marks the same location, green spot marks DEM crest point of same drumlin, grid reference 193660, 376315. The DEM is positioned slightly further north and west than Landsat ETM+. Error ~87 m. Scale: gridmarks at 1 km (labels at 2 km).

4.2.2.2 Visualisation

The key to landform mapping is landform detection by the observer; this depends upon the ability of the observer but, perhaps more importantly, also how the data is visualised. A key to data visualisation for landform mapping is illumination. Light reaching the surface serves to highlight topographic variation through brightening those slopes facing the light and casting shadows over the reverse slopes. Individual landforms are best highlighted when illuminated from a low elevation (long shadows) and oriented perpendicular to the direction of illumination. It follows that landform detection may be biased by the angle of illumination; landforms oriented perpendicular to the source of light will be preferentially highlighted over those aligned with the sun direction (Clark and Meehan, 2001).

Satellite imagery has a fixed point of illumination, the sun, therefore images are sought at times of year in which the sun is in the most suitable position: the winter sun is at a low *elevation*. However, problems of sun *angle* bias cannot be rectified in satellite imagery. DEMs, however, can be visualised according to user demands, simulating any 'solar' angle or elevation. The standard protocol employed here for landform mapping from DEMs is to use at least 3 differently illuminated visualisations for any area (Figure 4.3). Other directions of solar shading are often explored to best highlight features for accurate mapping. DEMs offer the additional capability to exaggerate topographic variation in the vertical direction. All surfaces shown in Figure 4.3 are vertically exaggerated by 4x. Typically an exaggeration of 3-5x is used; smoother surfaces with more subtle variation in relief are visualised with a greater vertical exaggeration.

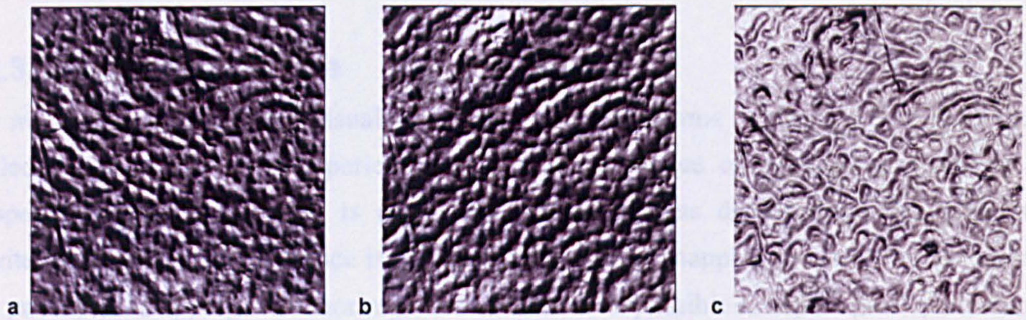


Figure 4.3 3 alternative visualisations of exactly the same area of ribbed moraine, differing only in simulated illumination angle: **a)** NE, **b)** NW, **c)** directly overhead. Visualisation **(c)** is created by positioning the 'sun' directly overhead and, whilst less intuitive to interpret, is the least biased representation of the surface topography. Slopes are shaded black whilst flat areas are white; this visualisation enables accurate break of slope mapping. To avoid bias all three visualisations are examined when mapping.

Once the data is processed as outlined above, it remains to visualise the images as best as possible on screen, usually through experimentation with different contrast and brightness parameters on an area by area, or image by image basis. The eye perceives the structure of the landscape better in monochrome imagery, distracted by colour (Gibson, 1993; Clark, 1997), although satellite image colour composites may provide useful insights such as a clear bedrock/sediment demarcation due to the different spectral responses (Figure 4.4). Satellite imagery was typically viewed using either solely the panchromatic band; ETM+ band 5 in isolation, which best minimises vegetation responses which distract the observer from landform structure (Jordan, 1997, 2002); as a false colour composite using ETM+ bands 5,3,2 (RGB); or as a hybrid image using the same three bands resolution-merged with the panchromatic band. This latter technique transfers the information in a colour composite onto the higher resolution panchromatic image, 'faking' a high resolution colour image.

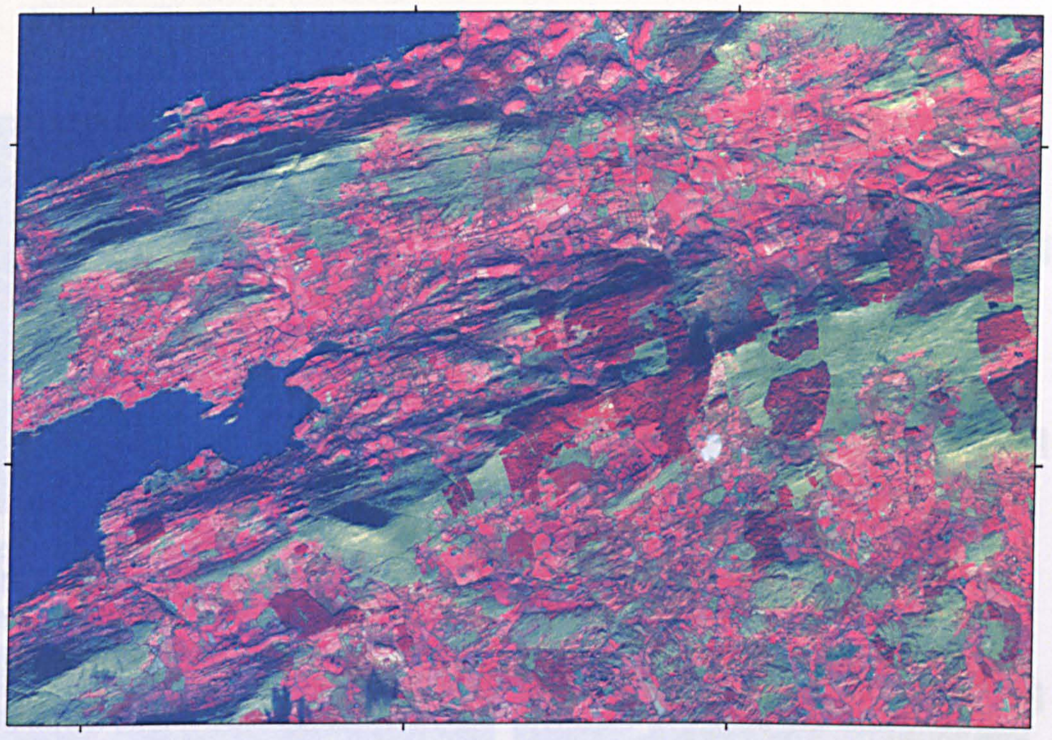


Figure 4.4 Bedrock-drift differentiation on a SPOT colour composite of Bantry Bay, Co. Cork. Green colours clearly highlight exposed bedrock or very thin soil cover, also indicated by structural characteristics. Vegetation covered surfaces appear pink-red according to whether they are agricultural fields or forest. Image resolution 10 m, tickmarks spaced at 5 km.

4.2.3 Mapping procedure

The ability of an observer to visually identify glacial landforms in the data described above is guided by knowledge and experience of a) the appearance of a landform from an aerial perspective, and b) how that is manifested in the various data sources. Mapping ability inevitably develops as experience is gained throughout the mapping programme. To ensure the end product of mapping is as thorough and consistent as possible a 'repeat-pass' procedure was adopted. Countrywide mapping was conducted landform type by landform type, which ensured there were multiple passes of the same area and the same imagery. As mapping ability grew, the previously conducted mapping could be refined. The first pass for any landform was always conducted on the Landmap DEM, the highest resolution of the spatially complete datasets. Subsequent passes for the same landform were made with other imagery in order to add any additional details or refine the initial mapping as necessary, before moving on to a new landform type. Mapping was conducted at a range of scales, typically from about 1:8000 to 1:150000, depending on the data type and the landform type in question. The same imagery was not always viewed at the same scale to ensure the full range of landform scales could be identified. For example, there is perhaps a tendency to view data zoomed in to the maximum feasible scale, in order to view the most subtle features, but mapping solely at such a scale would risk missing large features only visible as a coherent pattern when zoomed further out.

The following landforms were mapped to compile a glacial map of Ireland:

- Subglacial bedforms: glacial lineations (drumlins, crag and tails, mega-scale glacial lineations, bedrock apparently streamlined by ice flow) and ribbed moraine (Figure 4.5a)
- Meltwater features: meltwater channels and eskers (Figure 4.5b)
- Moraines (Figure 4.5c)

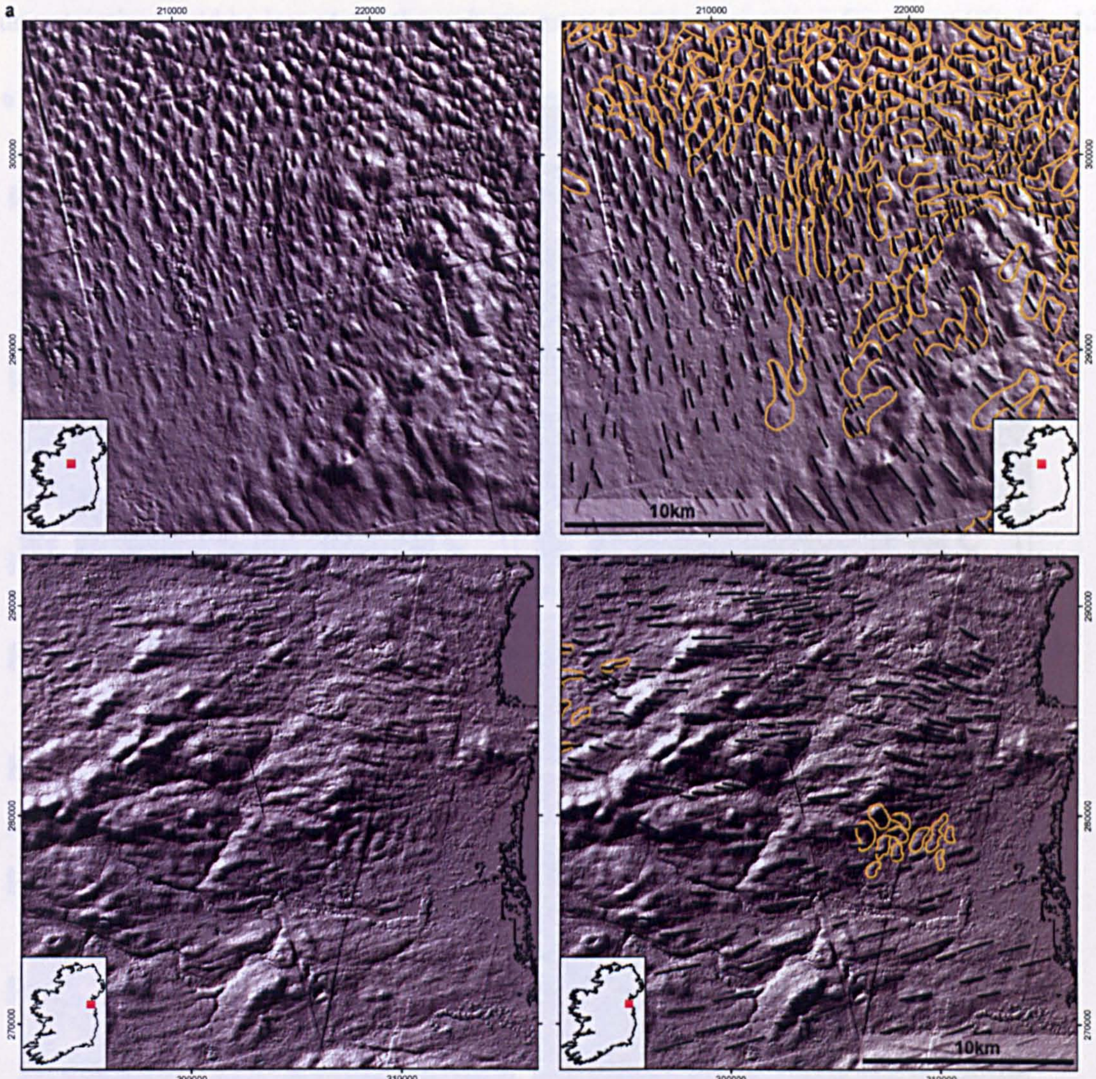
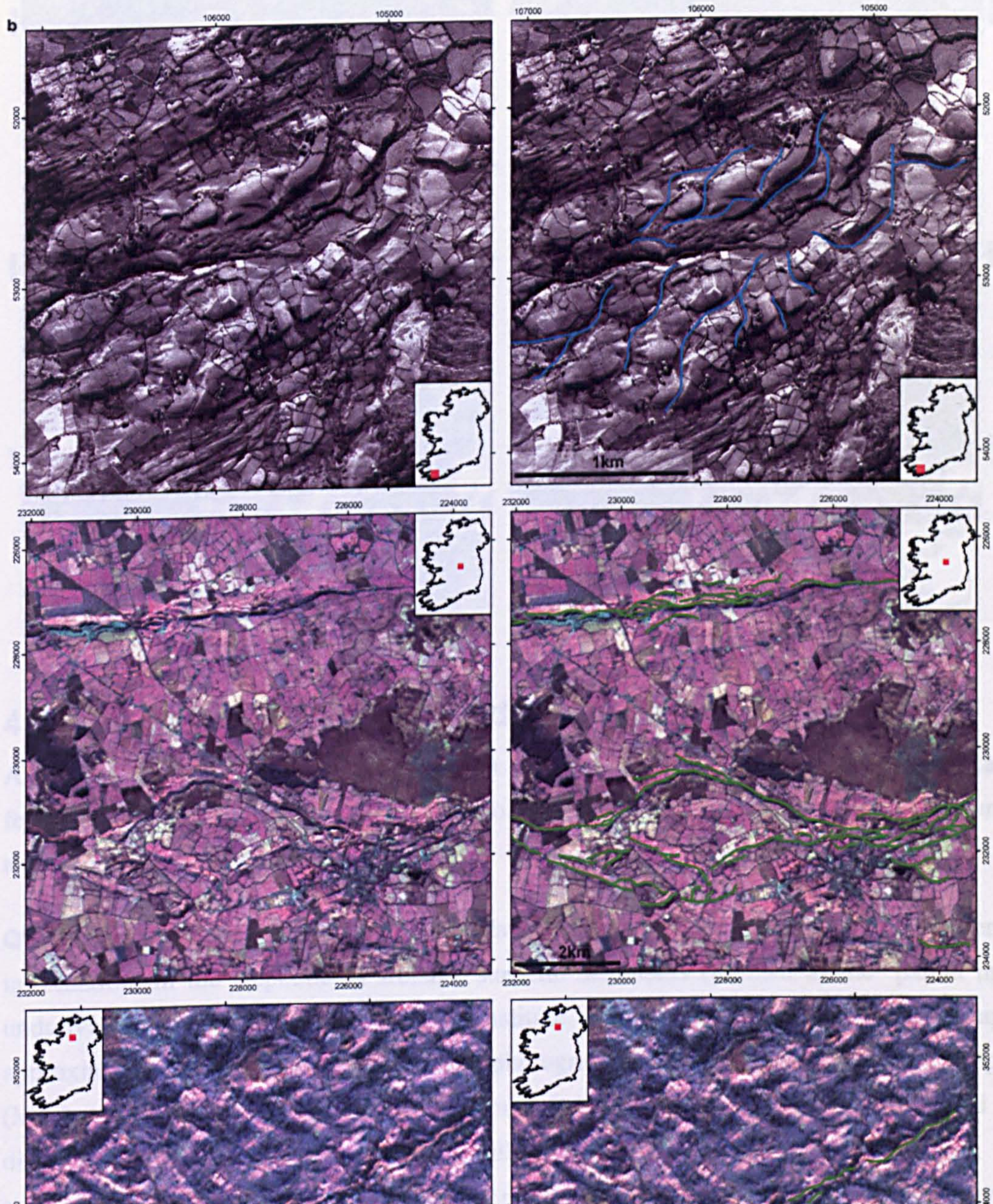
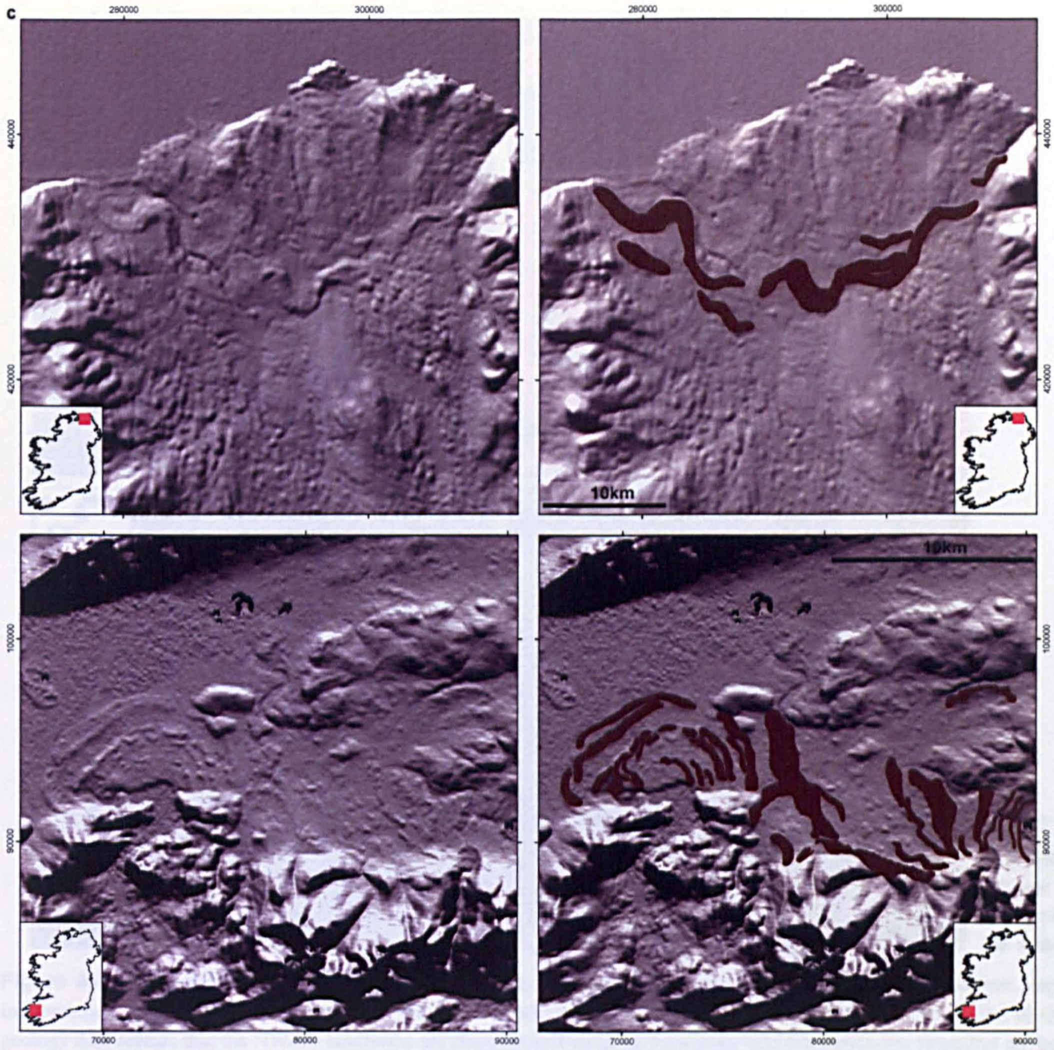


Figure 4.5 Left & right panels show examples of data sources and of landform mapping. **a)** Lineations (black) and ribbed moraine (yellow) are mapped as lines and polygons respectively, shown here on the Landmap DEM in Co. Cavan (upper panels) and in Co. Louth, near Drogheda (lower panels). **b (overleaf)** Satellite imagery was typically best for mapping meltwater features (note that all panels are rotated 180^0 to simulate a 'northern' sun angle). The trough axes of channels and the crestlines of eskers are mapped as lines: upper panels – subglacial channel network located close to Bantry Bay, Co. Cork (SPOT panchromatic image); middle panels - eskers in central Ireland (Landsat ETM+ resolution merge of colour onto panchromatic); lower panels - esker draping bedforms in Co. Tyrone (Landsat ETM+ resolution merge). **c (overleaf)** moraines are usually mapped as polygons, revealed clearly on the SRTM DEM at Armoy, Co. Antrim (upper panels) and spilling from the mountains of Co. Kerry (lower panels).

Mapping was conducted on-screen in a GIS framework, digitising features either as lines (arcs) or as polygons depending on whether it was deemed appropriate to map break-of-slope or simply crestlines/axes. This judgement depends on the scale of the feature relative to the data resolution. All lineations, meltwater channels and eskers were mapped as lines, corresponding either to crestlines or the central axis of a channel; ribbed moraine and moraines were generally mapped by break-of-slope, apart from the smallest of ridges which were mapped as separate layers by crestlines (e.g. 'minor ribbed moraine'.) Within the GIS, each landform was mapped in a separate layer, and assigned a subjective level of confidence: either 'confident' or 'speculative'. Speculative landforms were kept separate from the confident identifications, as individual layers. Uncertainties in landform identification typically arose due to questions of a glacial versus non-glacial origin, the correct categorisation of the feature from the spectrum of glacial landforms considered, or uncertainties over the correct shape of the feature. Many such uncertainties could be ironed out through reference to supplementary information (Section 4.3).





4.3 Quality control: secondary data sources

A number of extra sources of information assisted landform detection and identification of features, providing a degree of quality control over the mapping and ensuring only features with a glacial origin were included.

Quaternary geology maps and digital data were the most useful line of supplementary information. In the Republic of Ireland, surficial sediments (defined as the 'parent material' underlying the modern soils, and must constitute at least 1m in depth) have been mapped at approximately 1:50,000 largely from aerial photography and an extensive fieldwork programme (Meehan, 2006b – Teagasc/EPA/GSI National Soil and Subsoil Survey). This digital dataset distinguishes, amongst others, bedrock, till, glaciofluvial material, lake sediments, marine sediments, alluvium, peat, made ground and modern water bodies, which makes it an invaluable accompaniment to glacial landform mapping. A key area of potential mis-mapping of glacial geomorphology from remotely sensed data is the confusion of bedrock and 'drift' features. Whilst the Quaternary geology data does not include a depth measurement of surface sediments, merely distinguishing between bedrock and sediment exposed at the surface is a particularly useful asset (Figure 4.6), and complements more direct photo-interpretation of bedrock vs drift landforms from the high resolution satellite images.

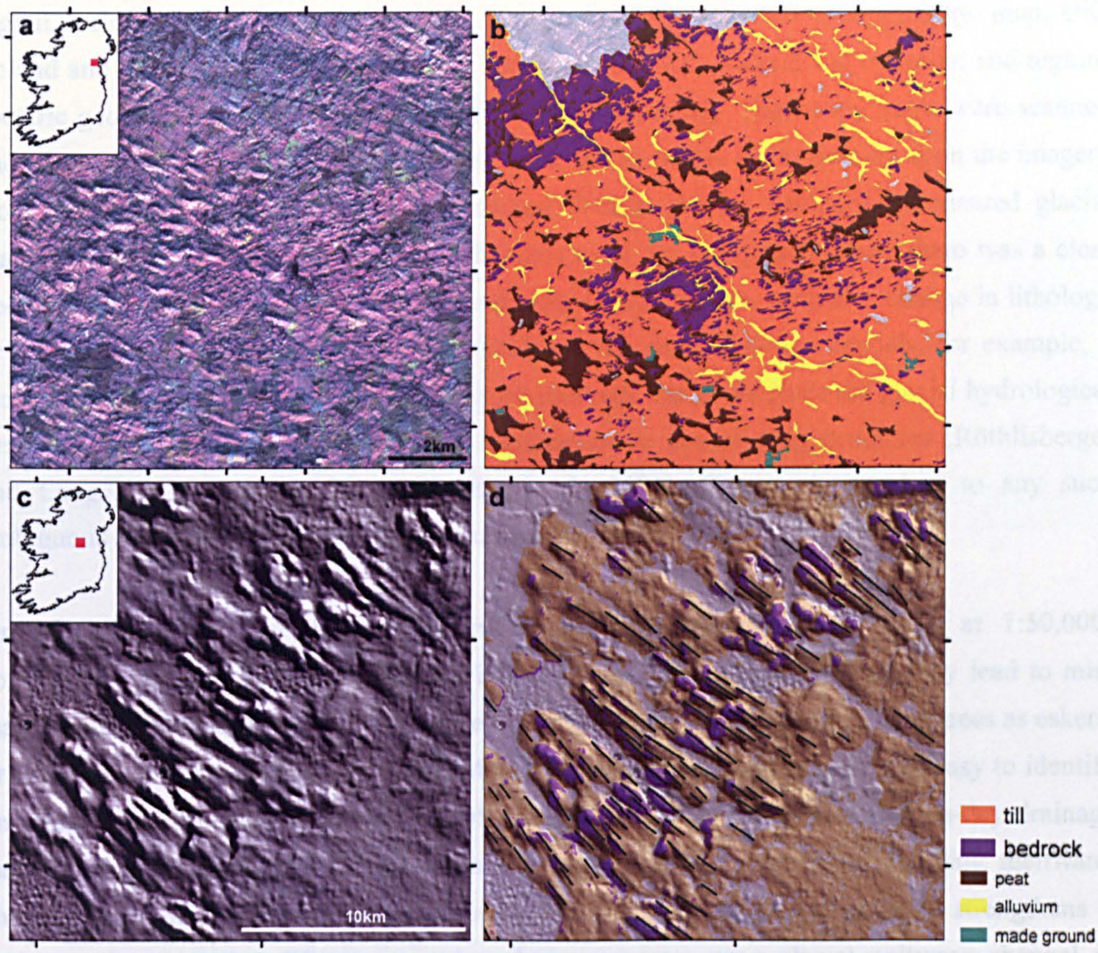


Figure 4.6 Image pairs **a&b** and **c&d** reveal how Quaternary geological data considerably supports landform mapping and interpretation. **a)** linear landforms (drumlins) oriented NW-SE overlie smaller-scale features oriented perpendicular. **b)** Quaternary geology data reveals that the NW-SE landforms are characterised by till at the surface and the underlying structures are bedrock. **c)** lineations oriented NW-SE are revealed by the distribution of till and bedrock at the surface in **(d)** to be a mix of drumlins and crag and tails.

Other properties of the Quaternary geology data were particularly useful. Knowledge of the distribution of peat, made ground and other postglacial materials greatly assisted explanation of subdued topography, although glacial landforms may of course be buried or partially buried beneath later sediments. The glaciofluvial data specifically differentiates eskers from the rest of the dataset, in effect providing an esker map for the Republic of Ireland. Finally a number of significant insights have been drawn from the till data, which specifically identifies the bulk lithology of the till, and hence alludes to its origin. These latter two points are returned to in Chapters 6 and 7, addressing the compilation of all information to be used in the reconstruction process.

The British Geological Survey 1:625,000 UK surficial sediment data and the 1:250,000 map of Northern Ireland Quaternary geology serve a similar purpose for Northern Ireland, albeit at much lower resolution with fewer categories and without lithological information.

Reference to the following **solid and structural geological datasets** and maps further reduced the likelihood of mis-mapping bedrock features as glacial in origin: 1:500,000 solid geology, digital, Ireland; 1:750,000 solid geology, map, Ireland; 1:1,000,000 solid geology, map, UK, Ireland and offshore; 1:1,500,000 tectonic geology, map, UK, Ireland and offshore; and region-specific geological memoirs were referred to where necessary. Hard copy maps were scanned and georeferenced to complement the digital data and to enable direct overlay upon the imagery from which landform mapping was conducted. Visual overlay comparisons ensured glacial features such as moraines or meltwater channels were not interpreted where there was a clear geological or structural explanation for the morphological feature, such as a change in lithology or the occurrence of a faultline. Unfortunately, in the case of large channels, for example, a glacial and structural interpretation may not be mutually exclusive since the glacial hydrological system may exploit underlying substrate weaknesses or pre-existing structures (Röthlisberger and Lang, 1987; Hegarty, 2002; Glasser *et al.*, 2004). Caution is attached to any such ambiguous features and they are mapped as 'speculative'.

Ordnance survey map data (countrywide at 1:250,000 and select areas at 1:50,000) complement the high resolution satellite images in detecting features which may lead to mis-mapping of glacial landforms. It is feasible, for example, to mis-interpret lines of trees as eskers, or the rough texture of forests in the DEM as moraines. Vegetation is generally easy to identify on satellite images but also marked on OS maps. OS data also identifies modern-day drainage patterns, the 'blue-line network', reference to which is important when mapping meltwater channels. Absence of modern-day drainage along a morphological channel strengthens a meltwater interpretation. Of course, modern drainage may re-use a glacial meltwater channel, in which case a judgement must be made by reference to factors such as channel size and stream order as to whether the modern drainage is a 'misfit'. Generation of a more detailed blue-line network through hydrological modelling of both DEMs was explored, in which the theoretical routing of water falling upon the DEM surface is modelled. However, due to insufficient data resolution and too few constraints upon thresholds of stream formation, this route of enquiry was not pursued and OS maps and satellite data were relied upon for this information.

Finally, reference to the **published literature** is a key element of mapping quality control and support. Confirmation in the literature of identification of ambiguous features lends support to the mapping, whilst literature reports of field mapping also guide the eye to landforms and their manifestation in the topographic, tonal and textural properties of the imagery. This is particularly useful for smaller-scale features which are less immediately obvious in the data (Figure 4.7).

Both the published literature and the Quaternary geological information have the potential to contribute additional data to the reconstruction process. The integration of such ancillary data with the new mapping will be considered in Chapters 6 and 7.

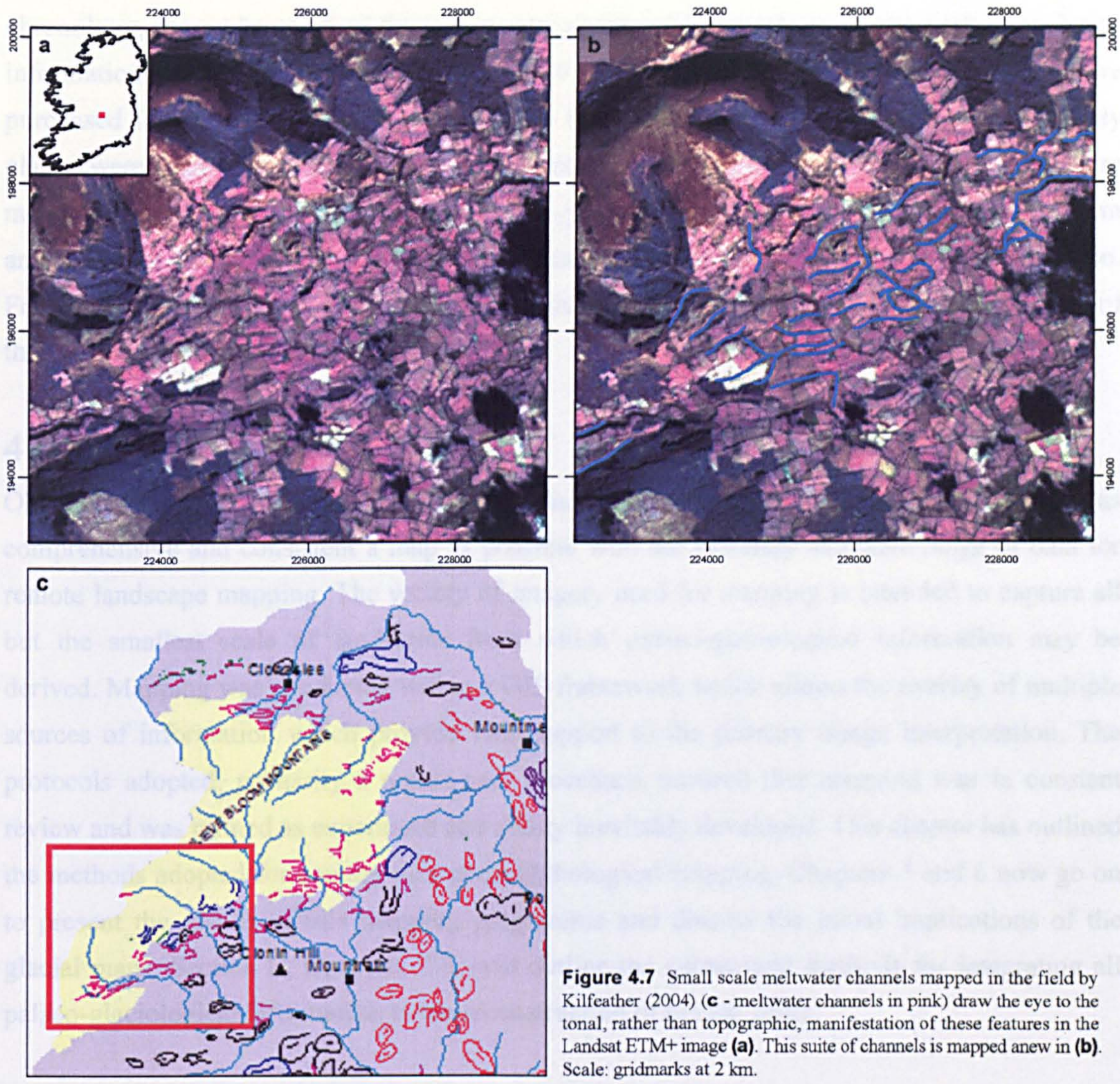


Figure 4.7 Small scale meltwater channels mapped in the field by Kilfeather (2004) (**c** - meltwater channels in pink) draw the eye to the tonal, rather than topographic, manifestation of these features in the Landsat ETM+ image **(a)**. This suite of channels is mapped anew in **(b)**. Scale: gridmarks at 2 km.

4.4 Quality control: final steps

The above two sections have outlined the variety of data sources considered and the procedures adopted to produce a countrywide glacial geomorphological map for Ireland. There are two final levels of 'quality control' to ensure the production of the most comprehensive, consistent and accurate map possible with the currently available data. These stages occur once the analysis of data has begun (i.e. after the main mapping effort), in a somewhat iterative process, but for completeness they are referred to here with the mapping methods and procedures.

Firstly, once bedforms have been summarised into flowsets (Chapter 7, also refer back to Chapter 3 for approach outline), the imagery and the mapping is once more viewed in order to verify that the flowsets proposed are a correct cartographic summary of the information evident. Therefore, there is a further repeat-pass of the data and a final opportunity to make any minor adjustments in mapping accuracy thought necessary.

The final opportunity for as thorough mapping as possible arises once it has become clear which regions are most critical to building a reconstruction. If a problem, for example of relative chronology, cannot be resolved for such a critical area with the data available, higher resolution information is sought. For example, five 20 x 20 km tiles of a high resolution (10 m) DEM were purchased for Cos. Clare and Galway and the Slieve Aughty mountains. There are inevitably places were uncertainty in mapping or chronological control remains. Such uncertainties are mostly questions of a glacial versus non-glacial origin, or where complex landform arrangements preclude either landform identification or deduction of chronological information. For the reconstruction task at hand, these few uncertainties amongst a resulting dataset of 10s of thousands of landforms can be accepted.

4.5 Summary

Objective 1 is to systematically map the glacial geomorphology of Ireland, producing as comprehensive and consistent a map as possible with the currently available range of data for remote landscape mapping. The variety of imagery used for mapping is intended to capture all but the smallest scale of landforms from which palaeo-glaciological information may be derived. Mapping was conducted within a GIS framework which allows the overlay of multiple sources of information which provide vital support to the primary image interpretation. The protocols adopted, primarily a repeat-pass procedure, ensured that mapping was in constant review and was refined as experience and ability inevitably developed. This chapter has outlined the methods adopted for countrywide geomorphological mapping. Chapters 5 and 6 now go on to present the results of this mapping programme and discuss the initial implications of the glacial maps. Section C, Chapters 7-9, will outline the subsequent methods for integrating all palaeo-glaciological information in the reconstruction of the ice sheet.

Chapter 5. Subglacial bedforms

5.1 Introduction

In Chapter 4, the data sources, methods and protocols for countrywide glacial landform mapping were outlined. By following the procedure described, with several levels of quality control, it is believed that the resulting glacial maps are a thorough and consistent documentation of Ireland's glacial landforms. The first outcome of the mapping programme is presented in this chapter: the Subglacial Bedform Map, Map 2 of the supplementary maps attached to this thesis.

5.2 Mapping results: subglacial bedforms

The Subglacial Bedform Map comprises 32,721 bedforms, covering approximately 44% of Ireland. Lineations comprise the bulk of the bedforms mapped (23,637 features) and drumlins are by far the most abundant of all lineations observed, unsurprising given their ubiquity across other palaeo-ice sheet beds. Crag and tails, mega-scale glacial lineations (MSGLs) and also bedrock forms have been recorded though these categories are much less populated. Ribbed moraine represent ~20% of the number of features mapped (Table 5.1). A significant number of landforms were revealed which are highly likely bedforms, but do not fit into the classical and neat categories of lineations or ribbed moraine. These were mapped as 'other bedforms' and were usually quasi-circular in form.

Table 5.1 Bedforms recorded in Map 2.

Feature	Confidence level	Number mapped
Drumlin	Confident	21,967
	Speculative	930
Crag and tail	Confident	384
	Speculative	20
MSGL	Confident	79
	Speculative	10
Bedrock streamlining	Confident	155
	Speculative	92
Ribbed moraine	Confident	6180
Minor ribbed moraine	Confident	1013
'Other bedforms'	Confident	1891

The imagery available to this research has been thoroughly examined through a number of repeat passes, and it is with confidence that the bedform dataset presented in Map 2 is as 'complete' a record of subglacial bedforms as revealed by this imagery. It is most unlikely that this is an entirely complete bedform record, i.e. 'truth'. Data resolution likely limits the number and accuracy of landforms mapped at the smaller end of the scale, although such under-representation within the mapped population is thought to be minimal. The mix of data sources and resolutions goes some way to minimising the effect of a resolution 'cut-off point' and the higher resolution imagery enables the mapper to learn how smaller features are manifested in coarser data (Figure 5.1). The range of lineation lengths mapped (127-10,522 m) is comparable to the ranges typically reported in the literature from other ice sheet beds (drumlins of >100 m – MSGLs of 10s km, Rose, 1987; Benn and Evans, 1998; Clark, 1993). It is anticipated that the mapping effort here has captured the range of shapes and scales of bedforms in Ireland. Most importantly for ice sheet reconstruction, it is argued to have captured the full distribution of bedforms, a signature of all the ice flow patterns which left an imprint in the bedform record, and has captured the details of spatial and temporal bedform relationships. The new, emerging generation of even higher resolution data will likely yield higher populations of the smallest features, but should not reveal any entirely new flow information which has a bearing on ice sheet-scale reconstruction.

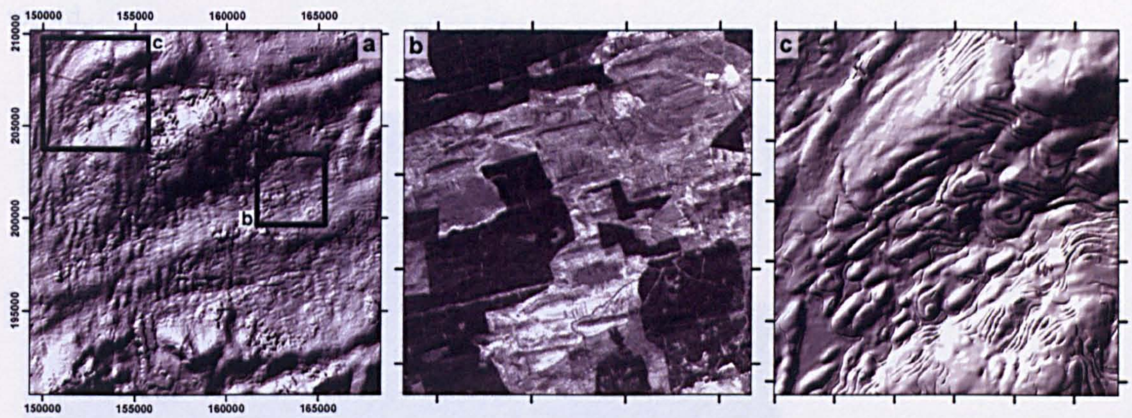


Figure 5.1 At the lower end of the size scale mapping is likely limited by data resolution. Very high resolution data go some way to reducing this under-representation of the smallest features. **a)** a regular ENE-WSW textural pattern suggests a drumlin field is present below data resolution suitable for mapping from the Landmap DEM (25 m resolution), crossing the Slieve Aughty mountains. **b)** SPOT image (10 m resolution) and **c)** 10 m resolution OSi DEM confirm the presence of drumlins < ~500m (contour artefacts in OSi DEM should be ignored). Scale: tickmarks at 5km **(a)** and 1km **(b & c)**.

Whilst all that can be extracted from the imagery has been mapped, there are two key areas in which 'completeness' is lacking. Both are aqueous environments, firstly large lakes, and secondly offshore. Water often can be of great assistance when it collects in inter-landform hollows and clearly outlines the landform perimeter (Figure 5.2). However, small gaps in the bedform distribution exist where larger lakes are situated, such as Lough Neagh, Lower Lough Erne, Loughs Mask & Corrib, which are capable of entirely submerging the bedforms within. Bedforms are found all around the shores of these lakes and the gaps are therefore likely to be data gaps rather than a real absence of features.

Secondly, consensus is growing towards the extent of the British-Irish Ice Sheet offshore onto the continental shelf (discussed in Chapter 2). The map cannot be considered complete since it is spatially restricted to the modern-day terrestrial parts of the ice sheet bed. This restriction on the mapping is one imposed by data availability at the time of the research: imagery of the offshore regions of relevance did not exist. This deficit is partly addressed by the data emerging from the Irish National Seabed Survey (INSS) and its successor programme INFOMAR, but these datasets are not yet complete, particularly with regards to the nearshore regions of most interest to this research. It is clear merely from the onshore map that we should expect the bedform record to extend into the modern marine environment. Bedforms feed offshore all around the coastline: off the North coast, through the main western embayments (Donegal, Sligo, Killala, Clew and Galway Bays), off the Clare coast, out of the Kerry/Cork mountains, off the Waterford coast and over long stretches of the east coast into the Irish Sea Basin. Investigation of offshore seabed imagery is an exciting prospect for further documenting the nature of the ice sheet bed, particularly the partitioning of flow between sheet and streaming behaviour. In offshore sectors, close to the margin, it is expected that ice flow patterns will be arranged relative to the margin in a reasonably straightforward, orthogonal pattern. The onshore record holds more potential for constraining ice divide positions, their movements, and reconstructing more fundamental changes in the overall ice sheet geometry and structure. It is argued that the major elements of ice sheet history may be reconstructed from the onshore record.

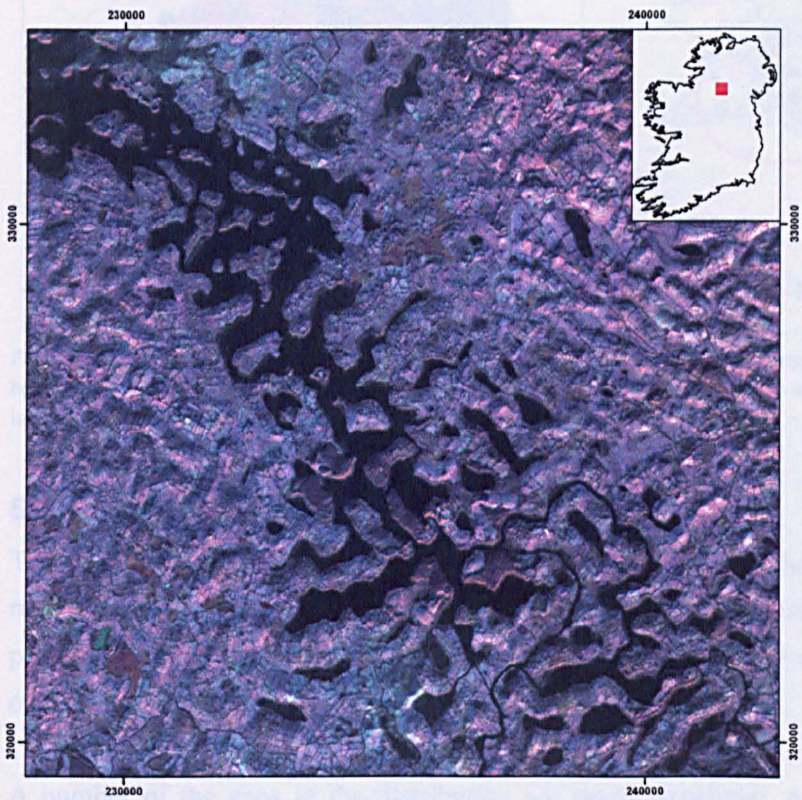


Figure 5.2 Around Upper Lough Erne, water helps delineate the shape of bedforms by collecting in inter-bedform hollows. However, where water is deep enough to submerge landforms, any bedforms 'drowned' by the lake are not visible and gaps in the record exist. Scale: gridmarks at 10 km.

The interpretation of bedform distribution and their spatial and temporal patterns, is fundamental to reconstructing the palaeo-geography and palaeo-glaciology of the ice sheet. The following sections consider the distribution of bedforms in Ireland, the specific distributions of lineations and ribbed moraine and their inter-relationship, how the new mapping relates to existing knowledge of subglacial bedforms in the Irish literature, and finally the directions of analysis which may be pursued from here.

5.3 Discussion: bedform distribution and arrangement

Subglacial bedforms cover ~44% of Ireland (Map 2 & Figure 5.3). The map reveals two key properties of the subglacial bedform record: bedforms have a patchy coverage, and a patchy distribution within this overall coverage. These properties of the record are discussed below.

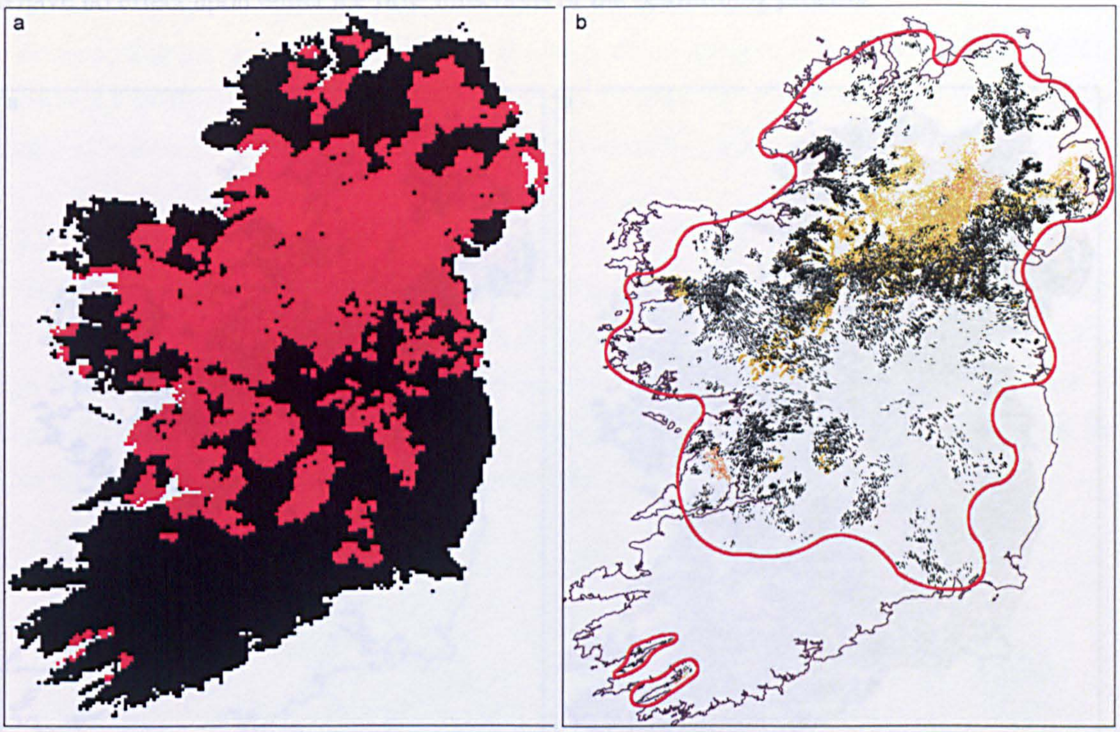


Figure 5.3 Bedforms cover 44% of Ireland. This is calculated from a presence/absence map **(a)** which records presence of bedforms on a 2x2km cell basis. The likely area over which bedforming ice flows exert an influence on the landscape appears much larger – ~80% **(b)**. Key for **(b)** as Map 2: black = lineations, yellow = ribbed moraine etc.

5.3.1 Patchy coverage

The subglacial bedform record (Map 2) is clearly a patchy one. It has been argued above that the record presented here is, except for the key absences relating to water bodies, to all intents and purposes 'complete'. Therefore the patchiness of the record must relate to either the properties of the ice sheet or the terrain over which it flowed.

A number of the gaps in the distribution are easily explained, and the implications of these explanations will be of interest to the bedform genetic process question. Figure 5.4 compares the subglacial bedform record with the general topography of Ireland and it becomes clear that bedforms are typically restricted to the lower ground. The peripheral mountain masses (such as in Donegal, Connemara, Kerry/Cork, the Wicklows) and pockets of the highest terrain within the interior of the land (Slieve Bloom, the Castlecomer Plateau, parts of the Slieve Aughtys, parts of the Cuilcaghs) are bedform-free. Of interest to the process question is the effect of terrain properties upon bedform genesis; topographic effects may be transmitted in a number of ways, through drift thickness (sediment availability), slope angle, terrain shape, geology, or purely elevation in relation to ice thickness. Of most relevance to the task of ice sheet reconstruction is the observation that topography may play a role in directing ice flow patterns, particularly in the south of the country where bedforms appear to be diverted *around* topography. This is in contrast to the bedform distribution towards the north where bedform morphology and distribution pays little regard to topographic obstacles (Figure 5.4c-d). Some rather qualitative interpretations may be made here regarding ice thickness: where topography controls ice flow, a thinner ice sheet may be envisaged than where topographic obstacles appear to have no effect upon either ice flow directions or the bedforming process.

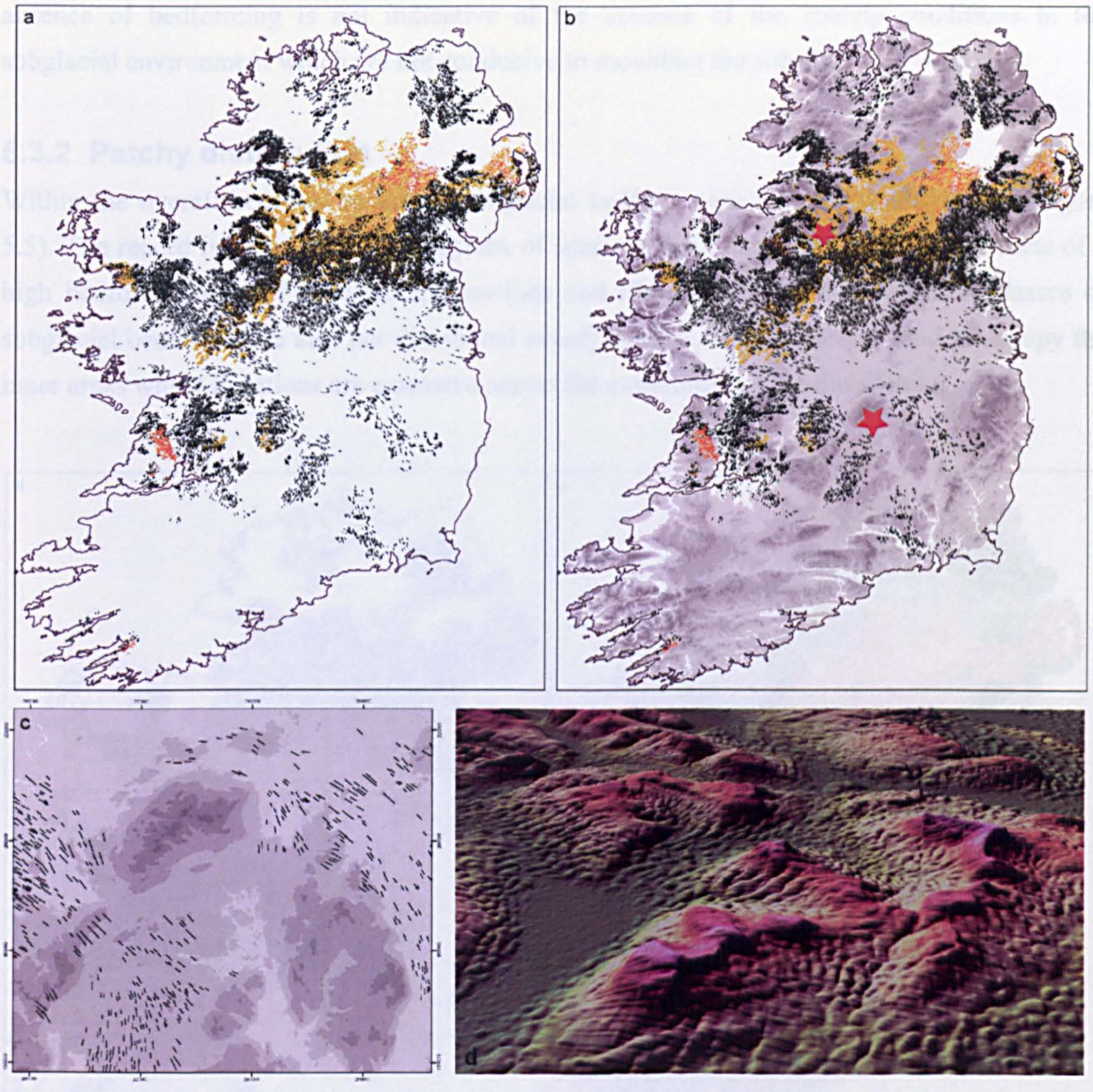


Figure 5.4 A number of the gaps in the bedform record revealed in **(a)** can be accounted for by the presence of upland terrain **(b)**. The degree to which upland areas disturb bedform distribution is variable. Bedforms wrap around the Slieve Bloom mountains (**c** – up to 400 m higher than surrounding plains) suggesting the hills entirely deflected ice flow, whereas only the highest points of the Cuilcagh mountains (**d** – ~300 m higher than surrounds) escape bedform generation. Lower & upper stars in **(b)** indicate locations of **(c)** and **(d)** respectively. Scale in **(c)**: gridmarks at 20 km.

A major gap in the coverage of bedforms which cannot be attributed to topography lies in the central counties of Offaly and Kildare. Bedforms (lineations) are found here but are very sparsely distributed across a subdued landscape dominated by glaciofluvial deposits and by peat. It is in this region that previous workers have described lacustrine sediments underlying the modern peat bogs and have proposed the existence of a proglacial lake(s) (Warren and

Ashley, 1994; van der Meer and Warren, 1997; Glanville, 1997; Delaney, 2002). It is possible that deglacial sedimentation and landform assemblages either erased or buried any earlier bedform patterns, should they have existed.

Interestingly, the overall bedform distribution is reminiscent of the glacial limits originally proposed by Synge (Synge and Stephens, 1960; Synge, 1970). However, it would be erroneous to return to this ice sheet interpretation on the basis of the subglacial bedform distribution. The absence of bedforming is not indicative of the absence of ice, merely conditions in the subglacial environment which are not conducive to moulding the substrate into bedforms.

5.3.2 Patchy distribution

Within the overall bedform coverage, subglacial bedforms are not evenly distributed (Figure 5.5). The record is characterised by regions of sparsely distributed landforms and pockets of a high bedform density. Furthermore, lineations and ribbed moraine, the two main classes of subglacial bedforms, are also not distributed evenly. Rather, ribbed moraine tend to occupy the inner areas whilst lineations are extensive across the extremities of the distribution.

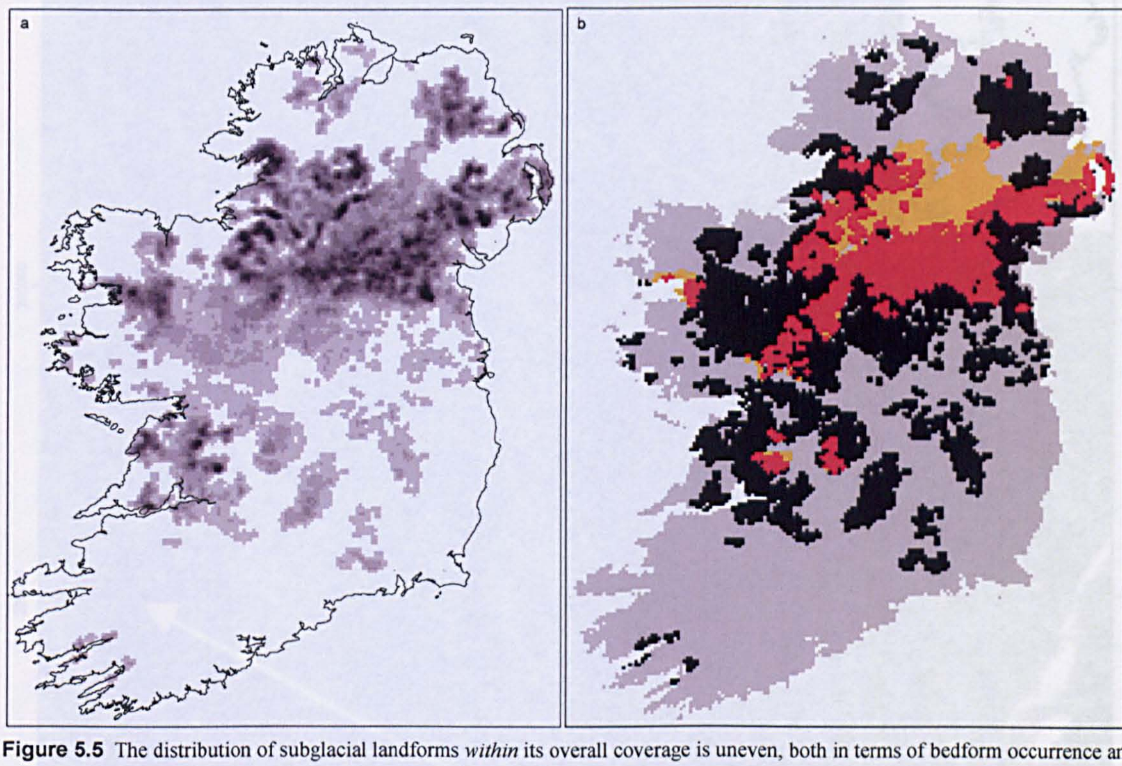


Figure 5.5 The distribution of subglacial landforms *within* its overall coverage is uneven, both in terms of bedform occurrence and in terms of the distributions of bedform types. **a)** density of bedforms (count per unit area, here 2 x 2 km). **b)** distribution of bedform types (presence or absence per unit area, 2 x 2 km): black = lineations; yellow = ribbed moraine; red = mixed population.

The most densely populated areas of bedforms are those lying in the interior of the ice sheet, such as Cos. Armagh, Monaghan, Cavan, Fermanagh and Leitrim. This coincides with a considerable area of overlap of the distributions of lineations and ribbed moraine (>25% of the bedform coverage area). Under a simple, radial ice sheet, one may expect such arrangements to develop as a consequence of a classic along-flow (downstream) bedform morphology continuum (e.g. Boulton, 1987; Menzies, 1987). Ribbed moraine should occupy the core, ridges become drumlinised in an inner zone surrounding the core, before more elongate lineations dominate the peripheral regions of the ice sheet. The zone of drumlinised ribbed moraine would account for the high individual bedform count and the overlapping distributions shown in Figure 5.5. Indeed, specific examples of such downstream transitions are evident in the observed bedform record (Figure 5.6).

Whilst the distribution of whole populations of bedforms could present such a simple story, the internal arrangements of bedforms suggest a more complex ice sheet history, and a simple count density masks the true nature of bedform distribution and arrangement. There is an abundance of overprinting within the bedform record in which two or more landforms or landform assemblages superimposed upon each other do not reflect the same direction of ice flow. Instead, the superimposed features often cross-cut the underlying imprint in an altogether different direction. Such landform relationships are signatures of ice sheet reorganisation, since a new configuration must be invoked to explain the change in flow direction. Bedform

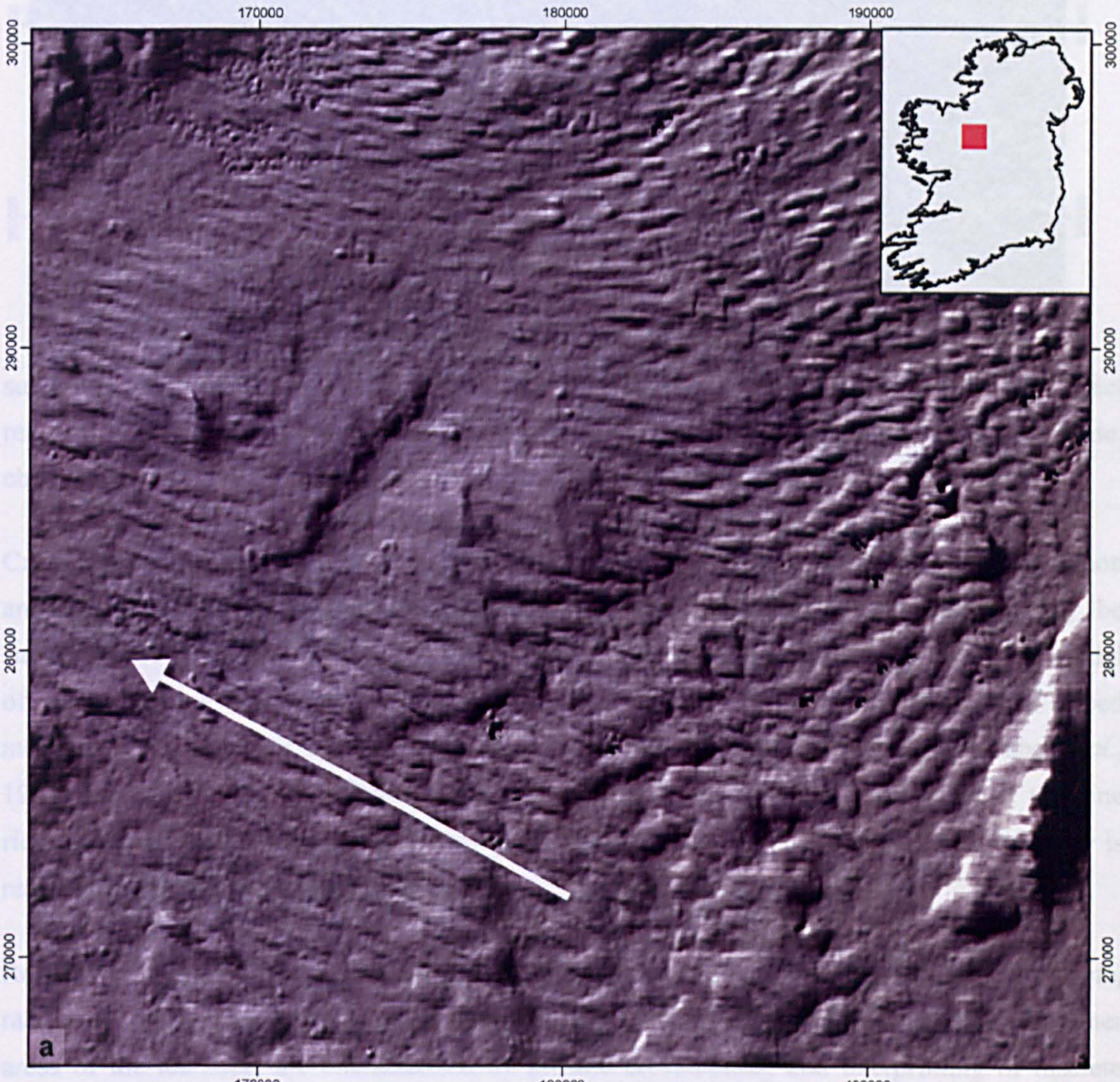
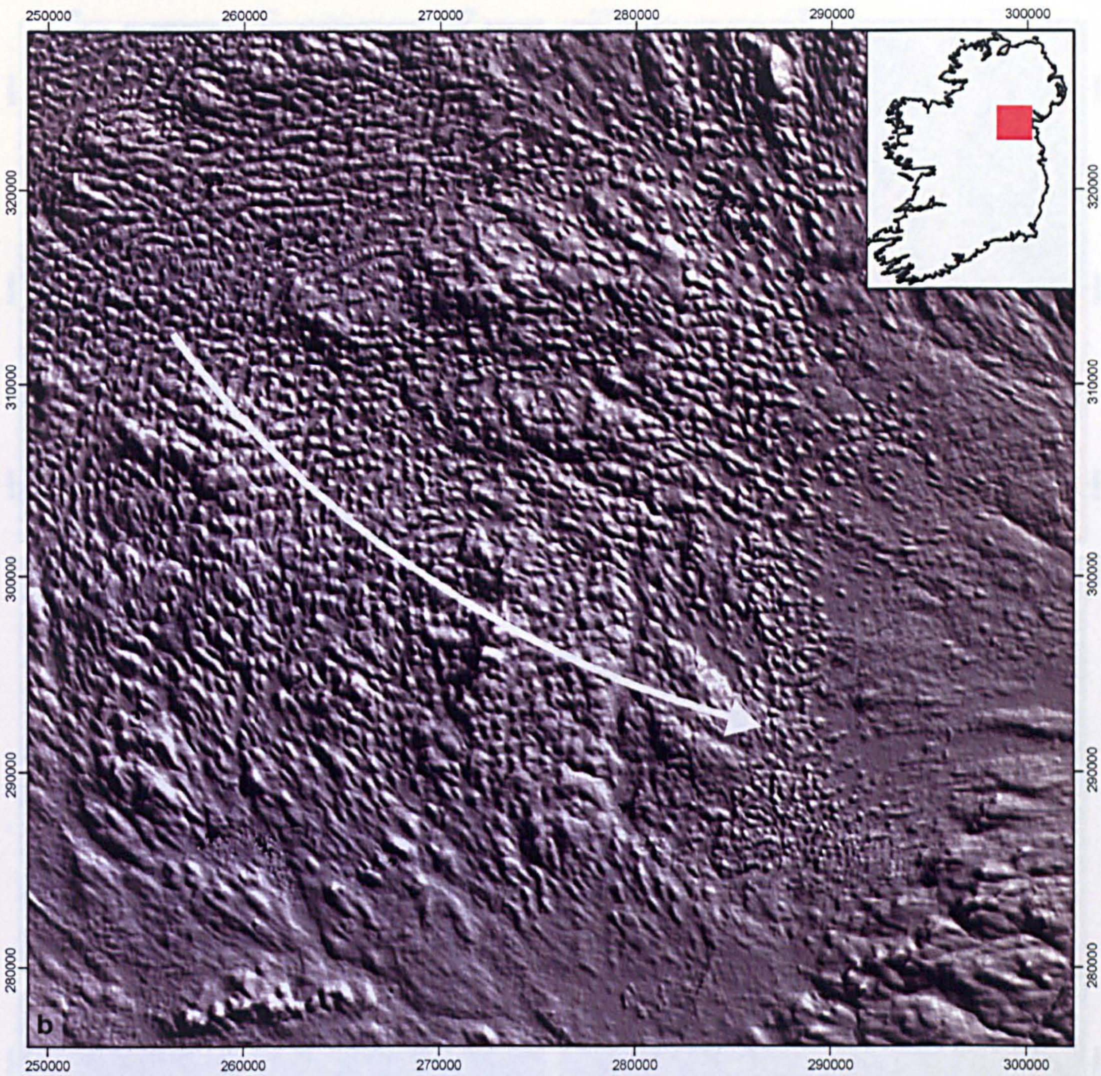


Figure 5.6 a & b: classic along-flow spatial transition reflecting a bedform continuum, from ribbed moraine at the head of the ice flow to elongate bedforms downstream. Arrows indicates ice flow direction. Scale: gridmarks at 10 km.



superimposition therefore holds vital spatial and temporal information for ice sheet reconstruction. Its prevalence in Ireland suggests the ice sheet must have been highly dynamic, characterised by changing configurations of an ice sheet which frequently reworked its bed.

Cross-cutting and superimposition is found both internally within the ribbed moraine population and the lineations, as well as the combinations in which the two populations may be superimposed (Figure 5.7). These landform relationships are incompatible with a simple model of radial ice flow and a concentric arrangement of bedforms. Indeed, the core area of ribbed moraine which has been deemed as "pristine" (e.g. McCabe and Clark, 1998; McCabe *et al.*, 1999; McCabe, 2005) is revealed here to be characterised by cross-cutting ribbed moraine ridges and ~circular bedforms of an unclear genetic origin; a more complex ice flow history is required to explain these relationships.

Regions of high bedform density (Figure 5.5a) cannot therefore be accounted for by a simple, radial ice flow model with a downstream evolution of bedform morphology. Rather, the inner areas of the ice sheet are characterised by prolific cross-cutting and overprinting of discrete suites of bedforms (Figure 5.8). These arrangements and bedform distribution have significant implications for the positions and movements of ice divides over Ireland.

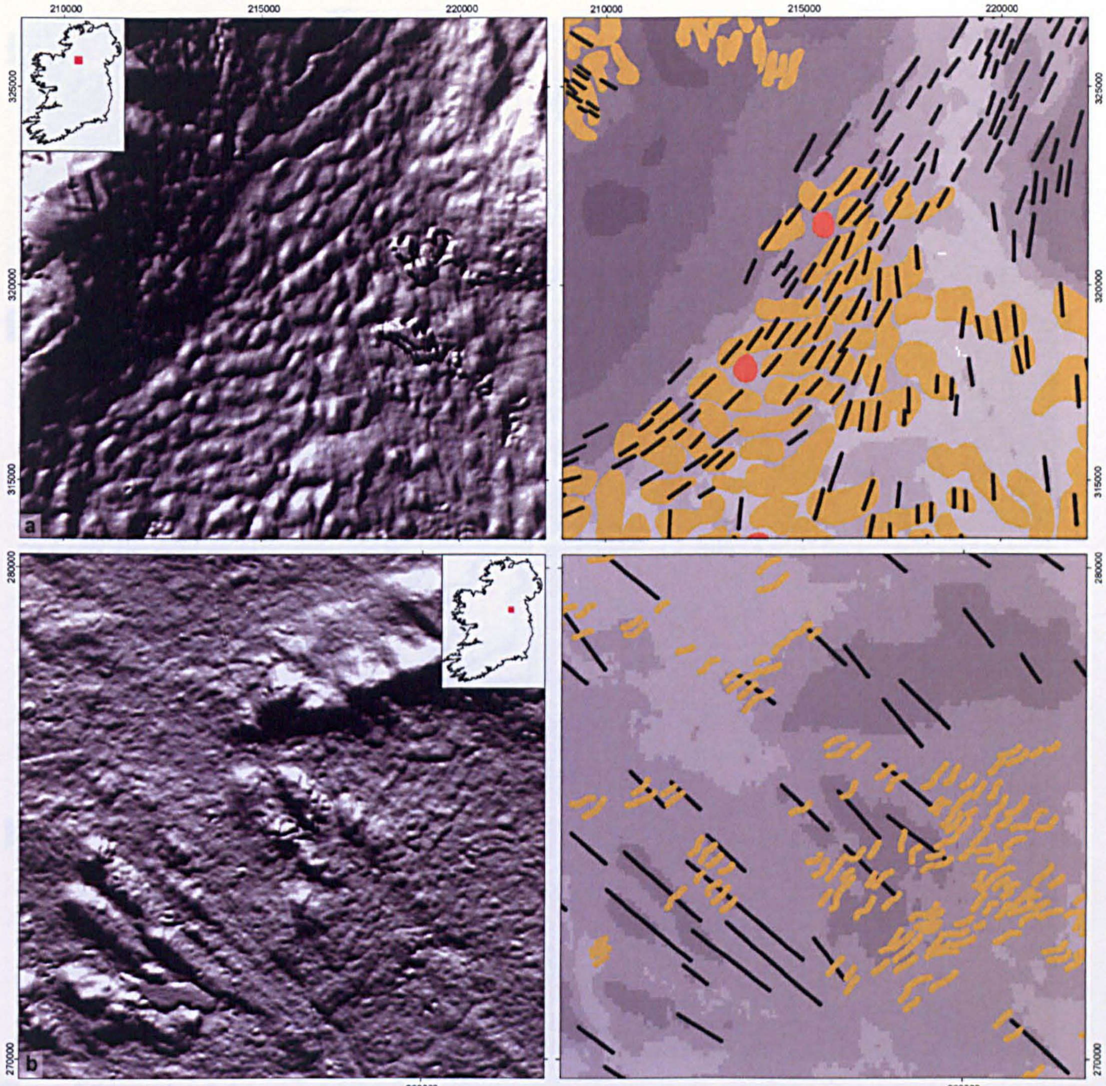


Figure 5.7 Superimposition relationships between bedforms. Left panels of each pair show imagery; right panels show the mapped landform interpretation. **a & b** illustrate relationships between ribbed moraine and lineations, in which drumlins are superimposed on ribbed moraine in **(a)** and minor ribbed moraine overprint crag and tails in **(b)**. Ice flow is generally in the same direction. **c & d (over page):** the same landform type is involved in a cross-cutting relationship: drumlins cross-cut MSGLs in **(c)**; ribbed moraine cross-cut in **(d)**. Note also that both sets of ribbed moraine in **(d)** are partially drumlinised. Flow directions in these examples are clearly different (arrows) and ice sheet re-configuration must have occurred in the time interval between the inscription of the different suites of landforms. (Note that black squares in **d** (left panel) are data artefacts.) Scale: gridmarks at **a)** 5 km; **b)** 10 km.

5.4 Discussion: comparison with the literature

Maps of glacial features in Ireland date back to Close (1867). The most often reproduced glacial landform map was first introduced by Synge and Stephens (1960), and has since appeared in numerous publications with minor modifications (Synge, 1970, 1979; McCabe, 1985; up to Farrell *et al.*, 2005). It is not strictly fair to compare this glacial map with the Bedform Map presented in this chapter (Figure 5.9); it is not a like-for-like comparison but rather a detailed map of individual landforms versus a schematic representation of patterns. However, this serves to reinforce the fact that the lack of countrywide consistency of mapping precluded a glacial map any more detailed than such a schematic image. Rather than needing to generalise some very detailed field evidence to achieve consistency, the bedform map presented here displays the details of landform morphologies, arrangements and patterns across the entire terrestrial bed of the ice sheet for the first time.

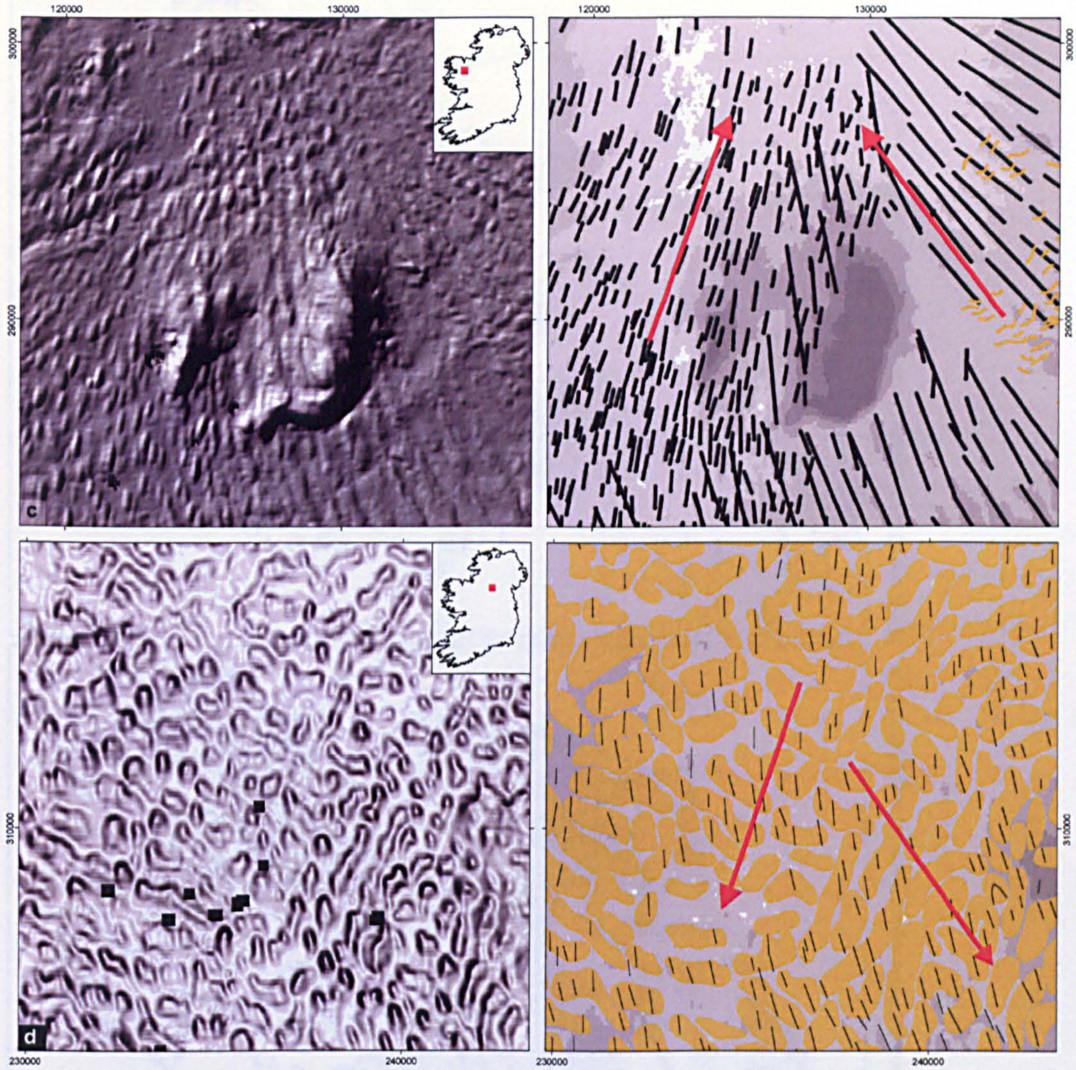


Figure 5.7 (cont.) c & d

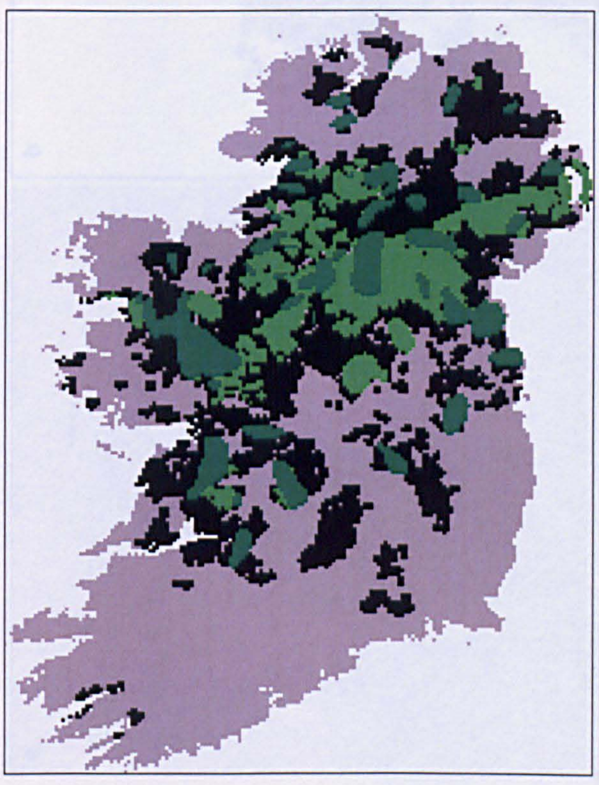


Figure 5.8 Cross-cutting and superimposed bedform patterns are widespread throughout the bedform record of Ireland. On a 2 x 2 km grid (left) black cells show the distribution of bedforms; light green cells indicate where superimposition types **a** and **b** (see Fig 5.7) occur; dark green cells indicate bedform cross-cutting (types **c** and **d**). The prevalence of these relationships demands an ice sheet model characterised by frequent changes of flow configuration to repeatedly rework the bed in changing directions.

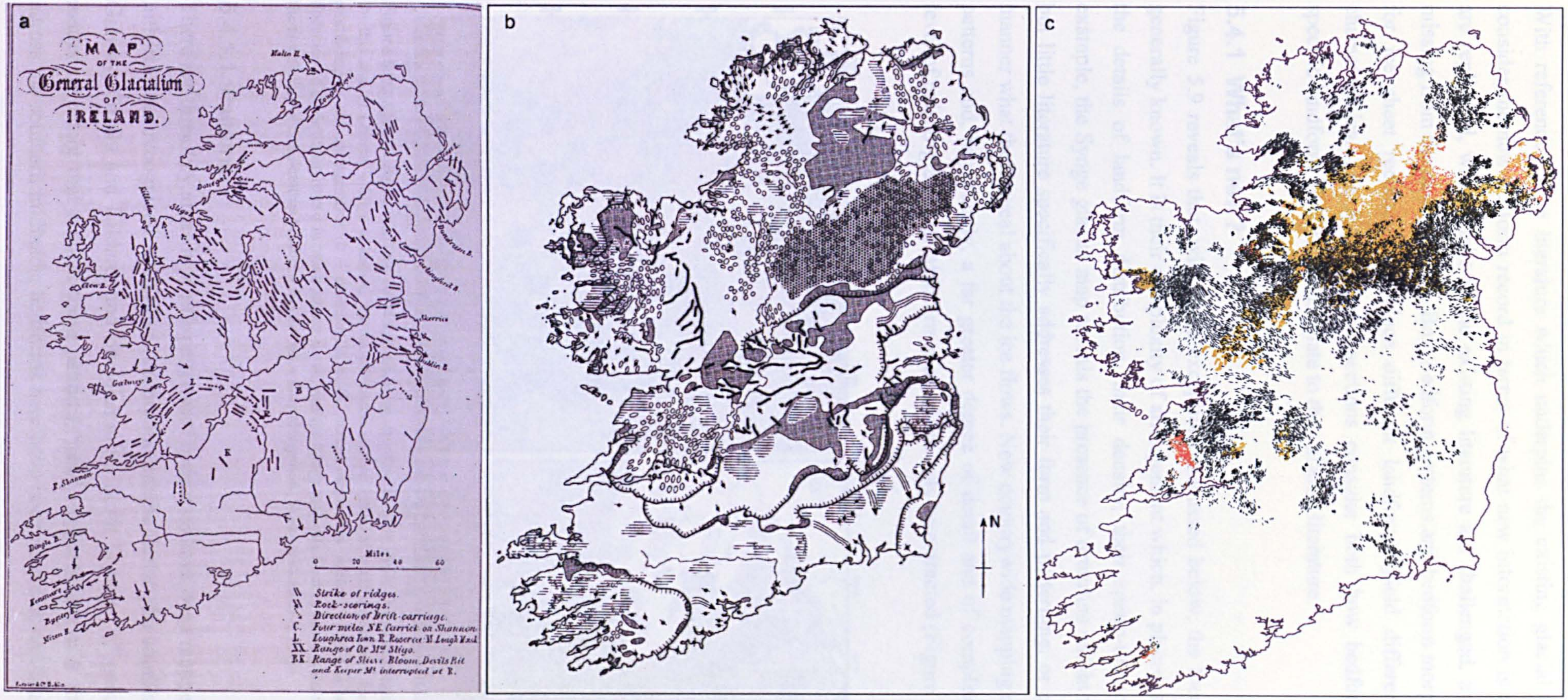


Figure 5.9 **a)** the first attempt to compile glacial landform information (Close, 1867); **b)** a recent incarnation of Synge's glacial map (Farrell *et al.*, 2005); and **c)** the subglacial bedform record presented in Map 2.

With reference to the literature which underpins the existing glacial maps this section will consider the new bedform record in terms of what new information is revealed, what patterns are replicated, what details in the existing literature are challenged, and what information is missing from the new mapping. Both bedform patterns and bedform morphologies are important for ice sheet reconstruction since different landforms yield different palaeo-glaciological characteristics. The following sub-sections consider both how bedform patterns and more specific landform identifications relate to the existing literature.

5.4.1 What's new?

Figure 5.9 reveals that, with some exceptions discussed below, the location of bedforms was generally known. It is their complexity of arrangement which, in places, was poorly understood: the details of landform distribution, their density, their spatio-temporal relationships. For example, the Synge glacial map reveals the presence of drumlins within the Leitrim mountains, but little literature specifically addresses their form and patterning, or considers in a rigorous manner what they reveal about the ice flows. New countrywide mapping reveals a few new flow patterns and, importantly, a far greater degree of detail and of complexity which adds to the level of palaeo-glaciological information which may be extracted (Figure 5.10).

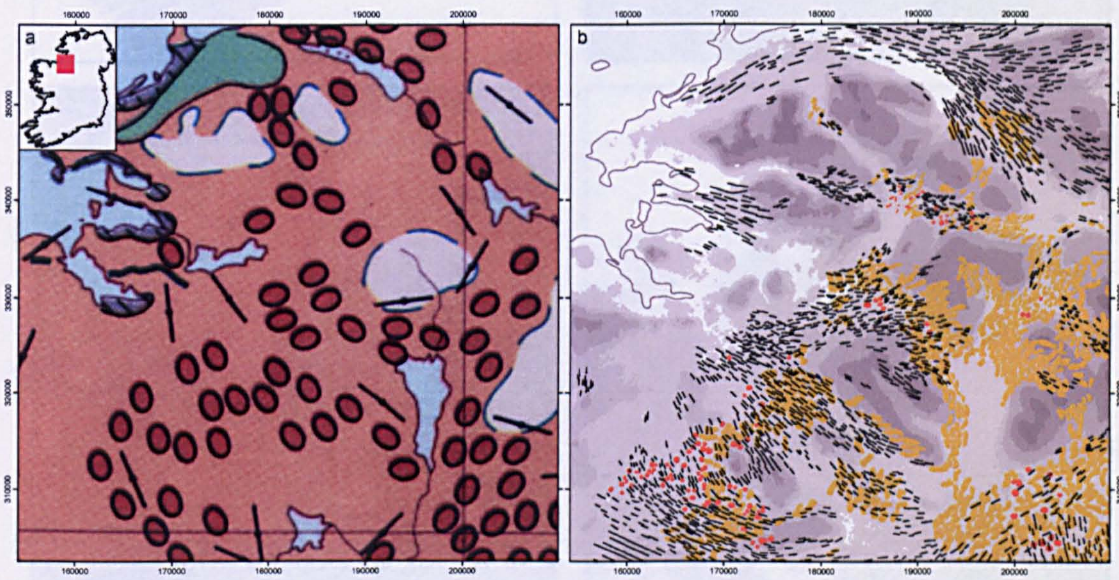


Figure 5.10 Synge's glacial map (**a** – striae as black lines, drumlins as filled ovoid shapes) indicates that the presence of drumlins for this area of Leitrim – Sligo is known, but its schematic representation of landforms masks the true details of bedform sizes, morphologies and arrangements (**b** – drumlins in black, ribbed moraine in yellow). Whilst in several locations workers have documented the bedform record in much greater detail than the Synge map, the level of detail is inconsistent across the country and the complexity of cross-cutting bedforms has not been fully recognised. Scale: gridmarks at 10km.

5.4.1.1 Patterns

There are three key areas in which patterns of bedforms have been mapped where they have not hitherto been recognised: the Slieve Aughty mountains, across the southern midland counties of Galway, Offaly and Kildare, and on Inishowen, north Donegal (Figure 5.11). It is largely a matter of extent that renders these patterns 'new'. In particular over the Slieve Aughtys and across the southern midlands, bedforms here have been hinted at previously. Close's early map

(1867) drew lineations curving *around* the Slieve Aughty's (a pattern which has received little subsequent attention) whereas here drumlins are additionally revealed to *cross* the mountains. Drumlins have been recorded dispersed through Co. Laois (Kilfeather, 2004) and between the Slieve Aughty's and Slieve Bloom, but their extent and connections are now revealed in detail across the south midlands. On Inishowen, striations oriented towards the N and NW have previously been documented (Synge, 1970; Colhoun, 1971); here drumlins, possibly crag and tails, are revealed aligned in the same direction.

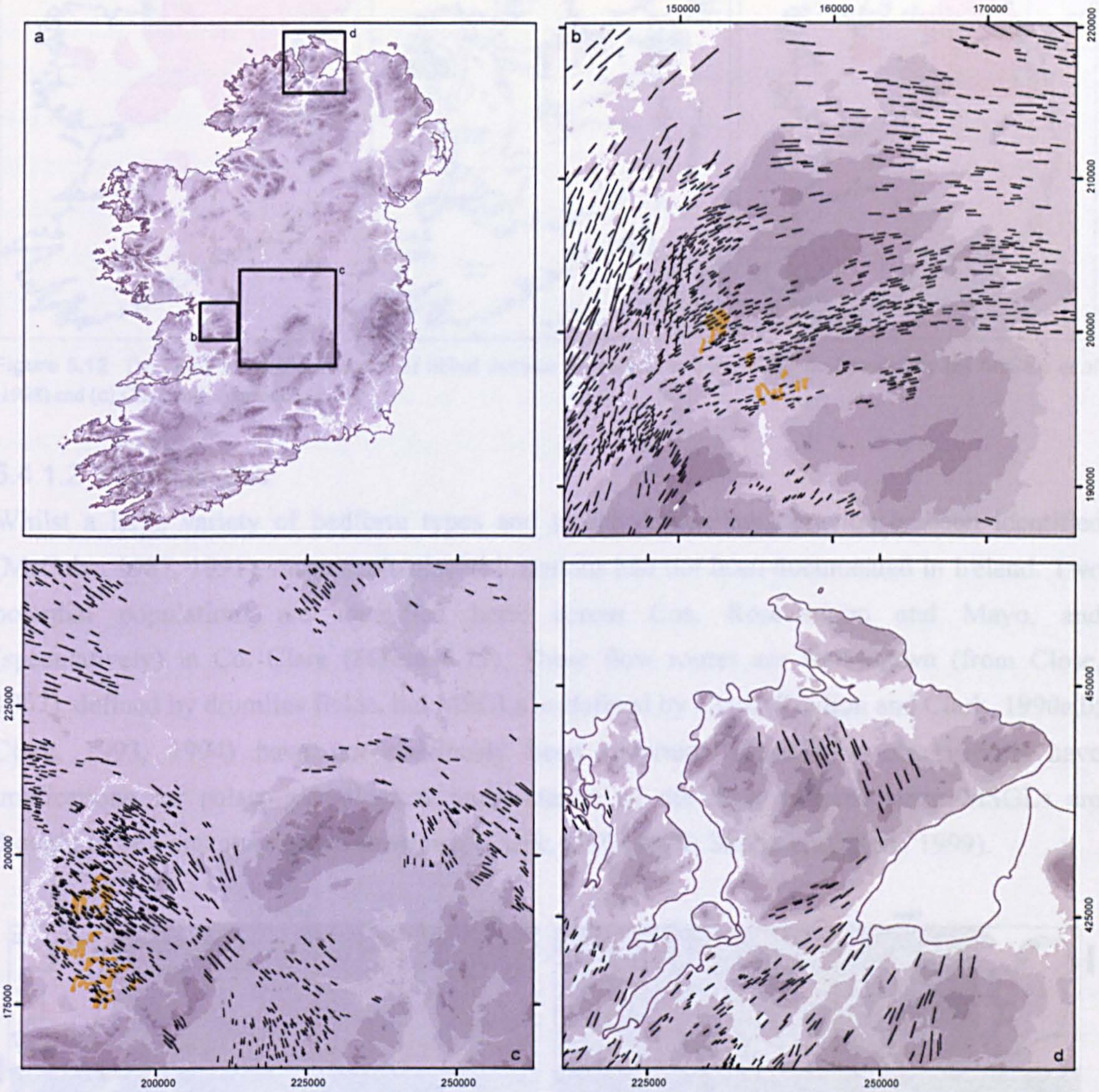


Figure 5.11 New patterns and enhanced details revealed by the new mapping. **b)** drumlins cross the Slieve Aughtys; **c)** lineations penetrate through the southern midlands into the south; **d)** drumlins (and possibly crag and tails) pass offshore over Inishowen. Locations in **(a)**. Scales: gridmarks at 10 km in **(b)**; 25 km in **(c)** and **(d)**.

Ribbed moraine in Ireland are a relatively new discovery (Knight and McCabe, 1997; Clark and Meehan, 2001) and have hitherto only been reported from the north and the north-east midlands of Ireland. The Subglacial Bedform Map considerably extends this ribbed moraine distribution (Figure 5.12) and reveals ribbed moraine which penetrate well towards the south and west, into Cos. Galway, Clare and Offaly. Much of the newly mapped ribbed moraine is situated underlying drumlins, often where 'transverse arrangements' or 'banding' of drumlins has been identified by past workers (e.g. Co. Down: Vernon, 1966). These discoveries are not so much a challenge to earlier mapping but provide an additional layer of flow information. Often the ribbed moraine indicate flow oriented in the same direction (e.g. Cos. Galway & Roscommon, Co. Down) but in some places a more complex flow and bedforming history is suggested.

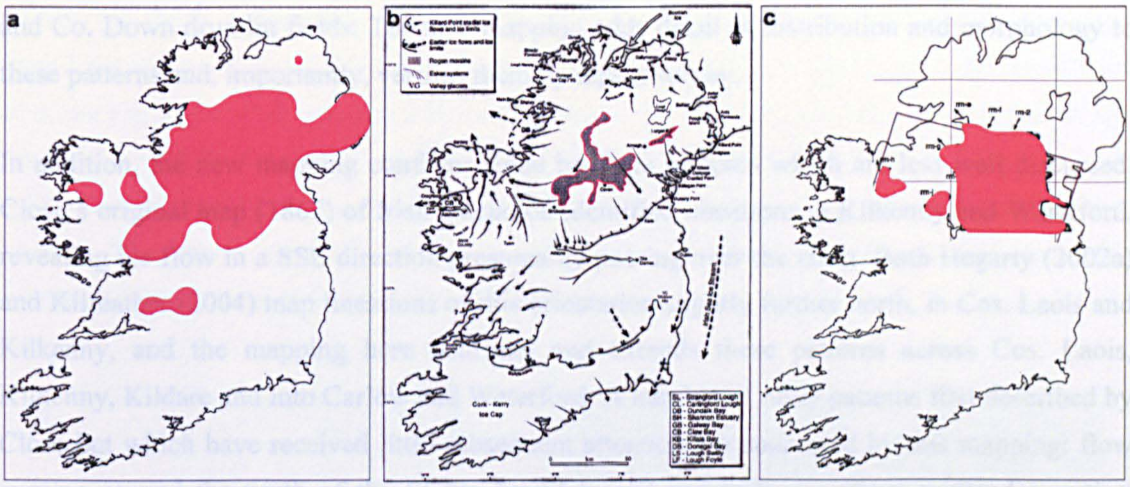


Figure 5.12 The newly mapped distribution of ribbed moraine **(a)** exceeds that previously documented by **(b)** McCabe *et al.* (1998) and **(c)** Clark and Meehan (2001).

5.4.1.2 Morphologies

Whilst a large variety of bedform types and morphologies have previously been identified (McCabe, 1987, 1991), mega-scale glacial lineations had not been documented in Ireland. Two potential populations are identified here: across Cos. Roscommon and Mayo, and (speculatively) in Co. Clare (Figure 5.13). These flow routes are well-known (from Close, 1867), defined by drumlins fields, but MSGLs as defined by Clark (Boulton and Clark, 1990a,b; Clark, 1993, 1994) have not previously been reported. These new observations have implications for palaeo-glaciological interpretation of the flow patterns since MSGLs are thought to be a signature of ice streaming (Clark, 1993, 1994; Stokes and Clark, 1999).

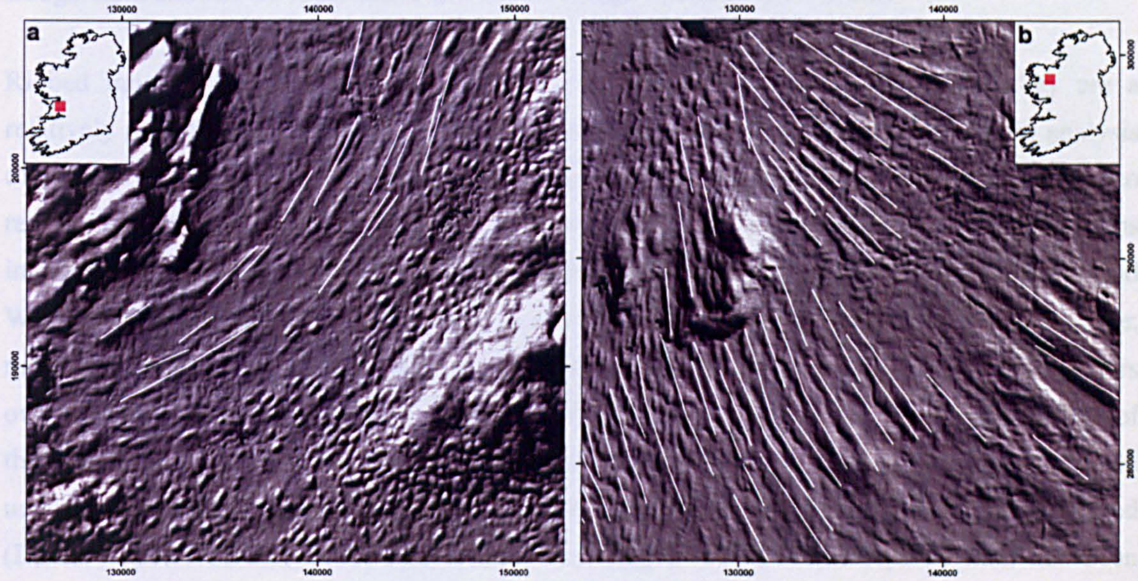


Figure 5.13 Two potential populations of MSGLs in Ireland. Whilst these flow patterns have long been known, MSGLs have not previously been recognised. Scale: gridmarks at 10 km.

5.4.2 What's replicated?

5.4.2.1 Patterns

The major bedform patterns in Ireland have long been known: the NE midlands 'drumlin belt', the south-westerly drumlin pattern in Co. Clare, patterns converging on Killala Bay from Connemara and from Co. Roscommon, the Donegal Bay drumlins, Galway Bay, Bantry Bay and Co. Down drumlin fields. The new mapping adds detail of distribution and morphology to these patterns and, importantly, verifies them by repeat survey.

In addition, the new mapping confirms some bedform patterns which are less well discussed. Close's original map (1867) of Irish glaciation identified lineations in Kilkenny and Waterford, revealing ice flow in a SSE direction presumably passing over the coast. Both Hegarty (2002a) and Kilfeather (2004) map lineations of this orientation slightly further north, in Cos. Laois and Kilkenny, and the mapping here confirms and extends these patterns across Cos. Laois, Kilkenny, Kildare and into Carlow and Waterford. A number of other patterns first described by Close but which have received little subsequent attention are supported by this mapping: flow curving around the north of the Slieve Aughty's and across the southern midland counties; drumlins oriented towards the SW on the northern flanks of the Wicklow mountains; and streamlining patterns on Island Magee, Co. Antrim are recognised here also.

5.4.2.2 Morphologies

Like the major flow patterns, the wide-ranging bedform morphologies found in Ireland have previously been observed (McCabe, 1987, 1991; Dunlop, 2004). Such observations are supported by the new mapping which recognises diverse bedform planforms and sizes. This includes ~circular 'drumlins' (Hill, 1973; Finch and Walsh, 1973; Dardis *et al.*, 1984; McCabe, 1991) described as 'other' on the Subglacial Bedform Map since their genetic origin and palaeo-glaciological significance is less well constrained than for lineations or ribbed moraine. These are observed in patches throughout Ireland, but particularly in SW Clare, in Co. Sligo between Lough Gara and the Ox mountains, and SW of Lough Neagh in Co. Antrim.

Ribbed moraine similarly exhibit a wide variety of morphologies and, though they are a relatively recent discovery in the bedform record of Ireland, this is consistent with the analysis of Dunlop (2004). At one end of the scale, the largest ribbed moraine in the world have been recorded in Ireland; at the other, small-scale transverse ridges are superimposed upon lineations in patches across the country. These have previously been documented in Cos. Meath and Westmeath (Clark and Meehan, 2001) where they were interpreted as minor ribbed moraine; their distribution is extended here to Co. Mayo where they are found in two clusters overprinting MSGLs and drumlins. The size of these features is almost at the resolution limit of the available imagery and it is therefore likely that the mapped population of minor ridges is an under-representation of their true number and distribution. Indeed, it has been suggested (Delaney, pers. comm., 2007) that these minor ridges are more widespread than has been previously reported, although their origin remains ambiguous.

The interpretation of these minor transverse ridges clearly has implications for ice sheet reconstruction: subglacial or ice-marginal? Meehan (1999) first suggested the ridges in Co. Meath were push moraines and therefore ice-marginal. However, they were re-interpreted as minor ribbed moraine by Clark and Meehan (2001) on the basis of their relation to the underlying macro-topography: their distribution is unaffected by topographic shape which would not be expected were the ridges ice-marginal. Following the same logic, the population of minor ridges mapped here was investigated with respect to its topographic context and an ice-marginal or subglacial origin was interpreted for each suite of landforms accordingly (Figure 5.14). Two of the three major clusters are interpreted as subglacial in origin and are presented in Map 2. The other cluster in north Co. Mayo could plausibly be ice-marginal, recording recession of an ice lobe through Killala Bay (Chapter 6).

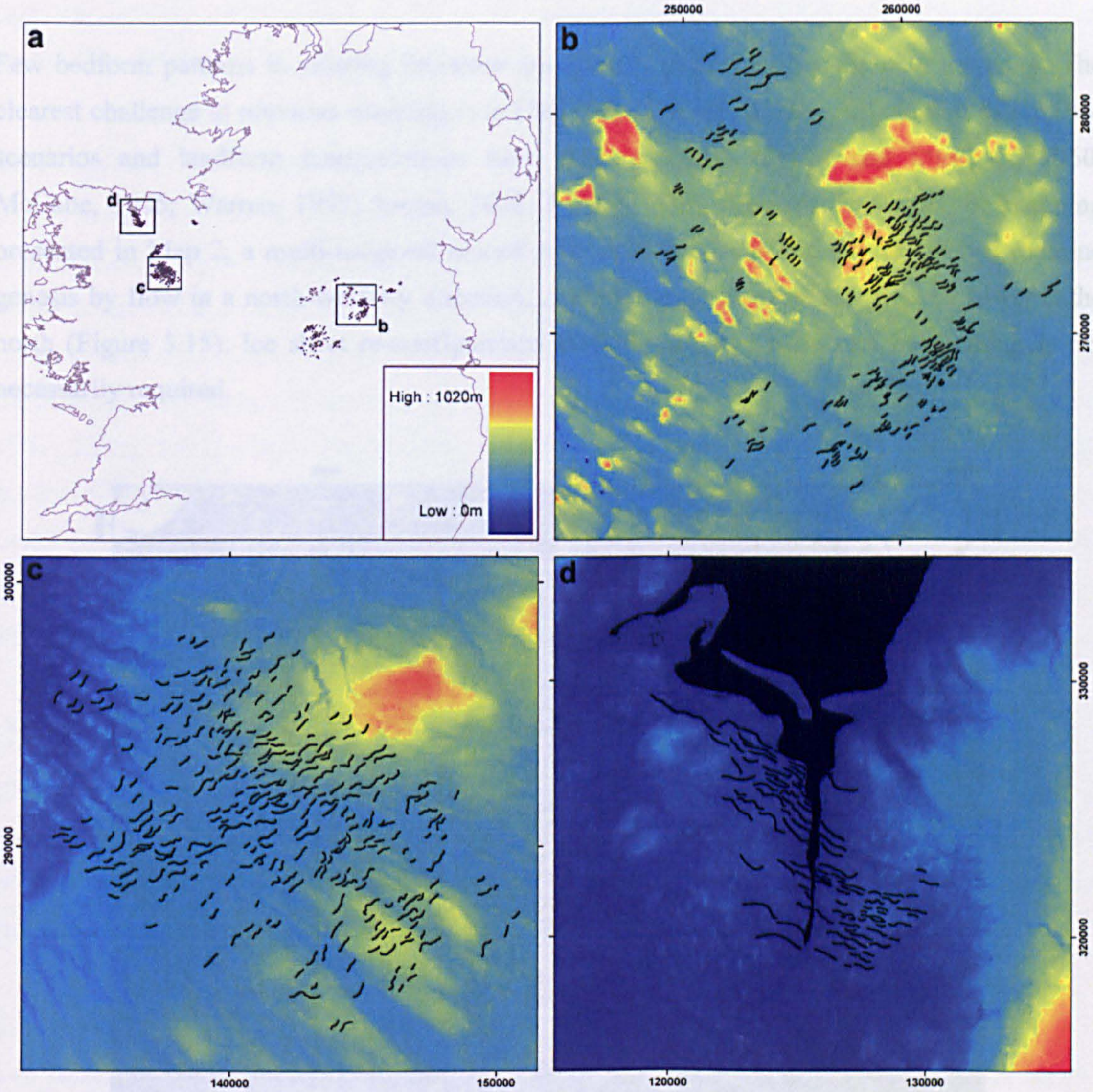


Figure 5.14 Classification of unknown minor ridges into ice-marginal or subglacial contexts on the basis of their relationship with the underlying macro-topography. **a)** total distribution of 'unknown minor ridges'. **b)** Sample of unknown ridges from Cos. Meath and Westmeath. Ridges are located over both high and low ground with little evidence of deflection by topography. Suggests ice is thick and ridges are subglacial, i.e. minor ribbed moraine. **c)** Ridges overlie MSGLs (orthogonal) in Co. Mayo and are not perturbed by the rising high ground in the NE of the area; these ridges are interpreted as subglacial. **d)** Ridges superimpose drumlins leading into Killala Bay, north Co. Mayo. These ridges feed into a topographically confined bay and an ice-marginal context is plausible for the development of these ridges. Scale: gridmarks at 10 km.

5.4.3 What's challenged?

A number of the bedform patterns evident in the Subglacial Bedform Map challenge previous models of the ice sheet's geography. For example, the lineation patterns which penetrate through Cos. Laois, Kildare, Kilkenny, into Carlow and Waterford clearly exceed the limit of the Southern Irish End Moraine, previously supposed by some to represent the LGM ice limit (Charlesworth, 1928; Synge and Stephens, 1960; Synge, 1969; McCabe, 1985). These bedforms, which are also recognised by Kilfeather (2004) and Hegarty (2002a,b) and deemed *not* to indicate a *pre*-Midlandian origin, clearly refute such a limit. Additionally, the abundance of cross-cutting throughout the country (Sections 5.3.2, above; 5.5.2, below) challenges existing models which describe only a single ice sheet configuration; this clearly cannot account for the complex bedform arrangements exhibited. However, these challenges are directed at the models interpreted from the glacial record rather than the record itself, and are discussed more fully in Sections C and D which consider landform interpretation and ice sheet reconstruction.

Few bedform patterns in existing literature are directly challenged by the new mapping. The clearest challenge to previous mapping is in Clew Bay, Co. Mayo. Here, all manner of ice flow scenarios and landform interpretations have been proposed (Synge and Stephens, 1960; McCabe, 1985; Warren, 1992; Jordan, 2002; Knight, 2006; Carolan, 2006). In the mapping presented in Map 2, a multi-temporal record is inferred, characterised first by ribbed moraine genesis by flow in a north-westerly direction, overprinted by drumlinisation more towards the north (Figure 5.15). Ice sheet re-configuration between the two phases of bedforming is not necessarily required.

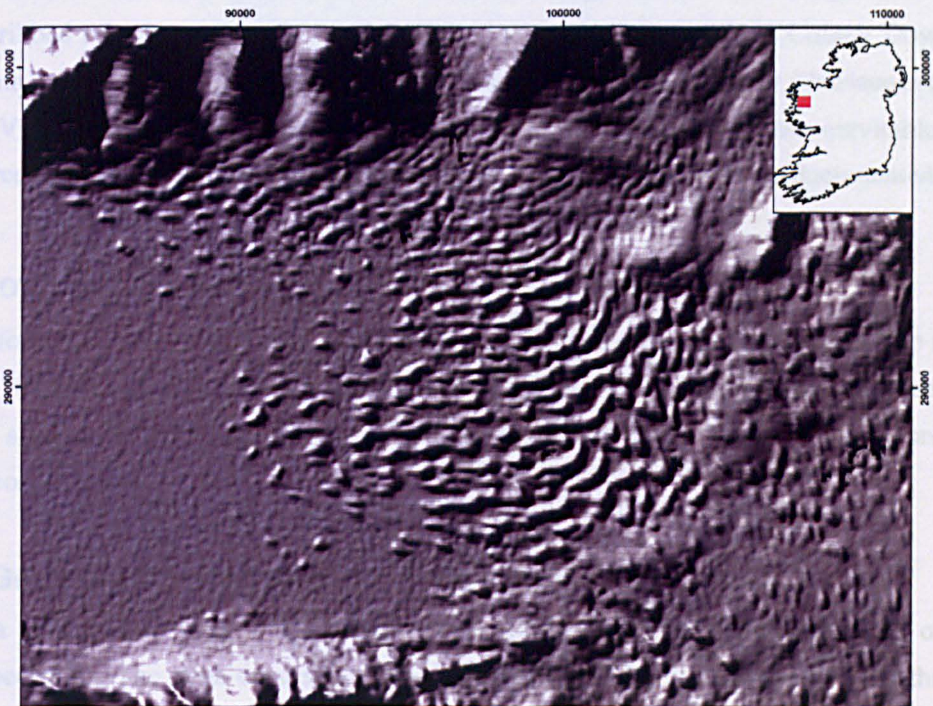


Figure 5.15 Landforms in Clew Bay are the source of much debate regarding their identification. Recent proposals suggest the landforms are composite in nature although there is still no consensus as to the nature of the separate ice flows which have moulded the features (Jordan, 2002; Knight, 2006; Carolan, 2006). Here, ribbed moraine are mapped with drumlins overprinting in a northerly direction. Scale: gridmarks at 10 km.

This interpretation contradicts recent work by Jordan (2002) and Knight (2006), both of whom interpret the landforms as a composite of two separate drumlin forming ice flows. The context invoked by Knight (2006) is glaciomarine, the sedimentological facies of three exposures interpreted as sub-ice shelf deposition. However, Knight does not link the period of ice shelf development to the landform assemblage in any way: it is not clear if a link is intended or the bedforming occurs prior to the establishment of a shelf setting. If the latter is the case then this deglacial setting is of little consequence to the question of bedform interpretation. Jordan (2002) invokes an entirely terrestrial setting, identifying deformation structures in the landforms consistent with *on*shore ice flow. This sedimentological information is clearly at odds with the morphological expression of the landforms which are interpreted here, and by Carolan (2006), as ribbed moraine and drumlinisation from the SE. This is clearly one of the most controversial landform interpretation sites in Ireland, with difficulties in reconciling the observed sedimentology with geomorphology. It is possible (likely?) there are more than two flow imprints here, potentially three or four. The sedimentological evidence may be a legacy of an earlier flow than revealed by the geomorphology.

5.4.4 What's missing?

As far as has been determined from a literature review, no bedform patterns are missing in their entirety from the new Subglacial Bedform Map and in the majority of cases the new map adds considerable detail and countrywide consistency of information. However, small-scale features at or below data resolution will have been under-mapped. This is the case south of the Connemara mountains, where small drumlins have potentially been missed (compare to Orme, 1967; Finch, 1977; Coxon and Browne, 1991); in Omagh Basin where Knight (1997, 2003) records ribbed moraine more heavily drumlinised than identified here; in County Down where DEM data quality is poorer than usual and the small drumlins mapped by Charlesworth (1953) and by Vernon (1966) are likely under-represented. Such deficiencies are inevitable but are considered to be minor. At ice sheet-scale bedforms have been consistently documented.

5.5 Potential for interpretation of the bedform record

The bedform map and dataset presented in this thesis has the potential to stimulate two routes of enquiry: the pursuit of a greater understanding of the geomorphological processes which produce subglacial bedforms, and the palaeo-glaciological interpretation of the record for ice sheet reconstruction.

5.5.1 Geomorphic processes and controls on bedforming

The data presented in Map 2 documents the morphological and spatial properties of almost 33,000 bedforms. The large dataset presented here is better able to examine and test theories of bedform genesis than smaller sample sizes from specific topographic, geologic or glaciological settings. Any bedforming theory must be able to account for the diversity of characteristics this record displays. This includes not only the 'classic' drumlin and ribbed moraine properties, but the atypical shapes, sizes, arrangements and settings exhibited here (Figures 5.16 and 5.17). Detailed geomorphological mapping and analysis of morphometric and spatial parameters enables the predictions of quantitative bedforming models to be tested (e.g. Dunlop, 2004) and enables comparisons with potential controlling variables to be examined: topographic properties (shape, slope, elevation), bedrock and surface sediment lithologies, ice thickness etc (Clark, Greenwood & Hughes, in preparation).

5.5.2 Ice sheet reconstruction

The second route of analysis is the one taken in this thesis. The bedform record is interpreted in terms of what it reveals regarding ice flow directions, the necessary flow geometry and flow behaviour to explain the record, the ice sheet configuration and configuration changes. The bedform mapping presented here largely echoes earlier summaries in terms of countrywide distribution and general landform patterns. The most significant new insight yielded by this mapping effort, and the most powerful indicator of the need for a new model of ice sheet history, is the prevalence of bedform cross-cutting throughout the Irish landform record (see Figure 5.8). The bedform record must clearly hold both spatial and temporal information regarding the history of the ice sheet's evolution. Well-accepted assumptions of bedform genetic origin are employed to assist interpretation of the record, which considers the spatial, the temporal and the glaciodynamic significance of discrete flow patterns. These interpretations and analyses are discussed in thesis Section C.

5.6 Summary

Almost 33,000 bedforms have been recorded in Ireland through a rigorous and thorough mapping programme, in which observations have been verified and confirmed by a repeat-pass survey of multiple datasets. Map 2 presents these results. Subglacial bedform sizes, morphologies, arrangements and settings are wide-ranging. The overall coverage and majority of flow patterns confirm what the existing literature reports and, in many places, adds considerable details of morphology, pattern and the complexities of landform arrangements. A significant contribution is the revelation of both spatial and temporal relationships between landforms, which have been poorly documented and not well recognised in the past. Cross-cutting overwhelms the bedform record. Bedforms are often heavily overprinted and the substrate clearly reworked by multiple ice flow events. The overall bedform distribution is consequently patchy, with pockets of high bedform density. Most importantly, the dominance of cross-cutting patterns demands an ice sheet model characterised by significant, and possibly repeated re-organisations of its geometry and structure. It is the spatial, temporal and glaciodynamic properties of bedform patterns that hold the key to deciphering ice flow configurations responsible for the bedform imprints.

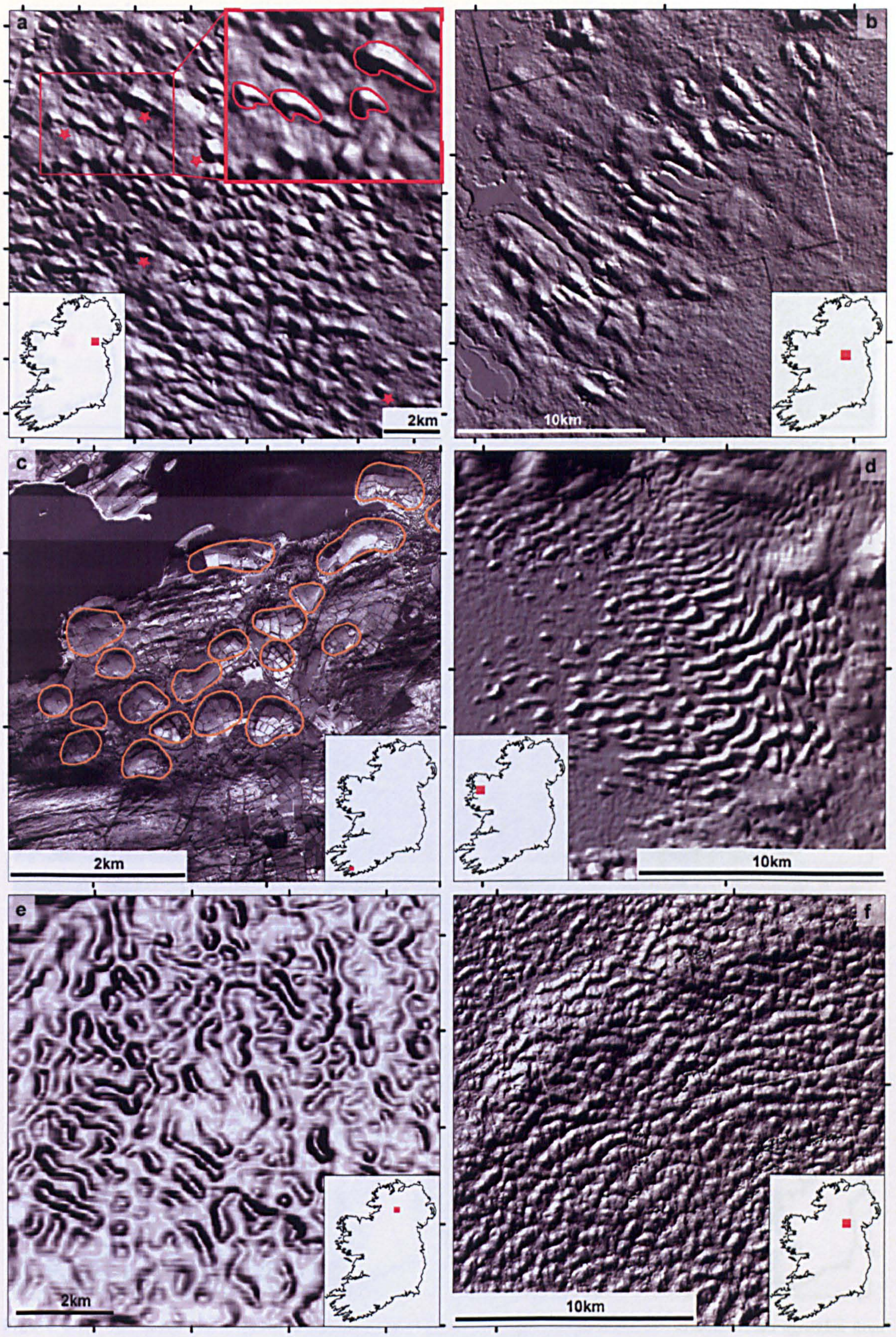


Figure 5.16 The new Subglacial Bedform Map reveals a wide range of bedform shapes and sizes which provide a test of bedform genesis theories: any theory must be able to account for these morphologies. **a)** barchan-type drumlins intermingled with more classic types (Co. Monaghan); **b)** crag and tails (Co. Westmeath); **c)** quasi-circular bedforms (Bantry Bay, Co. Cork); **d)** 'horned' ridges with drumlinised parts, interpreted as a composite product of more than one ice flow (Clew Bay, Co. Mayo); **e)** ribbed moraine with branching ridges displaying no coherent orientation (Omagh Basin, Co. Tyrone); **f)** drumlinised mega-scale ribbed moraine (Cos. Monaghan & Cavan).

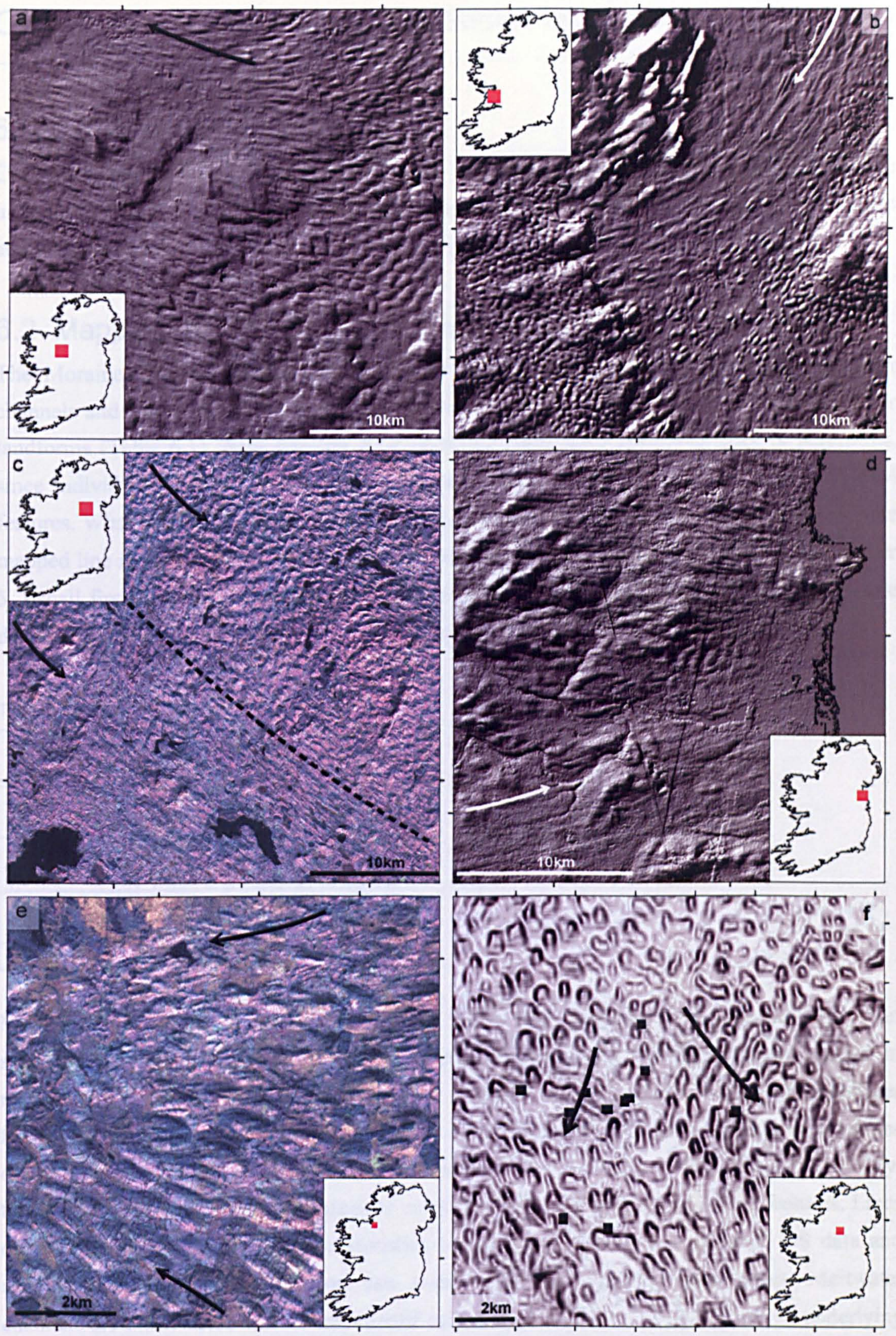


Figure 5.17 The spatial and temporal relationships between bedforms must be accounted for. **a)** downstream transition from ribbed moraine to lineations (Co. Roscommon); **b)** reverse downstream transition from elongate lineations to 'stunted' circular shaped bedforms (Co. Clare) – abrupt transitions such as these present an interesting opportunity to explore the role of potential controlling variables such as topographic and geologic properties; **c)** lateral transition from drumlinised ribbed moraine with low drumlin elongation to more highly elongate lineations (Co. Meath); **d)** patch of ribbed moraine within lineation dominated bedform imprint (near Drogheda, Co. Louth); **e)** temporal arrangement of lineations: WSW oriented drumlins overprint NW oriented drumlins (Co. Sligo); **f)** cross-cutting and drumlinised ribbed moraine (Co. Cavan).

Chapter 6. Moraines and meltwater landforms

6.1 Introduction

Chapter 5 presented and discussed the primary outcome of the landform mapping programme undertaken in this thesis. The second mapping output is presented in this chapter: the Moraines and Meltwater Landform Map, Map 3 of the supplementary maps attached to this thesis.

6.2 Mapping results: moraines and meltwater landforms

The Moraines and Meltwater Landform Map records the occurrence of eskers, meltwater channels and moraines, comprising 6,489 features, the majority of which (94%) are meltwater landforms (Table 6.1). Note that this total does not mean there are 6,489 discrete landforms, since individual segments of esker or meltwater channel networks are mapped as individual features. What may be considered a single route of meltwater flow may comprise more than one mapped line in the database. As with the previous discussion of subglacial bedforms, in Chapter 5, I shall first consider the accuracy and 'completeness' of the data presented in Map 3 before discussing the overall nature of the record and its relationships to the previous literature.

Table 6.1 Landforms recorded in Map 3.

Feature	Confidence level	Number mapped
Esker	Confident	1088
	Speculative	252
Meltwater channel	Confident	4256
	Speculative	512
Moraine	Confident	181
	Speculative	100
Minor ridges	Confident	100

Meltwater and morainic landforms tend to have been mapped more speculatively than subglacial bedforms. There are a number of potential reasons for exerting greater caution in mapping these landfroms from the imagery datasets employed here. Primarily, meltwater features, either channels or eskers, are typically closer in size to the data resolution, which raises doubt in some circumstances as to the identification of a signature in the imagery. Secondly, there are a number of potential sources of confusion in the identification of melt features. Lines of trees often display similar characteristics in the imagery to eskers although OS data and satellite image photo-interpretation can assist with distinguishing such cases. Meltwater channels are rather more open to mis-identification since modern drainage channels, underlying geological structure and inter-bedform hollows must be ruled out for the most confident interpretation of a meltwater origin of a channel. The potential for re-use of pre-existing channels or structural weaknesses by glacial meltwater presents further confusion. To best resolve such issues, careful attention has been paid to supplementary geological or literature information, channel size relative to any modern drainage and the modern catchment size (i.e. is the modern stream a 'misfit'?) and the shape of the incision. Finally, moraines in particular are not easily identifiable unless they possess a pronounced and arcuate morphology. Often ice-marginal sediment accumulations may be more like hummocky spreads of material than classic arcuate landforms, which are difficult to identify with confidence from the texture of the DEMs. The larger array of uncertainties therefore promotes more speculative mapping.

The degree of 'completeness' of the meltwater and moraine map is determined in part by some of the issues described above affecting mapping confidence. Since the smaller meltwater features are best detected from satellite imagery, they may have been under-mapped due to the spatially limited image coverage. The greater reliance on satellite imagery also introduces potential illumination angle biases into the mapped record. The difficulties in moraine detection may also have led to their under-representation in the map. However, comparison of the new esker mapping with the 1:50,000 Quaternary geological data for the Republic of Ireland is encouraging regarding the completeness of the main esker segments (Sections 6.3.2 and 6.5, below). The data presented in Map 3 should be regarded more as reconnaissance level mapping, as opposed to the subglacial bedforms, Map 2, which are regarded as a near complete record. A major value of Map 3, nonetheless, is its ice sheet-wide coverage which, when viewed in combination with that information reported rigorously in the literature, will support the bedform-based reconstruction of flow patterns and reveal some of the character and pattern of ice retreat.

6.3 Discussion: meltwater landforms

6.3.1 Landform distribution and arrangement

Meltwater channels and eskers have a more extensive overall coverage than subglacial bedforms (Figure 6.1), penetrating into the south of Ireland where bedforms are sparse. This distribution lends support to the earlier interpretation of ice cover here, and that subglacial conditions were merely not conducive to the bedforming process (Chapter 5, Section 5.3.1). Meltwater channels are more abundant than eskers in this region, where the terrain is both more mountainous and has a thinner drift cover. The scarcity of eskers here may relate to the mode of deglaciation, or was affected by reduced sediment availability for the deposition of eskers.

Similar to the bedform distribution, although less pronounced, the meltwater landform distribution is patchy in nature. There is an abundance of channels in certain areas of high bedform density in the north-east midlands and into Northern Ireland, although the Sperrin Mountains, devoid of bedforms, are also overwhelmed by meltwater channels. Other mountain masses towards the south of the country (such as Slieve Bloom – Figure 6.2) are encircled by meltwater channels, which likely originate from lateral positions rather than subglacial (see Chapter 8 for the glaciodynamic context of meltwater channels). Eskers are arranged in two or three major networks which dominate the main lowlands basin of the midlands, from Connemara to the east coast. Whilst high density patches such as these examples exist, a gap in the meltwater record is notable in Connemara and, to a lesser extent, in the Donegal mountains.

Here, one must question whether this gap arises from under-mapping or whether there is a real dearth of features in these areas. In Connemara, there is little literature evidence of meltwater landforms reported by a relatively large body of literature (e.g. Kinahan and Close, 1872; Hallissy, 1914; Charlesworth, 1929; McManus, 1967; Orme, 1967; Synge, 1968; Finch, 1977; Coxon and Browne, 1991; Jordan, 2002; Thomas and Chiverrell, 2006), suggesting this gap in the map may be a real and relevant observation.

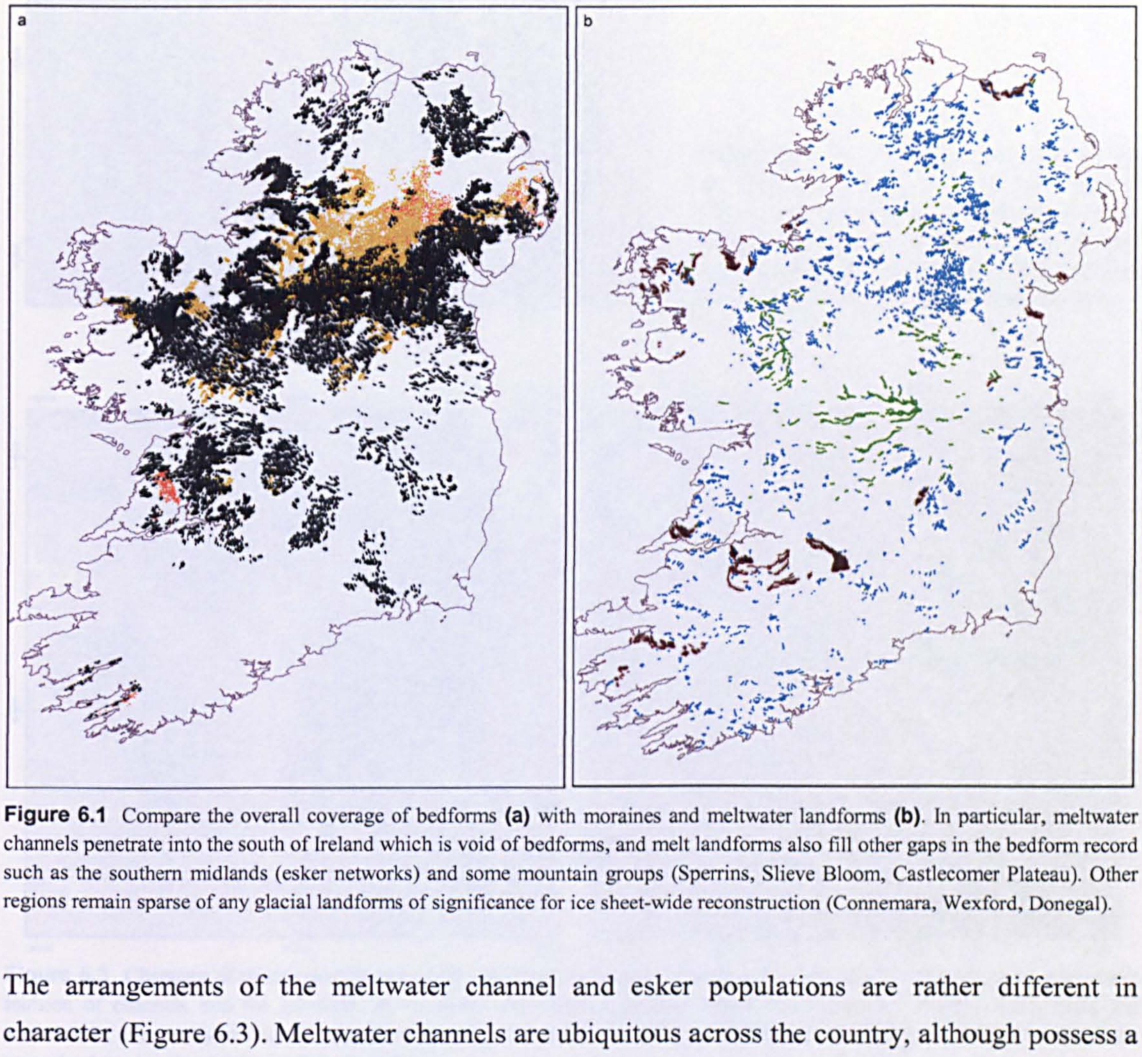


Figure 6.1 Compare the overall coverage of bedforms **(a)** with moraines and meltwater landforms **(b)**. In particular, meltwater channels penetrate into the south of Ireland which is void of bedforms, and melt landforms also fill other gaps in the bedform record such as the southern midlands (esker networks) and some mountain groups (Sperrins, Slieve Bloom, Castlecomer Plateau). Other regions remain sparse of any glacial landforms of significance for ice sheet-wide reconstruction (Connemara, Wexford, Donegal).

The arrangements of the meltwater channel and esker populations are rather different in character (Figure 6.3). Meltwater channels are ubiquitous across the country, although possess a chaotic arrangement of relatively short channel segments and poorly developed networks. Arborescent arrangements are largely absent from the mapped meltwater channel record; instead, the best developed networks are branching and anastomosing. Eskers, by contrast, are confined to more discrete, coherent systems. These systems are typically dendritic and are coherent on a large scale: the central midlands esker system extends from west to east over >60 km. This far exceeds the scale of channel networks. These differences in landform arrangements likely reflect both spatial and temporal heterogeneity of the subglacial environment, which encourages intermittent channel erosion into the bed and a chaotically appearing legacy of drainage. The more systematic arrangement and clearer genetic relationship of eskers with retreating margins makes these networks more valuable for interpreting the deglacial record .

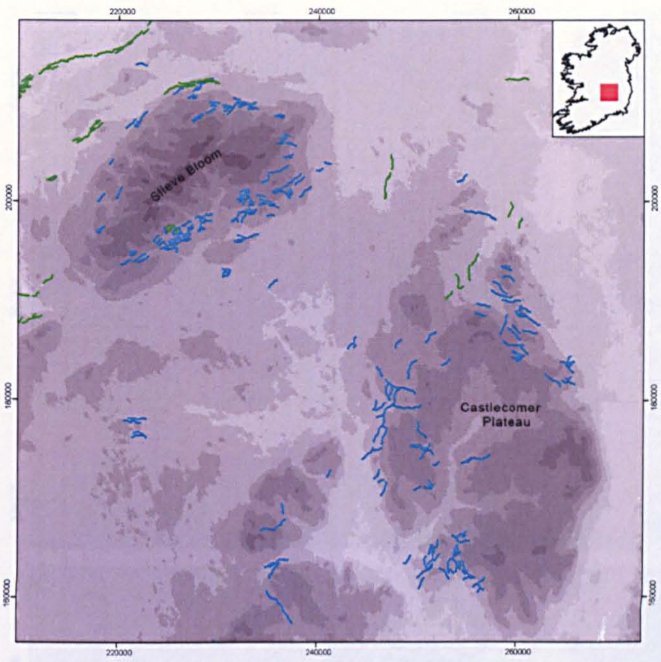


Figure 6.2 Meltwater channels encircle high ground in the southern midlands and south of Ireland, and likely relate to drainage close to the lateral margins as the mountain groups emerged from thinning ice (see Chapter 8 for meltwater channel interpretation). Scale: gridmarks at 20 km.

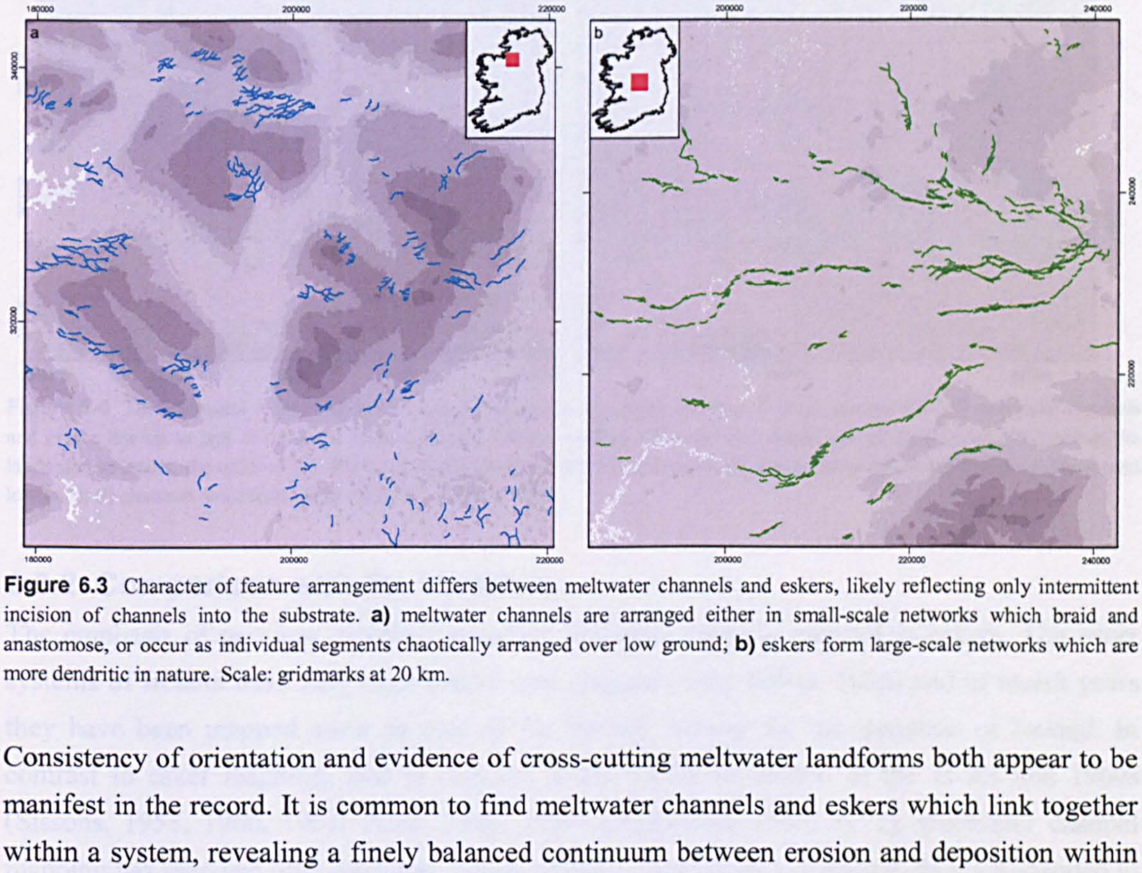


Figure 6.3 Character of feature arrangement differs between meltwater channels and eskers, likely reflecting only intermittent incision of channels into the substrate. **a)** meltwater channels are arranged either in small-scale networks which braid and anastomose, or occur as individual segments chaotically arranged over low ground; **b)** eskers form large-scale networks which are more dendritic in nature. Scale: gridmarks at 20 km.

Consistency of orientation and evidence of cross-cutting meltwater landforms both appear to be manifest in the record. It is common to find meltwater channels and eskers which link together within a system, revealing a finely balanced continuum between erosion and deposition within the hydrological network. Cross-cutting arrangements are also displayed, both internally within the channel and esker populations, and between the two (Figure 6.4). A multi-temporal record of the glacial hydrological system must therefore be interpreted, in which channels in particular are not solely related to ice sheet retreat stages, and in which meltwater was abundant at the ice-bed interface prior to the final retreat-stage ice sheet configuration. These observations have implications for the character of retreat and the geomorphic processes of landform generation and preservation.

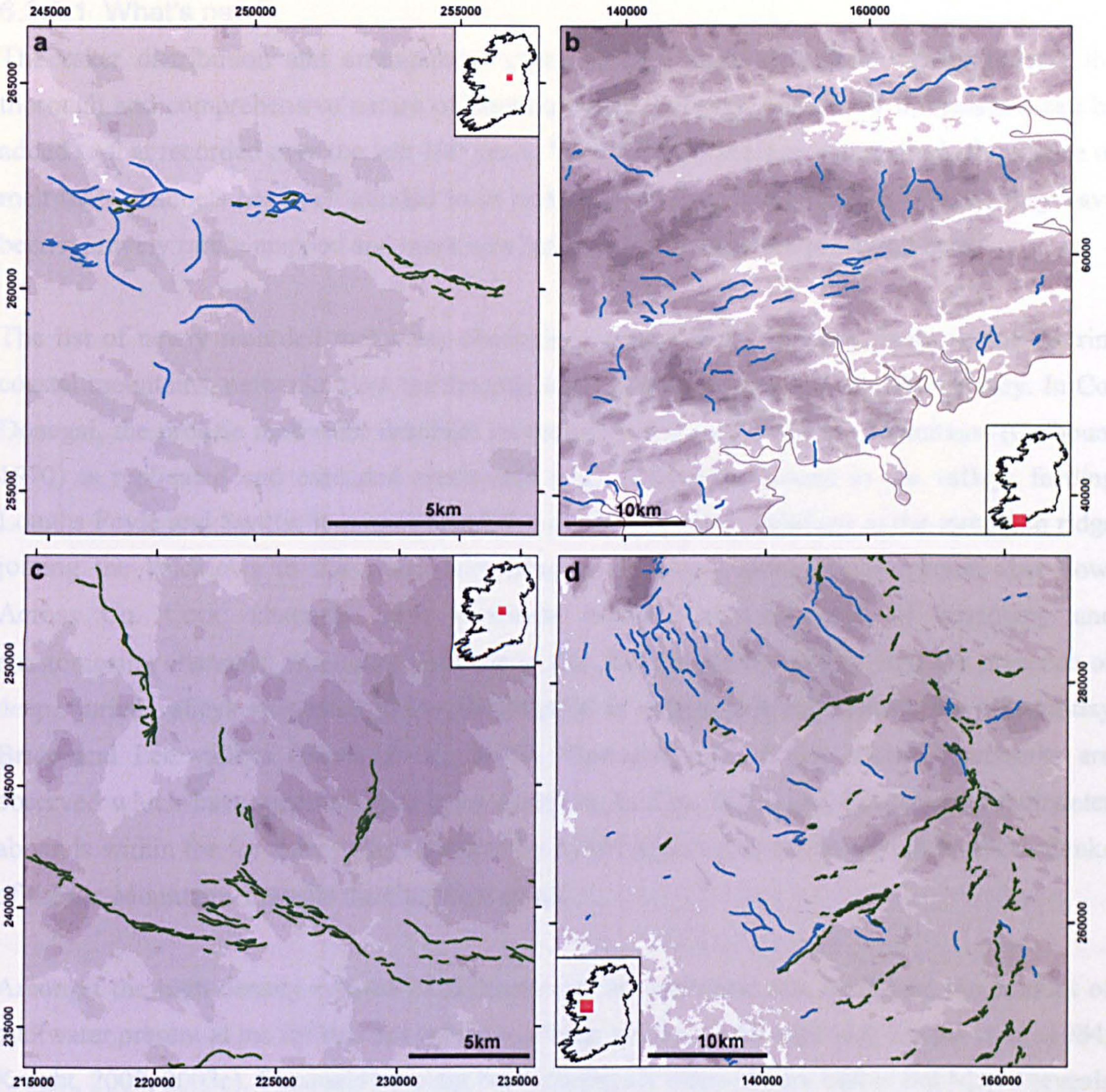


Figure 6.4 The meltwater record displays a variety of spatial relationships between different components. **a)** meltwater channels and eskers line up as part of the same system; **b)** two channel systems cross-cut each other, one group oriented ~N-S across the landscape structure, the other ~ENE-WSW along the structure; **c)** two esker systems appear to cross-cut each other in the central lowlands; **d)** channels and eskers cross-cut in Co. Mayo at ~90°.

6.3.2 Comparison with the literature

The emphasis of previous landform mapping has been strongly directed at eskers. The esker systems of Ireland have long been known and mapped (from Sollas, 1896) and in recent years they have been mapped anew as part of the Subsoil Survey for the Republic of Ireland. In contrast to esker mapping, and in contrast to the trends in Britain in the 1950s and 1960s (Sissons, 1958, 1960, 1961; Price, 1960, 1963; Clapperton, 1968, 1971), meltwater channel mapping has received little attention. Where channels have been considered, they are mapped in detail (e.g. Colhoun, 1970; McCabe and Ó Cofaigh, 1994; Hegarty, 2004); however, studies are spatially very patchy. The same key questions may be asked of the new mapping presented in Map 3 as those asked of the bedform map: what is new, what is replicated, what is challenged and what is missing? On the whole, it is the case that meltwater channels provide new information, whilst the esker mapping confirms what is already known.

6.3.2.1 What's new?

The esker distribution and arrangement captured here from systematic survey reveals the thorough and comprehensive nature of previous esker mapping. Little new information can be added to that recorded over the last 100 years. Whilst the occurrence and, indeed, abundance of meltwater channels has been alluded to in certain areas (e.g. Knight, 2002, 2003a), they have been relatively rarely mapped and more new information is therefore presented here.

The list of newly recorded meltwater channels is long. On the western flanks of the Antrim coastal mountains, networks flow northwards aligned with the present-day Main valley. In Co. Donegal, the prolific meltwater drainage previously noted in the Sperrin Mountains (Colhoun, 1970) is replicated and extended westwards where channels abound in the valleys feeding Loughs Foyle and Swilly. It is speculated that channels exploit incisions in the mountain ridge joining the Wicklows to the Blackstairs Mountains, where modern-day streams also flow. Across Co. Cork, channels form west-east oriented mini-networks of branching and anastomosing channels. Abundant drainage in this direction is consistent with the presence of deep, buried valleys suggested to be glaciofluvial in origin, flowing beneath the present-day Bride and Lee valleys (Davis *et al.*, 2006). Throughout Co. Clare, channel networks are observed which have received little prior attention. In Cos. Mayo and Roscommon meltwater abounds within the ice flow pattern marked by MSGLs, and also drains off the northern flanks of the Ox Mountains towards the Co. Sligo coast.

Amongst the high density regions of bedforms in the north and east midlands, the amount of meltwater present at the ice bed has previously been inferred to be high (e.g. Dardis *et al.*, 1984; Knight, 2002, 2003c). Channels have not been rigorously mapped here before but Map 3 reveals the prevalence of small channel segments incised over and between bedforms in a chaotic arrangement (Figure 6.5). Similarly, in the Sligo and Leitrim mountains meltwater channels flank the mountain sides in networks, and weave amongst the complex suites of bedforms which

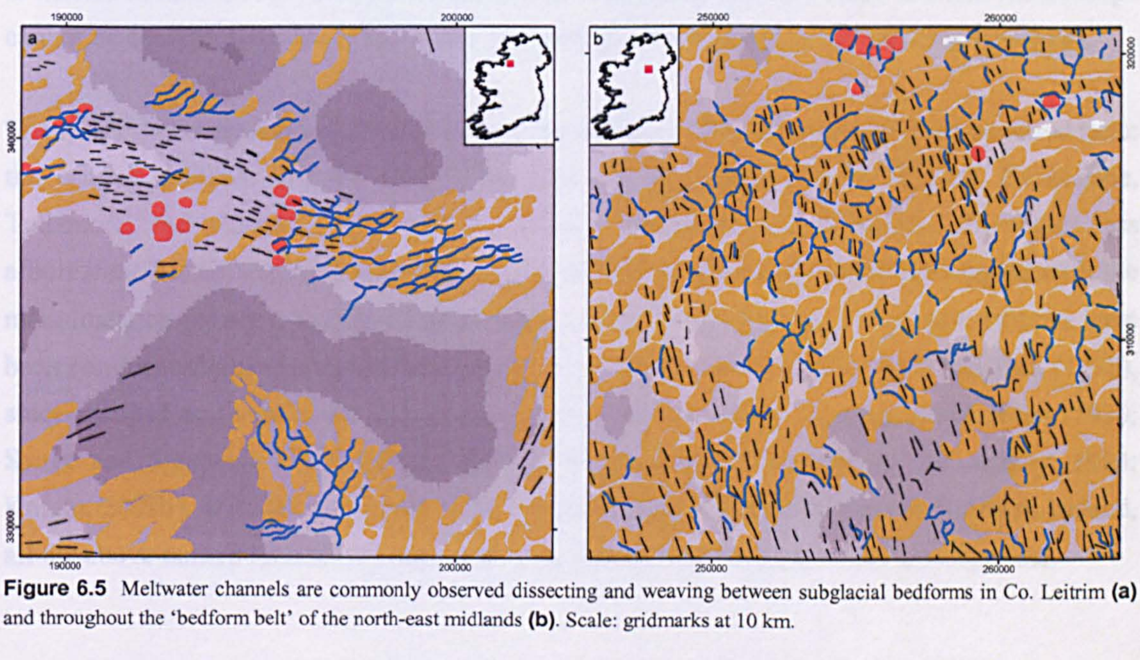


Figure 6.5 Meltwater channels are commonly observed dissecting and weaving between subglacial bedforms in Co. Leitrim **(a)** and throughout the 'bedform belt' of the north-east midlands **(b)**. Scale: gridmarks at 10 km.

inhabit the valleys. These are interesting observations, especially since meltwater has previously been implicated in bedforming processes and in ice dynamics in Ireland (Dardis *et al.*, 1984; Dardis, 1987; Hanvey, 1987; McCabe and Dardis, 1994; Knight, 2002, 2003a). Documentation of regions exhibiting particular abundance of meltwater channels is clearly of importance in making such process links and has a bearing on the reconstruction of ice sheet decay patterns.

6.3.2.2 What's replicated?

The meltwater channel mapping that has been previously conducted is largely confirmed by the new mapping effort. In places details are added, in others the new mapping cannot replicate the detail achieved in the field; these differences occur from channel network to network, even those described by the same author, and reflect subtle differences in their manifestation in the imagery used here. The findings of Colhoun (1970), McCabe and Ó Cofaigh (1994), Hegarty (2002a) and Kilfeather (2004) are broadly captured in Map 3. Additionally, as noted above, the abundance of channels in areas of high bedform density in the north midlands supports earlier suggestions of high volumes of meltwater at the ice-bed interface.

A number of channels mapped by McCabe and Ó Cofaigh (1996) and Hegarty (2002) are included here but with a degree of caution. The drift-poor upland terrain of the south of Ireland is heavily dissected by large and deep valleys which incise perpendicular to the main west-east structure of the landscape. These valleys appear to contain modern-day 'misfit' streams, i.e. they appear too small to account for the size of the channel which contains them. They begin and end abruptly, and may easily have been exploited by glacial meltwaters. However, these channels tend to occur in isolation and are not networked in any way. McCabe and Ó Cofaigh (1996) have mapped some of these incisions as meltwater channels in Co. Cork and Hegarty (2002a) identifies similar channels cutting through the west-east escarpment of Slieve Namon. Hegarty (2002a), however, interprets these as pre-glacial incisions which have been later exploited by subglacial meltwaters. Such features are included in the new mapping but caution is exerted in their interpretation. Reconstruction of an equipotential surface and ice surface slope cannot be confidently made if meltwater has been guided strongly by pre-existing structures.

The new esker mapping largely replicates what is known. The main systems are captured here: the central lowlands systems which dominate the landscapes around Athlone, Ballinasloe, Tullamore; the western system around Tuam – Dunmore – Ballyhaunis; the rather less arborescent but no less coherent systems in Cos. Cavan and Meath which are aligned with the main lineation patterns; and the Clogher Valley eskers in Co. Tyrone. These main systems have been commented upon in the literature since the earliest work of Close (1867) and Hull (1878), since mapped and replicated in numerous works (Sollas, 1896; Gregory, 1920; Flint, 1930; Synge and Stephens, 1960; Synge, 1970, 1979; McCabe, 1985; Warren and Ashley, 1994; Knight, 2003b). With the exception of the Clogher Valley eskers which are in Northern Ireland, all the above-named systems are captured in the Subsoil Survey Quaternary geology data.

6.3.2.3 What's challenged?

Very little of the new meltwater landform mapping directly challenges the record in the previous literature. There are, however, conflicts between two elements of the meltwater channel records. Firstly, Charlesworth's (e.g. 1924, 1939, 1953) mapping of meltwater channels, and their use for retreat pattern reconstruction, has been challenged previously by Colhoun (1970) and by a number of workers in Britain (e.g. Sissons, 1958, 1960, 1961). His interpretation of channels (as proglacial lake overflow routes, a since outdated school of thought) is not strictly the matter at hand here, but given this model there is a tendency for Charlesworth's meltwater channels to be long and isolated or independent of others. This style contrasts with the later mapping of Colhoun (1970), for example, who records numerous very small and networked channels which may plausibly be found in situations *without* needing to account for a glacial lake position for their explanation. The landforms presented in Map 3 support Colhoun's observations and style of mapping, and do not reveal the large, independent and isolated channels mapped by Charlesworth in the north of Ireland (e.g. 1924).

Secondly, it is proposed by Knight (2002) (although the terminology was applied previous to this paper) that a number of tunnel valleys are located in the vicinity of Lough Neagh. A number of deep channels are, indeed, present in this region, but the basis for interpreting them as tunnel valleys is not clear (Figure 6.6). Four out of five channels, including the most often cited valley, the Poyntz Pass 'Tunnel Valley', in fact lie upon structural fault lines or lithological boundaries. Their origin is perhaps more plausibly structural than entirely glaciofluvial, and in this way differs from tunnel valleys in Europe and in North America which are more typically cut into thick Quaternary sediments or a sedimentary substrate (e.g. Ehlers and Wingfield, 1991; Piotrowski, 1994, 1997; Huuse and Lykke-Andersen, 2000; Praeg, 2003; Jorgensen and Sandersen, 2006; Hooke and Jennings, 2006). Use of the term 'tunnel valley' may therefore be misleading, particularly if one were considering the erosional or ice-dynamical

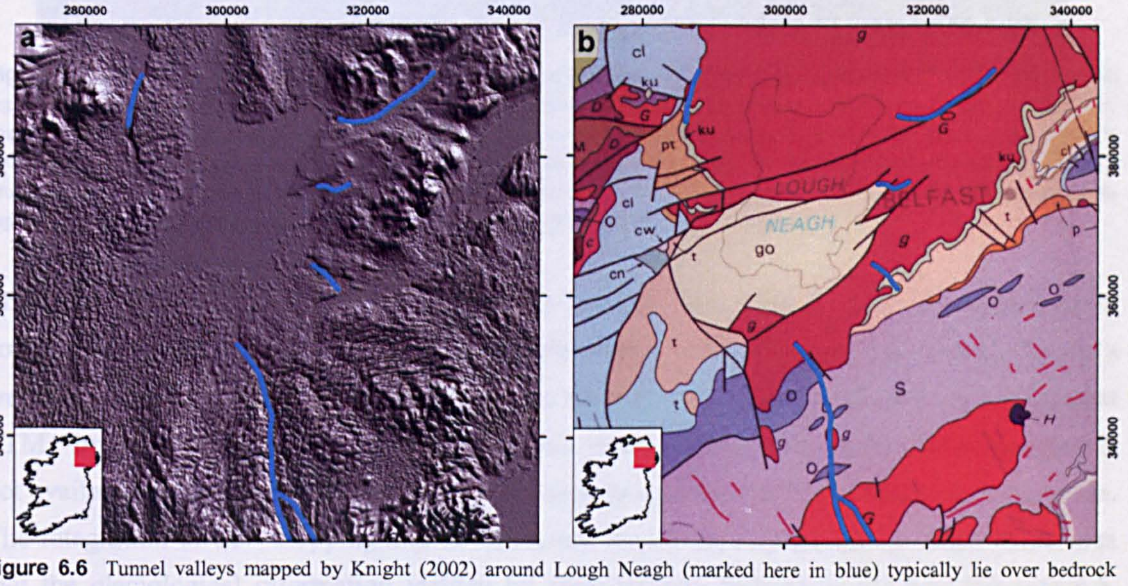


Figure 6.6 Tunnel valleys mapped by Knight (2002) around Lough Neagh (marked here in blue) typically lie over bedrock structural faults. The channel origin may therefore not be entirely glaciofluvial. **a)** DEM visualisation with Knight's tunnel valleys in blue; **b)** 1:1,000,000 solid geology reveals the valleys mostly coincide with faultlines (black lines). Scale: gridmarks at 20 km.

roles of subglacial meltwater. Here, segments of these incisions have been mapped as meltwater channels. The problem of re-use of pre-existing valleys persists, but classification of features as meltwater channels is a less loaded term for interpretation purposes than tunnel valleys.

6.3.2.4 What's missing?

It is argued here that the majority of what is missing from Map 3 relates to the scale of features with regard to data resolution. Where field mapping of meltwater channels exists in detail (e.g. Colhoun, 1970, Figure 6.7), it is clear that the smallest of features are often not captured here. Some details of esker segments are missing, particularly in the system crossing the north-east midlands bedform belt, and also those more isolated eskers dispersed through Cos. Laois, Kildare, Tipperary and Kilkenny. However, the main systems are successfully mapped.

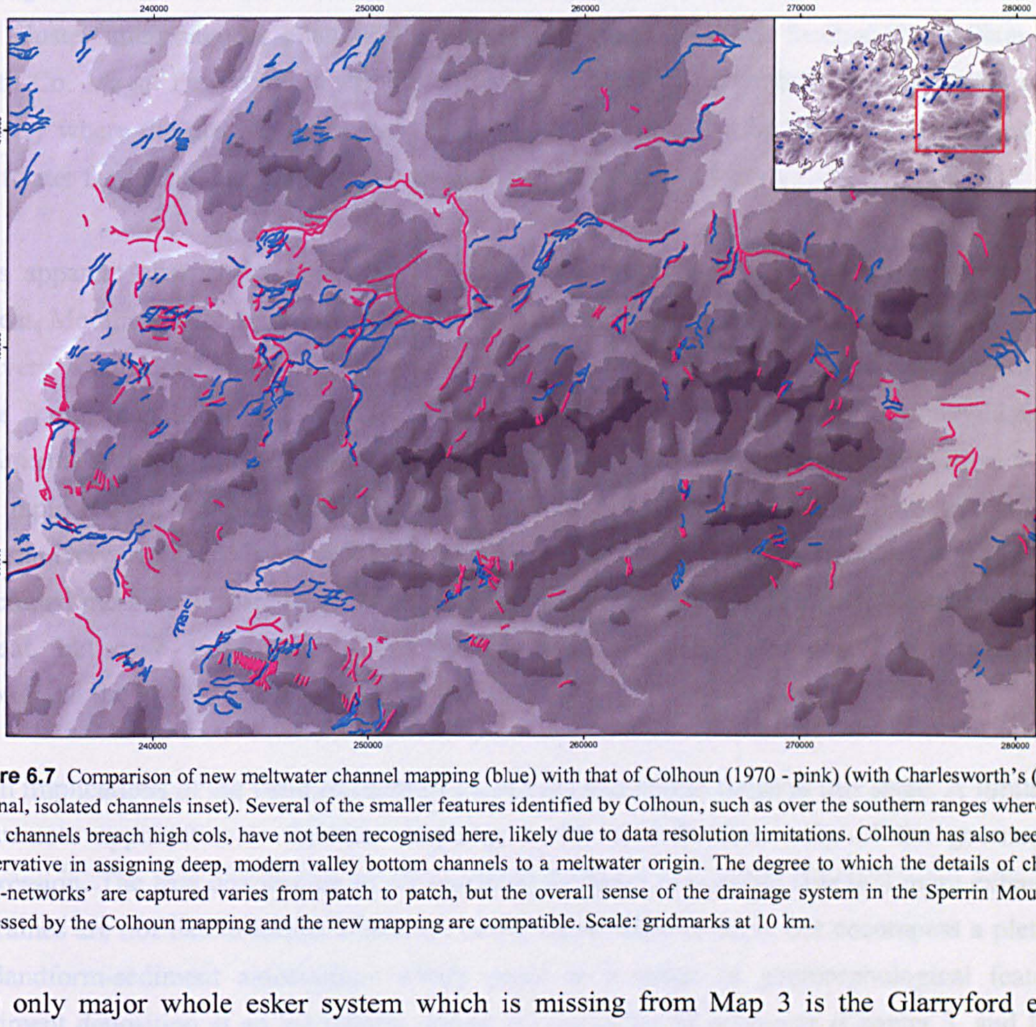


Figure 6.7 Comparison of new meltwater channel mapping (blue) with that of Colhoun (1970 - pink) (with Charlesworth's (1924) regional, isolated channels inset). Several of the smaller features identified by Colhoun, such as over the southern ranges where very small channels breach high cols, have not been recognised here, likely due to data resolution limitations. Colhoun has also been less conservative in assigning deep, modern valley bottom channels to a meltwater origin. The degree to which the details of channel 'mini-networks' are captured varies from patch to patch, but the overall sense of the drainage system in the Sperrin Mountains expressed by the Colhoun mapping and the new mapping are compatible. Scale: gridmarks at 10 km.

The only major whole esker system which is missing from Map 3 is the Glarryford esker complex in the Main Valley, Co. Antrim (Charlesworth, 1953; McCabe *et al.*, 1998). This is a well-known esker system but unfortunately lies beneath a patch of cloud cover in the Landsat ETM+ imagery. Since eskers are poorly detected in the DEMs, and suitable SPOT imagery is not available for this region, this esker system remains unrecorded in this mapping programme. The integration of new mapping and the literature record for reconstruction purposes ensures that the glaciological information yielded by such missing features is not lost (Section 6.5, below).

6.4 Discussion: moraines

6.4.1 Landform distribution and arrangement

Moraines are distributed sporadically across the country: in certain regions discrete landform evidence of ice sheet retreat occurs whilst it is absent in others. In general, the moraines mapped are either associated with mountain ranges or are distributed around coastal lowlands. Classic valley controlled moraines in the south-west record glaciers and ice lobes spilling out of the Kerry/Cork mountains. Most of these moraines cluster around Killorglin and Killarney, recording ice emanating from the mouths of the Caragh and Black valleys, either side of the MacGillycuddy's Reeks. In a number of coastal lowland regions, larger-scale arcuate moraines are nested in groups and likely record the retreat of larger ice lobes of the 'main ice sheet' in far western Mayo, the Co. Clare coast, Limerick, Dundalk Bay, the north Antrim coast. In a similar setting but at the other end of the size scale, small transverse ridges (described in Chapter 5 and one cluster interpreted as potentially ice-marginal) drape drumlins feeding into Killala Bay, north Co. Mayo. Few other moraines are recorded onshore, particularly in the interior of the country where the glacial geomorphological record is dominated by subglacial bedforms with meltwater features either draped over or incised through the bedforms.

This apparent absence of ice-marginal features has implications for the mode of ice sheet retreat. Moraines form when sediment delivery to a margin exceeds a 'background rate': either delivery is enhanced within a fixed time frame; or sediment is steadily delivered over a longer time frame than usual, i.e. a margin standstill, producing an ice-marginal accumulation of sediments. A dearth of moraines might therefore indicate one of three possible scenarios. Steady and rapid retreat, without standstills, would produce a till sheet rather than discrete moraines. Alternatively, a cessation of sediment delivery to the margin during deglaciation may have precluded moraine development. A third option is that moraines were deposited during margin retreat, but have since been buried by the extensive postglacial peat bog development throughout the lowlands of Ireland.

Such implications of the mapped moraine record are difficult to judge at this stage. A limitation of remote approaches to moraine mapping is the consideration only of the geomorphic expression. The true distribution of ice-marginal evidence is possible (likely?) more extensive. Moraines are not like drumlins which are easily identifiable as such, but encompass a plethora of landform-sediment associations which result in a range of geomorphological features. Sediment deposition at an ice margin occurs via a number of processes (Chapter 3, and Benn and Evans, 1998) and margin standstill does not necessarily produce a clear, easily detected arcuate landform such as those observed above associated with ice lobes or valley glaciers. Whilst the latter types of moraine have confidently been captured from the imagery and, indeed, DEMs can provide a superior tool for the accurate drawing of their planform (e.g. Clark *et al.*, 2004), certain ice margin positions may leave a more sedimentological than geomorphological expression. For a reconstruction of the pattern of margin retreat we must also appeal to the legacies of deglaciation recorded in the literature.

6.4.2 Comparison with the literature

The position, configuration and significance of moraines have long been discussed in Irish literature such that certain cross-country moraines have become paradigm defining features. Charlesworth's Southern Ireland End Moraine (1928b) became established in the literature and still appears on figures of the Irish Ice Sheet (Knight *et al.*, 2004; Knight, 2006) long after it has been questioned and challenged as a maximum ice sheet limit (e.g. Warren, 1991a; Gallagher and Thorp, 1997; Gallagher *et al.*, 2004; Hegarty, 2002a,b; Kilfeather, 2004; Ó Cofaigh and Evans, 2007). In more recent years a number of the moraines which appear in the traditional glacial maps of Synge and underpinned the old ice sheet model paradigms (Synge and Stephens, 1960; Synge, 1970, 1979; McCabe, 1985) have been questioned and, in places, disregarded (Warren, 1991a, 1992; Hegarty, 2002a,b; Kilfeather, 2004; Meehan, 2004, 2006a).

Much of Charlesworth's detailed moraine mapping in additional to the SIEM has also been subsequently disregarded. The extensive, sweeping moraines he depicts all across the lowlands (refer back to Figure 2.10) are not included on the subsequent glacial maps of Synge (1970; 1979). Colhoun (1970) has rejected Charlesworth's (1924) pattern of margin retreat over northern Ireland whilst Knight has reinterpreted many of his moraines as subglacial ribbed moraine (Knight and McCabe, 1997; Knight, 2003b). Finally, the interchangeable use of terminology such as moraine, drift limit and even ice limit has often served to propel ideas through the literature as fact. The following discussion considers the new mapping in light of both previous detailed moraine mapping and the recurring drift limit/moraine positions.

6.4.2.1 What's new?

Given the coverage of moraines Charlesworth envisaged across Ireland (1924, 1928a,b, 1929, 1953) little new mapping can strictly be interpreted as 'new' information, despite the fact that a number of Charlesworth's moraines have since been disregarded or reinterpreted (e.g. Warren, 1991a; Knight and McCabe, 1997; Knight, 2003b). Like the bedforms and meltwater landforms discussed above, in places the detail of mapping is perhaps 'new' but moraine locations in Ireland have generally been proposed previously. In north Mayo, a cluster of minor transverse ridges was interpreted in Chapter 5 (Section 5.4.2.2) as potentially ice-marginal in origin. These ridges overprint drumlins feeding into the bay and potentially record the retreat of a lobe back onshore. This is supported by larger moraines mapped (speculatively) between Killala Bay and the Ox Mountains, which have an arcuate form consistent with such a lobe.

6.4.2.2 What's replicated?

The majority of the moraine mapping presented in Map 3 has been captured by previous workers. The key regions of agreement are in Co. Limerick, Co. Kerry, west Co. Mayo, Dundalk Bay and the Armoy moraine in Co. Antrim. Perhaps the most significant are those which confirm a section of the contentious SIEM in Co. Limerick. Here, a suite of arcuate moraines confirm the early suggestions of ice limits here, which were termed the Ballylanders and Fedamore sections of the SIEM and Drumlin Readvance Moraine (Synge, 1969, 1970).

However, the clear cut division between these two is not supported by the new mapping. Rather than two discrete moraines, the new mapping reveals a single suite of arcuate landforms distributed across the plain between the Shannon river and the Mullaghareirk – Ballyhoura – Galty Mountains (Figure 6.8). This is, nonetheless, the sole location where there is firm landform evidence for any part of the so-called Southern Ireland End Moraine.

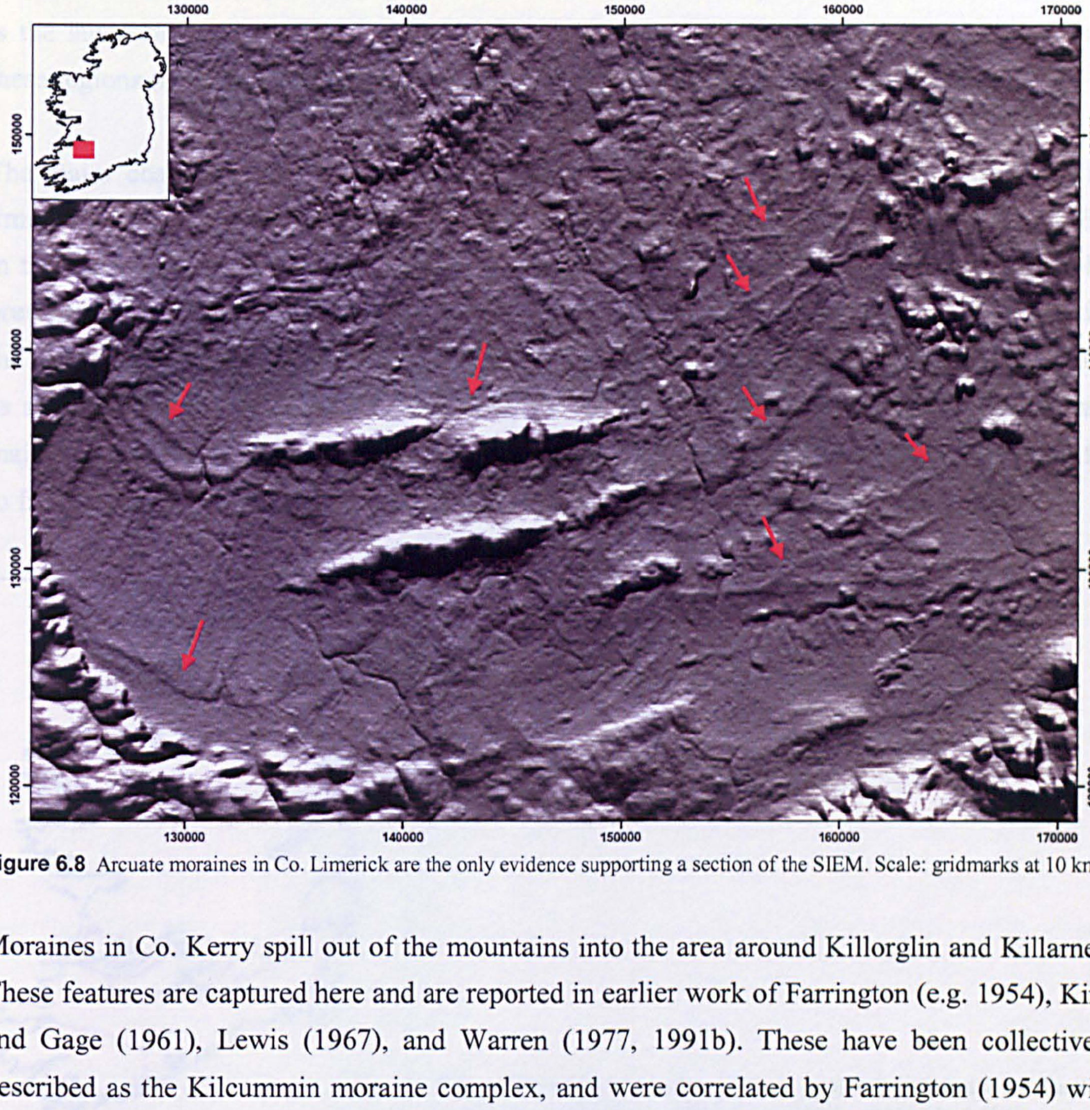


Figure 6.8 Arcuate moraines in Co. Limerick are the only evidence supporting a section of the SIEM. Scale: gridmarks at 10 km.

Moraines in Co. Kerry spill out of the mountains into the area around Killorglin and Killarney. These features are captured here and are reported in earlier work of Farrington (e.g. 1954), King and Gage (1961), Lewis (1967), and Warren (1977, 1991b). These have been collectively described as the Kilcummin moraine complex, and were correlated by Farrington (1954) with the Killumney moraine west of Cork (city) to form the bounding limit of the south-west ice cap. However, the new mapping finds little evidence of the Killumney moraines. In western Co. Mayo, moraines either side of the Nephin Beg range have been noted by Synge (1968), Finch (1977) and Jordan (2002), amongst others. These are moraines which are arcuate away from the mountains rather than recording ice emanating from the range, and are replicated in the new mapping. The moraines on the southern shores of Dundalk Bay (McCabe and Hoare, 1978; McCabe, 1985) are captured here, as is the well-known Armoy moraine which stretches across the Bann and Main valleys in north Co. Antrim (Charlesworth, 1953; Synge, 1970).

6.4.2.3 What's challenged?

In line with many others, Charlesworth's moraine mapping is largely rejected here, both by omission (there is simply no morphological evidence for the abundance of features depicted) and by reinterpretation of some features as ribbed moraine (as Knight and McCabe, 1997). The only other direct challenge on moraine mapping posed by Map 3 is in regard to end moraines in Omagh Basin and the Clogher Valley, Cos. Tyrone and Fermanagh, inferred by Knight (2003b; 2006). Knight's argument for an ice-marginal origin of a number of these features is their lack of alignment, their unusual planform shapes and their discordant ridge summits. These are all characteristics shown by Dunlop (2004) to be consistent with subglacial ribbed moraine and that is the landform interpretation favoured here. Deglacial signatures are undoubtedly present in these regions (note the esker system) but suites of end moraines are not mapped here.

The major challenges to previous ideas relate to the lack of observed large countrywide ice limits: the SIEM, the DRM, the Galtrim moraine (Figure 6.9). The lack of support for the SIEM in the literature has already been addressed and there is little renewed support in the mapping presented here. Except for the Limerick moraines noted above, and a possible moraine flanking the Slieve Ardagh hills and the Castlecomer Plateau in Co. Laois (recorded by Kilfeather (2004) as a gravel spread) there are no other features across the country resembling a moraine and major ice sheet limit. This concurs with Hegarty (2002a,b, 2004) and Kilfeather (2004) who fail to find any such evidence in the counties through which the moraine is supposed to pass.

Figure 6.9 Major limits of the ice sheet previously proposed in the literature: from Synge and Stephens (1960); Synge (1979) and McCabe (1985).

The other two major ice sheet limits which have been widely cited – the Galtrim Moraine and the Drumlin Readvance Moraine – also reveal no discernible regional geomorphic signature in the imagery consulted here (Figure 6.10). The Galtrim Moraine is defined in its clearest section by the lateral arrangement of deltas feeding a hypothesised Glacial Lake Summerhill (Synge, 1950; McCabe, 1985). This section is indeed visible but not part of a regionally continuous feature. The absence of the Drumlin Readvance Moraine in Cos. Louth and Meath supports the argument of Meehan (2004, 2006a) that there is no continuous morainic limit bounding drumlins in the north-east midlands. Satellite imagery hints at some subtle hummocky ground through the region in question but there is certainly no sufficient morphological expression to firmly delimit a hummocky region. Furthermore, such hummocky regions do not coincide with

Synge's 1979 map DRM. On this basis, the Drumlin Readvance Moraine, as a striking moraine in the landscape which clearly bounds a drumlin field, is strongly challenged.

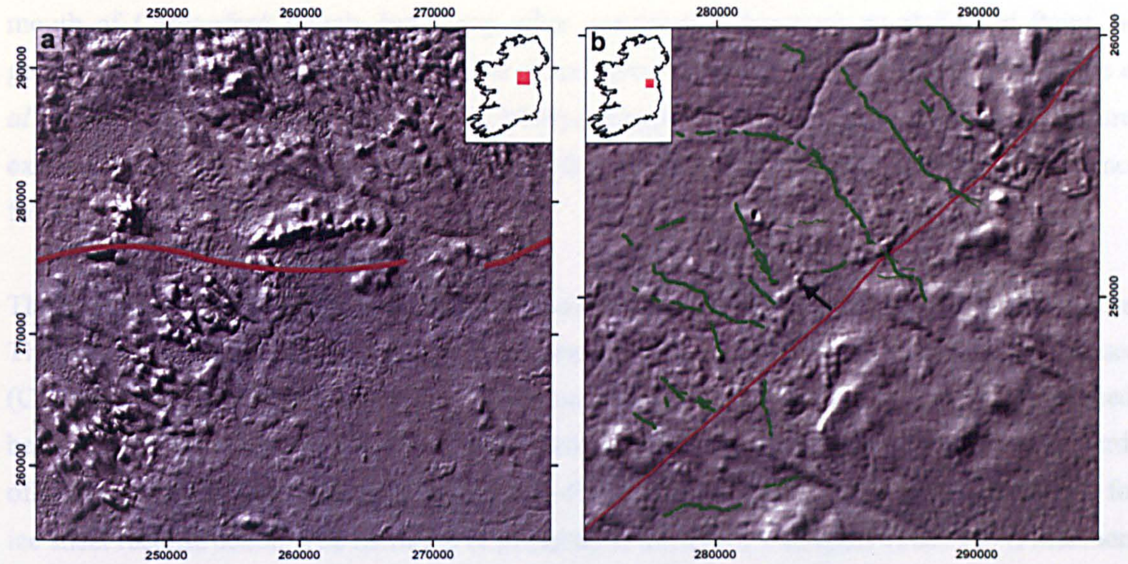


Figure 6.10 a) the Drumlin Readvance Moraine which appears in numerous iterations of Synge's glacial map is not apparent in the landscape as a consistent geomorphic feature: limit according to Synge (1979) in red, overlain on SRTM visualised in such a manner that any N/NW facing feature should be best highlighted. By contrast, the well-defined section of the Galtrim moraine is apparent (**b** – black arrow) as a feature perpendicular to the Trim eskers (green). However, this section is the only clearly visible evidence of the limit; it is not part of a longer, continuous feature all across eastern Ireland as drawn by Synge and Stephens (1960). Scale: gridmarks at 10 km.

6.4.2.4 What's missing?

Features reported in the literature but missing from Map 3 are generally small-scale features, and those moraines of a more sedimentological than geomorphological nature. Small-scale moraines missing from the new map are largely the classic valley moraines identified in mountain environments such as the Wicklows (Farrington, 1934; Charlesworth, 1953), the Sperrins (Colhoun, 1970), and Connemara (Charlesworth, 1929). The smallest valley glacier moraines (such as Warren, 1977; Harrison and Anderson, 2002) are also absent from within the Kerry and Cork mountains, though several are detected where they spill out onto the open plain. Note that across Counties Meath and Westmeath, the small-scale push moraines identified by Meehan (1999) have since been reinterpreted as minor ribbed moraine (Clark and Meehan, 2001; Meehan, 2004), with which this mapping concurs (Chapter 5, Section 5.4.2.2).

The Galtrim Moraine has only a subtle morphological expression and the ice-marginal environment is largely defined by the deltaic character of sediments (Synge, 1950; McCabe, 1985). The Screen Hills moraine complex in SE Co. Wexford is entirely missing from Map 3, again likely due to scale and a partly sedimentological definition. Terrain appears smooth, rolling and subdued but these properties do not exclusively reveal a moraine and it is the observation of thrust and deformation structures here (Thomas and Summers, 1983; Evans and Ó Cofaigh, 2003) which determines the origin of the complex as ice-marginal. The drift limits and Molville moraine on the north Donegal coast (Stephens and Synge, 1965) are not observed. Finally, a number of glaciomarine moraines have been identified along the east coasts of Cos.

Down, Louth and Meath (McCabe and Hoare, 1978; McCabe *et al.*, 1984; McCabe, 1985) which are only partially captured in Map 3. There is clear expression of hummocky, likely morainic topography on the south shores of Dundalk Bay, and classic arcuate moraines at the mouth of Carlingford Lough, but along other coastal stretches such as at Killard Point, no geomorphological moraine is evident. The description of the Killard Point moraine (McCabe *et al.*, 1984; McCabe, 1985; McCabe *et al.*, 1998) suggests it is largely a sedimentological feature, exposed in coastal section, with a subdued surface morphology, which accounts for its absence from the present mapping results.

The final absence from Map 3 are those moraine features which have been identified offshore. The spatial restriction of mapping to the modern-day onshore record has already been discussed (Chapter 5, Section 5.2). It is argued that the onshore bedform record is sufficient and, indeed, better suited to reveal the major ice flow history, but given the growing consensus towards offshore ice extent, the moraines identified on the continental shelf are of great importance for ice sheet reconstruction. The literature (e.g. Sejrup *et al.*, 2005; Gallagher *et al.*, 2004; Shannon, 2006; Bradwell *et al.*, 2008 in press) must be consulted for this information.

6.5 Potential for interpretation of the landform record

Subglacial bedform information is the key driver of the reconstruction of ice flow dynamics. Moraines and meltwater landforms act as support for the bedform-driven reconstruction, and help to define and refine the ice sheet retreat patterns. The newly-mapped record of subglacial bedforms is, for the purposes of ice sheet-scale reconstruction, ~complete and, at the scale of enquiry in this thesis supersedes that information which could be gathered from the literature. Moraines and meltwater landforms have, however, been mapped more at a reconnaissance level than a realistic effort to capture each and every landform in Ireland. To best fulfil their potential for ice sheet reconstruction, the new mapping (Map 3) is combined with landform information derived from the literature.

The approach and procedure for data compilation from the literature follows those set out by the BRITICE project (Clark *et al.*, 2004). A GIS framework was deemed most appropriate. Relevant figures and maps from published literature were scanned, geo-referenced, and landforms digitised into separate layers: meltwater channels, eskers, moraines. Features in the resultant database are fully attributed to their original source, with pertinent comments regarding the author's mapping approach, interpretation, and any caveats relating to the process of compilation into the GIS. Such caveats echo those discussed by Clark and colleagues (2004) regarding the BRITICE compilation of British glacial landforms. The level of geographic information to enable geocorrection of the published map or figure is variable, as is the scale of map production. Only landforms presented as individual features are included, as schematic landform representation is not considered useful. Additionally, observation is separated as rigorously as possible from subsequent interpretation. A motivation of this section of the thesis is to provide an objective observational record which stands alone from its interpretation in

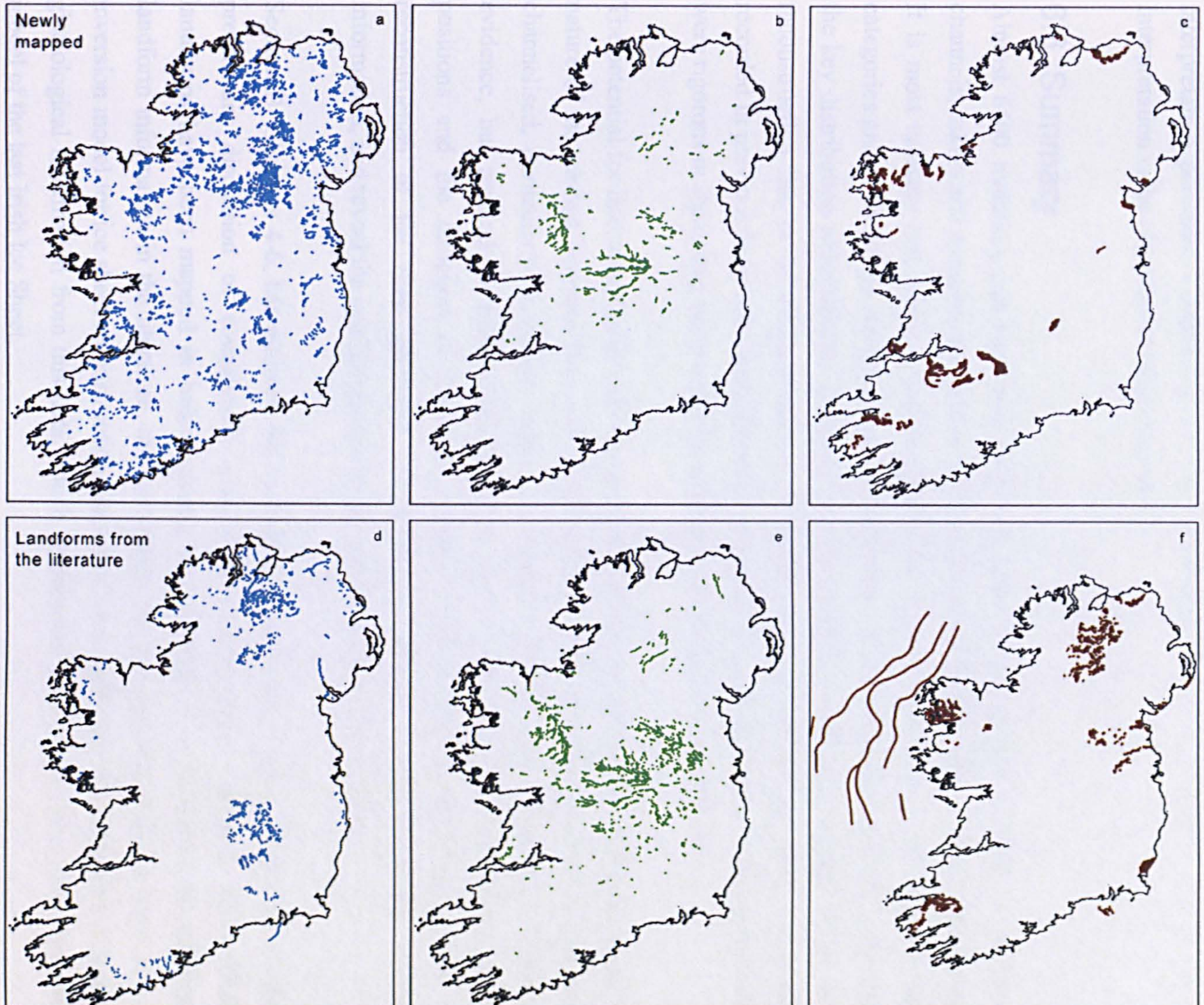


Figure 6.11 Meltwater landform and moraine information compiled from the published academic literature **(d,e,f)** complements the newly mapped geomorphology **(a,b,c)** for use in ice sheet reconstruction. Hitherto, esker mapping **(e)** has clearly been more comprehensive than channel mapping **(d)**; the recent subsoil survey specifically identifies esker sediments in the Republic of Ireland and effectively provides an esker map for the Republic. There has been a surprising lack of rigorous moraine mapping **(f)** given the volume of discussion generated regarding the Drumlin Readvance Moraine and the Southern Irish End Moraine. Charlesworth's moraine mapping is frequently rejected or the source of much contention in modern literature and his moraines are therefore not included in the data compilation. In combination, the new mapping and that compiled from academic literature provides the input data to an inversion procedure for ice sheet reconstruction.

Section C. The landform evidence compiled from the literature should be as objective as possible to complement the observations recorded in Maps 2 and 3.

The 'completeness' of the resultant database therefore depends upon the quality of the original presentation of information, and its relevance to the task at hand. This is not an attempt to record the status of knowledge, but a task conducted in order to complement new mapping and achieve the objectives of this thesis, i.e. *ice sheet-scale* reconstruction of ice sheet geometry and dynamics. Relevant information was identified through cross-referencing within the literature rather than an explicit search. The compilation therefore derives from an extensive, but not exhaustive bibliography. An additional 4468 meltwater and moraine features can be added to the newly mapped landform record for the purposes of ice sheet reconstruction (Figure 6.11). Some of these are inevitably repetitious where the new mapping captures previously recognised features. Separate layers are therefore maintained, and merely overlain for comparison and interpretation purposes. Comparison has been addressed above, in Sections 6.3.2 and 6.4.2. Interpretation is the objective of thesis Section C.

6.6 Summary

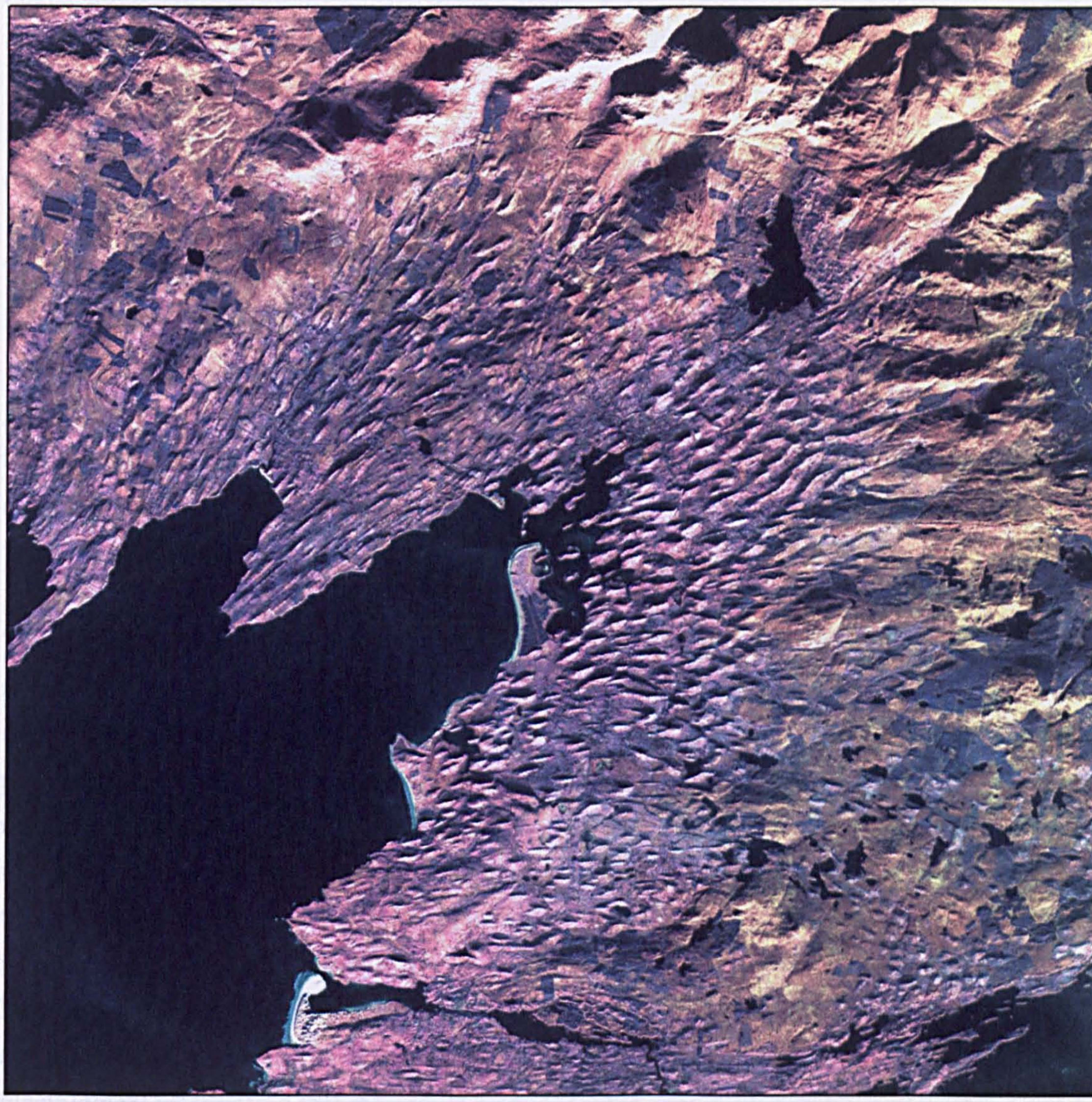
Almost 6500 moraines and meltwater landforms have been recorded on Map 3. Meltwater channels, eskers and moraines are distributed throughout the country, albeit in a patchy manner. It is most unlikely that this is a full representation of all the features which fall into these categories and it should be considered as reconnaissance level mapping which aims to capture the key distribution and character of features at a countrywide scale. Its potential for ice sheet reconstruction lies in its amalgamation with landforms (and sedimentological information) recorded in previous literature. Such information was only included for cases where the studies were rigorous in separating observation from palaeo-glaciological interpretation.

The potential for interpretation of such a compilation will be twofold. First, something about the nature of the ice-bed interface is revealed: meltwater is clearly abundant at the bed and easily channelised, particularly in certain regions of intensive bedforming. Secondly, all lines of evidence, but particularly eskers and moraines, reveal information concerning ice margin positions and the direction of ice sheet retreat. These landforms therefore support the reconstruction of ice flow geometry and evolution derived largely from the bedform information, and reveal the configuration and environment of ice sheet retreat.

Section B, Chapters 4-6, has outlined the methods for, presented results of and entered into a preliminary discussion of countrywide glacial geomorphological mapping. Over 39,000 landforms have been mapped in Ireland during this research. Complemented by additional landform information in the literature, this constitutes the primary data which is input into an inversion model for ice sheet reconstruction. Section C now addresses the extraction of palaeo-glaciological information from this data, which enables the presentation of a new conceptual model of the last Irish Ice Sheet.

SECTION C:

Reconstruction of the ice sheet



Landsat ETM+ image of Donegal Bay.

Chapter 7. Spatial summary: flowset building

7.1 Introduction

The glacial geomorphological maps presented in Section B are the basis for ice sheet reconstruction. The majority of features identified on these maps are subglacial bedforms, and it is these which hold the key to reconstructing ice flow dynamics. Bedforms have the potential to reveal the pattern, behaviour and chronology of ice flow events, and the necessary ice sheet configurations to produce these events. Moraines and meltwater landforms, meanwhile, assist the interpretation of ice flow behaviour, and reveal the pattern of ice margin retreat during deglaciation. All landforms possess spatial, temporal and glaciodynamic information, i.e. where the landform is situated within the palaeo-ice sheet and what it means for the glaciology or behaviour of the ice sheet. This thesis section, comprising Chapters 7-9, seeks to extract this information, and culminates in a reconstruction of the likely sequence of ice sheet configurations which best explain the complex geomorphological record.

The ensuing analysis follows the outline discussed in Chapter 3 and summarised in Figure 7.1. Landforms are interpreted for their spatial, temporal and glaciodynamic information. Interpretations are guided by assumptions of landform genesis and their significance for palaeo-glaciology, also outlined in Chapter 3. The reconstruction is assisted by some supplementary lines of non-landform evidence. This ancillary information must be brought into the framework in which the landform data is analysed, in order to facilitate coherent interpretations of the whole evidence base.

The 'hook' that binds all the lines of evidence together in this approach to ice sheet reconstruction is their spatial expression. Spatial properties of landform patterns reveal likely ice divide positions, ice sheet extent and ice flow paths. The degree of consistency in the spatial properties of individual landforms assists interpretations of the behaviour (streaming? retreating?) of the flow pattern they represent (Clark, 1999). Spatial arrangements of landforms indirectly reveal temporal relationships, via superimposition. How parcels of information relate to each other locationally is a key to unlocking ice sheet history. Tens of thousands of parcels of information underpin this reconstruction effort. To logistically piece together all the information held by these individuals the data must be synthesised. This chapter addresses the summary of all these data according to their spatial properties whilst maintaining all relevant palaeo-glaciological information that individual elements yield. This objective for spatial data summary is common to the analysis of subglacial bedforms, glaciofluvial landforms and non-landform information. These three lines of analysis form the main sections of this chapter.

First, some basic interpretative tools common to several stages of data analysis are outlined. This is followed by a brief consideration of the existing ideas regarding the configuration of the last Irish Ice Sheet, how the new mapping relates to these models, and I present a justification for continuing in search of a new, improved model. The chapter then moves into the main substance of the spatial interpretation of all data of palaeo-glaciological significance. This chapter has two objectives:

1. To bring together all relevant information into a single framework so they can be analysed and interpreted in an holistic manner for ice sheet reconstruction.
2. To summarise and extract the spatial properties of all the available information.

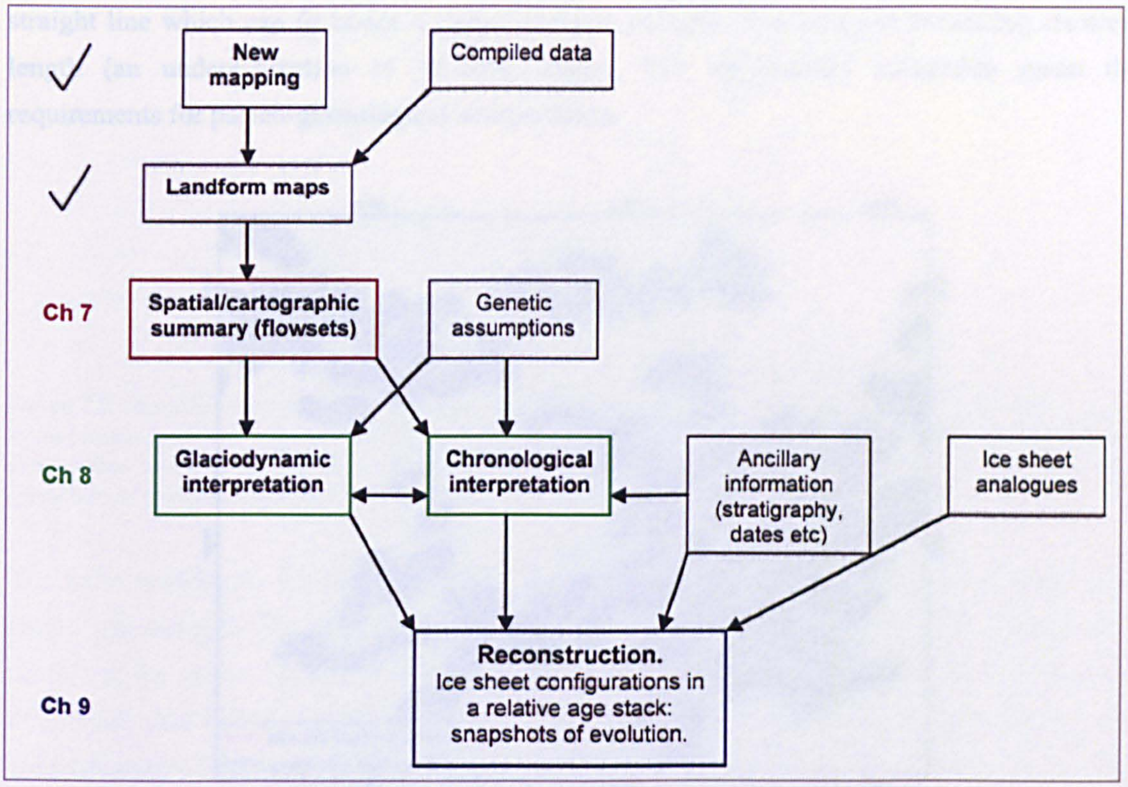


Figure 7.1 Inversion approach to ice sheet reconstruction (after Boulton and Clark, 1990a,b; Clark, 1997, 1999; Kleman and Borgström, 1996; Kleman *et al.*, 1997, 2006). Chapter 7 addresses the spatial summary of landform information into flowsets.

7.2 Initial landform analysis

To a large extent, approaches for using landform data for ice sheet reconstruction are qualitative and based on visual interpretation of landform patterns and arrangements. The potential for a more quantitative approach to spatial analysis and ice sheet reconstruction has been explored before (e.g. Smith, 2003) but found that automated procedures rarely enhance the process of reconstruction. However, by using quantitative information to underpin the primary visual interpretation, procedures of ice sheet reconstruction can be made more objective than has often been the case. The essence of data synthesis is to group like bedforms with like, such that one summary unit can represent the information of several individuals. To this end, we can appeal to the morphometric properties of individual bedforms. Derivation of the basic morphometric properties of individual landforms – their size, their orientation and their flow direction information – underpins many of the analyses to follow. Since the new mapping presented in this thesis is digital, held in a GIS, it is relatively simple to extract primary quantitative measures of glacial landforms.

7.2.1 Dimensions

Size properties of individual vector features can be automatically calculated within the GIS. Lengths, perimeters and areas are stored as attributes of line and polygon features as appropriate. An inherent complication in the mapping procedure adopted is the recording of lineations as lines and ribbed moraine as polygons. This means that size distributions, for example, are not strictly comparable and a surrogate for either ribbed moraine length or drumlin area is required. The most straightforward approach is to ask the GIS to draw the longest straight line which can fit inside a ribbed moraine polygon. The errors in estimating crestline length (an underestimation of ~5-10%; Figure 7.2) are deemed acceptable given the requirements for palaeo-glaciological interpretation.

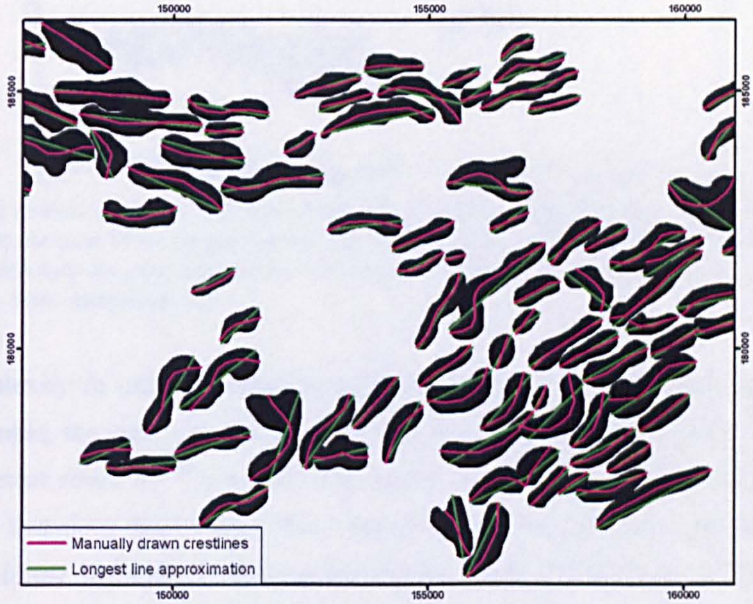


Figure 7.2 Comparison of ribbed moraine length determinations upon a sample of ridges in Cos. Clare and Galway (137 features) which have a range of shapes and sizes. The longest line typically underestimates the crestline by ~5-10%. Scale: gridmarks at 5 km.

7.2.2 Orientation

Landform orientation forms the basis for inferring ice flow directions and assessing the consistency and contiguity of the bedforming process. Its calculation is a simple GIS operation, either with an automated tool or manually via simple trigonometry and Pythagoras rules. Orientation is therefore easily appended to the lineation attributes. Again, for ribbed moraine, determining feature orientation is more complex, due to mapping as polygons and due to the sinuosity of the feature. It was not practical to manually draw an appropriate orientation line for each ridge, and therefore several ways to approximate a ridge orientation were explored:

- Orientation of the longest line to fill the polygon (as above).
- Mean orientation of the individual line segments which form a polygon.
- Orientation modal class of the individual line segments forming a polygon.

The above methods were evaluated for a random selection of ridges with respect to a manually determined line approximating the feature orientation (Figure 7.3). The sum of the square of the errors was used as a crude measure of relative success. The mean orientation of the polygon segment lines was found to be the most successful. This statistic was used to calculate landform orientation for the entire ribbed moraine population.

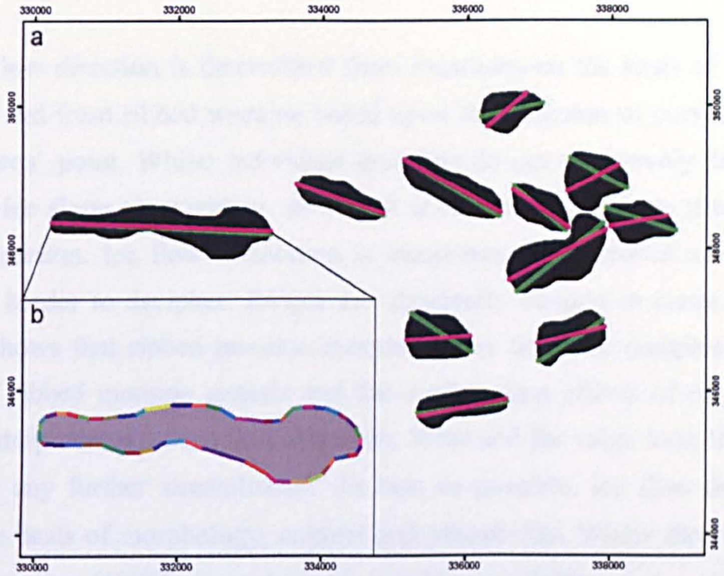


Figure 7.3 Different methods were explored to approximate the orientation of a ribbed moraine ridge: the longest line contained by the polygon (green), the mean of the polygon segment lines (see panel b) or the mode of the segment lines. From a sample of four 10x10km tiles (53 ridges) the mean segment line orientation proved most successful at replicating a manually drawn ridge orientation line (pink). Scale: gridmarks at 2km.

The main complexity in using orientation quantitatively lies in its circular, rather than linear nature. For example, the mean orientation of two drumlins oriented at 1° and 359° should be due north, not the linear result of $^{360}/_{2} = 180°$, due south. Any statistics performed upon a group of orientation data therefore must follow the rules of directional (vector) statistics as opposed to straightforward linear statistics. Following Mardia and Jupp (2000), lines are treated as vectors of unit length = 1. The mean orientation, $\overline{\vartheta}$ radians, is:

$$\overline{\vartheta} = \begin{cases} \tan^{-1}(\overline{S}/\overline{C}) & \text{if } \overline{C} \geq 0 \\ \tan^{-1}(\overline{S}/\overline{C}) + \pi & \text{if } \overline{C} < 0 \end{cases} \quad \text{Eq. 7.1}$$

$$\text{where:} \quad \overline{C} = \frac{\sum_{i=1}^{n} \cos \vartheta_i}{n} \quad \text{and} \quad \overline{S} = \frac{\sum_{i=1}^{n} \sin \vartheta_i}{n} \quad \text{Eq. 7.2}$$

The standard deviation is approximated by the mean resultant length $\overline{R}$:

$$\overline{R} = (\overline{C}^2 + \overline{S}^2)^{\frac{1}{2}} \quad \text{Eq. 7.3}$$

Orientation is a property used a number of times in the following analyses; any further caveats with its use are addressed where appropriate, below.

7.2.3 Determining ice flow direction

Direction differs in significance from orientation values. The orientation calculations consider the bearing from the digitised start point to the end point. However, lines were rarely digitised paying attention to landform direction and, of course, ribbed moraine orientation is perpendicular to landform direction. The orientation values recorded therefore have no significance for *flow direction* and this must be determined on an independent, visual basis.

Classically, ice flow direction is determined from lineations on the basis of a steep stoss and gentle lee slope, and from ribbed moraine based upon the direction of curvature, i.e. in which direction the 'horns' point. Whilst individual drumlins do not exclusively display the steeper stoss and gentle lee slope arrangement, in bulk it is relatively simple to determine a drumlin pattern's flow direction. Ice flow orientation is transverse to the ribbed moraine axis but its direction can be harder to decipher. Ridges are classically thought to curve downstream, but Dunlop (2004) shows that ribbed moraine morphology is far more complex. Our inadequate understanding of ribbed moraine genesis and the confounding effects of ridge drumlinisation complicate the interpretation of ice flow direction. What did the ridge look like after its initial formation before any further streamlining? As best as possible, ice flow direction has been interpreted on the basis of morphology, context and plausibility. Where direction could not be deciphered, both options (180° from each other) remain a possibility.

7.3 Testing traditional ice sheet models

Conceptual models of the last Irish Ice Sheet have been in existence since the seminal papers of Close (1867) and Hull (1878). Chapter 2 revealed much divergence of opinion and controversy between Close, Hull and subsequent workers over the basic ice sheet properties. These models were based upon an assessment of the spatial patterns of glacial landforms observed in the Irish landscape. The new mapping presented in this thesis undoubtedly exceeds (in volume and spatial consistency) that on which traditional models were based. In light of this, it is necessary to examine whether any earlier models can be confirmed or rejected in part or in entirety. McCabe (1985) and Warren's (1992) models echo those of Hull (1878) and Close (1867) respectively. These two traditional models are evaluated here, followed by an examination of more recent ideas about the behaviour of the Irish Ice Sheet. Figure 7.4 presents the McCabe

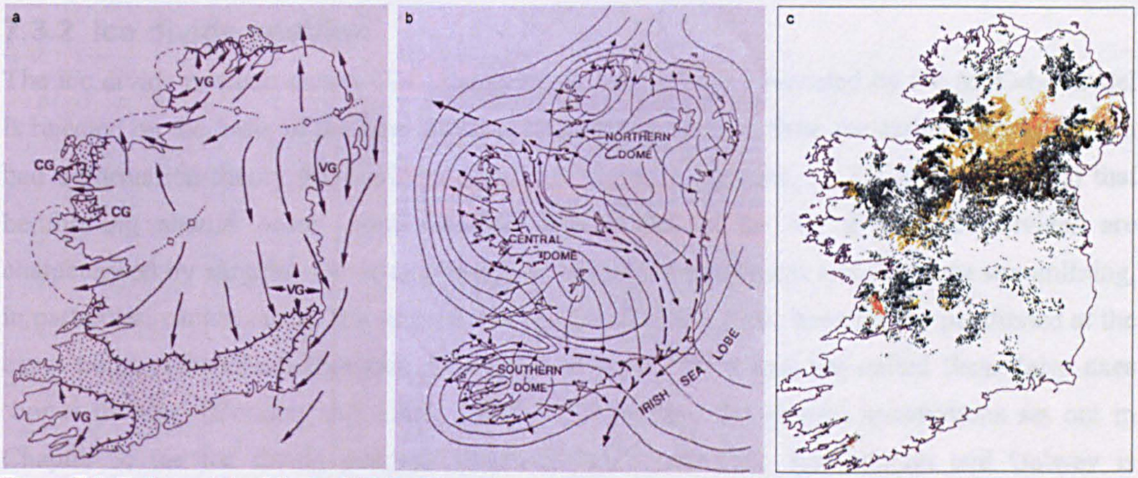


Figure 7.4 Earlier models of the last Irish Ice Sheet viewed against new mapping of subglacial bedforms. **a)** McCabe, 1985; **b)** Warren and Ashley, 1994; **c)** new bedform map (see Map 2).

model, the Warren model, and an image of the new bedform mapping. Three elements of the ice sheet are considered: ice extent, ice divide position, and ice flow patterns.

7.3.1 Ice extent

The Warren model (Figure 7.4b) represents total ice cover of the modern terrestrial land mass, apart from a small enclave in Co. Kerry. The traditional McCabe model (Figure 7.4a), in contrast, limits the last ice sheet to the Southern Irish End Moraine, after Charlesworth (1928b). The new mapping of subglacial bedforms, whose distribution is shown in Figure 7.4c, requires a modification of this limit. Bedforms continue past the SIEM with no apparent change in either morphology or sedimentology (Hegarty, 2002a,b, 2004; Kilfeather, 2004) which would be expected if an older ice sheet was responsible for their genesis (Figure 7.5). The simplest interpretation is that the ice that formed the bedforms extended further south than the SIEM 'limit'.

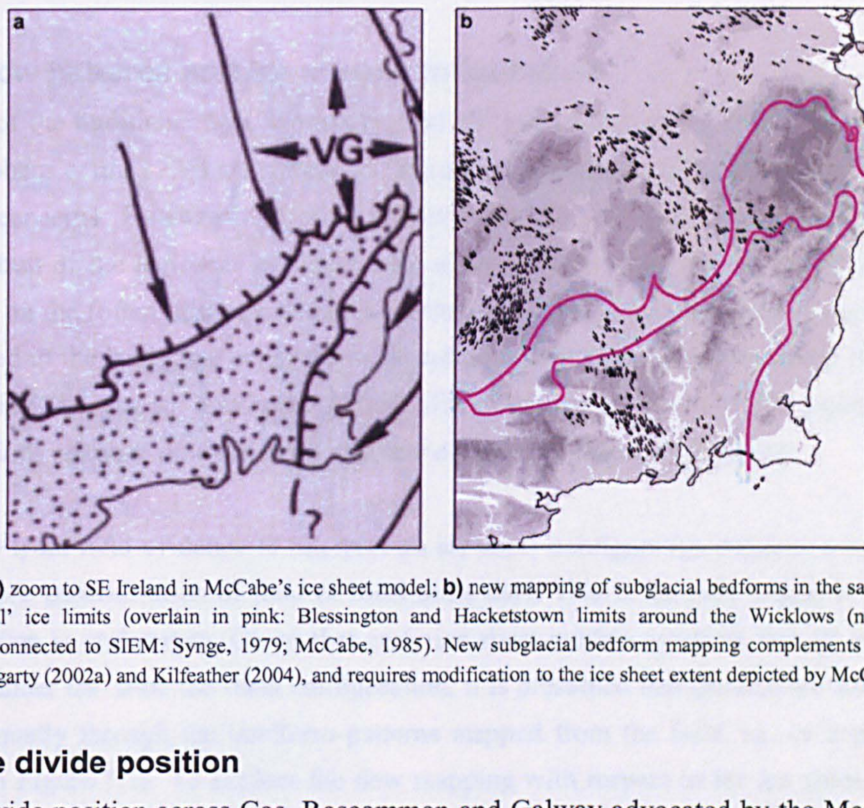


Figure 7.5 a) zoom to SE Ireland in McCabe's ice sheet model; **b)** new mapping of subglacial bedforms in the same area exceeds the 'traditional' ice limits (overlain in pink: Blessington and Hacketstown limits around the Wicklows (north and south, respectively) connected to SIEM: Synge, 1979; McCabe, 1985). New subglacial bedform mapping complements and extends the findings of Hegarty (2002a) and Kilfeather (2004), and requires modification to the ice sheet extent depicted by McCabe (1985).

7.3.2 Ice divide position

The ice divide position across Cos. Roscommon and Galway advocated by the McCabe model is rejected on the basis of the new bedform mapping. It follows from the earlier discussion of a bed deformation theory for bedform genesis (Chapter 3, Section 3.2.1.2 and Figure 3.6) that bedforming should occur some distance downstream of an ice divide. Ice divides are characterised by sluggish ice or an absence of lateral ice movement and therefore streamlining, in particular, cannot occur. It is argued that ice divides have often been falsely positioned at the exact point of landform direction divergence (Figure 7.6). Clark has called these false axes 'bogus divides' (Boulton and Clark, 1990a,b). Following the genetic assumptions set out in Chapter 3, the ice divide position reconstructed across Cos. Roscommon and Galway is rejected. Instead, an ice divide migration must be invoked.

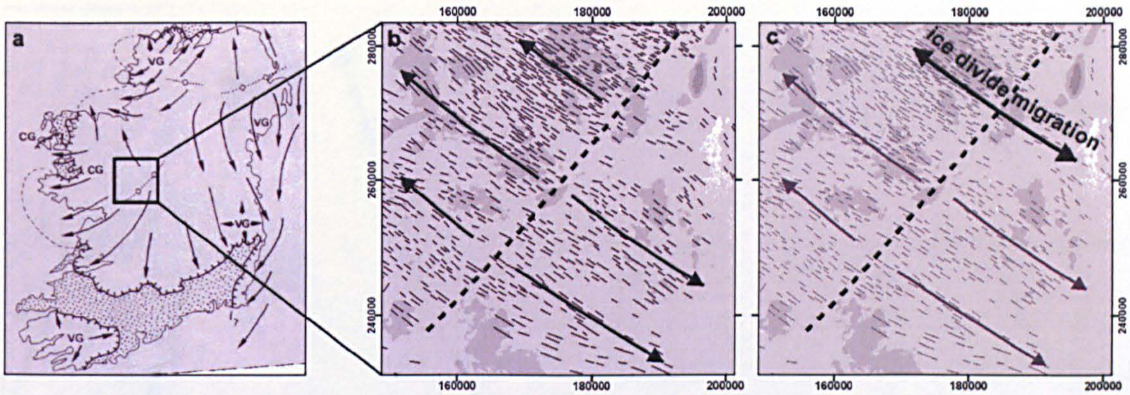


Figure 7.6 The McCabe model (and all those it echoes) positions an ice divide NE-SW across Cos. Roscommon and Galway, towards Galway Bay **(a)**. This is based upon the divergence of drumlins from an apparent axis. New mapping reveals such a landform assemblage and panel **(b)** illustrates the potential interpretation. Lineations in the south and east of this area indicate flow towards the SE; those in the opposite sector indicate north-westwards flowing ice. Early interpretations of this drumlin arrangement positioned an ice divide along the axis of flow direction divergence. However, modern understanding of bedform generation with respect to glaciological context renders this interpretation untenable. Bedforming is inhibited under ice divide zones, and therefore apparent landform divergence from such a narrow zone cannot support an ice divide interpretation. Instead, a divide must be positioned some further distance upstream of each lineation set, and contemporaneity of the two groups cannot be feasible. A migrating ice divide is the preferred explanation of this suite of landforms **(c)**.

7.3.3 Flow patterns and ice sheet configuration

Elements of the traditional McCabe model, and all those which precede it (Hull, 1878; Synge, 1970; Stephens *et al.*, 1975) are rejected on the above grounds. The Warren model is unaffected by these concerns. However, common to both the McCabe and the Warren model is the representation of the ice sheet as a single ice sheet configuration. Derivation of these models was based on the (often unstated) assumption that all evidence may be grouped together, it was all inscribed in the landscape under the same configuration of ice divides and ice flow patterns, likely during the glacial maximum period. This assumption and the consequent ice sheet configurations are now explored given the new database of landform mapping.

Scaling up from field evidence to interpret an ice sheet configuration requires some synthesis, and therefore generalisation of field or local-scale data. This is the case whatever approach to reconstruction is undertaken. Given that early ice sheet models assumed that all evidence was inscribed under the same ice sheet configuration, it is presumed that generalised flowlines were drawn manually through the landform patterns mapped from the field, i.e. on a purely visual basis, as in Figure 7.7a. To explore the new mapping with respect to the ice sheet models this process of visual generalisation is quantitatively simulated within the GIS. Given the earlier calculated feature orientations and their interpreted direction, the average flow direction indicated by landforms can be calculated on an area by area basis (Figure 7.7b).

Flow directions captured in both the McCabe and Warren models are largely based upon drumlin fields. My analysis was therefore performed initially on the lineation layer. Figure 7.8a presents the resultant average flow direction map for Ireland. Reconstruction of the necessary flow configuration to account for the landform evidence is simply a matter of tracing flowlines parallel to the flow direction arrows, until such a point where two flowlines meet and an ice divide is inferred. An ice sheet configuration derived in this way is presented in Figure 7.8b.

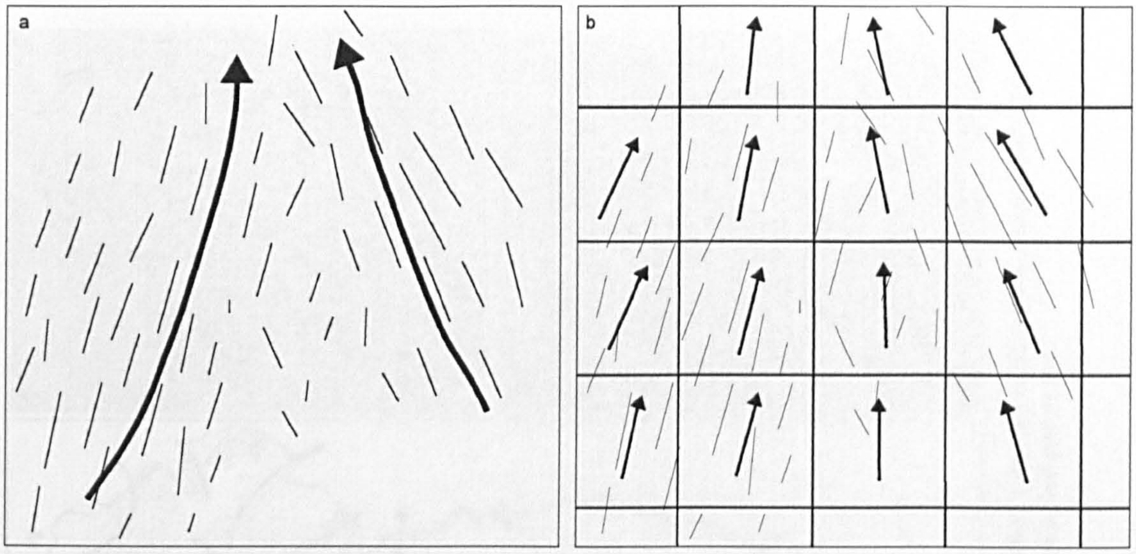


Figure 7.7 Early models are based on an assumption that all evidence may be grouped together, and drumlins can be generalised by flowlines accordingly. Schematic panel **a** visually synthesises the ice flow directions indicated by the landform evidence. The assumption of synchronicity is explored quantitatively **(b)** by calculating average ice flow directions per unit cell size (5 x 5 km in the case of Figure 7.8) across the country based on the new mapping.

It is interesting to see that given the assumptions outlined above, the new mapping of the Irish drumlin population could be taken in support of either of the traditional models of the last Irish Ice Sheet. However, these models can be invalidated both by the mapping details and the assumptions on which this analysis has been performed (Figure 7.9). Firstly, the same analysis performed upon the ribbed moraine layer of mapping reveals a far more complex story. Taking an average flow direction from a complex record produces a number of glaciologically implausible scenarios, such as flow circulating around the same spot, in a 'plughole' effect. Secondly, the key underlying assumption of synchroneity of evidence is invalidated by the landform arrangements displayed. Examples of cross-cutting have already been presented and discussed in both Chapters 5 and 6 – for both subglacial bedforms and meltwater landforms. Such arrangements clearly cannot be accounted for under the same, unchanging ice sheet configuration, and their occurrence throughout the record (Figure 7.9d) falsifies the principles upon which the traditional models of the last Irish Ice Sheet have been conceived.

7.3.4 Existing models: summary

The traditional conceptual models of the last Irish Ice Sheet can be falsified by the new landform mapping on three grounds: ice extent, ice divide position, and interpretation of flow patterns and ice sheet configuration. Concepts of the ice sheet have undoubtedly progressed since the proposal of the traditional models. Two more recent models are based upon a multi-temporal interpretation of the landform evidence (McCabe *et al.*, 1999; McCabe, 2005; Clark and Meehan, 2001) although neither is yet capable of identifying the character and sequence of ice flow dynamics and the requisite ice sheet configurations at ice sheet-scale. This thesis seeks a rigorous and more objective interpretation of the complex landform record which recognises its multi-temporal nature. It will be appropriate to return to the more recent models following the analysis of the new data and the presentation of potential ice sheet reconstructions.

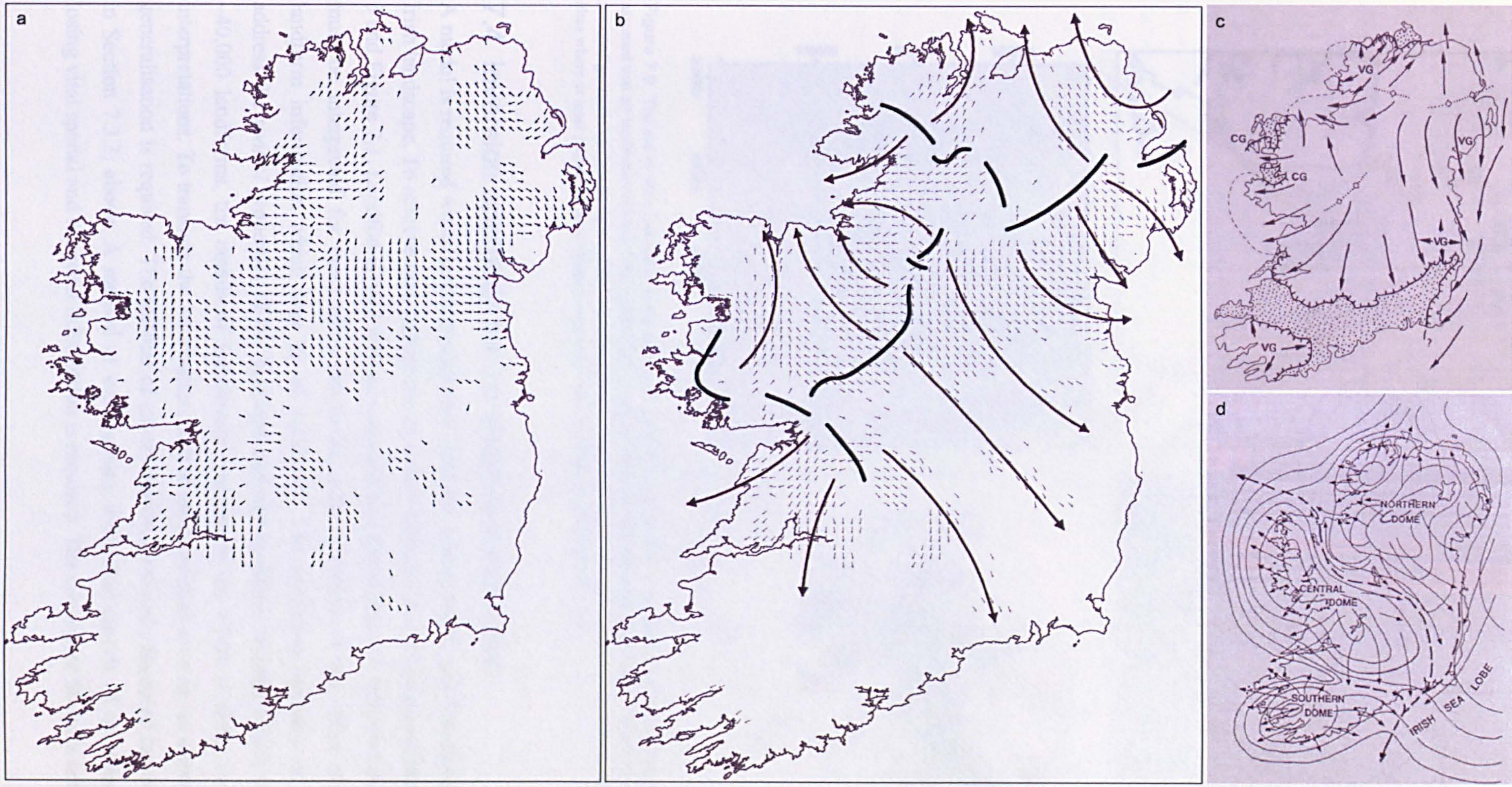


Figure 7.8 Each arrow in panel **(a)** represents the average flow direction revealed by lineations within that 5 x 5 km area. Based on this summary information, an ice sheet configuration as shown in panel **(b)** could be reconstructed. There are evidently similarities between this ice sheet and those proposed by both McCabe (1985), Warren (1992) (panels **c** and **d**) and similar models which precede these.

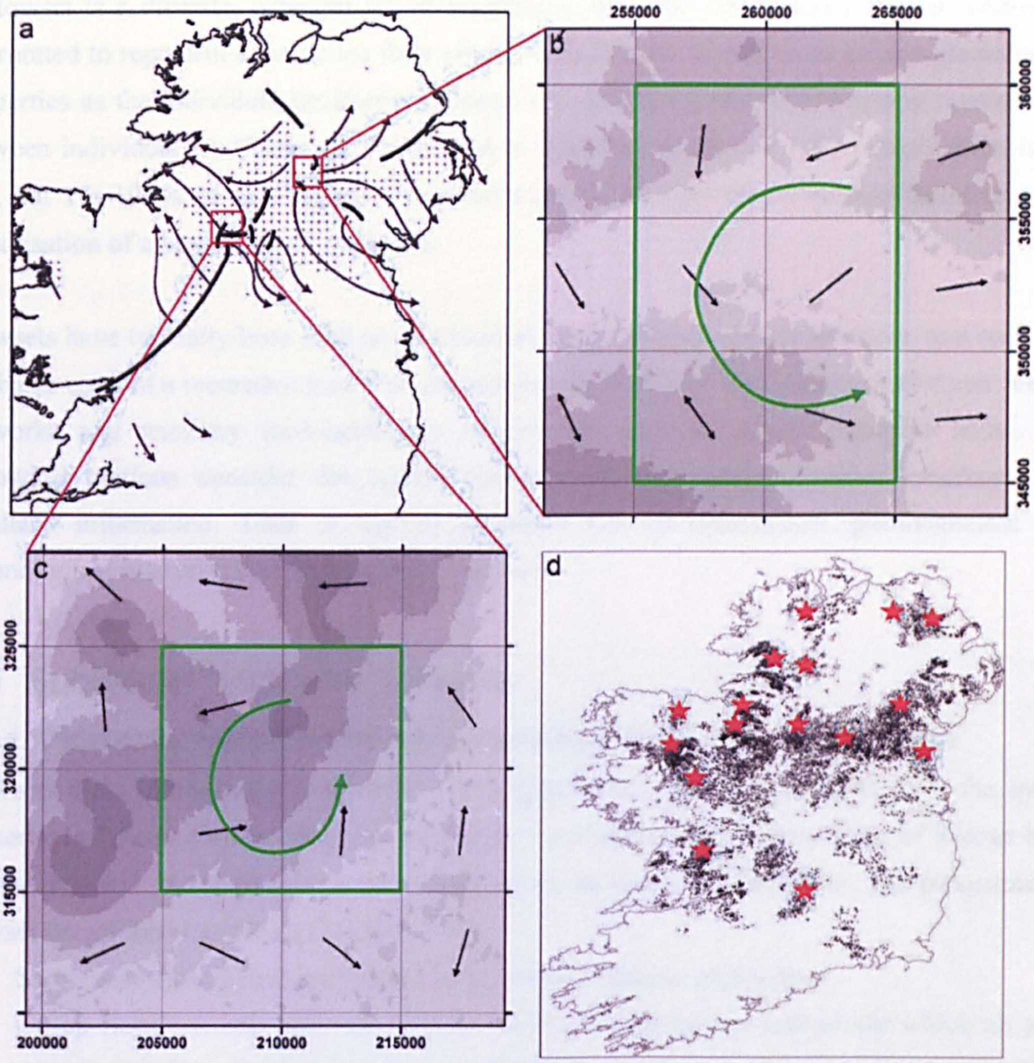


Figure 7.9 The use of flow indicators in the manner adopted by early workers is invalidated by the new mapping. It cannot be assumed that all landform evidence is the product of a single ice sheet configuration, since this produces glaciologically implausible ice configurations (panels **a, b, c**: ribbed moraine generalisation) and ignores sites of abundant cross-cutting (panel **d** highlights sites where at least 3 lineation assemblages cross-cut). Scale for **b** and **c**: gridmarks at 5 km.

7.4 Inversion approach for ice sheet reconstruction

A model is required which better explains the landform arrangements and distribution across the Irish landscape. To achieve this, I adopt the inversion approach and methods outlined in Chapter 3 and Figure 7.1. Landforms hold *spatial*, *temporal* and *glaciodynamic* information. The record must be interpreted for these three properties, with reference to any other available non-landform information which may be of assistance. The remaining sections of this chapter address the *spatial* properties of the landform and non-landform records. Given a database of ~40,000 landforms, the details of individuals overwhelm the effort to make ice sheet-wide interpretations. To translate the information held at the individual level to ice sheet-scale, some generalisation is required. The method of generalisation previously favoured has been falsified in Section 7.3.3, above. A method of summarising individual parcels of information without losing vital spatial and temporal information is required. The concept of *flowsets* achieves this.

A flowset is a discrete, coherent set of morphologically and directionally similar landforms, interpreted to represent a single ice flow phase. Each flowset has the same palaeo-glaciological properties as the individual landforms it comprises, and the spatial and temporal relationships between individual landforms are transferred to flowsets. In this way, vital information is not lost, but 10s-1000s of data parcels are summarised as a single unit. Flowsets facilitate easier visualisation of a large body of evidence.

Flowsets have typically been used as a method of summarising *bedform* evidence, and represent the basic units of a reconstruction. The concept is extended here to synthesise meltwater feature networks and ancillary (non-landform) information such as erratic transport paths. The following sections consider the spatial summary of bedforms, meltwater landforms and ancillary information. Data is thereby prepared for the subsequent glaciodynamic and chronological interpretation addressed in Chapter 8.

7.5 Subglacial bedforms: flowsets

7.5.1 Flowsets: introduction and procedure for bedform synthesis

Flowsets are a cartographic summary of a subglacial bedform record based upon the spatial properties of the bedforms. They facilitate easy visualisation and interpretation of a large body of evidence and therefore are the basic units of an ice sheet reconstruction. The procedure for flowset derivation is as follows (Figure 7.10):

- Summarise flow directions yielded by individual features as *flowlines*.
- Group flowlines into coherent *flowsets*. A flowset comprises individuals which all yield the same palaeo-glaciological information and represents a discrete phase of bedform genesis under a consistent ice sheet configuration.

Figure 7.10 Individual lineations are summarised by flow parallel lines, in turn grouped into flowsets. Within each flowset lineations should display internally consistent properties, representing a discrete phase of ice flow.

7.5.2 Methods and examples of flowset derivation

7.5.2.1 Data to be summarised

Lineations have been the traditional drivers of ice flow path reconstruction. Nonetheless, where ribbed moraine have been recognised, these have been summarised in the same way as lineations by proponents of the flowset approach (e.g. Clark *et al.*, 2000; Clark and Meehan, 2001; De Angelis and Kleman, 2007). Here, both types of bedform are grouped into flowsets, but I treat ribbed moraine and lineations separately since there is insufficient understanding of their genetic relationship to group them.

All mapped features are considered for flowset building, with the caveat that if 'speculative' landforms are the only features to comprise a single flowset, then the speculative description is translated to the flowset. All lineation types (drumlins, crag and tails, MSGLs, streamlined bedrock) are considered and a single flowset may comprise lineations of each of these types. Streamlined bedrock is not, however, considered sufficiently strong evidence to define a flowset in its own right; its occurrence is used to strengthen or extend an otherwise identified flow pattern. The significance of streamlined bedrock for the *last* period of glaciation is not well constrained and is more likely to be an inherited signature than are drift bedforms.

7.5.2.2 Flowlines

Flowline drawing is a visual, rather than quantitative or automated task. The individual data are treated as abstract items – lines or polygons overlain upon the broad-scale topography of Ireland. The DEM is *not* visualised to display landforms. Orientation is the main property considered, and close attention is paid to any divergence from a parallel arrangement with an

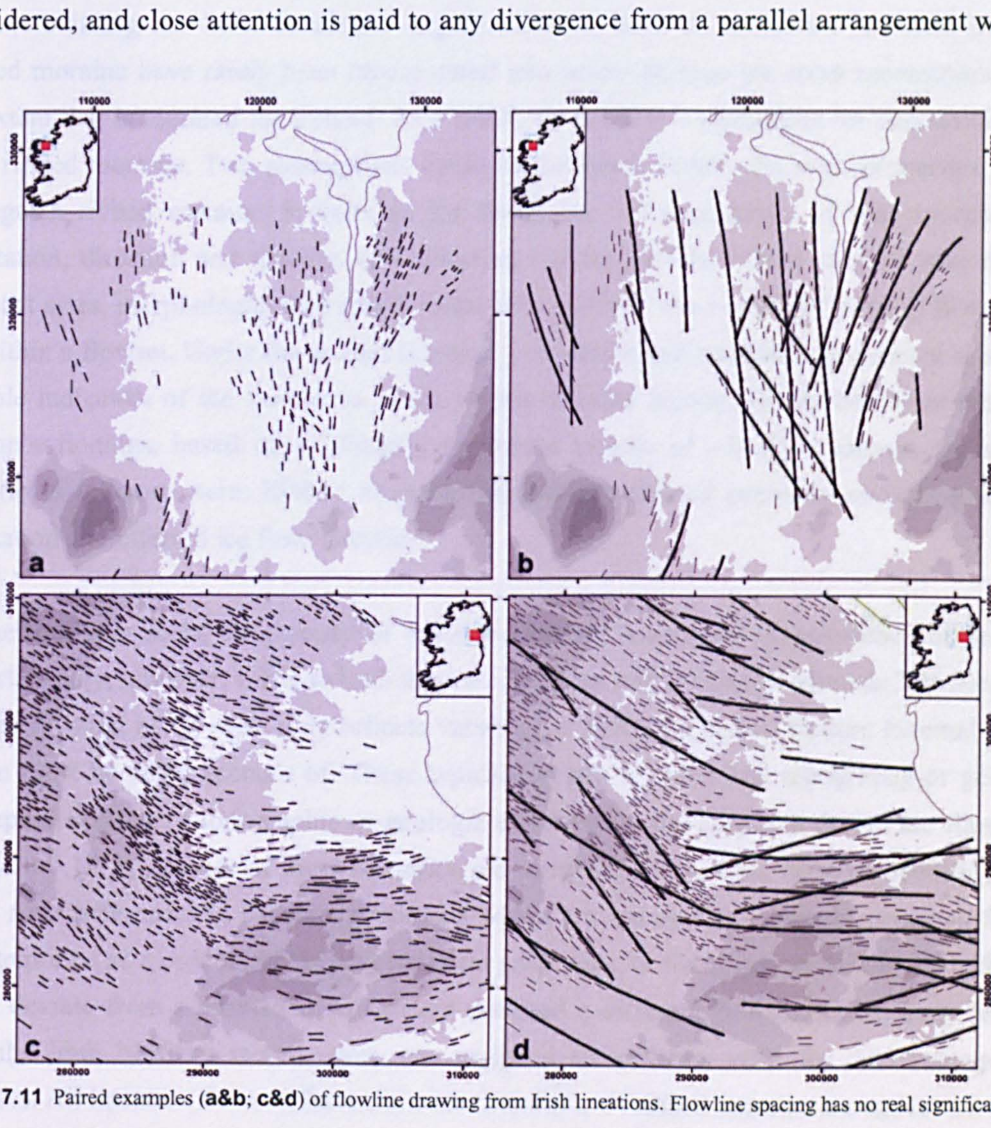


Figure 7.11 Paired examples (**a&b**; **c&d**) of flowline drawing from Irish lineations. Flowline spacing has no real significance.

individual's neighbours. At this stage it is irrelevant whether a divergence is a large change or subtle: all information is recorded. In the subsequent stage of flowset derivation it should be decided whether subtle direction differences are sufficient to warrant grouping as a separate flowset. Flowlines should be an accurate summary of all available information (Figure 7.11).

7.5.2.3 Flowsets

Flowsets are built by grouping flowlines. The aim is to arrive at a flowset which comprises features formed at one time, under one ice sheet configuration. To achieve this, a number of assumptions must be employed. Typically, we expect features formed in the same area under the same ice flow event to display roughly consistent characteristics. Therefore, in determining which flowlines can be grouped to form one flowset, similarities in the following properties of individual landforms are considered:

- Size (length)
- Morphology (qualitative description)
- Orientation (parallel conformity)
- Direction
- Spacing

Flowset building has been developed largely from the need to summarise lineation patterns. Ribbed moraine have rarely been incorporated into inversion-type ice sheet reconstructions to the extent that is required for Ireland. As a result, there are few precedents for flowset building from ribbed moraine. Two assumptions could be followed. Either, the same properties should distinguish ribbed moraine flowsets as for lineations, i.e. consistency of size, morphology, orientation, direction and spacing. Or, following Dunlop (2004), ribbed moraine may display different sizes, morphologies and spatial relationships *within* the imprint of a single flow event, i.e. within a flowset. Under the second scenario, orientation and direction consistency should be the sole indicators of the flowset to which ribbed moraine belong. Given the robust nature of Dunlop's findings, based on a globally distributed sample of ~36,000 features, the second scenario is followed here. Ribbed moraine flowsets are defined primarily according to their orientation and inferred ice flow direction.

Flowset building seeks consistency of the above-named properties. *In*consistency of bedform properties may, however, relate to both the ice conditions and the bed conditions. It is necessary that the division of flowsets only reflects varying ice sheet properties. Factors external to this system must be taken account of. These typically relate to either bed topography or geology. Conceptual models of topographic or geologic effects upon the landform record are illustrated in Figure 7.12. A number of these scenarios are identified in the Irish bedform record (Figure 7.13). Any differences in bedform properties which are not readily explicable by such factors are interpreted as a product of varying ice sheet properties. In these circumstances the bedforms which deviate from a consistent pattern are assigned a different flowset. In building flowsets from the Irish bedform record, each was assigned an arbitrary code for data management purposes. All lineation flowsets have the code 'lins fs*X*'; all ribbed moraine are coded 'rm fs*X*'.

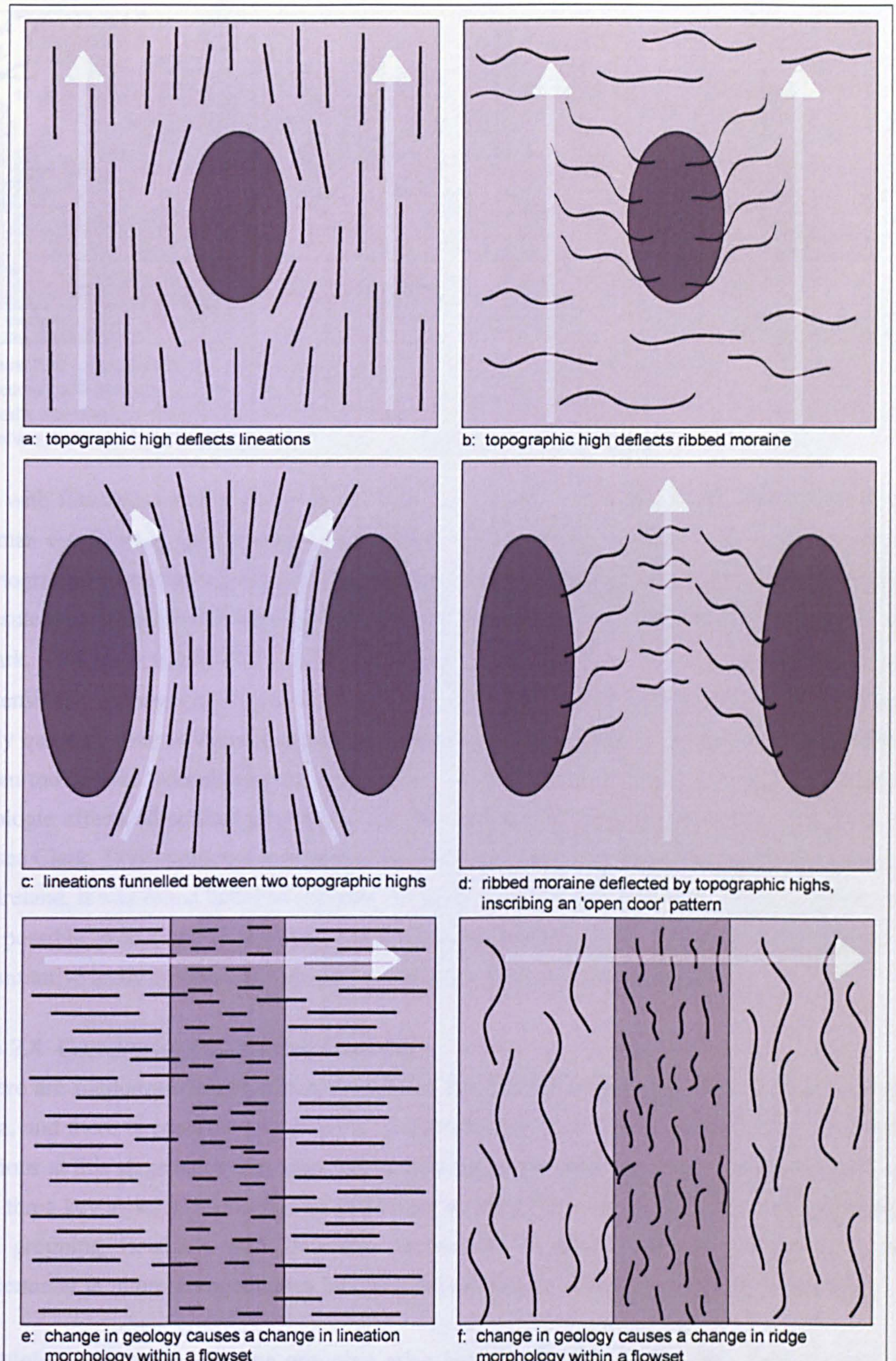


Figure 7.12 Conceptual models of the effect of topographic highs and changes in geology upon bedform morphology. Where morphological changes can be explained in such a manner, i.e. by a factor other than purely ice sheet characteristics, landforms should still be grouped within the same flowset. Flowsets should separate those bedforms which are inscribed under different ice flow regimes and ice sheet configurations. For this reason it is important to work on flowset building with the mapped vector information overlain on the broad-scale topography (as in Figure 7.13) and geology.

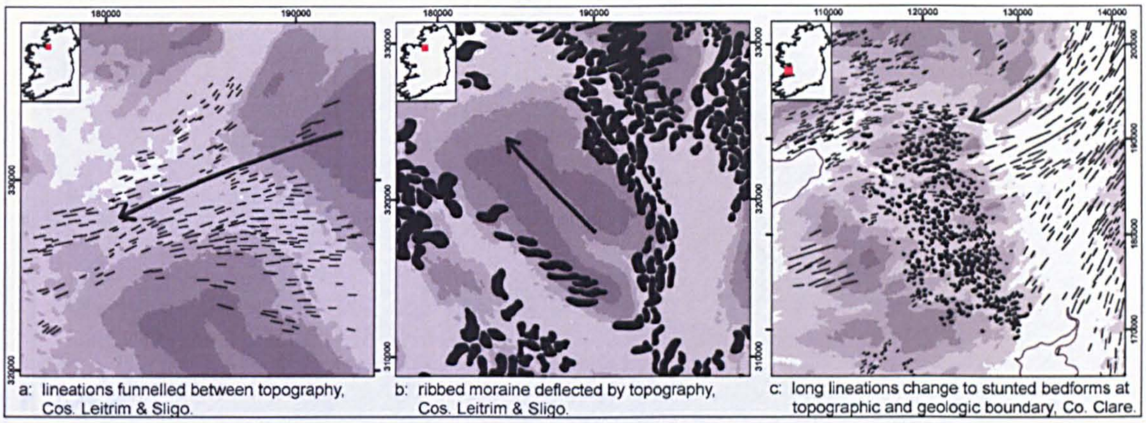


Figure 7.13 Examples from the Irish bedforms of some of the conceptual models outlined above (arrows indicate inferred ice flow directions). **a & b)** bedforms are funnelled or deflected by topographic highs, causing some inconsistency of orientation, but still logically classified as a single flowset. **c)** over a topographic and geological boundary, bedforms change in morphology from long lineations to 'stunted' bedforms; flow direction is, however, the same and a single flowset is interpreted. Scale: gridmarks at 10 km.

As with flowline drawing, grouping into flowsets is largely a visual interpretative exercise. The human eye is very good at pattern recognition but, more than simply conducting an abstract cartographic exercise, we can also impart glaciological knowledge to the process which is hard to automate. Quantitative properties of the individual landforms can assist the procedure (see Clark, 1997) and methods of visualising spatial inconsistencies of length and orientation were extensively explored (e.g. Figures 7.14 & 7.15). However, such methods were found to typically only quantify what is visually apparent. Furthermore, the objectivity of quantitative analysis is often too severe. Inconsistency of a parameter has been shown to arise due to topographic and geologic effects (described above) and the very nature of time-transgressive flowsets (Chapter 8; see Clark, 1999) produces less consistent landform properties. Therefore, in deriving flowsets in Ireland, it was found better to interpret the data visually rather than quantitatively. In this way all possible exceptions to the rules could easily be accounted for. The objectivity offered by quantitative analysis does not necessarily produce a more successful result.

7.5.2.4 Complexities in building flowsets

There are numerous factors which complicate the process of building flowsets from bedform data, and there is consequently rarely a unique solution. It is best to acknowledge all possible options at this stage since they may have a bearing on the final reconstruction scenarios. There are three key aspects of uncertainty in flowset building from the Irish record: multiple options for grouping flowlines into flowsets; uncertainty in ribbed moraine interpretation; and uncertainty in interpreting complex landform morphologies. These are each now considered.

Multiple options for flowline grouping arise because the questions with which the data are interrogated have unknown or imprecise answers:

- How *un*parallel can lineations be within a flowset? (Figure 7.16)
- How *in*consistent can the feature length distribution be? (Figure 7.16)
- How sharply can a flowset curve? (Figure 7.17)
- How much 'blank space' can there be between groups of landforms and the landforms still be logically classed as a single flowset? (Figure 7.18)

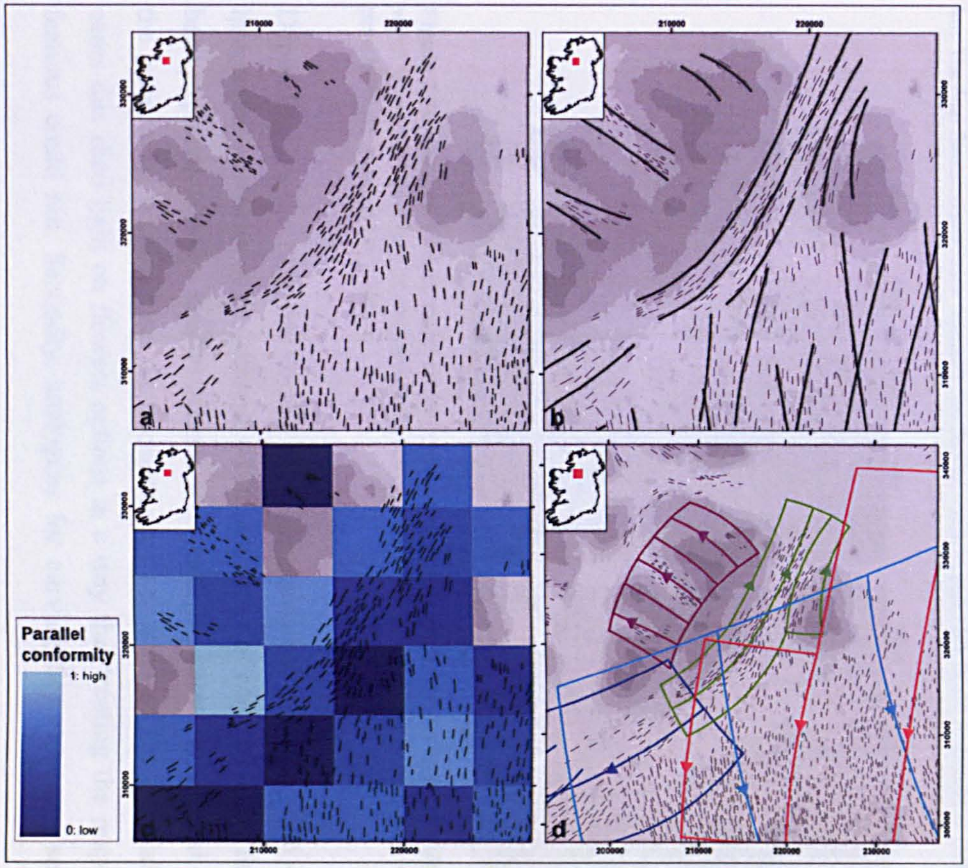


Figure 7.14 Four panels show the use of parallel conformity (the standard deviation, or mean resultant length statistic of orientation) as a tool for assisting flowset derivation. **a)** lineations in the region around the Cuilcagh mountains and Slieve Rushen, Cos. Leitrim and Cavan. **b)** flowlines based on lineations. **c)** gridded measure of parallel conformity: mean resultant length scales from 1 (pale blue – highly conformable) to 0 (dark blue – very low conformity). Darkest grids indicate low conformity of lineation orientation and likely location of cross-cutting, suggesting multiple flowsets. **d)** regional zoom-out reveals flowsets identified in this area. Scale: gridmarks at 10 km.

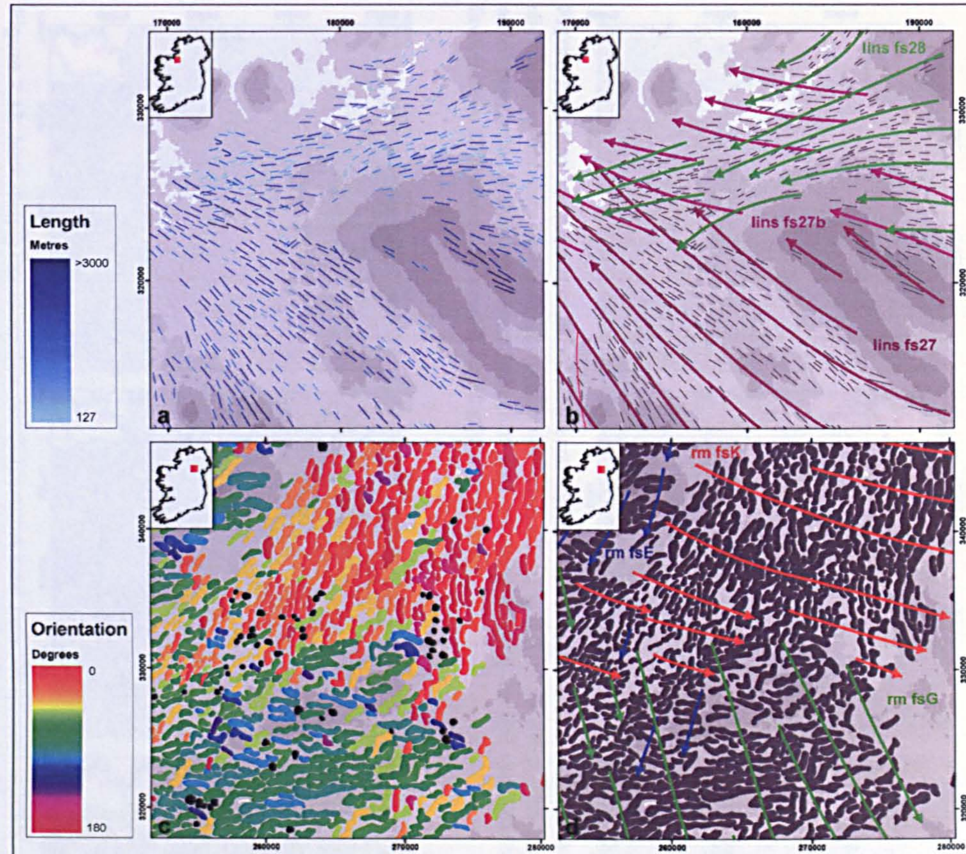


Figure 7.15 Image pairs **a&b** and **c&d** illustrate the use of length and orientation properties to assist the identification of flowlines and grouping into flowsets. **a & b)** Length: *flowset 27* has a larger population of longer lineations (darker blue in **a**) than *fs28* which is dominated by shorter features (paler blue). Line lengths in **a** range from ~180 - ~1820 m. **c & d)** Orientation: the colour scale indicated is applied to ribbed moraine ridges in classes of 10°. Two populations are immediately revealed with a sharp boundary between them: *flowsets G* and *K*. *fsE* extends into this area from further west. Colour scales must be carefully selected since the eye will be drawn to colour differences over and above length or orientation difference. Scale: gridmarks at 10 km.

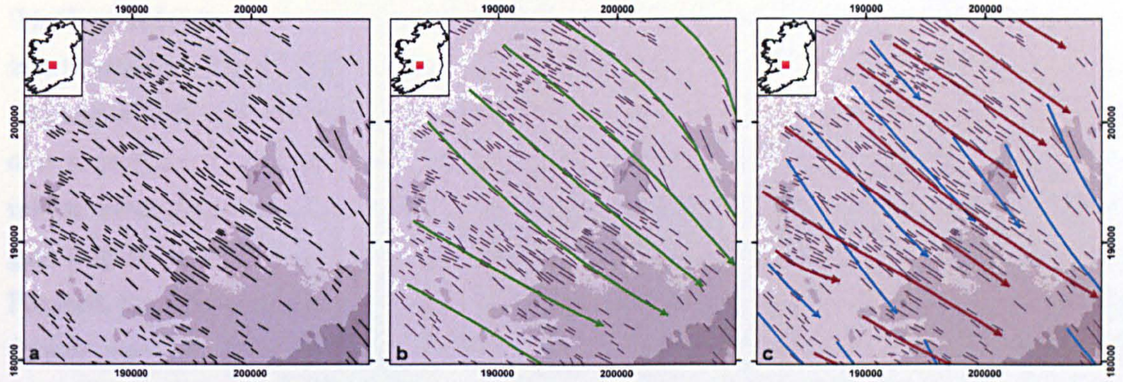


Figure 7.16 How much deviation in both length and orientation is necessary to invoke more than one flowset in Co. Offaly? Some slightly longer lineations have a slightly steeper orientation (closer to N-S) in the SW and NE quadrants of this area, but there is a mixed population of short and longer features aligned NW-SE and highly parallel conformable. The final flowset compilation favours a two flowset scenario, panel **c**. Scale: gridmarks at 10 km.

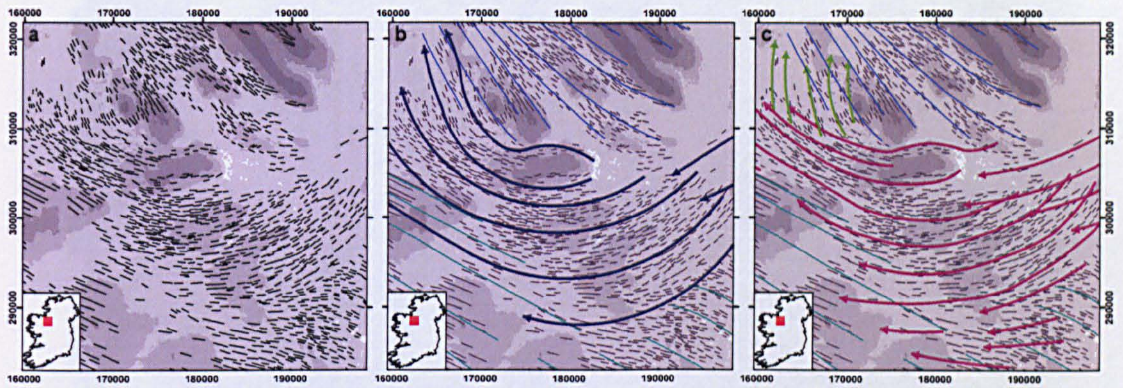


Figure 7.17 How sharply can an ice flow curve? Lineations bend from SW oriented to NNW oriented within approximately 25 km. The final flowset compilation favours a two flowset scenario, panel **(c)**. Scale: gridmarks at 10 km.

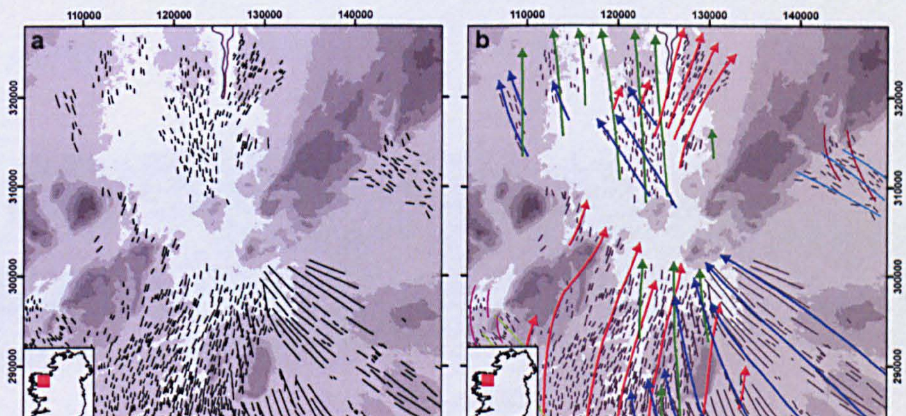


Figure 7.18 How much 'blank space' can exist between bedform patches without invoking multiple flowsets? Can the flowsets which summarise two groups of lineations north and south of Foxford, Co. Mayo, be reasonably correlated across the gap, as in panel **b**? Scale: gridmarks at 10 km.

Depending on the response to any of these questions, a single suite of landforms could be interpreted in two or three different ways. A number of ways to refine the available options has been explored. Firstly, flowset options were overlain upon the original imagery, to verify that the summaries proposed are an accurate representation of the original information. In some cases this shed light on flowset options in a way that treating the mapping as abstract vector features could not. Secondly, analogues for curving flowsets were sought. The question of 'blank space' presented the biggest uncertainty in flowset delineation and the available data was interrogated further in order to reduce this uncertainty. Is there a postglacial reason for an absence of bedforms (i.e. burial)? Is there a reason why bedforms may not have been generated over a small patch within a larger flowset? Can grouping across the blank space be ruled out (or in) via other means, such as exploring chronological landform relationships either side of the gap? Figure 7.19 illustrates such exploration of ideas for flowsets which leave a gap around Foxford, Co. Mayo. When all avenues have been explored for narrowing the range of potential flowset options, each remaining possibility has been recorded and is considered in the reconstruction stage of interpretation.

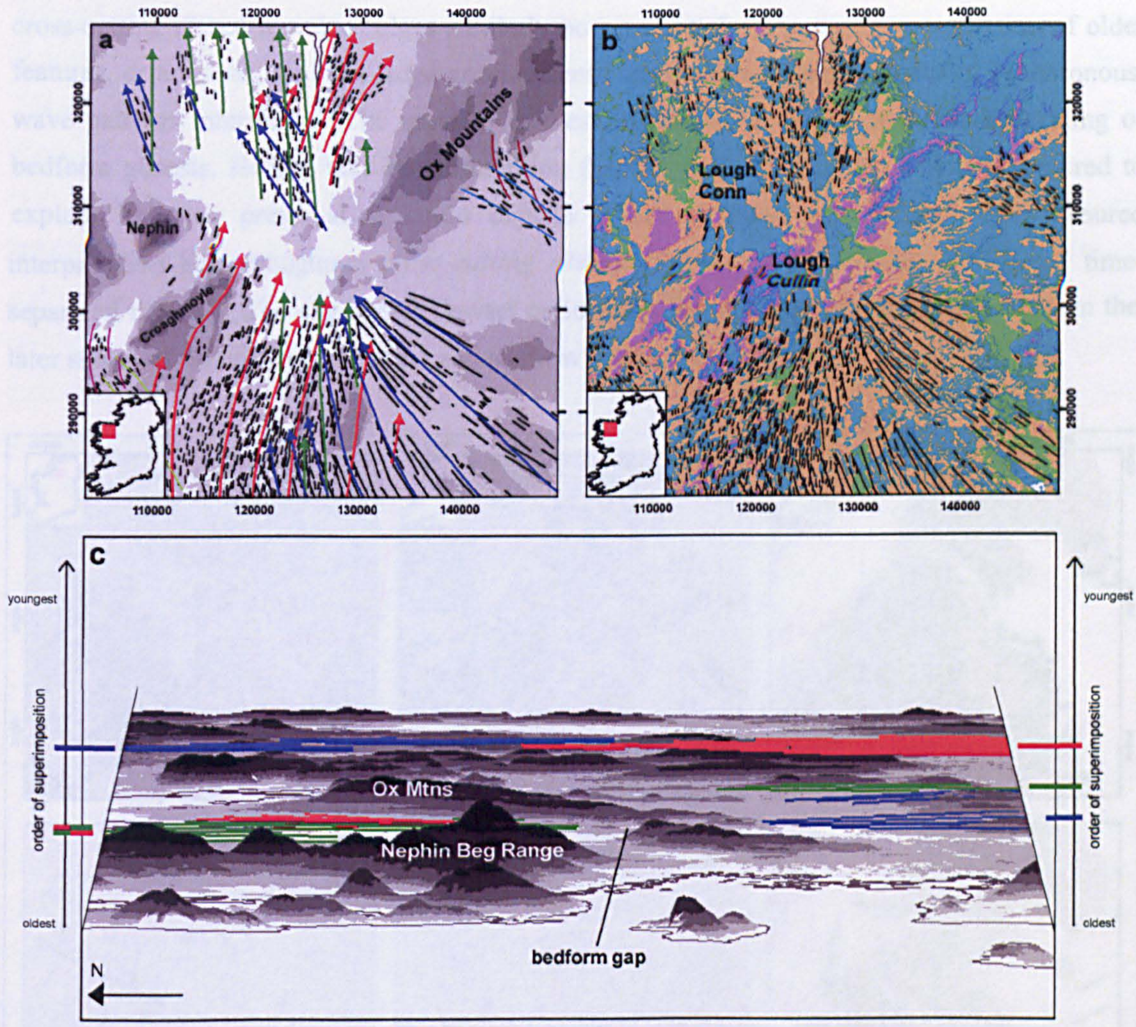


Figure 7.19 Three potential flowsets summarise lineations both north and south of the Nephin – Ox Mountains ridge **(a)**. However, at the breach in the ridge itself, there is a gap in the bedform record. Can the two groups of flowlines be correlated across the gap: red with red, green with green, blue with blue? The distribution of surface sediments in **(b)** does *not* rule this out: all regions shaded blue have postglacial material at the surface, including two lakes, and therefore the bedforms to connect the two groups may exist but are now buried. However, the relative chronology of flowlines within the two groups *does reject* a correlation **(c)**: to the south of the ridge, the blue flowlines are at the base of the sequence with red at the top; in the north, the relative positions are reversed. Blue flowlines and red flowlines therefore cannot be correlated as two flowsets. Scale for **(a)** and **(b)**: gridmarks at 10 km. **c)** perspective view looking east over Co. Mayo.

Ribbed moraine in Ireland have highly complex morphologies and a number of complexities arose in flowset building. The potential interaction between topography and ribbed moraine properties has been considered above, Figures 7.12 and 7.13. A key remaining uncertainty for flowset derivation is the interpretation of cross-cutting ribbed moraine (Figure 7.20).

Cross-cutting ribbed moraine has rarely been described. Clark and Meehan (2001) identify such arrangements in the Irish record, and Dunlop (2004) has found cross-cutting ridges in Newfoundland, but the significance both for flowsets and for bedform genesis has been little addressed. Uncertainty in how to interpret such arrangements is largely a matter of inadequate understanding of the ribbed moraine genetic problem. Unlike lineations, which are a product of streamlining, ribbed moraine are a wave phenomena, therefore should the same 'rules' apply to the interpretation of each? It is generally accepted that lineation overprinting may be interpreted as the partial preservation of an older pattern below a more recent, cross-cutting ice flow. Can cross-cutting ribbed moraine ridges similarly be interpreted as the partial preservation of older features, or are such complex ridge arrangements the product of two, potentially synchronous, wave patterns interfering? The answers to these questions lie in the better understanding of bedform genesis. Here, I take the assumption that the same mechanism which is required to explain lineation preservation could explain ribbed moraine preservation. The favoured interpretation here recognises cross-cutting ribbed moraine as the imprint of distinct, time-separated flowsets. The alternative flowset options are nonetheless kept in consideration in the later stages of flowset interpretation and ice flow reconstruction.

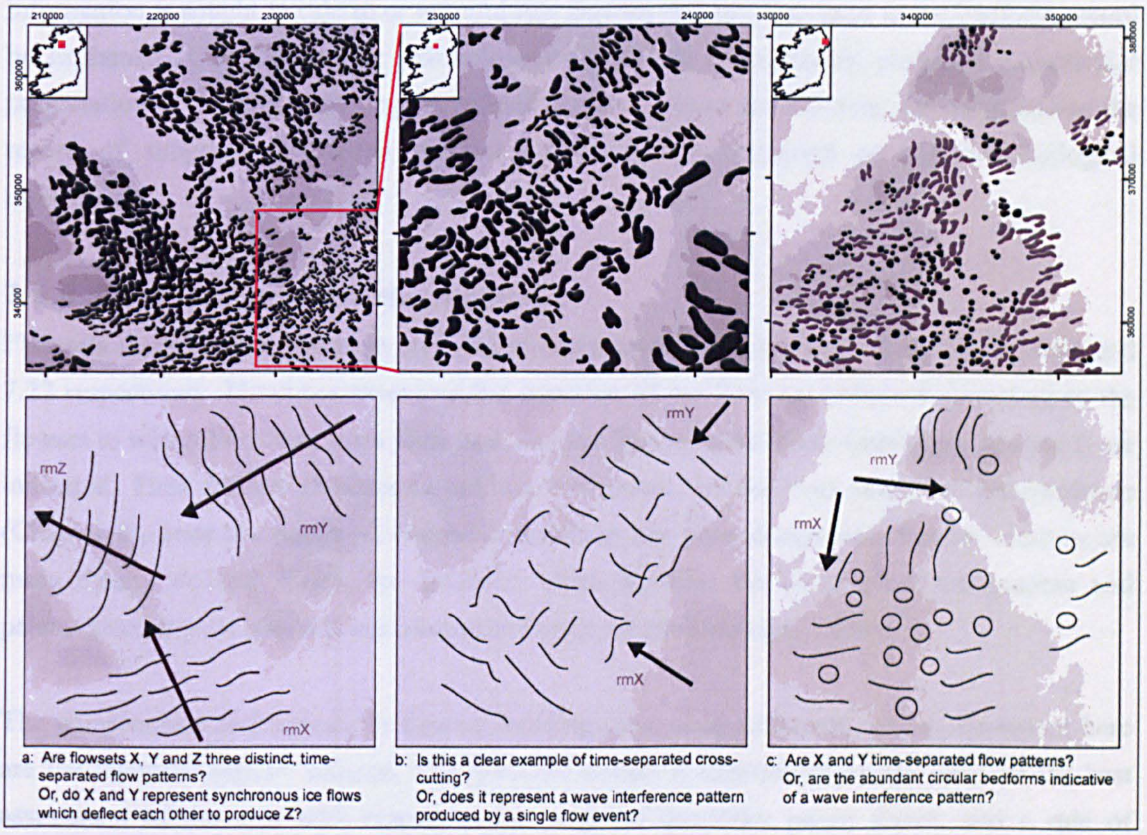


Figure 7.20 Uncertainty in flowset building from cross-cutting ribbed moraine.

Finally, **'other bedforms'** were identified in Chapter 5. Amongst these are bedforms which are almost circular in shape. Not only is their mode of genesis unknown but they also provide no flow directional information. Are they 'stunted' drumlins which were not streamlined for some reason? Are they erosional, or even buried remains of ribbed moraine ridges? Without understanding their origin their significance for palaeo-glaciology is not known. In terms of flowset building, they are temporarily ignored from the landform data, to be brought back into the reconstruction process as qualitative ancillary data informing us of a change in the operation of bedforming processes at certain sites. An exception to this occurs where circular bedforms are found within a lineation-based flowset and there is a good explanation for a change in bedform morphology, such as illustrated in Figures 7.12e and 7.13c.

7.5.2.5 Quality control and procedure summary

The sequence of steps taken to derive summary flowsets of the Irish bedform record sets out a logical procedure for effectively synthesising the information imparted by a large body of data. The individual data are interrogated at each stage, first to derive flow-parallel flowlines, and secondly to inform the process of grouping these flowlines into distinct flowsets. Initially the task considers only the abstract mapping output, removed from the visualised imagery. Inevitably multiple options arise for a cartographic summary. To verify the resulting flowsets and to attempt to narrow the range of options for flowline grouping, at this stage flowsets are laid back over the original imagery. Do the flowsets do a good job of summarising the bedform data, and can any of the flowset options be eliminated on review of the data? Additional information is sought to rule in or out multiple flowset options. Can gaps in the bedform record be explained? Can the relative chronology of landform arrangements eliminate a particular permutation of flowline grouping? A refined suite of options are achieved for summarising the record of subglacial bedforms without loss of spatial, temporal or palaeo-glaciological information.

7.5.3 Flowset maps and discussion

Flowsets derived from lineation and ribbed moraine mapping are shown in Figures 7.21 and 7.22 respectively. Flowlines revealing the direction of ice flow are coloured according to the flowset to which they have been allocated, and the flowset code labels (arbitrarily assigned) are indicated. Firm flowset boundaries are not yet drawn. In the next stages of interpretation (Chapter 8), once the nature of event encapsulated has been deciphered, flowset outlines are more clearly defined. Then, the landform characteristics, the geographic, topographic and palaeo-glaciological contexts are commented upon for each flowset (Table 8.3).

The complexities and caveats in flowset building have been addressed, above. Presented here are the favoured flowset options. The favoured option is determined on the basis of the best assessment of the data with regard to the range of questions posed above, and a rule of minimum complexity: the simplest explanation for the landform imprint is usually preferred.

7.5.3.1 Lineation flowsets

Lineation flowsets clearly display a complex flow history of the ice sheet. The cross-cutting observed between individual landforms is translated up to flowset scale and there are numerous locations where flowsets diverge, or oppose each other, or are positioned in such a configuration that entirely refutes any simple model of ice sheet history. The flowsets summarise and visualise the many complex landform arrangements observed at the individual level, and these become the basic units used for a reconstruction of ice flow patterns and the history of ice sheet configurations.

Figure 7.23 reveals that the favoured flowline – flowset groupings have generally been made with confidence. Only a few groups are uncertain, typically in regions of particularly complex bedform arrangements where it is difficult to decipher the number of discrete flow patterns present. Often this is not simply a case of one or two flowsets in a particular area, but potentially three, four, or five flow patterns. This is the case in north Co. Donegal and in Co. Sligo. In Donegal, *lins fs39, fs40, fs41* and *fs42* represent a very mixed population of lineations, comprising very small features, more 'typical' drumlin sizes, large crag and tails and potentially some streamlining of the underlying bedrock. As a population, these lineations display quite low parallel conformity whilst being generally oriented towards the N and NE. The questions posed earlier (Section 7.5.2.3) regarding inconsistency of length and orientation properties are pertinent here. In Co. Sligo, there is a complex relationship between *lins fs21, fs22, fs23, fs27* and *fs27b* and the underlying topographic shape. Ice flow must negotiate topographic barriers which are generally aligned with the flow direction and around which ice is deflected and funnelled. Ice flow must then confront the much larger obstacle of the Ox Mountains positioned directly perpendicular to the general flow direction. Subtleties of orientation and length inconsistency underpin these flowline – flowset groupings. A few flowsets in the lineation population are based upon more speculative initial mapping and are therefore regarded with a greater degree of uncertainty than others (e.g. *lins fs61, fs62, fs55, fs51, fs52*).

The area around Carrigatuke and Slieve Gullion, Co. Armagh, is a crux region where ~SSE flowlines from Co. Down join ~SE flowlines across Cos. Cavan, Monaghan, Louth and Meath (*lins fs9, fs11*). Added to the question of spatial contiguity is the role of the high terrain in deflecting individual drumlin orientations and producing local bedform patterns unrelated to the larger, main flowsets. The option of minimum complexity is selected: the flowlines may be joined across the region and lower parallel conformity is allowed within the flowsets around the area of high topography. An alternative is that *fs11* should be split into many different flowsets.

7.5.3.2 Ribbed moraine flowsets

Knowledge of ice flow direction is a key element of uncertainty in ribbed moraine flowset derivation. Direction is often a harder property to identify from ribbed moraine than lineations, especially given later streamlining of ridges which confounds attempts to be objective about their original form. This affects *rm fsN, fsD* and parts of *fsJ* and *fsL*, which are drawn without flow direction arrows in Figure 7.22. A rule of simplicity is applied: where flowlines of unknown direction display a similar orientation to others nearby for which the ice flow direction

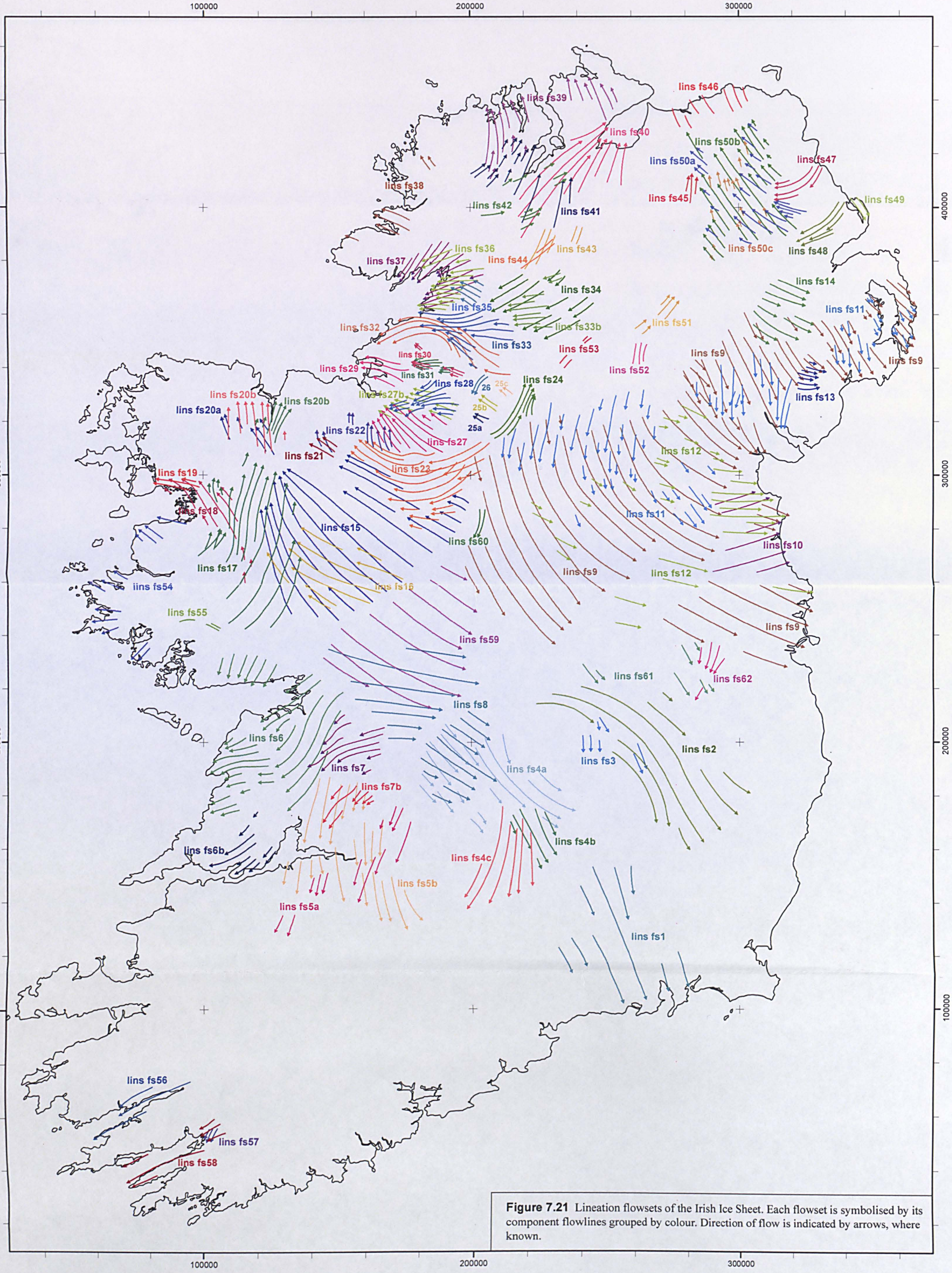


Figure 7.21 Lineation flowsets of the Irish Ice Sheet. Each flowset is symbolised by its component flowlines grouped by colour. Direction of flow is indicated by arrows, where known.

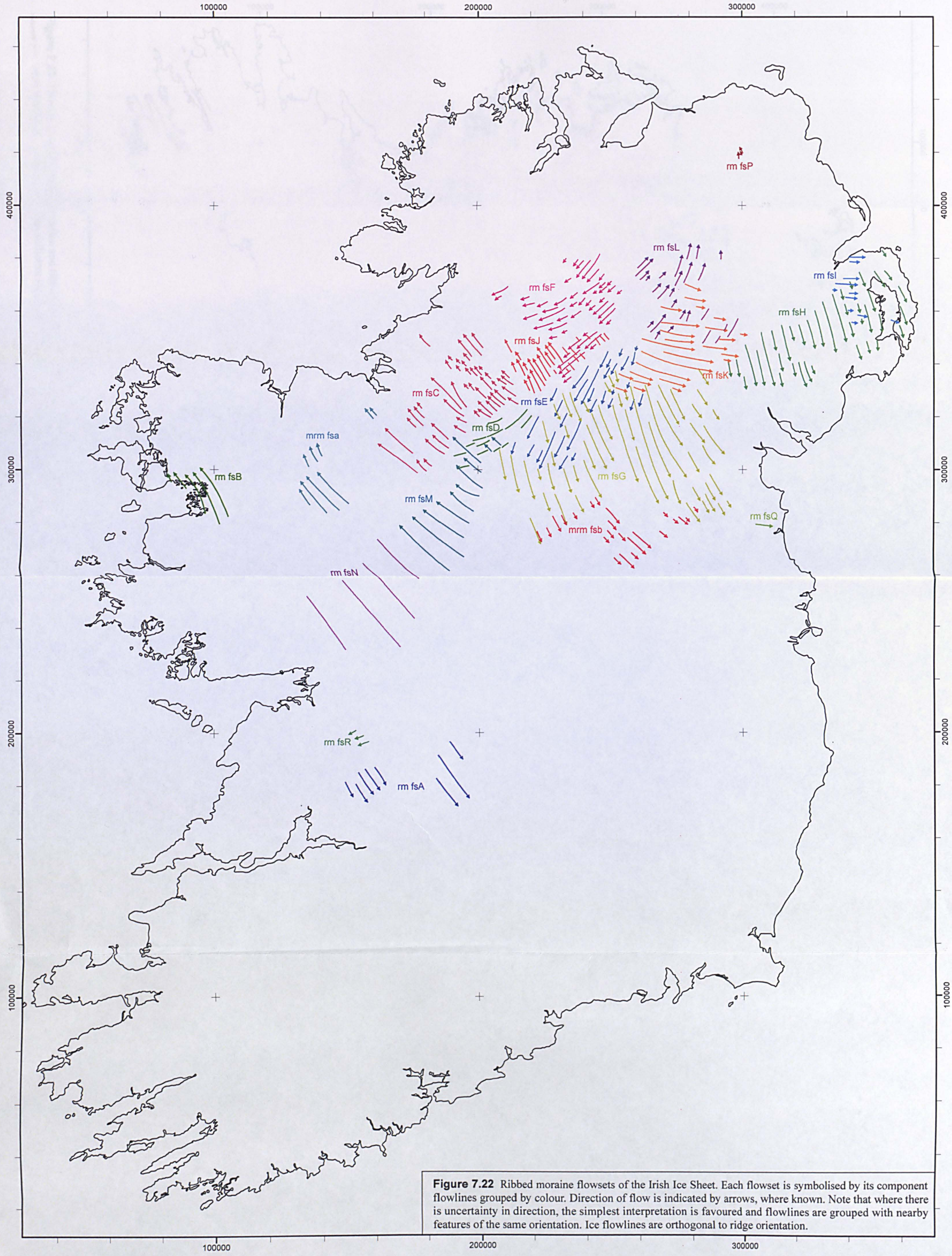


Figure 7.22 Ribbed moraine flowsets of the Irish Ice Sheet. Each flowset is symbolised by its component flowlines grouped by colour. Direction of flow is indicated by arrows, where known. Note that where there is uncertainty in direction, the simplest interpretation is favoured and flowlines are grouped with nearby features of the same orientation. Ice flowlines are orthogonal to ridge orientation.

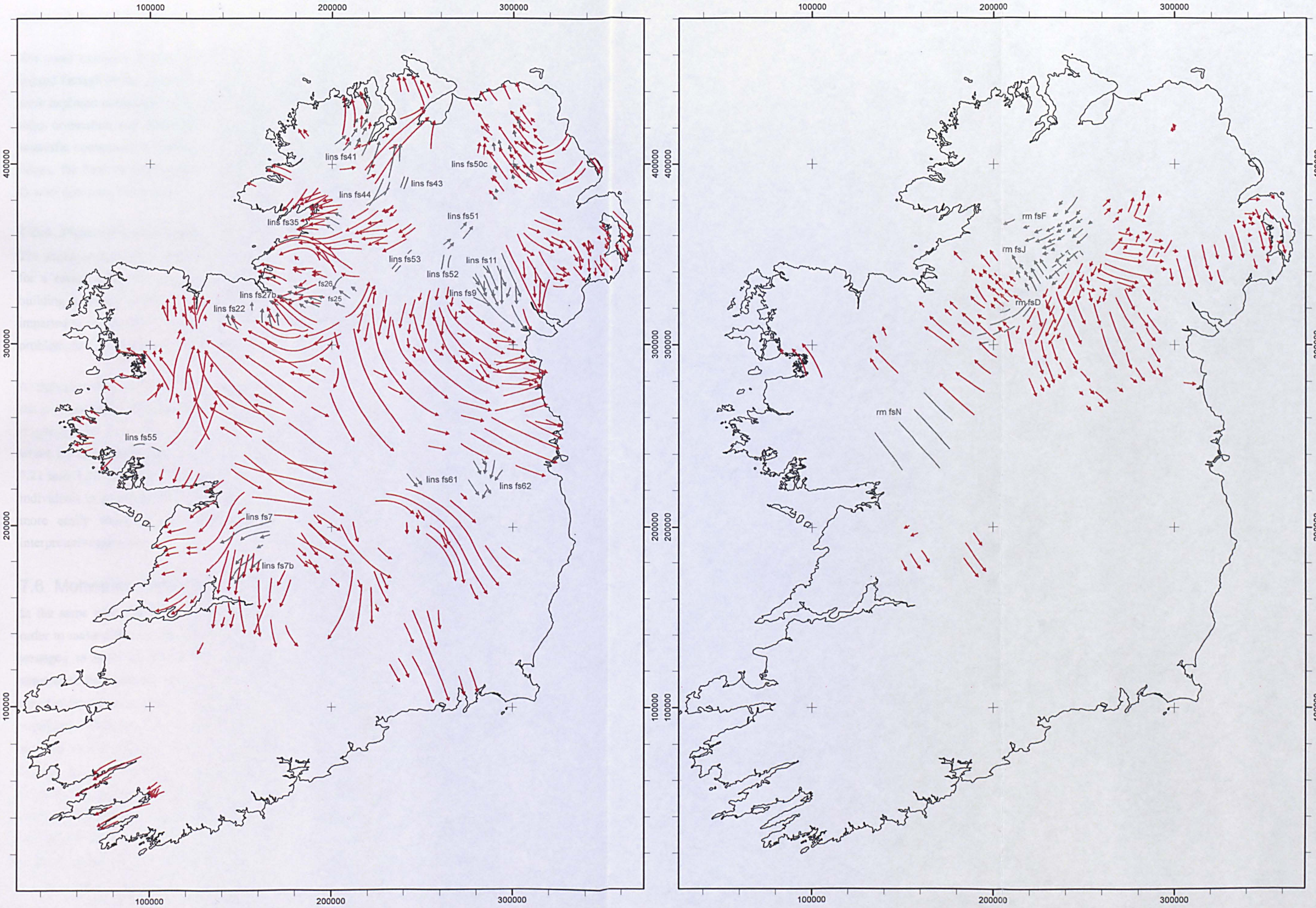


Figure 7.23 There is no unique solution to the problem of flowset building. Certain flowsets are derived with greater confidence than others. Panels (a) and (b) reveal the key regions of uncertainty in lineation and ribbed moraine flowset building respectively. more confident; less confident. Note that for purposes of cartographic reproduction at this scale flowlines have been thinned, i.e. selected flowlines have been removed whilst maintaining sufficient representation of every flowset in the database.

is better constrained, flowlines have been grouped (*rm fsJ* and *fsL*).

The most complex area of ribbed moraine from which to unravel flowsets is undoubtedly around Omagh Basin, Lower Lough Erne and the Clogher Valley. Up to four possible flowsets were explored in Omagh Basin on the basis of both a visual and semi-quantitative assessment of ridge orientation and morphology. However, given an insufficient understanding amongst the scientific community of ribbed moraine genesis and the potential significance of cross-cutting ridges, the final, favoured option adheres to a rule of minimum complexity and presents a two flowset scenario. Potentially the ice flow history is more complex than captured here.

7.5.4 Flowset building: summary and significance

The above sections have presented the methods, some working examples and the resulting maps for a cartographic, or spatial summary of subglacial bedforms mapped in Ireland. Flowset building is largely based on visual interpretation, which enables glaciological plausibility to be imparted to the process of pattern recognition. There is no unique solution to the countrywide problem, but the procedure adopted makes the visual interpretation as objective as possible.

At this first stage of bedform interpretation, which separates lineations from ribbed moraine for the purposes of spatial summary, 81 discrete flowsets have been identified. The distribution and disposition of these flowsets reiterate the complexity and dynamism of ice flow behaviour which the raw bedform data earlier intimated (Map 2 and Chapter 5). The flowset maps (Figures 7.21 and 7.22, see also Map 4) summarise this raw data yet all the information held by the individuals is translated, or scaled up to the flowset level of data presentation. Flowsets much more easily visualise the information held by subglacial bedforms for ice sheet-scale interpretative purposes.

7.6 Meltwater landforms: network summaries

In the same way that individual bedforms must be summarised by their spatial properties in order to make effective use of a large data body, so too must meltwater features. Bedforms are arranged in both lateral and longitudinal patterns and it is appropriate to cartographically summarise their distribution using a bounding box with flow-parallel lines. Meltwater features are distributed in a more longitudinal manner, often as networks, and it is appropriate to summarise them as such. The approach to melt feature synthesis is simply to represent a network as a drainage direction flowline (Figure 7.24). Drainage direction is largely governed by ice surface slope, but strong local relative relief may drive local drainage in a slightly different direction to the regional flow (Figure 7.25). Therefore, as for bedform flowset building, the detailed mapping is overlain upon topographic data when deriving melt network summaries. In this way it is ensured that local effects are accounted for and it is the regional directional information which is recorded for the reconstruction of ice sheet-scale properties.

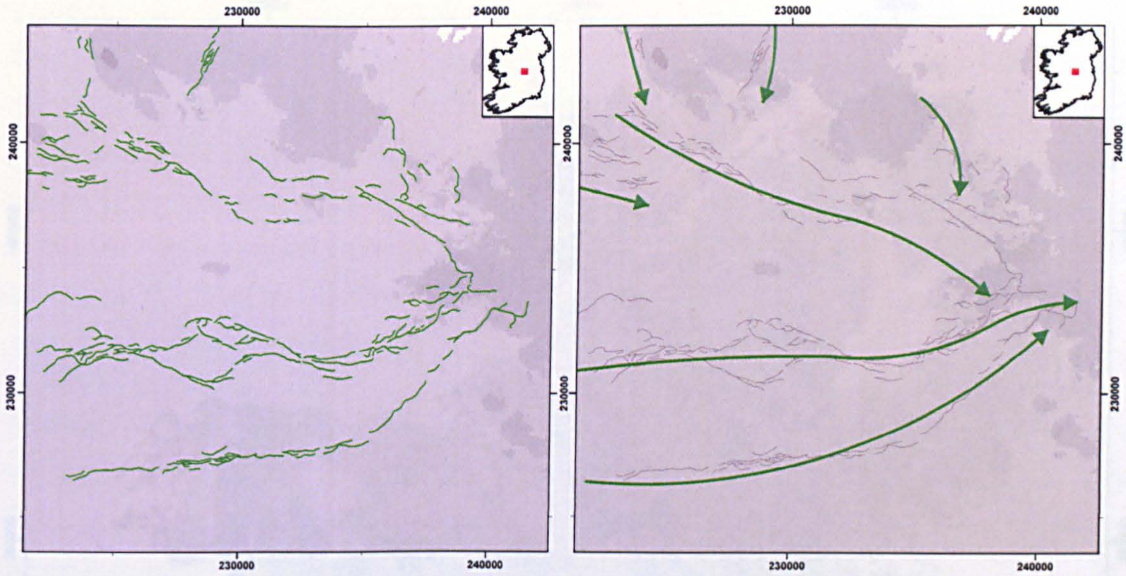


Figure 7.24 The details of individual esker segments are summarised by the network they form as single flowline, or drainage line, arrows. Scale: gridmarks at 10 km.

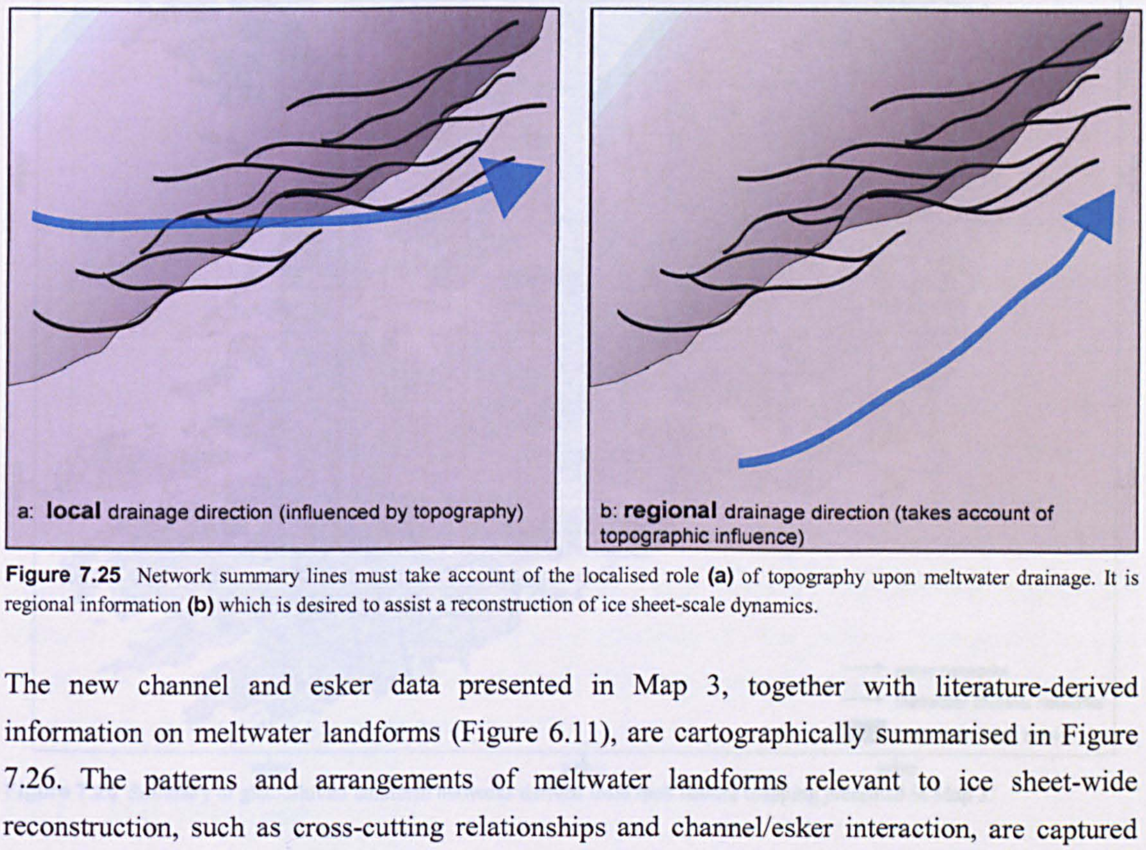


Figure 7.25 Network summary lines must take account of the localised role **(a)** of topography upon meltwater drainage. It is regional information **(b)** which is desired to assist a reconstruction of ice sheet-scale dynamics.

The new channel and esker data presented in Map 3, together with literature-derived information on meltwater landforms (Figure 6.11), are cartographically summarised in Figure 7.26. The patterns and arrangements of meltwater landforms relevant to ice sheet-wide reconstruction, such as cross-cutting relationships and channel/esker interaction, are captured from the individual data, and zones are identified where it is clear that the ice-bed interface is characterised by an abundance of meltwater but it is not arranged in any coherent or consistent manner with regard to direction. As for bedforms, summarising individuals into groups according to the flow information that they yield means that all information relevant to reconstruction is maintained but the number of data items is reduced.

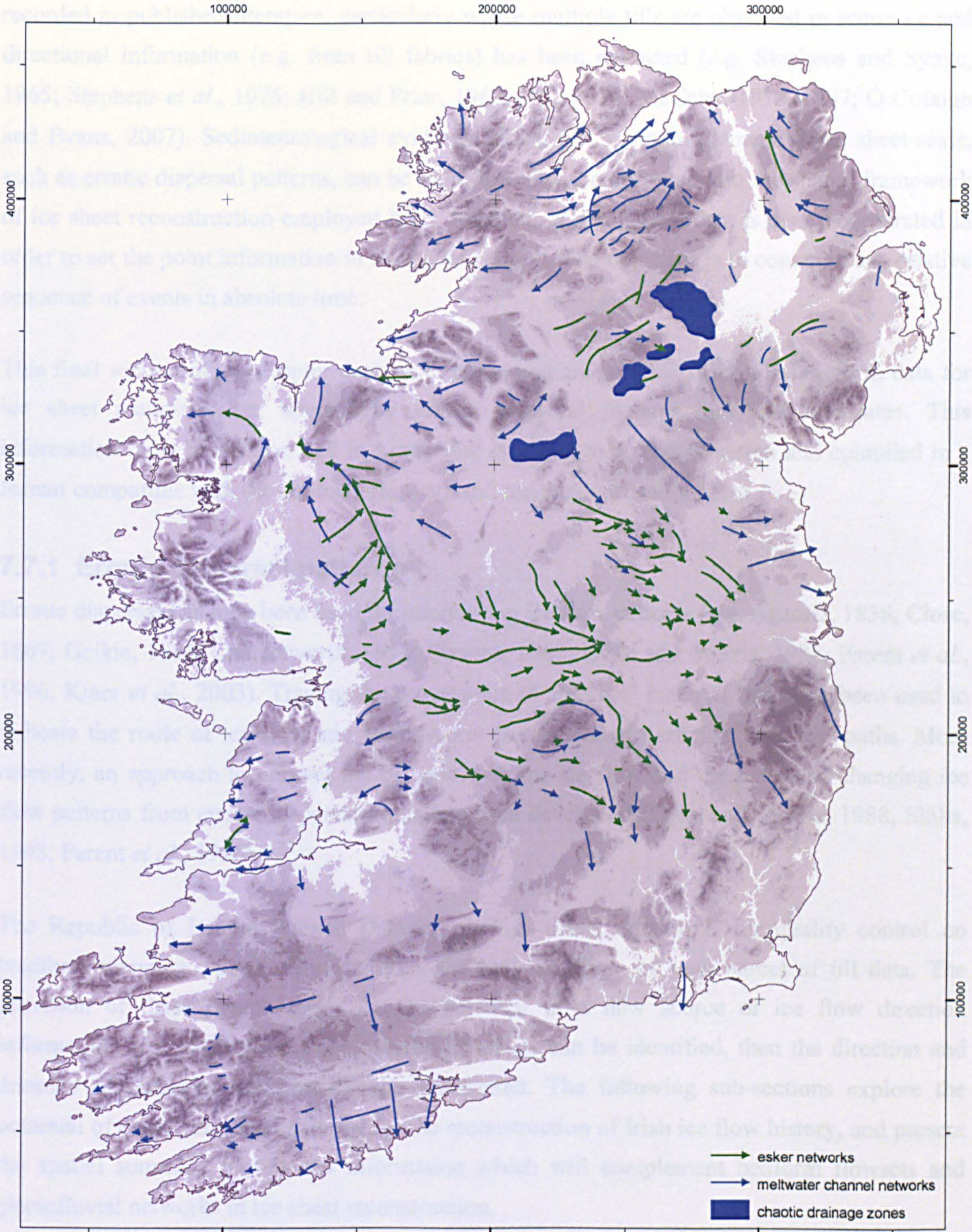


Figure 7.26 Summary of glaciofluvial landform networks derived from melt feature mapping presented in Map 3.

7.7 Ancillary information for reconstruction

In Sections 7.5 and 7.6, above, the large body of landform evidence presented in Maps 2 and 3 has been summarised according to the spatial properties of the landforms. The primary units taken forward for ice sheet reconstruction are the bedform flowsets, with additional or supporting information coming from the glaciofluvial networks.

Non-landform information also holds vital information regarding the configuration and behaviour of the last ice sheet. It is essential to bear in mind key stratigraphic information recorded in published literature, particularly where multiple tills are observed in sequence and directional information (e.g. from till fabrics) has been extracted (e.g. Stephens and Synge, 1965; Stephens *et al.*, 1975; Hill and Prior, 1968; Hill, 1971; McCabe, 1972, 1987; Ó Cofaigh and Evans, 2007). Sedimentological evidence which has a spatial element at ice sheet-scale, such as erratic dispersal patterns, can be more formally incorporated into the spatial framework of ice sheet reconstruction employed here. Absolute chronological data is also incorporated in order to set the point information in its spatial context. The objective is to constrain any relative sequence of events in absolute time.

This final section of the chapter deals with compiling and summarising non-landform data for ice sheet reconstruction, specifically erratic dispersal patterns and absolute dates. This information must be summarised in a way that is useful to a reconstruction and compiled in a format compatible with the bedform flowsets and melt network summaries.

7.7.1 Erratic dispersal patterns

Erratic dispersal has long been used for interpreting ice flow patterns (e.g. Agassiz, 1838; Close, 1867; Geikie, 1894; Charlesworth, 1953; Sissons, 1967; Dyke and Morris, 1988; Parent *et al.*, 1996; Kjaer *et al.*, 2003). Tracing the provenance of 'foreign' material has often been used to indicate the route of ice flow and to pin-point the source of particular ice flow paths. More recently, an approach to unravel the behaviour of the ice flow and the nature of changing ice flow patterns from erratic dispersal trains has been developed (Dyke and Morris, 1988; Shilts, 1993; Parent *et al.*, 1996).

The Republic of Ireland Subsoil Dataset, used in thesis Section B for quality control on landform mapping, specifically identifies the bulk lithology of each parcel of till data. The provision of these details opens up the potential of a new source of ice flow direction information. If a likely source for specific till clasts can be identified, then the direction and distance of sediment transport can be interpreted. The following sub-sections explore the potential of erratic dispersal patterns for the reconstruction of Irish ice flow history, and present the spatial summary of relevant information which will complement bedform flowsets and glaciofluvial networks in ice sheet reconstruction.

7.7.1.1 Dispersal trains

There is a long history of investigation of glacial dispersal trains, or 'drift prospecting', originally in Fennoscandia and developed in Canada as part of the Geological Survey's mineral exploration initiatives (see Shilts, 1993). Dispersal trains are belts or bands of glacial debris transported down-ice from a distinctive source from which the material has been entrained or mobilised. In the same way that landforms can be 'inverted' to reveal the responsible ice sheet properties, erratic dispersal patterns have a similar potential. Dispersal trains take different forms depending on where the source outcrop is situated with respect to centres of ice outflow and with respect to dynamic features of the ice sheet such as ice streams. A number of conceptual models have been put forward from which such palaeo-glaciological information may be deciphered (Figure 7.27). These models enable ice flow properties such as sheet or stream flow to be interpreted (Dyke and Morris, 1988; Shilts, 1993), and also recognise the potential for reworking of pre-existing dispersal trains into new patterns, leaving a multi-temporal record (Parent *et al.*, 1996).

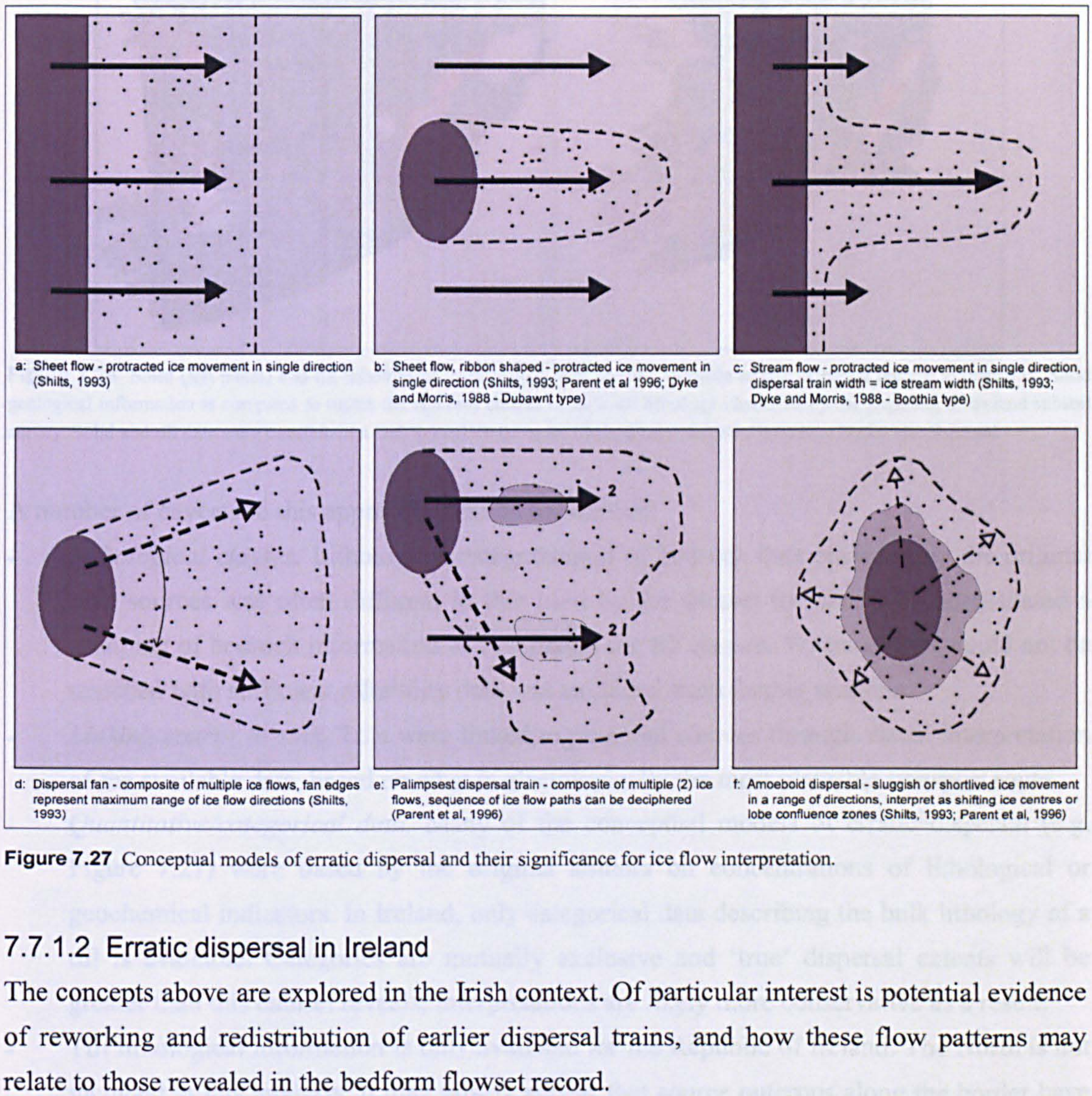


Figure 7.27 Conceptual models of erratic dispersal and their significance for ice flow interpretation.

7.7.1.2 Erratic dispersal in Ireland

The concepts above are explored in the Irish context. Of particular interest is potential evidence of reworking and redistribution of earlier dispersal trains, and how these flow patterns may relate to those revealed in the bedform flowset record.

Detailed surface sediment data for the Republic of Ireland (~1:50,000 Subsoil map) provide information of the bulk lithology of individual till parcels. The distribution of till lithologies represents the final product of glacial sediment dispersal from their source location. Bedrock geological information for both on and offshore (GSI digital data and digitised BGS information from hard copy map) was combined in a GIS shapefile. Two data layers were thereby provided: one for the potential sediment entrainment areas, the other for the end product of sediment dispersal (Figure 7.28). Overlain in a GIS, these data were explored to identify any arrangements similar to the conceptual models of dispersal described above, or any other configurations of source and dispersal areas which reveal relevant ice flow history information.

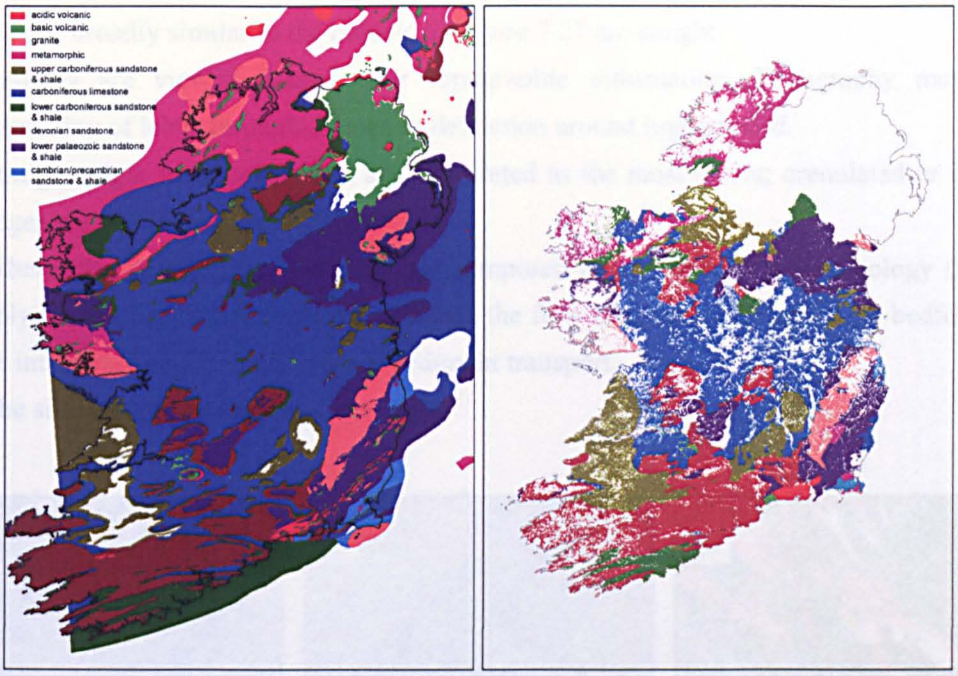


Figure 7.28 Solid (left panel) and till lithological (right panel) data provide valuable erratic dispersal pattern information. Solid geological information is compiled to match the relevant classes of bulk till lithology identified by the Republic of Ireland subsoil survey. Solid and till data were overlain in a GIS to explore the most likely directions and distances of sediment dispersal.

A number of caveats to this approach must be considered:

- *Lithological classes.* Lithological categorisation of bedrock data provided by the original map sources was often different to that used by the dataset for tills. This necessitated a grouping of bedrock information to best match the till classes. Where classes could not be matched with sufficient reliability data was excluded from further analysis.
- *Linking source to sink.* Tills were linked to potential sources through visual interpretation of the available data, based on what is glaciologically the most plausible transport route.
- *Quantitative/categorical data.* Many of the conceptual models of erratic dispersal (e.g. Figure 7.27) were based by the original authors on concentrations of lithological or geochemical indicators. In Ireland, only categorical data describing the bulk lithology of a till is available. Categories are mutually exclusive and 'true' dispersal extents will be greater than this dataset reveals; interpretations are likely more conservative as a result.
- Till lithological information is only available for the Republic of Ireland. The North is not included in this analysis. It may falsely appear that source outcrops along the border have a simpler dispersal pattern than is the case.
- *Topography.* Funnelling of ice will produce a similar pattern to Figure 7.27c, a stream signature or Boothia type erratic train. Enhanced transport velocity either through funnelling or independent ice streaming will produce a similar signature.

Figure 7.29 illustrates a selection of the source/sediment arrangements observed in the Irish data. The flow directions yielded by these patterns are recorded as single flowline arrows for each parcel of information. In this way, the inherently spatial sediment dispersal information is summarised in a similar manner to bedform–flowline or esker–network data summary. Erratic flowline interpretation follows a suite of principles and guidelines:

- Shapes broadly similar to the models in Figure 7.27 are sought.
- Datasets are viewed draped over topographic information. Topography may cause funnelling of lobes through valleys or deflection around high ground.
- Straight edges to dispersal fans are interpreted as the most recent; crenulated or irregular edges are the product of re-dispersal.
- Where till data suggests bedforms are composed of the identified till lithology (i.e. data polygon outlines follow bedform outlines) the flow direction revealed by the bedforms can be interpreted as the latest stage of sediment transport.
- The simplest interpretation is favoured.

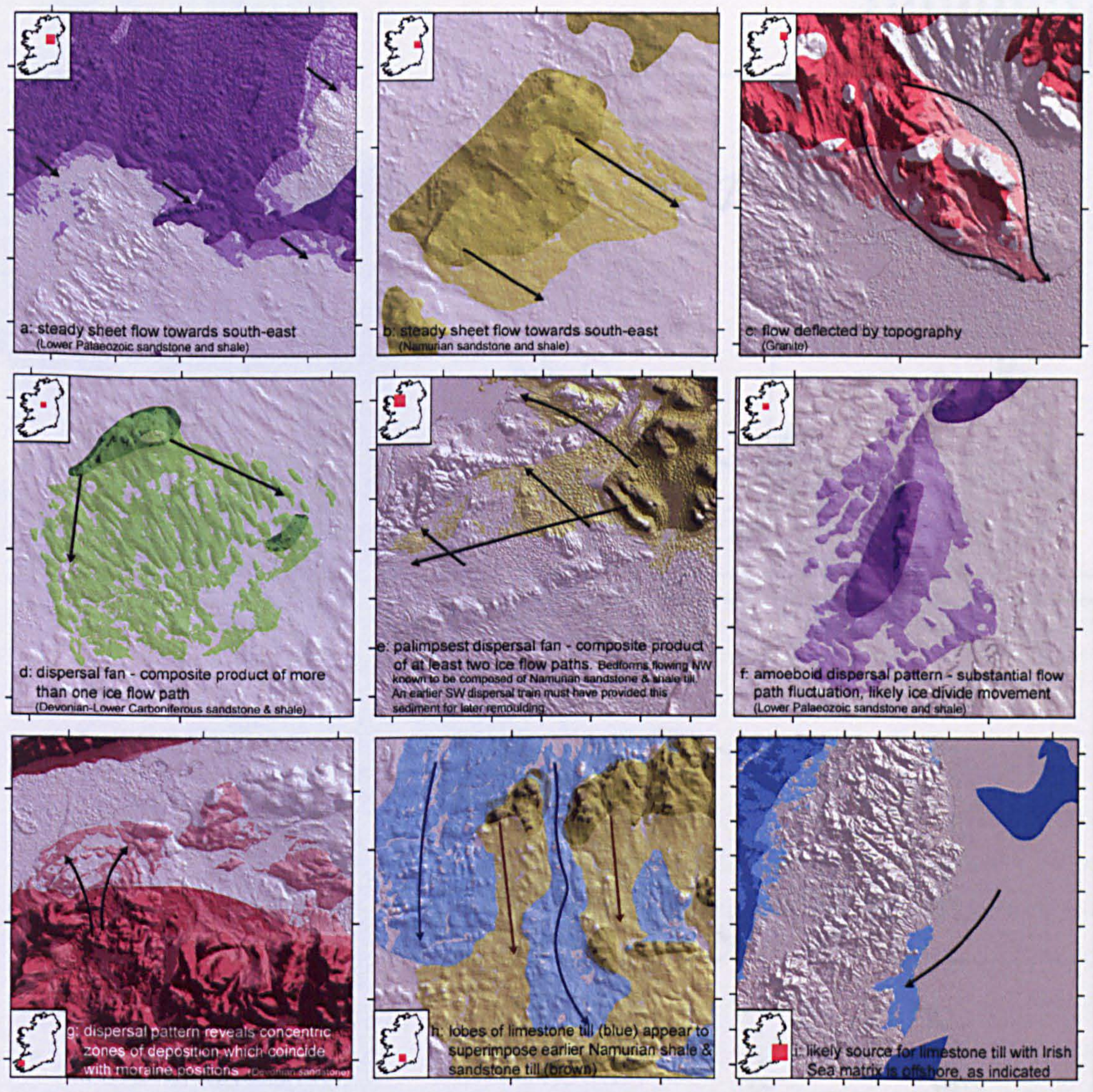
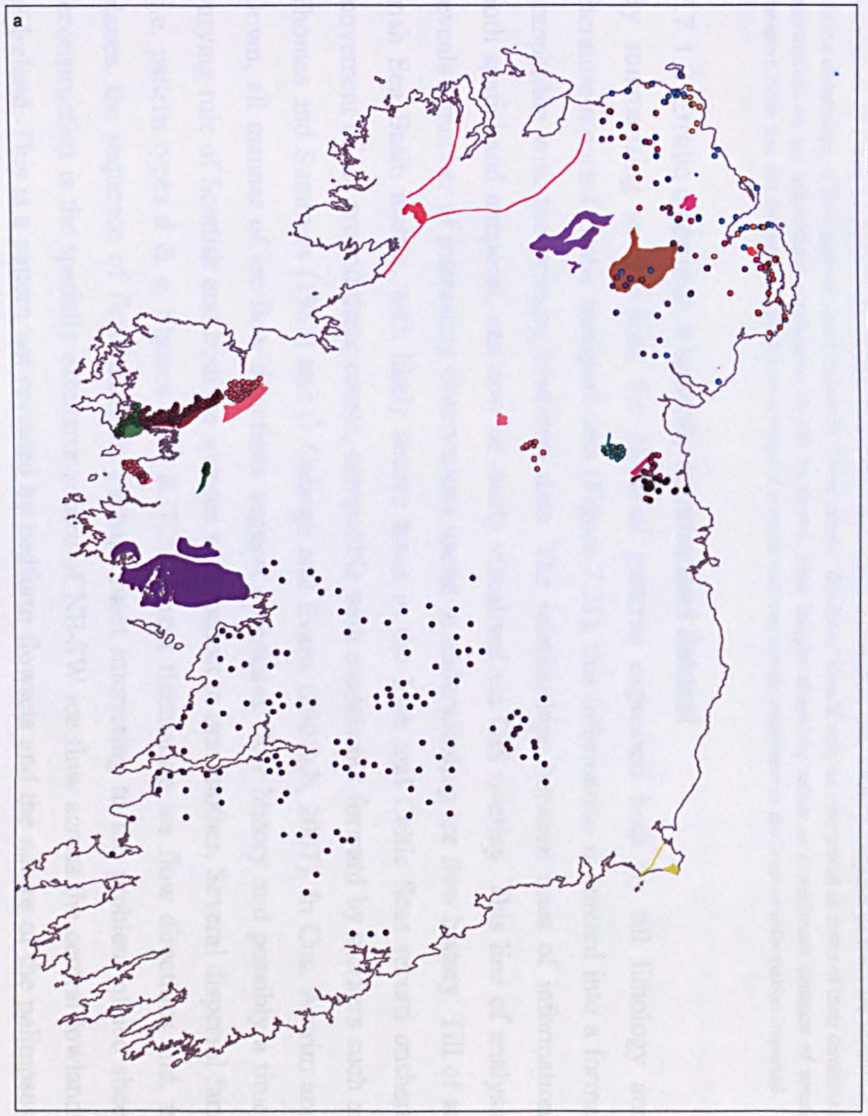
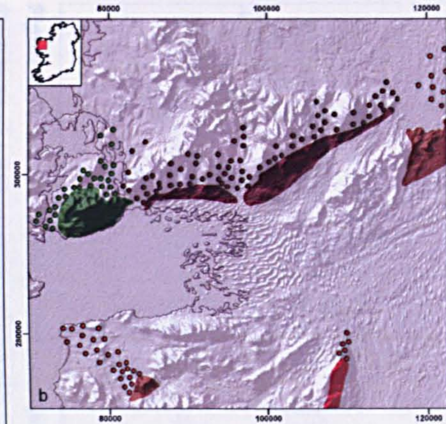


Figure 7.29 Example dispersal patterns identified in Ireland. Panels **a-f** are similar scenarios to those proposed in earlier literature. Panels **g-i** reveal other interesting observations regarding ice flow history. In each panel the bedrock source area is the darkest colour, till carried beyond its source area is lightest, and till draped upon its own source lithology is the middle shade. All data draped over the SRTM DEM. Scale: tickmarks at 10 km.

Having determined the potential of erratic dispersal patterns from the above analysis, additional information encountered in the published literature was compiled (Figure 7.30). For cases where both the source and sink of erratic transport has been described in the literature, both were recorded, and dispersal patterns have been analysed in a similar manner as above.





Erratic source areas:

FID	Shape	Reference	Erratic
0	Polygon	Warren, 1991	Galway granite
1	Polygon	Warren, 1991	Galway granite
2	Polygon	Warren, 1991	Galway granite
3	Polygon	Culleton, 1978	Carnsore granite
4	Polygon	Jordan, 2002	Lower Carboniferous sandstone
5	Polygon	Jordan, 2002	Devonian sandstone
6	Polygon	Jordan, 2002	Devonian sandstone
7	Polygon	Jordan, 2002	Granite
8	Polygon	Jordan, 2002	Granite
9	Polygon	Jordan, 2002	Rhyolite & volcanic rocks rich in silica
10	Polygon	McCabe 1972	Slane volcanics
11	Polygon	McCabe 1972	Grangegeeth volcanics
12	Polygon	Meehan 1999	Granite
13	Polygon	Meehan 1999	Dolerite
14	Polygon	Hill & Prior 1968	Cushendun microgranite

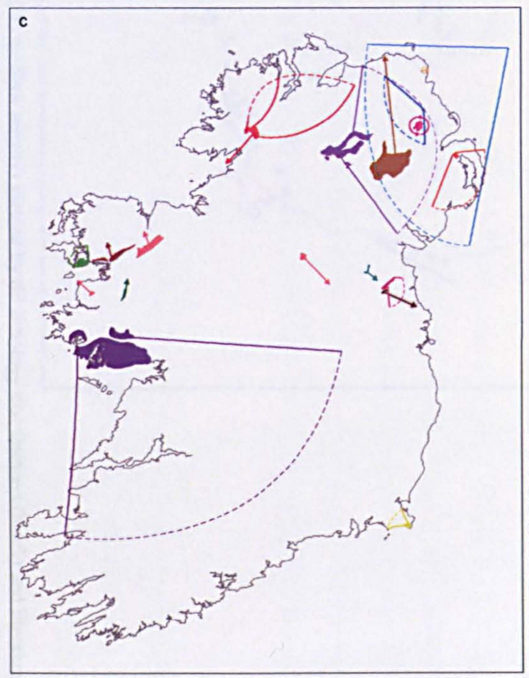


Figure 7.30 Erratic information compiled from published literature. **a)** database of erratic source areas and end points of transport; only information which specifically identifies both has been included, and is fully attributed to the original literature source. Colours are arbitrarily assigned but are coded such that dispersal locations match source colour. **b)** extract from full database: Jordan (2002) identifies several source outcrops and end points of erratic transport in Co. Mayo. Such patterns can be analysed in a similar way to the till lithology data **(c)**. Both ribbon and sheet flow contexts have been identified (single arrows), and broader dispersal fans (enclosed by solid lateral limits and dashed terminus). Palimpsest patterns may be present but point data provides insufficient information for interpreting a relative chronology of dispersal. Amoeboid patterns have been identified but are not as tightly dispersed as such patterns within the till lithological data; these patterns record a wider spread of material in all directions from the source outcrop.

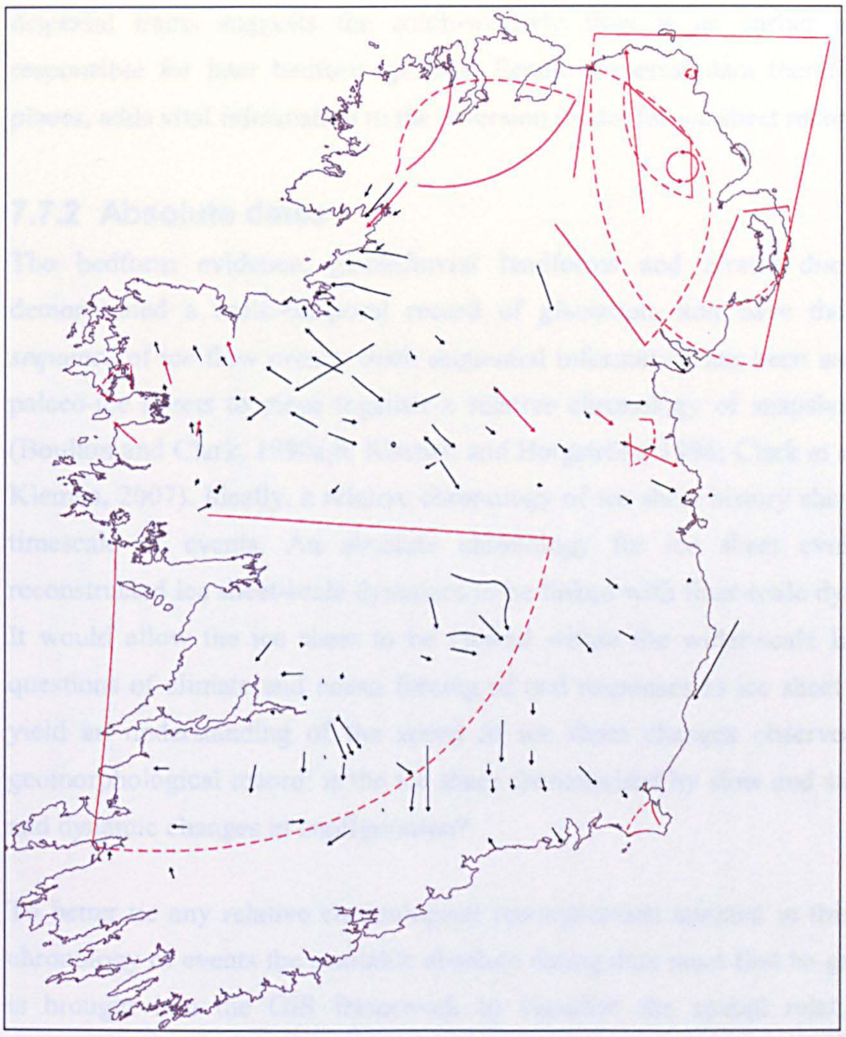


Figure 7.31 Erratic dispersal patterns (summarised as ice flow arrows) yielded by till lithology distributions (black) and literature descriptions of erratic transport (red). Erratics reveal flow directional information and, where palimpsest patterns are identified, a relative chronology of flow patterns (see Chapter 8). These erratic 'flowlines' should only be interpreted in terms of their directional information; no ice behavioural conclusions should be drawn. Line lengths should be taken as a minimum distance of erratic transport. Note that this dataset is collated from a range of sources and may not be consistent in the level of information imparted.

7.7.1.3 Erratic dispersal: a spatially summarised dataset

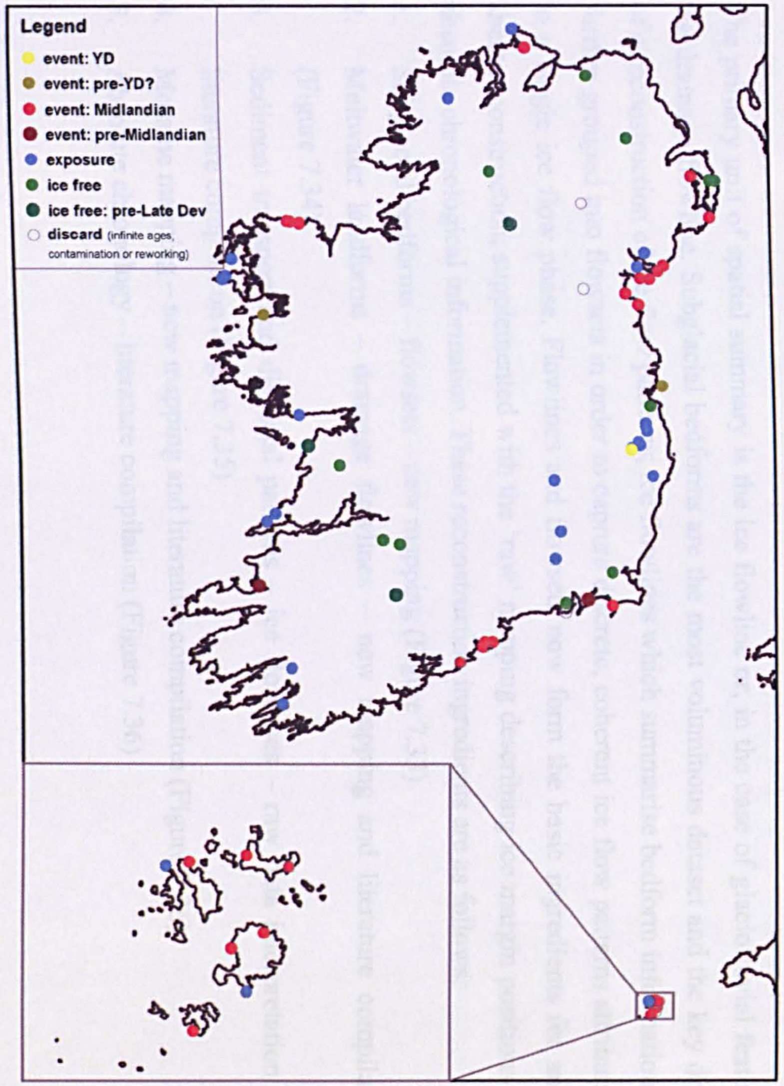
By summarising as flowlines the dispersal patterns expressed both by till lithology and literature-reported erratic transport data (Figure 7.31), this information is entered into a format compatible with the primary landform data. The relationships between lines of information, both spatial and temporal, can now be easily visualised via GIS overlay. This line of analysis reveals a number of interesting observations useful to understanding ice flow history. Till of an Irish Sea Basin matrix, with likely source areas in the Irish and Celtic Seas record onshore movement of ice around these coasts, compatible with models put forward by workers such as Thomas and Summers (1983) and Ó Cofaigh and Evans (2001a,b, 2007). In Cos. Antrim and Down, all manner of ice flow directions suggest a complex flow history and possibly a time-varying role of Scottish and Irish ice sources with respect to one another. Several dispersal fans (i.e. pattern types d & e, Figures 7.27 & 7.29) reveal fluctuating ice flow directions and, in places, the sequence of flow changes. Perhaps most interesting to the problem of ice sheet reconstruction is the spatially extensive record of NE-SW ice flow across the central lowlands of Ireland. This is a pattern not revealed by bedform flowsets and the nature of the palimpsest dispersal trains suggests the south-westerly flow is an earlier ice movement than that responsible for later bedform genesis. Erratic dispersal data therefore complements and, in places, adds vital information to the inversion model for ice sheet reconstruction.

7.7.2 Absolute dates

The bedform evidence, glaciofluvial landforms and erratic dispersal patterns have all demonstrated a multi-temporal record of glaciation, and have the potential to reveal the *sequence* of ice flow events. Such sequential information has been used with success for other palaeo-ice sheets to piece together a relative chronology of snapshots of ice sheet evolution (Boulton and Clark, 1990a,b; Kleman and Borgström, 1996; Clark *et al.*, 2000; De Angelis and Kleman, 2007). Ideally, a relative chronology of ice sheet history should be tied to an absolute timescale of events. An absolute chronology for ice sheet evolution would allow the reconstructed ice sheet-scale dynamics to be linked with finer-scale dynamics dated in the field. It would allow the ice sheet to be viewed within the wider-scale Earth system and address questions of climate and ocean forcing of and responses to ice sheet dynamics. It would also yield an understanding of the speed of ice sheet changes observed in the geological and geomorphological record: is the ice sheet characterised by slow and steady changes or by rapid and dynamic changes in configuration?

To better tie any relative chronological reconstruction attained in this research to an absolute chronology of events the available absolute dating data must first be gathered. This information is brought into the GIS framework to visualise the spatial relationships between dating information and the ice flow patterns yielded by the landform and erratic data. This also brings all data into a format in which layers of information are mutually compatible. All dates encountered in a wide literature search and which have a bearing on the period from MIS4-2 have been entered into a GIS layer. Only dates which are ice sheet-relevant have been captured. For example, from a late-glacial or post-glacial core or sediment section, only the lowest date from the sequence is recorded since this is the first ice-free date. Finally, dates from on and offshore are recorded and maintained as separate databases. Offshore chronological information of relevance to the Irish Ice Sheet derives from continental slope cores, in which observed events are described relative to an interpolated age-depth model rather than a precise age.

Dates are recorded as single points in a GIS shapefile. Locational information is derived from the original publication and therefore locational accuracy is as good as the original information. Each point is attributed with all the information pertinent to the palaeo-glaciological interpretation of the data item (Figure 7.32 & Appendix). This includes, amongst other attributes, the original reference and laboratory code for the sample, the date given, its errors and its calibration (where necessary), the environmental setting and the glaciological context – exposure, ice free, or a specific event such as glacial maximum, margin readvance, or sea level rise. The objective is to compile a dataset which is internally consistent in the information it provides. All ^{14}C ages have been calibrated using the Fairbanks scale (which exceeds the



Dates: selected records - attributes

FID	Reference	Date_ka	Error_1sd	Technique	Calibr.	Material
2	Ballantyne et al 06	18.5	1.2	10Be cosmogenic	18.5	vein quartz
26	Lowe et al 2004	12.295	0.05	14C conventional	14.096	humic
27	Lowe et al 2004	12.43	0.085	14C AMS	14.337	humin
29	Diefendorf et al 2006	16.175	0.245	14C	16.175	bulk macrofossil
30	Ahlberg et al 1996	11.88	0.08	14C AMS	13.717	seed
66	Colhoun et al 1972	30.5	1.17	14C conventional	35.888	
67	Simms 2005	53	?	U-Th	53	flowstone
68	Simms 2005	38	?	U-Th	38	flowstone
92	Gallagher & Thorp 1997	161.785	18.462	IRSL	161.78	
93	Gallagher & Thorp 1997	128.61	16.795	IRSL	128.61	
123	McCabe et al 07b	13.125	0.07	14C AMS	14.826	foram
124	McCabe et al 07b	15.19	0.085	14C AMS	17.682	foram
125	McCabe et al 07b	15.3	0.09	14C AMS	17.904	foram
126	O Cofaigh & Evans 2007	29.805	0.35	14C AMS	35.336	shell fragment
127	O Cofaigh & Evans 2007	36.605	0.44	14C AMS	41.901	shell fragment

...Dates (cont.)

FID	Setting	Context	Elevation	Ref_code
2	near mountain summits	exposure	600	SCA-01
26	lowest sample from peat bog bottomed in till	ice free	60	SLG-1 SRR-6427
27	lowest sample from peat bog bottomed in till	ice free	60	SLG-1 AA-34265
29	base of core bottomed in till	ice free	25	LINC-1 AA56896
30	lowest date from bog core (unknown if bottomed)	ice free	247	Table1-f CAMS-2193
66	freshwater organic silts between 2 tills	ice free: pre-Late Dev	?	Birm. 166
67	flowstone stratig below NW-derived till	ice free: pre-Mid/Early Dev	?	
68	flowstone stratig between 2 tills	ice free: pre-Late Dev	?	
92	beach deposit	event: pre-Devensian	?	
93	beach deposit	event: pre-Devensian	?	
123	marine mud drapes drumlin	event: RSL rise	?	AA68680
124	marine mud included in till	event: ice free (marine) prior to readv	?	AA68976
125	marine mud included in till	event: ice free (marine) prior to readv	?	AA68975
126	ISB till, under glaciolac seds, under inland till	event: pre-ISB ice advance	?	Poz-15803
127	ISB till, under glaciolac seds, under inland till	event: pre-ISB ice advance	?	Beta-222311

Figure 7.32 Dates compiled from published literature to constrain the dynamics of the Irish Ice Sheet. Attributes pertinent to their interpretation are recorded: a random selection are shown here.

temporal coverage of other calibration curves; Fairbanks *et al.*, 2005) including those for which a calibration was presented in the original publication. This best enables site-to-site comparisons, for which internal consistency of the database is considered the most important virtue.

Figure 7.32 presents the compiled data layer and indicates the distribution of absolute dates constraining ice sheet history in Ireland. 169 dates have been recorded from 78 sites, and span an age range from 181ka (^{36}Cl exposure) to 11.53ka (calibrated from ^{14}C age). Information was sought via literature cross-referencing rather than an exhaustive search and, whilst possibly not complete, the dataset derives from a thorough search. Edwards *et al.* (1985) provide the only known compilation of absolute dating information prior to this dataset. They record 965 radiocarbon dates in Ireland (census 1984). However, these are not limited to ice sheet-relevant dates and only ~40 relate to the period before 10 ^{14}C ka (only ~10 precede 13 ^{14}C ka). Compared to the volume of chronological information (3948 dates – Dyke *et al.*, 2003) which constrains the deglaciation of the (albeit much larger) Laurentide Ice Sheet, for example, the information available for Ireland is limited. It is, however, valuable to the reconstruction explored in this research and therefore provides the final layer of information which serves as 'input' into an inversion model of palaeo-glaciological interpretation.

7.8 Summary: ingredients for an ice sheet reconstruction

This chapter set out to achieve two objectives: to bring together all information required by an inversion model for ice sheet reconstruction, into a format in which data are mutually compatible and comparable; and to address the summary of this data into coherent ice flow patterns according to the spatial properties of the data.

The primary unit of spatial summary is the ice flowline or, in the case of glaciofluvial features, the drainage flowline. Subglacial bedforms are the most voluminous dataset and the key driver of a reconstruction of ice flow patterns; ice flowlines which summarise bedform information are further grouped into flowsets in order to capture discrete, coherent ice flow patterns attributable to a single ice flow phase. Flowlines and flowsets now form the basic ingredients for an ice sheet reconstruction, supplemented with the 'raw' mapping describing ice margin positions and absolute chronological information. These reconstruction ingredients are as follows:

1. Subglacial bedforms – flowsets – new mapping (Figure 7.33)
2. Meltwater landforms – drainage flowlines – new mapping and literature compilation (Figure 7.34)
3. Sediment transport and dispersal patterns – ice flowlines – raw data interpretation and literature compilation (Figure 7.35)
4. Moraine mapping – new mapping and literature compilation (Figure 7.36)
5. Absolute chronology – literature compilation (Figure 7.36)

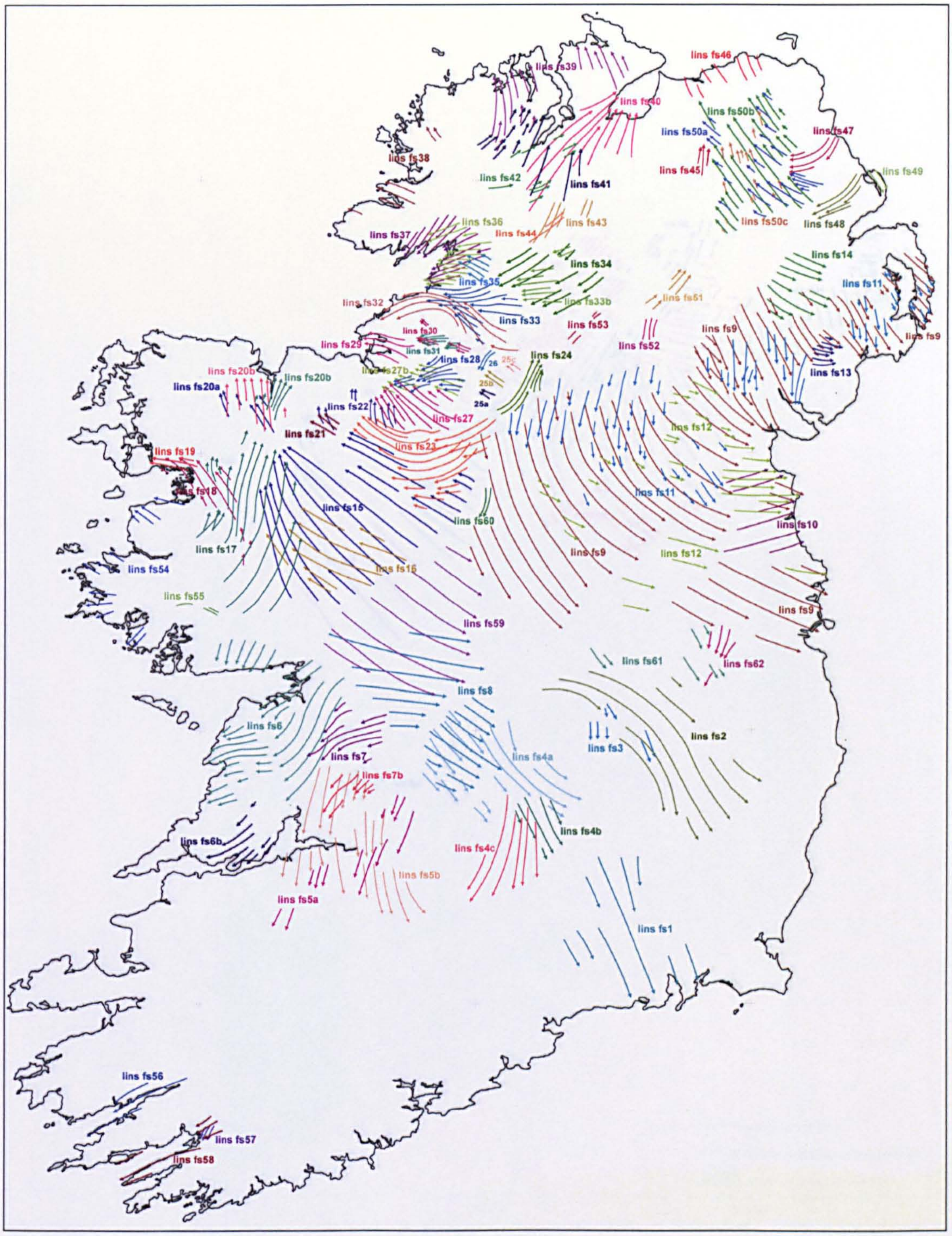


Figure 7.33a Lineation flowsets. Summary of new mapping.

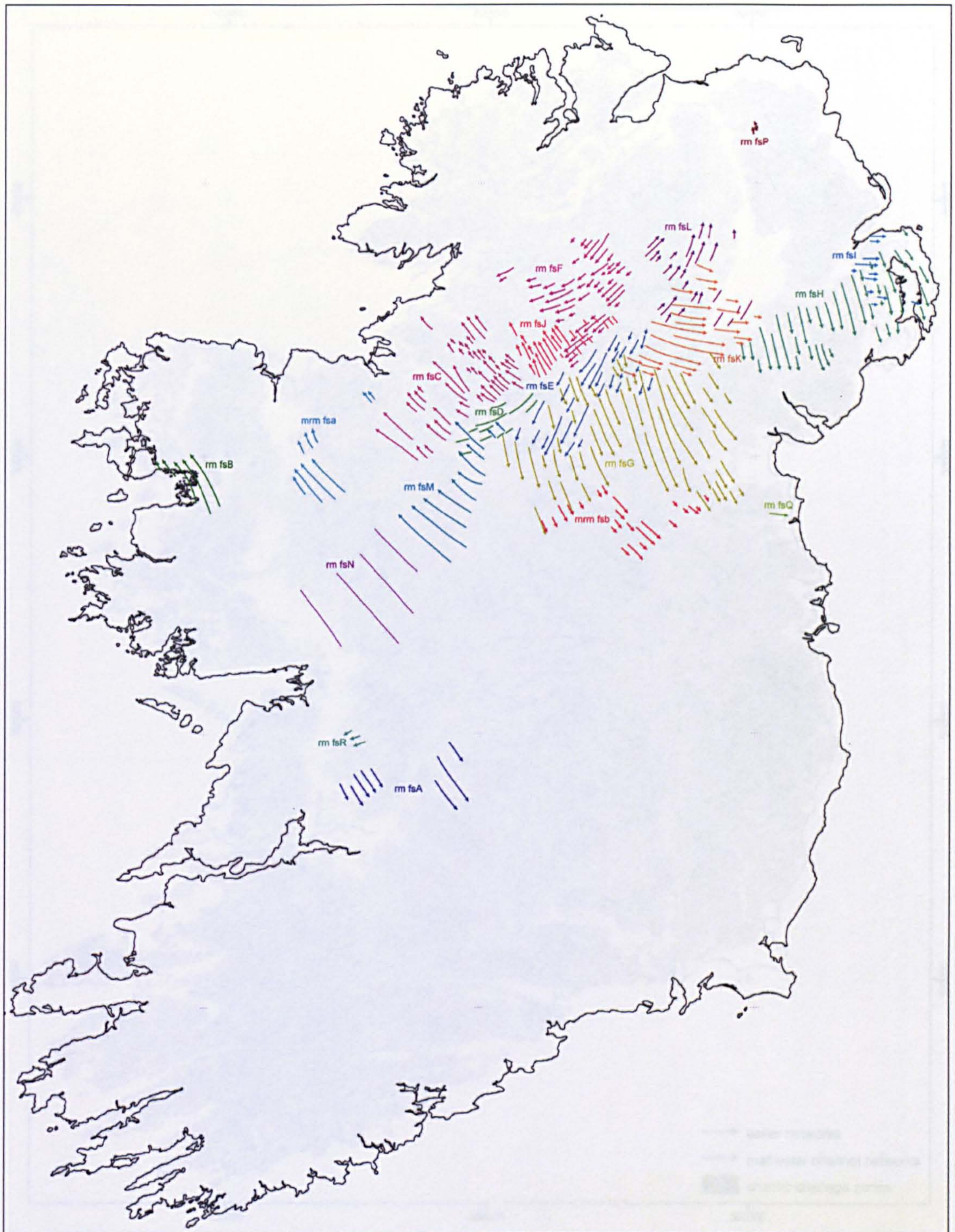


Figure 7.33b Ribbed moraine flowsets (ice flowlines are orthogonal to ridge orientation). Summary of new mapping.

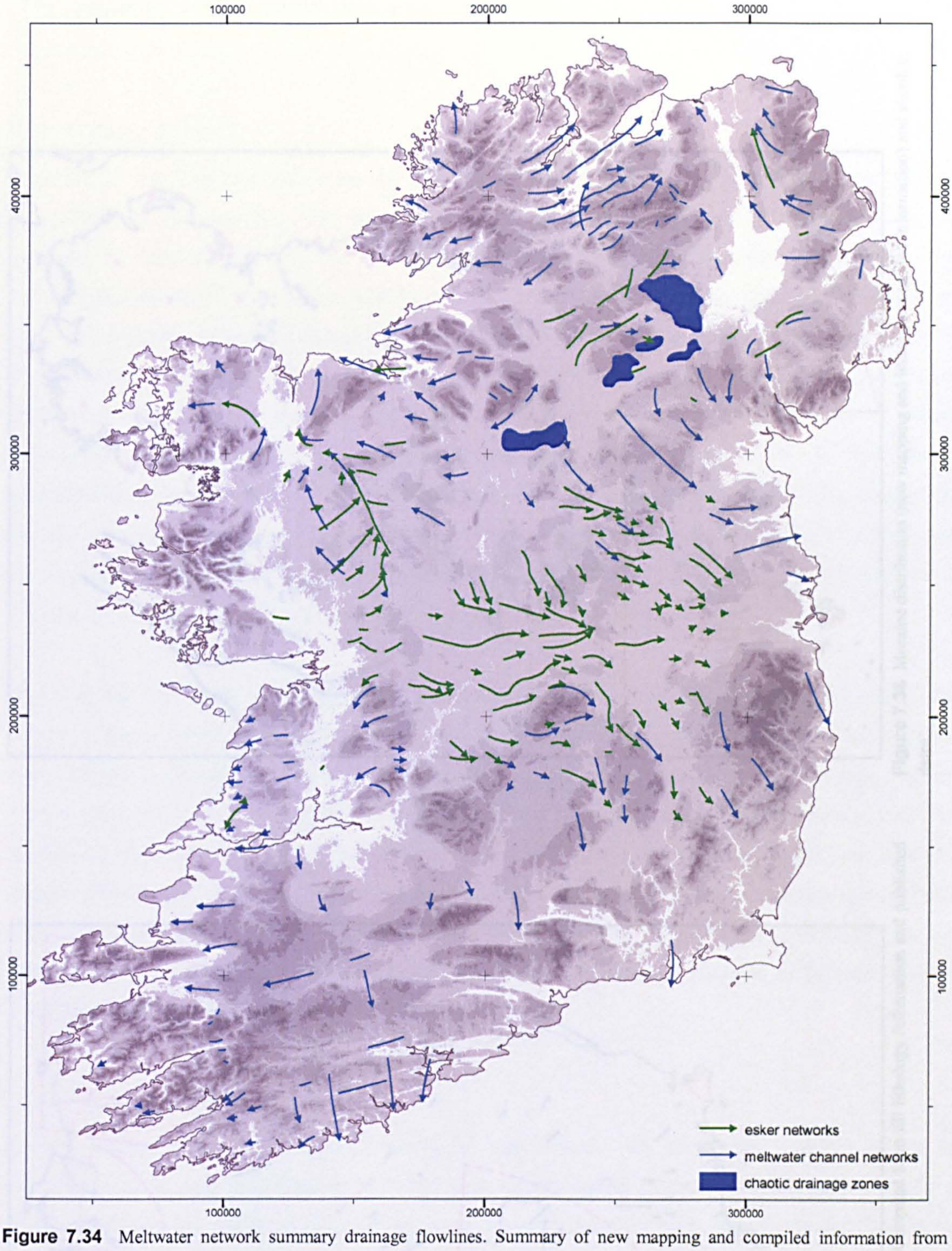


Figure 7.34 Meltwater network summary drainage flowlines. Summary of new mapping and compiled information from published literature.

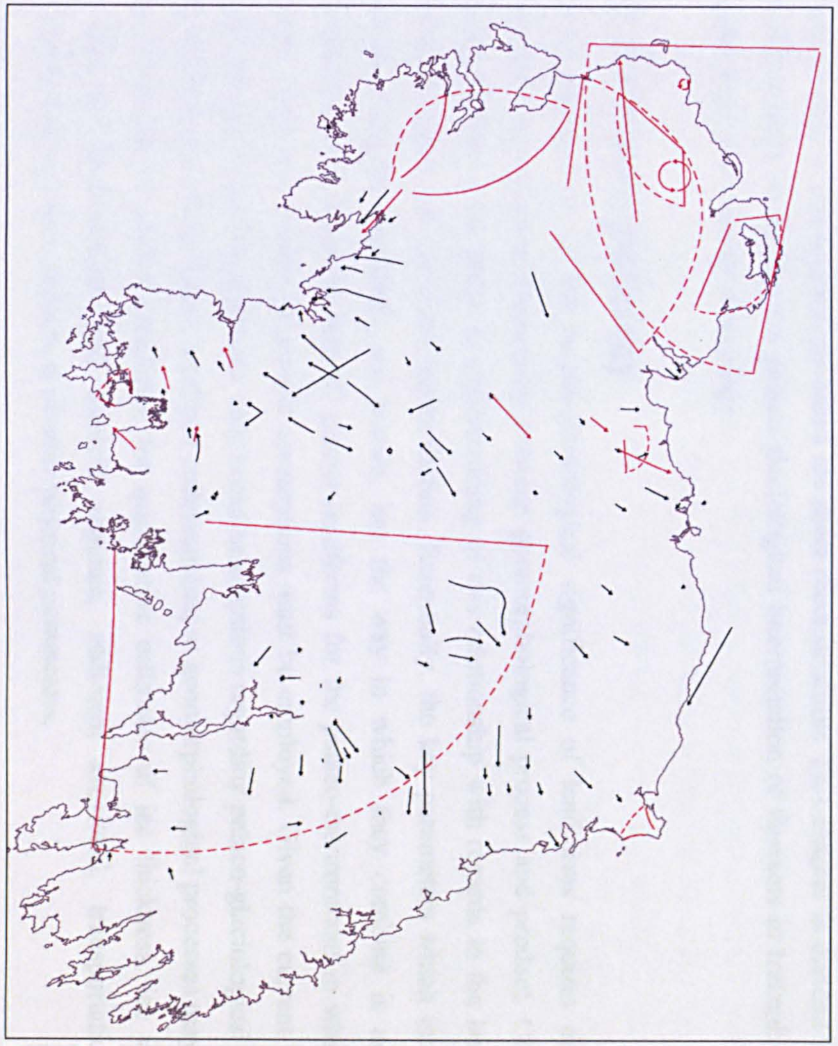


Figure 7.35 Erratic dispersal pattern flowlines. Compiled from till lithology information and published literature.

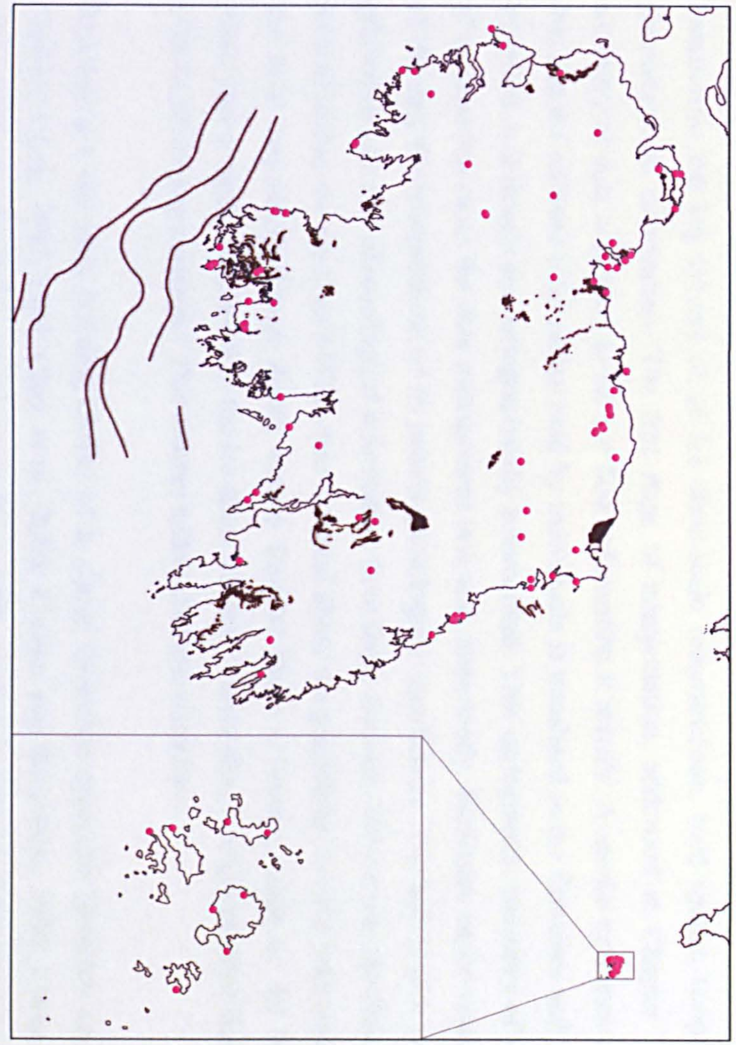


Figure 7.36 Moraine distribution (new mapping and literature compiled information) and absolute dates.

Chapter 8. Flowset palaeo-glaciology

8.1 Introduction

Landforms, the key drivers of an ice sheet-scale reconstruction, hold spatial, temporal and glaciodynamic information. The first stage of interpretation, addressed in Chapter 7, is the summary of data according to the ice flow information it reveals. A *spatial* synthesis achieves this and the relevant information held by individuals is translated to the flowlines and flowsets by which individuals are cartographically summarised. This cartographic summary of a wealth of information eases the data management task and, importantly, facilitates easier visualisation of the data for interpretation of its palaeo-glaciological significance. The task is now to extract *glaciodynamic* and *chronological* information from these flowsets. Where was the flow pattern located within the ice sheet? What does it reveal about the glaciology, i.e. the behaviour of the ice flow responsible (sheet flow?; stream flow?)? Does a flowset relate to the build-up, maximum or deglacial phases of the ice sheet's history? How does it relate to other flowsets in relative chronological terms? This chapter addresses these questions.

Flowsets are the main building blocks of a glacial inversion approach (Boulton and Clark, 1990a,b; Clark, 1997, 1999; Clark *et al.*, 2000; Kleman and Borgström, 1996; Kleman *et al.*, 1997, 2006). Bedform flowsets are typically spatially extensive with respect to the area covered by the former ice sheet, they are often voluminous in number, they directly reveal ice flow directions, indirectly suggest requisite ice sheet configurations and can be related to early, maximum or deglacial stages of the ice sheet's history. They are therefore the most useful basic unit to drive a geomorphology-based ice sheet reconstruction. This chapter is divided into two main sections to address the palaeo-glaciological interpretation of flowsets in Ireland: flowset glaciology, and flowset chronology.

8.2 Flowset glaciology

An interpretation of the palaeo-glaciological significance of landforms requires either an assumed or a known relationship between geomorphological process and product. Chapter 3 briefly outlined the status of understanding of this relationship with regards to the landforms employed here for ice sheet reconstruction. Essentially, the key parameters which interact to produce glacial landforms are known, but the way in which they combine is not fully understood. Therefore to 'invert' glacial landforms for the palaeo-environment in which they were created, a number of genetic assumptions must be employed. Given the current level of process understanding, these are only broad assumptions regarding palaeo-glaciological context and behaviour. In the future, a refined understanding of geomorphological processes may enable an inversion of glacial landforms for quantitative estimates of ice thickness, ice velocity, subglacial hydrological and thermal regimes, sediment erosional, transportation and depositional regimes, and a host of other physical parameters.

Although bedform flowsets are the building blocks of an ice sheet reconstruction their interpretation must be an holistic process. The whole landsystem reveals the glaciodynamic context of the flowset more so than simply considering any one landform type. The palaeo-glaciological significance of the meltwater features – channels and eskers – is first considered, before bringing together meltwater and bedform patterns to interpret the flowsets themselves.

8.2.1 Meltwater landforms: glaciodynamic interpretation

8.2.1.1 Meltwater channels

The basic genetic understanding of meltwater channels was addressed in Chapter 3. Channels may be incised into the landscape by meltwater conduits in all domains of the glacial system, but are largely related to lateral and subglacial positions (Figure 8.1). Different channel types leave different geomorphological imprints in the landscape due to the different controls on their development. It is important to distinguish between those channels formed in a lateral environment and those in a subglacial context to derive the appropriate palaeo-glaciological information. Lateral channels can be invaluable in reconstructing lateral margin positions, the thinning of ice during glacial retreat, and a cold thermal regime (e.g. Dyke, 1993; Hättestrand, 1998; Hättestrand and Clark, 2006b). Subglacial channels are less well-constrained in terms of their palaeo-glaciological significance (Chapter 3, Section 3.2.2.2). Meltwater can be generated and stored in supra-, en- and subglacial domains of the glacial system and its role in subglacial dynamics is still coming to light (Zwally *et al.*, 2002; Siegert *et al.*, 2005; Wingham *et al.*, 2006; Bell *et al.*, 2007; Bindschadler and Choi, 2007). At the very least, their network drainage direction indicates the direction of ice surface slope (a good indicator of the ice flow direction). Their association with a particular glaciodynamic context, such as ice retreat, is less certain.

Greenwood *et al.* (2007) present geomorphological criteria for distinguishing between different types of meltwater channel (Table 8.1), which helps to interpret the glaciodynamic context of a whole system or network. These criteria are based primarily on channel form and topographic context. The criteria are applied to the meltwater channel dataset presented in Chapter 6, in order to interpret the significance of the flowlines derived in Chapter 7. Individual channels (mapped lines) are viewed overlain on the broad-scale topography. Their interpretation is stored as a channel attribute and the interpretation of the system is attached to the summary flowline. Figure 8.2 records the categorisation of all meltwater channels according to the method above.

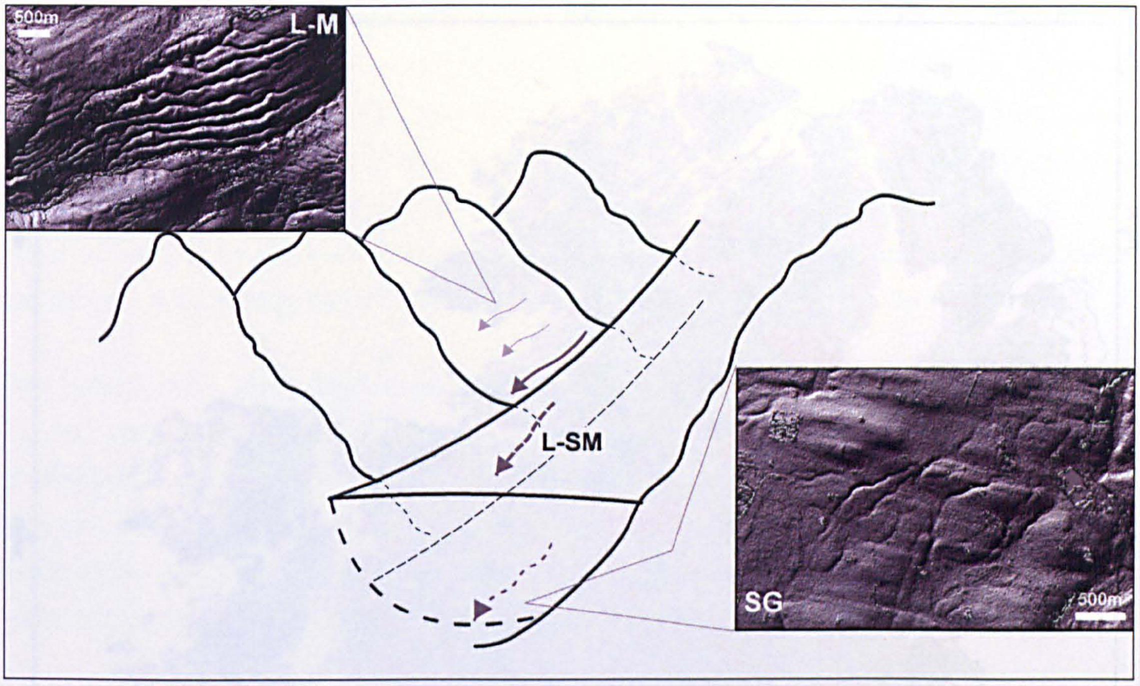


Figure 8.1 Schematic illustration of meltwater channel context in the glacial system (from Greenwood *et al.*, 2007). Lateral channels flow along the ice margin. They can be divided into marginal channels (L-M) and sub-marginal channels (L-SM), which flow at the lateral margin but beneath the ice. Subglacial channels (SG) flow at the ice bed. Different channel types have different forms and contexts with regards to the surrounding topography, and distinguishing these from each other is important in extracting the appropriate palaeo-glaciological information.

Table 8.1 Diagnostic criteria for classification of meltwater channels (from Greenwood *et al.*, 2007; the italicising of criteria is relevant to the publication but of no significance here).

Subglacial	Lateral		Proglacial	Supraglacial/englacial
	Marginal	Submarginal		
• Undulating long profile[1,2]	• Parallel with contemporary contours[4,7]		• Regular meander bends[10]	• Meander forms crescentic valley on face of hill[1]
• Descent downslope may be oblique[1,3]	• Forms 'series' of channels parallel to each other[1,8,9]		• Occasional bifurcation[10]	• Low gradient[7]
• Descent downslope may form steep chutes[1]	• Approximately straight[4]		• Flows direct downslope[7]	• Sinuous[7]
• Complex systems—bifurcating and anastomosing[3,4]	• Perched on valley sides[10]		• *Large dimensions — wide and deep*[10]	• *Approximately constant width*[7]
• High sinuosity[4]	• May terminate in downslope chutes[1,8]		• *Crater chains*[10]	
• *Abandoned loops*[4]	• Absence of networks[4]	• May form networks[1]		
• *Abrupt beginning and end*[1,2]	• Gentle gradient[1]	• Steeper gradient (oblique downslope)[1]		
• *Absence of alluvial fans*[1]	• Parallel for long distance[1]	• Sudden change in direction[1]		
• *Cavity systems and potholes*[3]	• *May terminate abruptly*[10]			
• *Ungraded confluences*[3]	• *May be found in isolation from all other glacial features*[6,9]			
• *Variety of size and form within the same connected system*[5]				
• *Association with eskers*[6]				

Sources: [1]Sissons (1961); [2]Glasser and Sambrook Smith (1999); [3]Sugden *et al.* (1991); [4]Clapperton (1968); [5]Sissons (1960); [6]Kleman and Borgström (1996); [7]Price (1960); [8]Schytt (1956); [9]Dyke (1993); [10]Benn and Evans (1998).

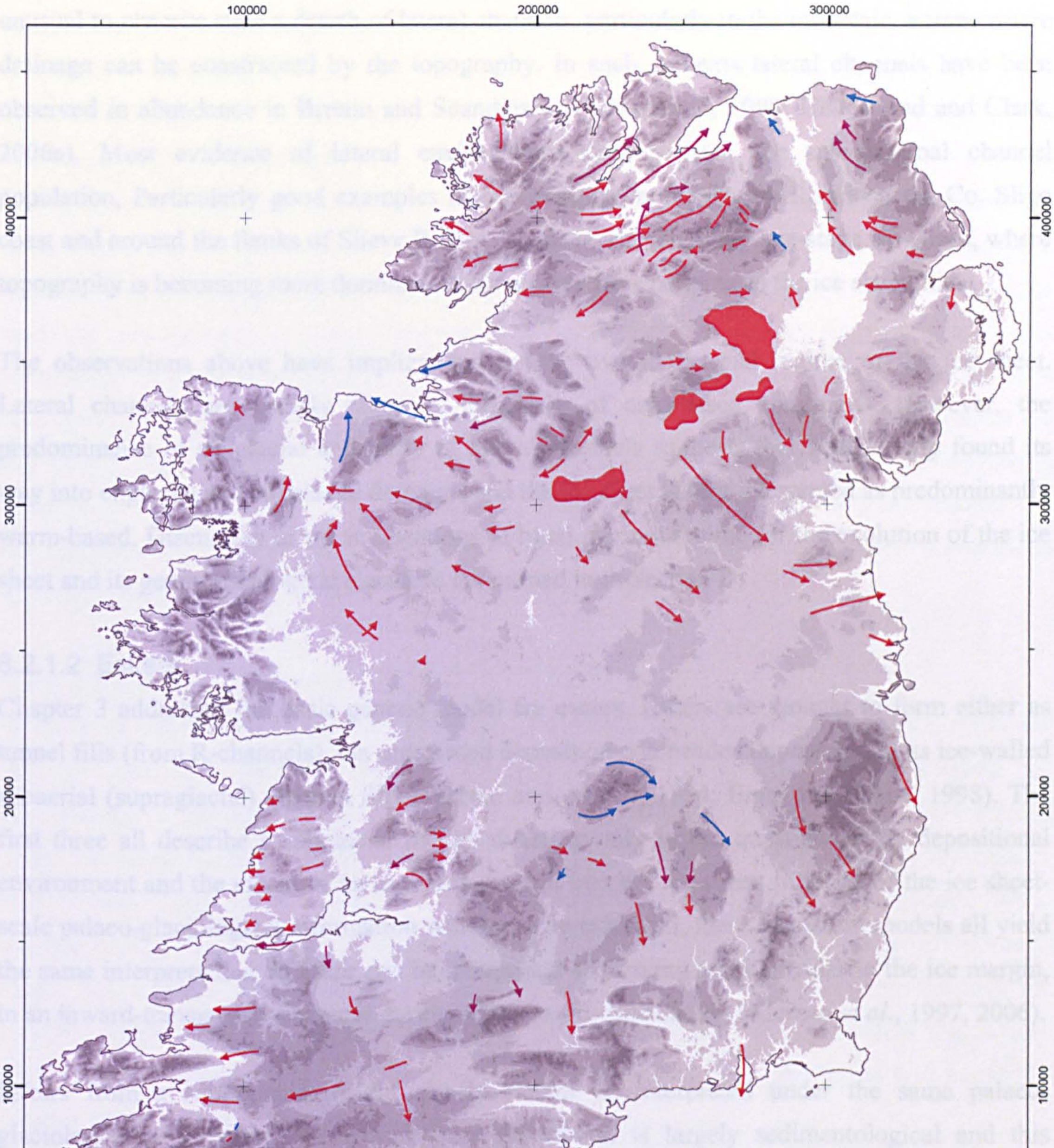


Figure 8.2 Classification of meltwater channel networks according to glaciological context of channel operation.

The vast majority of meltwater channel information in Ireland clearly relates to the subglacial system. Subglacial channels are liberally distributed across the central lowland plains (see Map 3), with some particularly large and deep systems penetrating the Sperrin Mountains and also the southern mountain ranges of Co. Cork. Surprisingly, there are virtually no truly lateral (i.e. marginal, in the sense outlined in Figure 8.1) channels. Possibly, they are under-represented due to the relative size of channels with respect to data resolution, but this is deemed unlikely since several small subglacial networks have been mapped, and lateral channels have been successfully mapped elsewhere using similar imagery (e.g. Hättestrand and Clark, 2006a). It is unusual to observe such a dearth of lateral channels, particularly in the mountain masses where drainage can be constrained by the topography. In such contexts lateral channels have been observed in abundance in Britain and Scandinavia (Hättestrand, 1998; Hättestrand and Clark, 2006a). Most evidence of lateral environments derives from the sub-marginal channel population. Particularly good examples of sub-marginal networks are found on the Co. Sligo coast and around the flanks of Slieve Bloom. These reveal relatively late-stage flowlines, where topography is becoming more dominant in driving ice flow patterns as the ice sheet thins.

The observations above have implications for the overall thermal regime of the ice sheet. Lateral channels are usually taken as indicative of cold-based conditions. However, the predominance of subglacial and rarity of lateral channels suggests that water easily found its way into englacial and subglacial domains, and the ice sheet is best interpreted as predominantly warm-based. Discussion of the implications of basal thermal regime for the evolution of the ice sheet and its geomorphological signature is returned to in Section D.

8.2.1.2 Eskers

Chapter 3 addressed the basic genetic model for eskers. Eskers are thought to form either as tunnel fills (from R-channels), via segmented deposition, via beaded deposition, or as ice-walled subaerial (supraglacial) channel fills (Warren and Ashley, 1994; Benn and Evans, 1998). The first three all describe a subglacial model, differing only in the question of the depositional environment and the extent of an at-a-time conduit into the ice sheet. In terms of the ice sheet-scale palaeo-glaciological information which can be extracted, these formation models all yield the same interpretation: an esker can be interpreted as forming perpendicular to the ice margin, in an inward-transgressive manner during warm-based deglaciation (Kleman *et al.*, 1997, 2006).

Eskers from a supraglacial origin clearly cannot be interpreted under the same palaeo-glaciological assumptions. However, their description is largely sedimentological and this information is not available for every esker. Without geomorphological criteria by which subaerial and subglacial eskers can be distinguished, subaerial eskers cannot be accounted for in the following analysis. There is therefore likely an over-interpretation of the subglacial types. However, in terms of ice sheet-scale palaeo-glaciology, it is unlikely this over-interpretation translates up to flowline scale since this would require the preservation of spatially very extensive supraglacial drainage systems.

Contrary to subglacial meltwater channels, subglacial eskers are accepted as decay and ice-margin related. Their position and configuration therefore yields information on margin positions and flowset timing. Margins cannot be exactly placed at this scale of analysis but their general direction and trend can be determined. Flowset interpretation is aided by the disposition of eskers: when eskers are found aligned with bedforms, the simplest interpretation is the two suites of landforms are coeval. That is, they belong to the same flow configuration and the same relative chronological position within a time-stack of flow patterns. This relative chronological position is deglacial (see below, Section 8.2.2).

8.2.2 Bedform flowsets: glaciodynamic interpretation

The task of extracting the glaciodynamic context from bedform flowsets has received much attention from the two flowset approach schools (Clark, 1997, 1999; Clark *et al.*, 2000; Kleman and Borgström, 1996; Kleman *et al.*, 1997, 2006). Essentially, we wish to determine how the flowset relates to the palaeo-geography of the ice sheet, its chronology, and the type of ice flow behaviour it represents. To achieve this goal, the Clark and Kleman schools each adopt a slightly different terminology and approach, but are based in the same philosophy. The whole landform assemblage, and the internal arrangement of individual features within this assemblage, will reveal the geography and the glaciology of the ice flow(s) responsible for their inscription. Based on our understanding (albeit limited in some respects) of bedform genesis we can predict the character of lineation patterns under different glaciological environments (Boulton *et al.*, 1985, 2001; Clark, 1994, 1999; Stokes and Clark, 1999). We can thereby use our expectations of how lineation arrangements and properties differ under different scenarios to invert the observational record for its palaeo-glaciology.

8.2.2.1 Flowset classification models

In order to extract the relevant information, a suite of landscape classification models are required. For each potential context of bedforming, a template should encapsulate our expectations of the bedform arrangement and landform associations within a flowset created under that scenario. Each model should present diagnostic criteria for interpreting the palaeo-record. Both Clark (1999; Clark *et al.*, 2000) and Kleman (Kleman and Borgström, 1996; Kleman *et al.*, 1997, 2006) have proposed such a suite of models for the subglacial environment (Table 8.2, Figures 8.3 & 8.4). Whilst the two flowset schools use different terminology for flowset classification, they capture the intrinsic association of palaeo-*geographical* and palaeo-*glaciological* properties of a flowset. The diagnosis of one of these properties will implicitly suggest certain characteristics of the other.

A flow pattern must be created either near the margin or towards the interior of the ice sheet. A landform assemblage created near the margin will be *time-transgressive*. The assemblage will be built up incrementally and undergoes constant modification by an ice flow direction which is in constant flux in response to an evolving ice margin position. Where such an assemblage has survived, it is likely *deglacial* and related to a retreating margin. Two environments of deglaciation can be distinguished (Kleman *et al.*, 1997, 2006). A 'wet-bed' scenario describes warm-based deglaciation, conducive to the generation of subglacial landforms. A 'dry-bed' scenario is cold-based, unable to inscribe landforms other than lateral meltwater channels.

The alternative palaeo-geographical position of a flowset is sited further into the ice sheet interior. Here, thicker ice leads us to expect a greater stability of ice flow direction than nearer the margin, and the whole resultant landform pattern reflects a single snapshot of ice flow history. Such assemblages are classified as *isochronous*, *event*, or *stream* (a special case of *event*) flowsets according to the different terminologies. Distinguishing between different flowset types reveals the geographical and glaciodynamic context under which the landform assemblage was created.

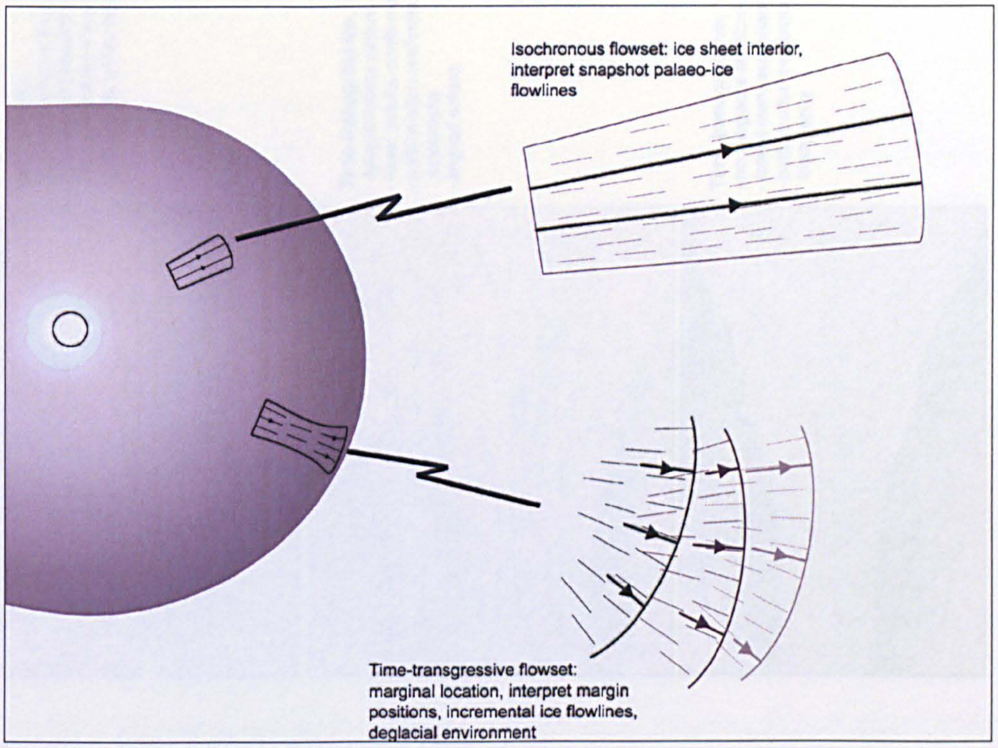


Figure 8.3 Palaeo-geography and palaeo-glaciological significance of isochronous and time-transgressive flowsets (after Clark, 1999).

To distinguish these flowset classification models, diagnostic criteria for the landform record are required. These criteria relate both to bedform (lineation) properties internal to the flowset, and to overall landform assemblages, and are outlined and illustrated in Table 8.2 & Figure 8.4.

The discussion has so far focussed on deciphering the glaciodynamic context of lineation dominated flowsets. Ribbed moraine have been less well addressed in the literature in this respect. This is due to their less frequent use in flowset-based reconstructions, and the relatively poorer understanding of the geographical and glaciological context of ribbed moraine genesis (see Chapter 3, Section 3.2.1.2). Ribbed moraine have been hypothesised to form under a model of bed deformation (Boulton and Hindmarsh, 1987; Hindmarsh, 1998a,b, 1999; Dunlop, 2004), and under both compressive (Bouchard, 1989; Aylsworth and Shilts, 1989) and extensional (Hättestrand, 1997) flow settings, each of which may be initiated both by topographic shape and subglacial thermal regime transitions. In this thesis, given the uncertainty regarding ribbed moraine formation, and since neither the palaeo-geography nor glaciology of ribbed moraine are well constrained, ribbed moraine are subjected to only limited palaeo-glaciological interpretation. They are merely used as ice flow direction indicators, and provide relative chronological information where they are associated with drumlin overprinting. Whilst a genetic model is not imposed upon the ribbed moraine, implicit in the reconstruction presented is an assumption that ribbed moraine are *not exclusively* explained by a cold to warm transition of thermal regime. Note that this model of interpretation differs distinctly from that employed by

Table 8.2 Diagnostic criteria for glaciodynamic flowset classification (after Clark, 1999; Stokes and Clark, 1999; Kleman and Borgström, 1996; Kleman *et al.*, 2006).

Flowset classification	**Glaciodynamic context**	**Bedform properties**	**Landform associations**
Isochronous	Ice sheet interior – sheet flow • Conforms to internal rather than marginal flow patterns • Stability of flow directions • Range of ice thicknesses • Warm-based	• Predominantly parallel flow pattern • May ignore local topography • High lineation parallel conformity • No cross-cutting within flowset • Gradual downstream and/or lateral trends in lineation morphometry and distribution	• No aligned eskers • No association with end moraines
	Ice sheet interior – stream flow • (as above) • Order of magnitude faster ice velocity • Warm-based	• High lineation parallel conformity • No cross-cutting within flowset • Highly attenuated lineations • Abrupt lateral margins • Highly convergent flow patterns	• (as above) • Lateral shear moraines • Trough mouth fans
Time-transgressive	Behind retreating ice sheet margin • Rapidly varying flow directions • Thin ice • Sheet or stream flow • Warm-based i.e. "wet bed"	• Lobate / splaying flow pattern • Pattern exhibits correspondence to local topography • Lower parallel conformity of lineations • Cross-cutting lineations internal to flowset • Abrupt spatial discontinuities in lineation morphometry and distribution	• Aligned eskers • Associated with end moraines
	Behind retreating ice sheet margin – "dry bed" • Thin ice • Topographically constrained • Sheet flow • Frozen bed	• Absence of bedforms – landform record dominated by lateral meltwater channels	• Lateral meltwater channels only – patterns constrained by local topography

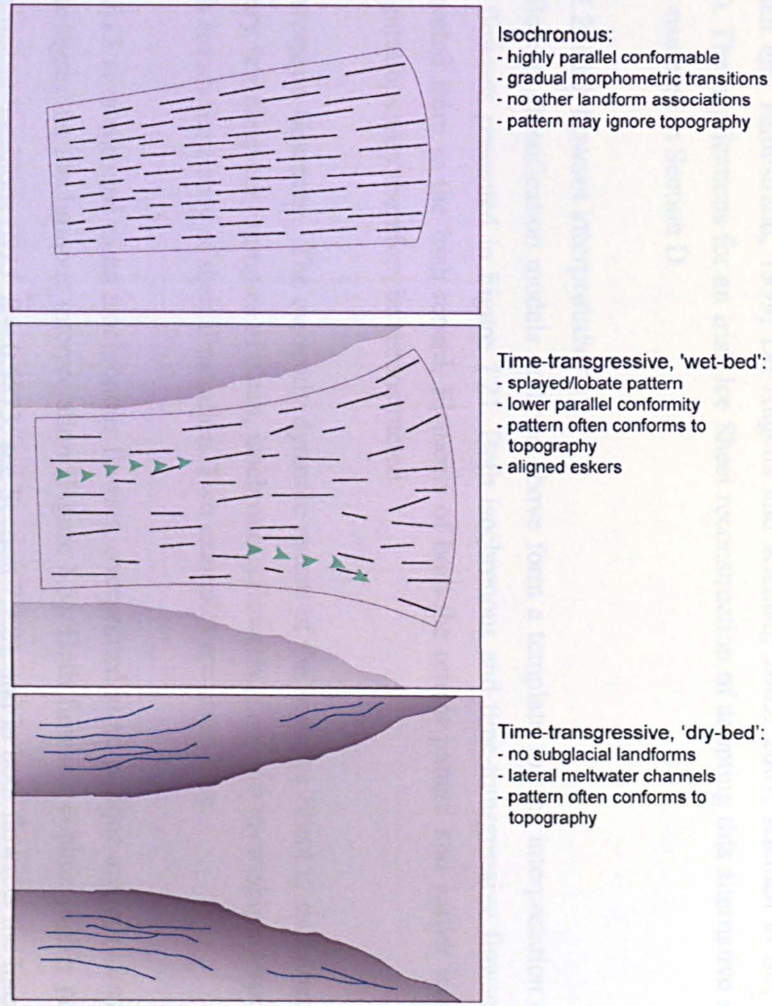


Figure 8.4 Schematic illustration of glaciodynamic context and diagnostic criteria for flowset classification (after Clark, 1999 and Kleman *et al.*, 2006).

the Kleman school, in which ribbed moraine are heavily used to infer cold-based zones (e.g. Kleman and Hättestrand, 1999; De Angelis and Kleman, 2005, 2007; Kleman *et al.*, 1997, 2006). The implications for an Irish Ice Sheet reconstruction of adopting this alternative model are considered in Section D.

8.2.2.2 Irish flowset interpretations

The flowset classification models outlined above form a template for the interpretation of the Irish flowsets presented in Figure 7.21. Both isochronous and time-transgressive flowsets are interpreted from in the Irish record. Elements of both the retreat pattern and earlier ice sheet configurations may therefore be reconstructed.

Isochronous flowsets. The evidently dynamic nature of the Irish Ice Sheet is such that there are very few clear-cut examples of clean, isochronous flowsets. They are invariably overprinted, which clouds the clarity of their illustration. Two examples are given here.

Lins fs15 is interpreted as an isochronous flowset, overprinted at an oblique angle by *lins fs16,* also assigned an isochronous interpretation (Figure 8.5). Both flowsets contain highly parallel conformable lineations (*fs15* $\overline{R}$ = 0.9873; see Section 7.2.2), and in both flowsets the lineations gradually become more elongate downstream. Indeed, from the head of *fs15* drumlins steadily become mega-scale glacial lineations within a relatively short distance downstream. Eskers are observed within this landform assemblage but cross-cut the lineations at an almost perpendicular angle. The eskers clearly must be associated with an independent, later stage flowset.

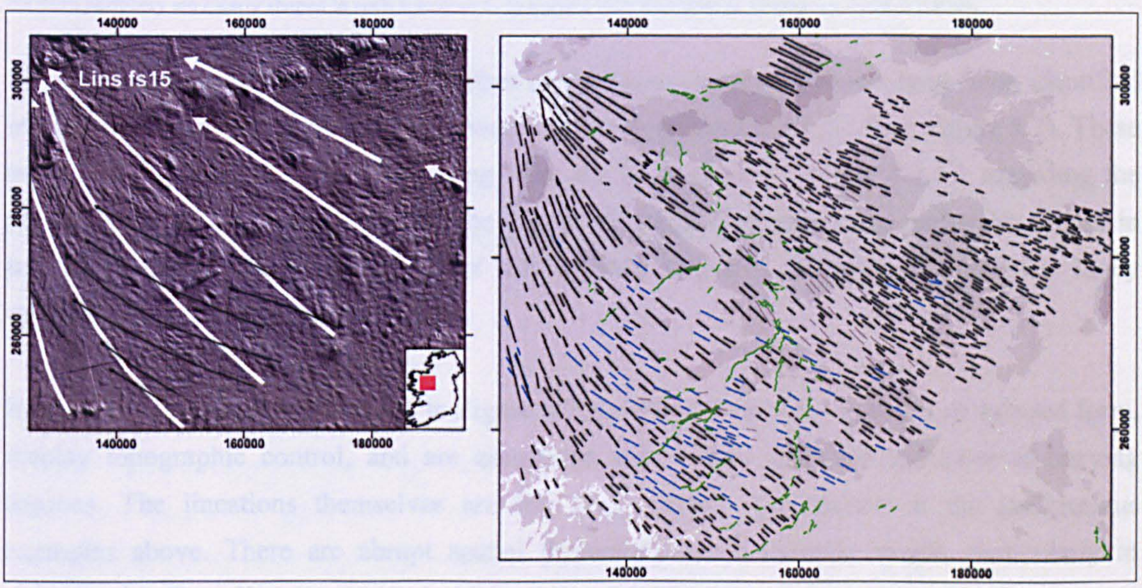


Figure 8.5 Both *lins fs15* and *fs16* are interpreted as isochronous flowsets. Lineations belonging to *fs15* are shown in black (right panel); drumlins from *fs16* are in blue. Eskers, in green, cross-cut both lineation patterns. Other lineations (and landform types) have been removed from this figure for clarity of display. Scale: gridmarks at 20 km.

Lins fs10 is interpreted as an isochronous flowset which is later overprinted by *lins fs9* and *fs12* (Figure 8.6). This overprinting has clearly erased a number of lineations from a sector through the middle of fs10. Lineations are not so well organised as in *fs15*, above. Parallel conformity is marginally lower ($\overline{R}$ = 0.9813) and there are some morphometric (length) discontinuities within the flowset. However, these may be attributable to the topographic high over which the flowset passes. Lineations display a stronger parallel conformity over the lower, more southerly sector of the flowset, are not associated with any eskers or moraines, and on these grounds *lins fs10* is interpreted as an isochronous flowset.

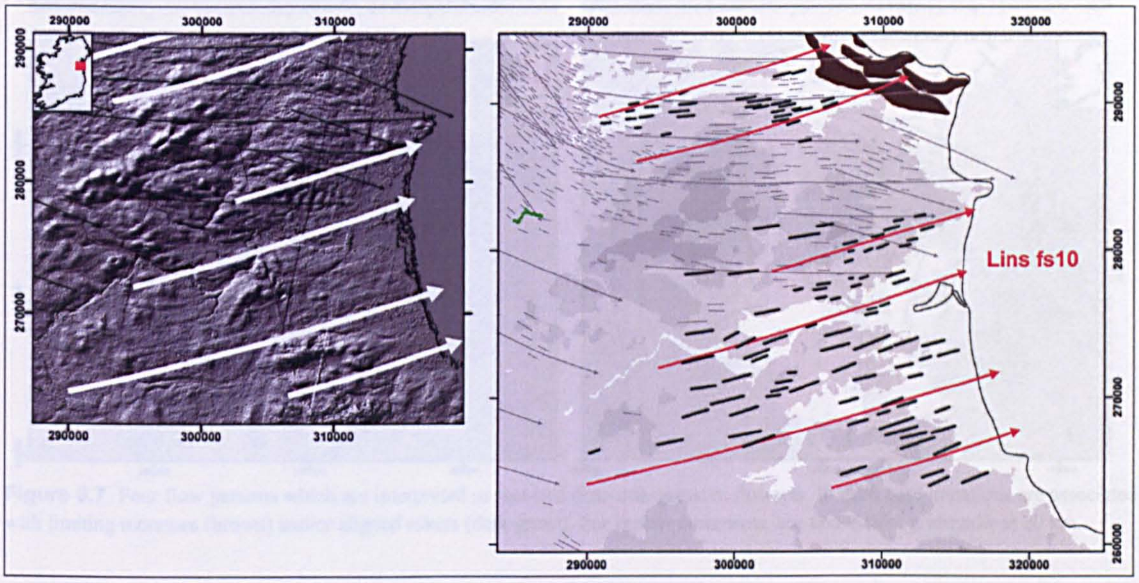


Figure 8.6 *Lins fs10* is interpreted as isochronously formed. Lineations display high parallel conformity, their orientation is not significantly perturbed by the local topography, and there is an underlying 'grain' to the landscape, also highly parallel conformable, which is too subtle to map as coherent landforms (left panel). Eskers are not present within this flowset, and moraines at the northern periphery are clearly shaped in such a manner as to suggest they belong to an alternative ice flow pattern.

Time-transgressive flowsets. A number of time-transgressive flowsets have been identified in the Irish record on the basis of the models outlined in Section 8.2.2.1 (e.g. Figure 8.7). These are all of the 'wet-bed' type. Following from the discussion in Section 8.2.1.1 regarding the classification of meltwater channels, the dearth of lateral channels in the meltwater record in Ireland precludes the identification of any dry-bed deglacial flowsets. Deglaciation likely operated under a warm-based regime.

Each of the flow patterns revealed in Figure 8.7 are characterised by a lobate, or splayed form, display topographic control, and are associated with eskers and with moraines to varying degrees. The lineations themselves are less well-ordered than shown in the isochronous examples above. There are abrupt spatial discontinuities in drumlin length, particularly in example (a). Drumlin occurrence is often not evenly distributed throughout the flow pattern (examples a, c, and to a certain extent in d although Lough Conn explains a large lineation gap). There is also a much lesser degree of consistency of lineation orientation. This inconsistency is such that on lineation properties alone, summary flowlines were initially drawn describing

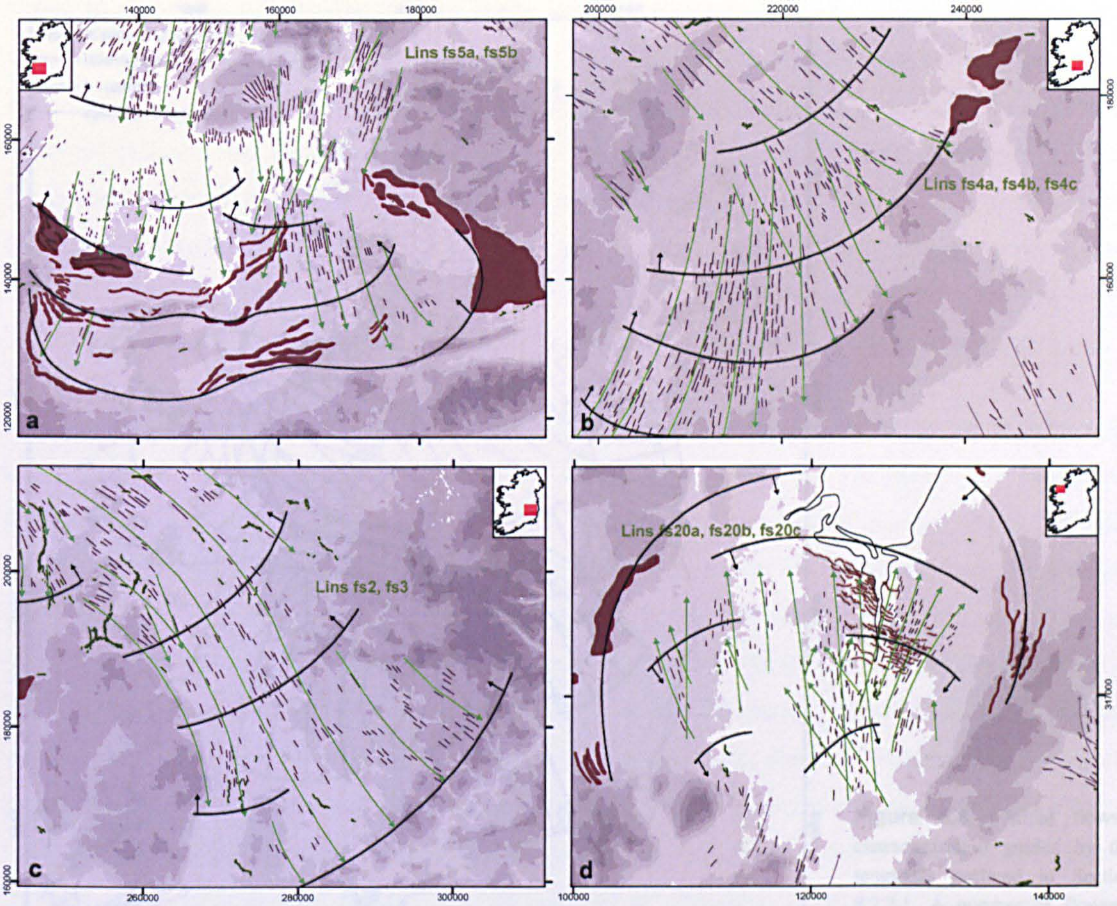


Figure 8.7 Four flow patterns which are interpreted as wet-bed time-transgressive flowsets. In each case lineations are associated with limiting moraines (brown) and/or aligned eskers (dark green). For further comments, see text. Scale: gridmarks at 20 km.

multiple flowsets. On consideration of their glaciodynamic context, particularly their landform associations, this initial spatial summary was revised and in each case multiple flowsets are regrouped to form one, single time-transgressive landform assemblage. This highlights the iterative nature of flowset delineation (Kleman *et al.*, 2006). Where conflicts or new lines of evidence arise, it is necessary to return and regroup information into a slightly different data reduction (spatial summary). These instances largely relate to the interpretation of time-transgressive flowsets, within which the spatial-only summary placed a weighting on lineation orientation suggested to be too great once the glaciodynamic context is considered.

Classification of the Irish flowset record according to the templates outlined in Section 8.2.2.1 is presented in Figure 8.8. Initial observation reveals that isochronous and time-transgressive flowsets have different geographies in the Irish landscape. Isochronous flowsets generally flow offshore, particularly off the west coast, and could therefore be linked to the build-up and maximum stages of glaciation when continental shelf ice cover is most likely. Time-transgressive patterns are typically located a short distance inward of the present-day coast, and characterise a period of stabilisation and subsequent ice sheet withdrawal back into a terrestrial environment. Clearly the flowsets hold a more detailed picture of palaeo-glaciation than this simple summary, and this is addressed below and in the following chapters. First, however, it is immediately apparent that a number of flowsets cannot be classified following the model templates. New models for the interpretation of a flowset's palaeo-glaciology are required.

Figure 8.8 Initial flowset characterisation guided by the templates outlined in Section 8.2.2.1. A number of flowsets could not be classified from these models; new templates for derivation of a flowset's palaeo-glaciology are required.

8.2.2.3 New classification models

Lineation patterns in Ireland are rarely 'clean' imprints. Rather, they often have a 'smudged' appearance, in stark contrast to the highly parallel conformable flow patterns witnessed in Canada, for example (e.g. Clark, 1993; Stokes and Clark, 2003). Under the LIS, snapshots of well-ordered bedform patterns are the product of wide, open, flat plains, which lay beneath thick ice, slower to respond to forcing drivers and thereby producing stable flowlines and 'clean' bedform imprints. Here in Ireland, the context is vastly different. A small, maritime ice sheet would likely have responded swiftly to forcing and experienced a sensitive relationship with atmospheric and oceanic (particularly sea level) drivers. As a result, ice sheet configurations and flowline positions would have been inherently less stable. This theoretical prediction is indeed what is observed in the bedform record.

Existing templates for flowset interpretation have proven inadequate for fully deriving palaeo-glaciological information from the Irish record. A number of lineation groups lack independent evidence of proximity to an ice margin (time-transgressive), yet neither do they display characteristics typical of an isochronous scenario. In such cases lineations often possess a lower parallel conformity and a lower degree of organisation, but to force two (or multiple) discrete flowsets upon the assemblage would imply that clear-cut end members of different ice flow configurations could be deciphered: an imprint inscribed at time *A*, followed some time later by a second imprint at time *B*. Rather, the lineation assemblages typically reveal only a loosely coherent pattern, best described as a 'smudged' imprint. A smudged imprint can more honestly be interpreted as the record of a *transition* between potential, but not always clear-cut end members: it records the *transition between* times *A* and *B*. That is to say, we rarely see a clear 'rubber stamp' imprint of stable flow patterns, but rather we can observe 'second-order' dynamics of an ice flow regime superimposed upon the 'first-order' ice sheet configuration.

It is useful to conceptualise different 'orders' of ice sheet dynamics. First- or higher-order properties characterise the ice sheet-scale: broad ice divide positions, ice extent, the main flow directions. Significant changes in these mark first-order dynamics of the ice sheet. Meehan (2006a) usefully distinguishes between first-order ice advances or margin retreat episodes which are regionally significant, and second-order dynamics which weakly overprint the dominant pattern. These may relate to oscillations of a margin or of a flowline, which reveal a response to local, or secondary forcing and do not require a fundamental change in ice sheet configuration or behaviour for their explanation. Margin retreat, for example, may characterise the first-order palaeo-glaciology of a flowset, but superimposed are subtle fluctuations of margin orientation reflected in an inconsistent orientation of lineations inscribed behind the margin. Time-transgressive flowsets may therefore be thought of as revealing lower-order behaviour which has 'smudged' the primary geological or geomorphological evidence of the flow pattern.

Smudged patterns are inherently time-transgressive. This suggests we need to conceptualise time-transgressive imprints in more ways than simply the incremental development of a bedform pattern behind a retreating ice margin. In addition to ice margin retreat, two further types of time-transgressive ice flow behaviour can be hypothesised: smudging due to *ice thinning*, and smudging due to *flowline migration* (Figure 8.9). These models are informed by and demanded by the observations of flowset and lineation patterns in Ireland.

During **ice thinning** the degree of deflection exerted upon ice flow by the local topography becomes greater. This is manifested in the lineation record as a flowset with internal cross-cutting. Later lineations with a more pronounced deflection remould and overprint earlier bedforms whose orientation is only slightly perturbed by an underlying topographic high. The ice sheet likely maintains the same broad configuration, but locally lower-order behaviour is observed as deglaciation ensues.

Flowline migration will 'smudge' a bedform imprint, recording time-transgressive behaviour but, unlike margin retreat and ice thinning, may not exclusively relate to the decay phases of glaciation. Flowline migration could be the result of either of two dynamic changes: either the ice divide moves (flowline source) or the outlet moves (flowline terminus). Each of these scenarios would divert the line orientation.

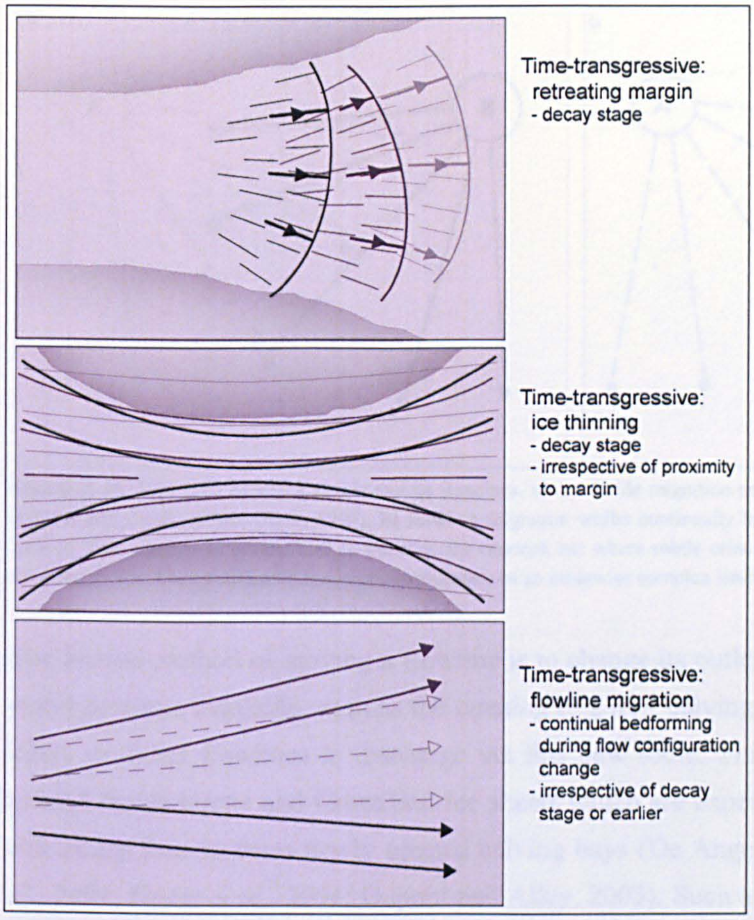


Figure 8.9 New hypothesised flowset classification models. Time-transgressive flowset interpretations have previously invoked a retreating margin setting. The Irish lineation record requires additional conceptualisations of time-transgressive bedforming. Smudging due to ice thinning, and smudging due to flowline migration are proposed. These new conceptualisations see time-transgressive flowsets as recording a transition from one state, or flow configuration to another, during which the bed is repeatedly modified such that neither end member is clearly decipherable, but a record of the transition remains.

It is generally accepted that ice divides migrate. With them, the flowlines which emanate from ice sources must also change direction. Under the Clark model of flowset interpretation (Clark, 1997, 1999) an ice divide migration is used to explain two (or more) cross-cutting flow patterns (Figure 8.10a). This conceptualisation requires that at some point following stage *A* the 'switch' controlling the bedforming process turns off. Lineations (*a*) are preserved as the ice divide migrates to position *B*. When the bedforming switch turns on again, a new, discrete landform pattern is created. However, if the bedforming 'switch' were to remain active as the ice divide migrates along path *A-B*, the bed would be continually reworked and remoulded (Figure 8.10b). A landform pattern is produced which contains elements of the first pattern (*a*), elements of the second pattern (*b*) and some smudged lineations produced during the phases in between. The more stable periods *A* and *B* will manifest themselves as the strongest bedform imprints but the whole landform assemblage will resemble a transition more than two discrete records of bedforming. (Of course if the ice divide remains at *B* for sufficiently long it might completely reorganise the bed such that the history of the divide shift is lost.)

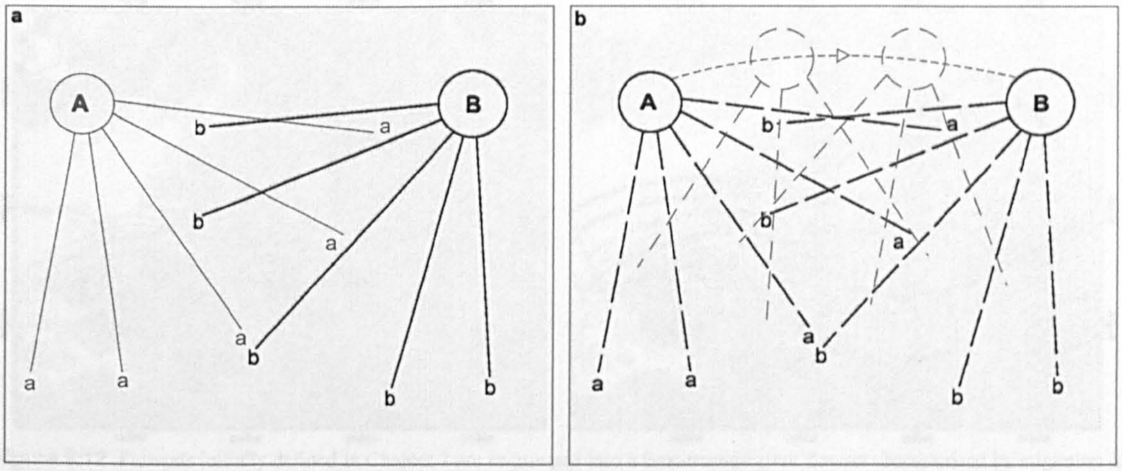


Figure 8.10 Migration of an ice divide and its flowlines. **a)** ice divide migration produces 2 discrete overprinted flowsets (after Boulton and Clark, 1990b; Clark, 1997). **b)** flowline migration whilst continually bedforming will produce a time-transgressive imprint. This example is exaggerated to illustrate the concept, but where subtle orientation differences are observed in a lineation assemblage this conceptualisation is a useful explanation of an otherwise complex landform record.

The second method of moving a flowline is to change its outlet location (Figure 8.11). If a new outlet becomes available, such as the opening of a new calving bay during ice sheet retreat, it is likely to divert flowlines to discharge via this new route. This scenario is currently observed around the Antarctic and Greenland ice sheets which are experiencing loss of their ice shelves, enhancing flow to these newly opened calving bays (De Angelis and Skvarca, 2003; Rignot *et al.*, 2004; Payne *et al.*, 2004; Dupont and Alley, 2005). Such a scenario could explain smudged flowline imprints in Ireland.

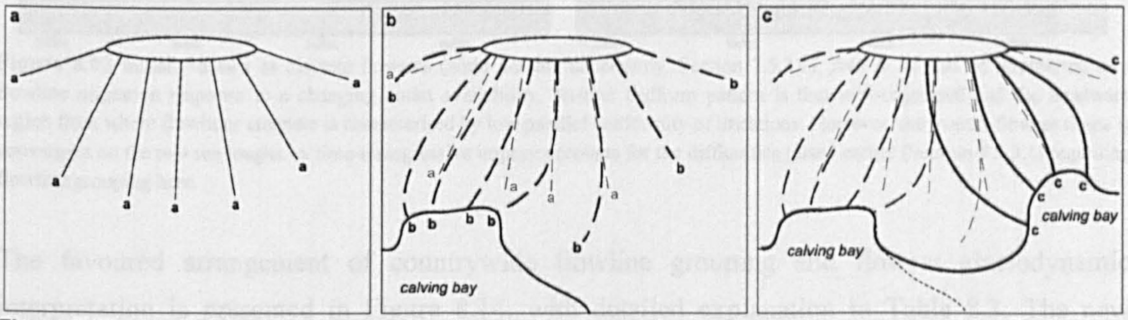


Figure 8.11 Stimulation of flowline migration from the flowline terminus: as new outlets become available for discharge, flowlines are drawn down to this point causing cross-cutting of lineations at the headward extent of the flowset. If the bed is continually reworked during this phase, a smudged imprint will result.

Both of these scenarios are observed in the Irish record. *Lins fs32, fs33, fs33b* and *fs34* (Omagh Basin and Lower Lough Erne) are better summarised as a single, time-transgressive flowset experiencing flowline migration (Figure 8.12). The lineation assemblage displays patches of low orientation consistency. However, there is a gradual increase in lineation length along the flowline and, furthermore, there is no association with either eskers or moraines which would suggest a deglacial context. In north Co. Donegal, *lins fs40* and *fs41* are interpreted using the template of a changing discharge outlet (Figure 8.13). Lineations are funnelled through both Loughs Swilly (*fs41*) and Foyle (*fs40*) but display some smudging in the headward regions of the flowset which can be attributed to flow diversion from one outlet to the other.

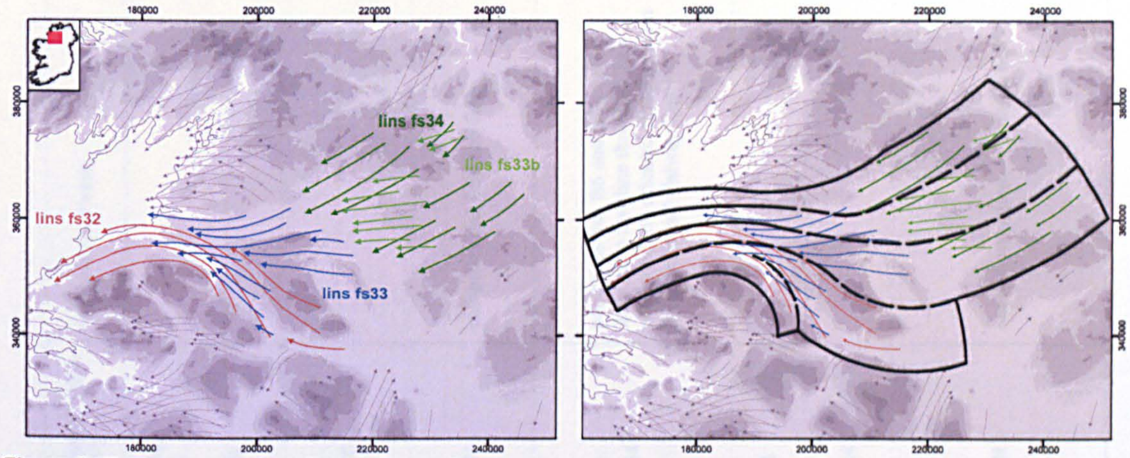


Figure 8.12 Flowsets initially defined in Chapter 7 are re-grouped into a time-transgressive flowset characterised by migration of the flowline direction during the period of landform genesis. The overall ice flow configuration is not required to change, nor is margin retreat required, but some subtle fluctuations of flow direction produce a smudged lineation imprint. At the first order, this smudged imprint can be packaged into a single flowset.

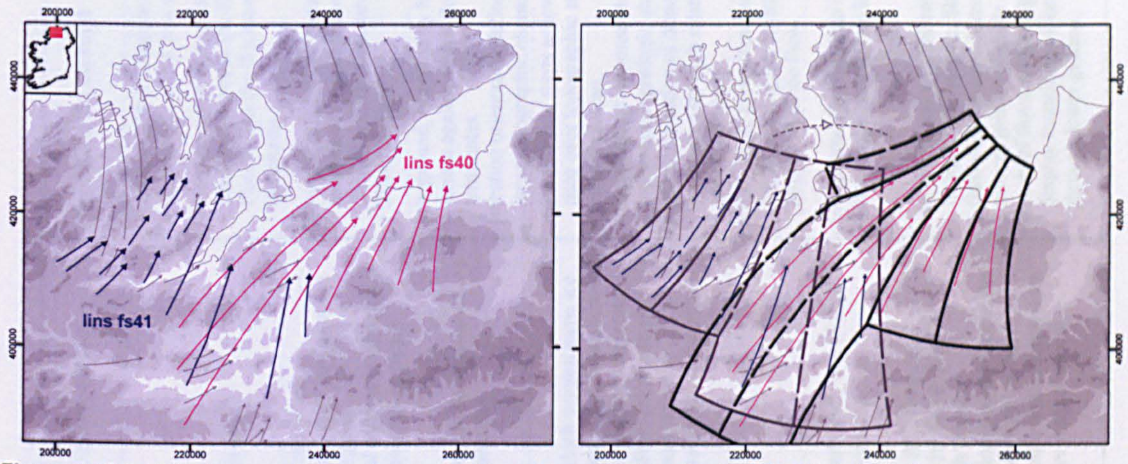


Figure 8.13 Initially drawn as discrete flowsets (amid notable uncertainty, Section 7.5.3.1), *fs40* & *41* can be interpreted as a flowline migration response to a changing outlet availability. Neither bedform pattern is that well-organised and the headward region from where flowlines emanate is characterised by low parallel conformity of lineations. However, the overall flowset shape is convergent on the two sea loughs. A time-transgressive imprint accounts for the difficulties raised earlier (Section 7.5.3.1) regarding flowline grouping here.

The favoured arrangement of countrywide flowline grouping and flowset glaciodynamic interpretation is presented in Figure 8.14, with detailed explanation in Table 8.3. The new conceptual models of time-transgressive flowset palaeo-glaciology are much easier to fit to the Irish record, rather than forcing flowsets into categories which are not as suitable. There is a profusion of time-transgressive patterns, many of which are of the flowline migration type. This has interesting implications for the overall glaciology of the ice sheet as well as its geometric reconstruction. It suggests a rapidly evolving ice sheet which appears to be almost continually carrying out subglacial geomorphic work. If 'snapshot' or 'rubber stamp' imprints are indicative of stable flowlines (Clark, 1999) then undoubtedly a number of flow regimes of the last Irish Ice Sheet were inherently unstable. Rather, the timescales of ice sheet behaviour are much closer to the timescales of bedforming than under larger, more steadily evolving ice sheets, with cleaner flowset imprints, such as the Laurentide. These implications are returned to in thesis Section D.

Table 8.3 Results of interpretation of lineation flowset glaciology (refer also to Figure 8.14).

Lins fsX	Glaciodynamic interpretation	Lineation properties	Landform associations	Topographic context	Flowset area (km²)	Other comments
fs1	isochronous	patchy drumlin coverage, variable length, mixed with some streamlined bedrock	none	crosses the Slieve Namon range with little deflection of flow direction	2701	
fs2	time-transgressive: lobate retreat	drumlins of variable length, minor internal cross-cutting, patchy distribution, lobate/splayed flowset shape	aligned with eskers	flowset occupies low ground, funnelled between the Castlecomer Plateau and the Wicklow mountains	3252	
fs4	time-transgressive: lobate retreat	short drumlins, some minor internal cross-cutting, lobate flowset shape, well populated	short esker segments flowset bounded by (speculative) moraine spread submarginal meltwater channels at lateral flowset boundaries	flowset occupies low ground, funnelled between Slieve Bloom, the Silvermine Mountains and Slieve Ardagh	3390	
fs5	time-transgressive: lobate retreat	inconsistent (but abundant) distribution, considerable variability in morphometry, low parallel conformity, lobate/splayed flowset shape	lineations terminate at series of arcuate moraines	low ground, bounded by higher terrain against which flowset terminates. lineation orientation deflected by large topographic obstacles	3533	comprises lins fs5a and fs5b
fs6	time-transgressive: flowline migration	mix of long lineations (MSGLs, crag and tails) and drumlins, smudged imprint, some internal cross-cutting, convergent flowset shape	moraines which suggest same ice flow direction but dispostion with respect to lineations suggests relate to different phases (ie advance and retreat in approximately same direction).	main flowline starts as low ground, rises over topographic step onto coastal plateau. morphometric responses to topographic/geologic changes some perturbation of drumlin orientation by high relative relief over the Burren.	4514	comprises lins fs6 and fs6b. links main flowline through Clare with similarly oriented flowlines over the Burren and Galway Bay.
fs7	isochronous	small, subtle drumlins, dense population, high parallel conformity	none	high terrain, flowset crosses Slieve Aughtys using the structural lows aligned with ice flow	698	
fs8	time-transgressive: lobate retreat	patchy distribution, spatial discontinuities in drumlin morphometry (length)	2 esker populations: one aligned, one cross-cutting	low ground (moving into open plain), flanking higher terrain laterally	3614	
fs9	time-transgressive: flowline migration	large flowset, abundantly populated with drumlins, increasing in length downstream. low parallel conformity in places with internal cross-cutting. curving flowline, convergent flowset shape.	lins fs11 & fs12 ('smudged' imprint), rm fsG & fsH. aligned with eskers. some moraine groups relate to the same flow direction but disposition with lineations does not always suggest coeval genesis.	uneven ground in southern part of flowset; Carrigatuke, Slieve Gullion & Mourne Mountains present greater obstacle in north. sectors of flowset crossing mountains display funnelling of ice flow through lower ground	17812	major flow pattern - "drumlin belt"

Table 8.3 (cont.)

Lins fsX	Glaciodynamic interpretation	Lineation properties	Landform associations	Topographic context	Flowset area (km^2)	Other comments
fs10	isochronous	drumlins, display parallel conformity, uneven distribution	none	uneven ground, higher terrain more sparsely populated with lineations. no apparent deflection of orientation	1319	
fs11	time-transgressive: flowline migration	large flowset, abundantly populated with drumlins. low parallel conformity in places with internal cross-cutting. curving flowline, convergent flowset shape	lins fs9 and fs12 ('smudged imprint'), rm fsG and fsH.	(see fs9)	7460	part of major flow pattern - "drumlin belt"
fs12	time-transgressive: flowline migration	large flowset, patchy distribution of drumlins, low parallel conformity.	lins fs9 and fs11 ('smudged imprint'), rm fsG and fsH.	(see fs9)	12093	part of major flow pattern - "drumlin belt"
fs13	time-transgressive: thinning	small drumlins, parallel conformable, convergent flowset shape	lins fs9, fs11 and fs12 ('smudged imprint'), rm fsG and fsH.	wide valley between Slieve Croob and Mourne Mountains	222	product of thinning and increased topographic control
fs14	time-transgressive: flowline migration	large flowset, patchy distribution of drumlins, low parallel conformity.	lins fs9, fs11 and fs12 ('smudged imprint'), rm fsG and fsH.	low ground	830	part of major flow pattern - "drumlin belt"
fs15	isochronous	well organised lineations, high parallel conformity, downstream transition from drumlins to MSGLs	cross-cut by eskers	open plain	4964	interpret as ice stream onset
fs16	isochronous	high parallel conformity, downstream increase in length	cross-cut by eskers	open plain	1739	
fs17	isochronous	short drumlins, high density, high parallel conformity	cross-cut by eskers	curving flowline responds to topographic obstacles	2579	
fs18	isochronous	drumlins decrease in length downstream, patchy distribution	close association with rm fsB. no associations with deglacial landforms	open plain entering into marine bay	764	
fs20	time-transgressive: lobate retreat	short drumlins, low parallel conformity, internal cross-cutting, patchy distribution, lobate/splayed	possible association with eskers. bounded by moraines and fronted by (superimposed by) small ridges interpreted as marginal	low ground entering marine bay, flanked by higher terrain	564	
fs22	time-transgressive: lobate retreat	short drumlins, low parallel conformity, internal cross-cutting, lobate/splayed shape	association with circular bedforms	low ground, flowset fronted by Ox Mountains	526	
fs23	isochronous	highly parallel conformable lineations, grow in length downstream, curving flowline	none	low ground (moving into open plain), curving flowline reflects lateral topographic obstacle	1506	
fs24	isochronous	consistently sized drumlins along flowline length, display parallel conformity, convergent flowset shape	none	funnelled in low ground between Cuilcagh mountains and Slieve Rushen	200	

Table 8.3 (cont.)

Lins fsX	Glaciodynamic interpretation	Lineation properties	Landform associations	Topographic context	Flowset area (km^2)	Other comments
fs25	unknown (too small)	short drumlins, low parallel conformity	none	amalgam of drumlins from upper reaches of two separate valleys and position flanking mountain mass	152	comprises lins fs25a, fs25b, fs25c
fs26	unknown (too small)	very small flowset, <20 small drumlins	none	valley, wrapping around mountain flanks	25	
fs27	time-transgressive: flowline migration	consistently sized drumlins, some patches of lower parallel conformity produces 'smudged' appearance, 'missing' drumlins around topographic high but little deflection of orientation.	none	low ground (wide valley) with higher terrain laterally	837	comprises lins fs27, fs27b
fs28	time-transgressive: lobate retreat	small drumlins, uneven distribution and some spatial discontinuities in morphometry (length), lobate/splayed flowset shape controlled by topography	none	funnelled into low ground (wide valley) by mountain masses	388	
fs29	isochronous	mix of drumlins and crag and tails, high parallel conformity, even distribution	none	stems from high ground feeding marine bay	259	
fs30	isochronous	small flowset, very small drumlins, low parallel conformity	none	constrained by (& aligned with) deep valley	117	
fs31	isochronous	small flowset, very small drumlins, low parallel conformity	none	crosses deep valley at oblique angle	109	
fs32	time-transgressive: flowline migration	well populated flowset, increasing in organisation downstream (distribution becomes less patchy, more highly parallel conformable, more well formed and longer drumlins). some lateral 'smudging' particularly in upper regions of flowset	none	begins in wide basin, crosses/ deflected around high topographic obstacle, wraps around mountain flanks as flows offshore	2213	combines lins fs32, fs33, fs33b, fs34
fs35	isochronous	large drumlins, uneven distribution interspersed with fs37	none	crosses high terrain, then oblique to Donegal Bay	791	combines lins fs35 and fs36
fs37	isochronous	large drumlins, well organised, high parallel conformity, convergent flowset shape	none	funnelled into Donegal Bay	884	
fs38	unknown (too sparse)	sparsely distributed drumlins across large area, low elongation.	none	coastal plains, fringing Donegal mountains. heavily scoured landscape	633	sparse distribution of drumlins in similar context. grouped together for simplicity

Table 8.3 (cont.)

Lins fsX	Glaciodynamic interpretation	Lineation properties	Landform associations	Topographic context	Flowset area (km^2)	Other comments
fs39	isochronous	sparsely distributed lineations, mix of drumlins, crag and tails and streamlined bedrock. slightly curving flowline	none	crosses high terrain	1557	correlates flowlines either side of Lough Swilly
fs40	time-transgressive: flowline migration	uneven distribution of mostly long lineations (drumlins and crag and tails) but some smaller drumlins interspersed, display parallel conformity within convergent flowset shape	no deglacial landform associations. 'smudged' imprint with lins fs41	funnelled along Foyle valley, converging into Lough Foyle	1321	
fs41	time-transgressive: flowline migration	uneven distribution of short drumlins, lower parallel conformity in places, convergent flowset shape	no deglacial landform associations. 'smudged' imprint with lins fs40	crosses high relative relief terrain, obliquely to structure of landscape, funnelled into Lough Swilly	1252	
fs42	unknown (too sparse)	very small drumlins, unevenly and sparsely distributed	none	valley constrained, amalgam of features from three separate valleys	816	
fs43	isochronous	very small flowset (~100 drumlins), very small drumlins, display high parallel conformity	none	cross landscape structure obliquely with little perturbation to size or orientation	264	direction unknown
fs44	unknown (too small)	very small flowset (~10 drumlins), very small drumlins	none	cross landscape structure obliquely, more valley constrained than lins fs43	60	direction unknown
fs45	unknown (too small)	small patch of drumlins, high parallel conformity	none	mountain flanks	61	
fs46	time-transgressive: lobate retreat	long lineations but sparsely distributed	fronted by Armoy moraine	low ground flanked by higher terrain	411	
fs47	isochronous	short drumlins, patchy distribution but display parallel conformity, convergent flow shape	none	valley constrained	183	
fs48	isochronous	short drumlins but with downstream increase in length, convergent flow shape, patchy distribution but display parallel conformity	none	valley constrained	175	
fs49	isochronous	v. small population (<10) of long lineations, speculate drumlins, or streamlined bedrock with drift cover, highly parallel conformable	none	peninsula protruding into the North Channel	82	
fs50	time-transgressive: flowline migration	small drumlins, densely populated, low parallel conformity in places	Glarryford esker complex	wide valley between 2 mountain ranges oriented obliquely to ice flow	2181	during flowline migration, flow direction becomes increasingly aligned with the valley orientation. additional signature of thinning??

Table 8.3 (cont.)

Lins fsX	Glaciodynamic interpretation	Lineation properties	Landform associations	Topographic context	Flowset area (km^2)	Other comments
fs51	unknown (too small)	very small flowset, ~20 drumlins (speculative), sporadically distributed	complex landform associations at meeting point of rm fsE, fsK, fsL	flowset crosses topographic obstacle (superimposed on ribbed moraine)	137	direction unknown
fs52	unknown (too small)	very small flowset, ~25 drumlins (speculative), low parallel conformity	complex landform associations at meeting point of rm fsE, fsK, fsL	flanks mountain side	58	direction unknown
fs53	unknown (too small)	very small flowset, <25 drumlins, occur in two discrete patches, low parallel conformity	landform assemblage dominated by rm fsF and fsJ	low ground (wide valley)	71	direction unknown
fs54	unknown (too sparse)	sparsely distributed drumlins across large area, low elongation.	none	coastal lowlands surrounding Connemara mountains, heavily scoured landscape.	1107	sparse distribution of drumlins in similar context with respect to mountains (emanating from). grouped together for simplicity
fs55	unknown (too small)	very small and sparsely populated flowset, <10 drumlins	none	mountain flanks	39	
fs56	isochronous	patchy drumlin distribution but display parallel conformity	none	valley constrained	482	
fs57	unknown (too small)	low parallel conformity drumlins at angle to fs58	none	valley constrained	41	
fs58	isochronous	patchy drumlin distribution but display parallel conformity	association with circular bedforms	valley constrained	559	
fs59	isochronous	even distribution of drumlins, display parallel conformity	cross-cut by eskers	open plain	3279	
fs60	unknown (too small)	v. small population (<10), small drumlins	none	low ground	55	
fs61	isochronous	sparsely distributed and subtle drumlins	cross-cut by eskers	low ground	1746	
fs62	isochronous	sparsely distributed and subtle drumlins	cross-cut by eskers	low ground flanking Wicklow mountains	326	

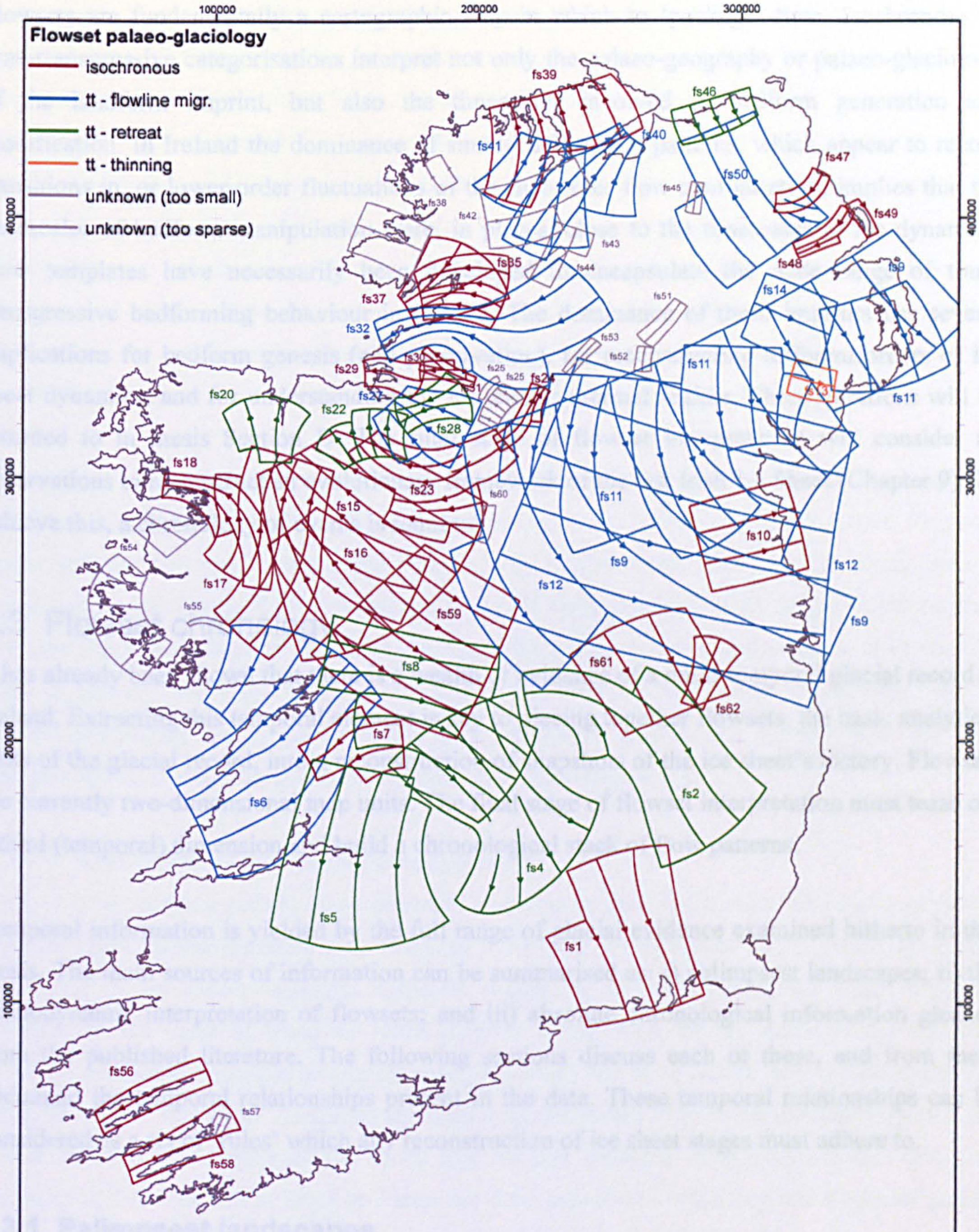


Figure 8.14 Interpretation of lineation-based flowsets according to their glaciodynamic context. Interpretation is based on the templates of Clark (1999), Kleman *et al.* (2006) and those outlined in this chapter. Flow direction is indicated by arrows, where known. For detailed description of the basis for interpreting each flowset, see Table 8.3.

8.2.2.4 Bedform flowset glaciology: summary

Flowsets, the basic interpretative units which summarise the populous bedform record, have been classified according to their interpreted palaeo-glaciological context. The interpretative framework first considers the internal synchrony of the flowset and secondly draws some conclusions regarding the glaciological context of such an imprint. Analysis of the Irish record reveals glaciological contexts not previously accounted for in conceptual templates for flowset interpretation, demanding new conceptualisations of flowset palaeo-glaciology.

Flowsets are fundamentally a cartographic way in which to 'package' time. Isochronous or time-transgressive categorisations interpret not only the palaeo-geography or palaeo-glaciology of the landform imprint, but also the timescales involved in bedform generation and modification. In Ireland the dominance of smudged lineation patterns, which appear to record transitions in, or lower-order fluctuations of the first-order flow configuration, implies that the timescales of bedform manipulation were, in places, close to the timescales of ice dynamics. New templates have necessarily been developed to encapsulate the wide range of time-transgressive bedforming behaviour in Ireland. The dominance of these imprints has several implications for bedform genesis (and preservation), for reconstructing different orders of ice sheet dynamics, and for understanding the ice sheet's thermal regime. These questions will be returned to in thesis Section D. The final stage of flowset interpretation will consider all observations to reconstruct an evolutionary framework of the last Irish Ice Sheet (Chapter 9). To achieve this, a chronology of events is required.

8.3 Flowset chronology

It has already been shown that there is a wealth of evidence of a multi-temporal glacial record in Ireland. Extracting this temporal element is key to piecing together flowsets, the basic analytical units of the glacial record, into a reconstruction of snapshots of the ice sheet's history. Flowsets are currently two-dimensional map units. The final stage of flowset interpretation must tease out a third (temporal) dimension and build a chronological stack of flow patterns.

Temporal information is yielded by the full range of glacial evidence examined hitherto in this thesis. The main sources of information can be summarised as: i) palimpsest landscapes; ii) the glaciodynamic interpretation of flowsets; and iii) absolute chronological information gleaned from the published literature. The following sections discuss each of these, and from them document the temporal relationships present in the data. These temporal relationships can be considered as a set of 'rules' which any reconstruction of ice sheet stages must adhere to.

8.3.1 Palimpsest landscapes

8.3.1.1 Palimpsest landform patterns

Cross-cutting and superimposition of all landform types were described in Chapters 5 and 6. Superimposition is an inherently temporal relationship and, where this relationship is also cross-cutting, a time-varying ice flow direction must be invoked. Data summary as discrete flowsets maintains these landform associations and it is apparent from Figures 7.21 and 8.14 that flowset cross-cutting dominates the record. However, so far only its spatial pattern has been recorded. This section documents the temporal information held by landform arrangements.

All permutations of bedform superimposition exist: lineations on ribbed moraine, lineations on lineations, (minor) ribbed moraine on lineations, and ribbed moraine cross-cutting ribbed moraine. Lineations are always found on top of ribbed moraine where the two landform types are found in spatial coincidence. Minor ribbed moraine are an exception to this rule; in this dataset these are always revealed to superimpose lineations. These latter relationships provide two very simple temporal rules. More complex are the circumstances in which landforms of the same type are superimposed. The nature of the ribbed moraine – ribbed moraine relationship is such that with the available imagery resolution, any superimposition 'rules' these patterns yield are unlikely to be made with any confidence. For this reason cross-cutting ribbed moraine relationships are not considered further. Lineation – lineation superimposition is widespread and the temporal relationships are much more clear. Figures 7.21 and 8.14 reveal the locations where flowlines and flowsets cross-cut. With this guidance, the original imagery is reconsidered in order to document the instances and order of lineation superimposition.

Instances of cross-cutting and superimposed landform arrangements were marked by two flowlines, labelled older or younger. These superimposition markers were not drawn for every single instance, but may be representative of several landform relationships of the same order in a particular area. Figure 8.15 illustrates all sites in Ireland which yield temporal information from the superimposition of lineations. The superimposition markers are overlain upon the GIS layer of flowsets for visual comparison, and on the basis of the marker information rules of flowset chronology can begin to be built. All temporal information derived from the Irish bedform record in this way is presented in Table 8.4 and Figure 8.16.

8.3.1.2 Palimpsest sediment dispersal patterns

Implicit in identifying certain types of erratic dispersal pattern is the recognition of a *sequence* of events. Palimpsest dispersal fans (Figures 7.27e and 7.29e; Parent *et al.*, 1996) reveal the reworking of an earlier sediment dispersal pattern by a more recent ice flow direction. Deciphering the order of these ice flows may be based solely on the shape of the dispersal pattern, in which the straight or dominant edge is likely the most recent flow direction and the irregular edge is reworked. Alternatively, bedforms composed of a certain till lithology provide a known ice flow direction under which this till was moulded. It is assumed that this flow direction is the most recent since any later ice flow capable of reworking the dispersal pattern would disturb the spatial coincidence of till type with landform outline.

Erratic flowlines are attributed with the chronological information in the same way as for bedforms. The key patterns with a decipherable chronology have been labelled, and rules built as a relative chronology stack, as above (Figure 8.17). Three key stacks add information to that gleaned from the bedform record: a south-westerly ice movement must occur prior to any NW or SE bedform imprint across the midlands; the relationship between *er D* and *er E* may shed light on *lins fs9* and *fs11*; and in Donegal *er G* (*lins fs40, fs41*?) must come after a more northerly ice flow.

Table 8.4 Flowset relative chronological relationships

Flowset	Relationships	
	Overprints	Underlies
Lins 1	-	-
Lins 2	-	-
Lins 4	RM A	-
Lins 5	-	-
Lins 6	RM A	Lins 7
Lins 7	RM R, Lins 6	-
Lins 8	RM A, N, Lins 59	-
Lins 9	RM D, E, G, Q, K?, M?, Lins 10, 23	mrm b
Lins 10	RM Q, G?	Lins 9
Lins 11	RM G, H, I, K, L?	mrm b
Lins 12	RM G	mrm b
Lins 13	RM H	-
Lins 14	RM H	-
Lins 15	RM M, N,	Lins 16, 17, mrm a
Lins 16	RM N, Lins 15	mrm a
Lins 17	RM B, N, Lins 15	-
Lins 18	RM B	-
Lins 20	-	-
Lins 22	RM C	-
Lins 23	RM C, D, M	Lins 9
Lins 24	RM D, J	-
Lins 25	RM C	-
Lins 26	RM C	-
Lins 27	RM C	Lins 28
Lins 28	RM C, Lins 27	-
Lins 29	-	-
Lins 30	RM C	Lins 31
Lins 31	Lins 30	-
Lins 32	RM C, F, J	-
Lins 35	Lins 37	-
Lins 37	-	Lins 35
Lins 38	-	-
Lins 39	-	-
Lins 40	Lins 41?	Lins 42
Lins 41	-	Lins 42, 40?
Lins 42	Lins 40, 41	-
Lins 43	-	-
Lins 44	-	-
Lins 45	-	-
Lins 46	-	-
Lins 47	-	Lins 50?
Lins 48	-	-
Lins 49	-	-
Lins 50	RM P, L?, Lins 47?	-
Lins 51	-	-
Lins 52	-	-
Lins 53	RM F	-
Lins 54	-	-
Lins 55	-	-
Lins 56	-	-
Lins 57	-	-
Lins 58	-	-
Lins 59	RM N	Lins 8
Lins 60	-	-
Lins 61	-	-
Lins 62	-	-
RM A	-	Lins 4, 6, 8
RM B	-	Lins 17, 18
RM C	-	Lins 22, 23, 25, 26, 27, 28, 30, 32
RM D	-	Lins 9, 23, 24
RM E	-	Lins 9
RM F	-	Lins 32, 53
RM G	-	Lins 9, 11, 12, 10?
RM H	-	Lins 11, 13, 14
RM I	-	Lins 11
RM J	-	Lins 24, 32
RM K	-	Lins 11, 9?
RM L	-	Lins 11?, 50?
RM M	-	Lins 15, 23, 9?
RM N	-	Lins 8, 15, 16, 17, 59
RM P	-	Lins 50
RM Q	-	Lins 9, 10
RM R	-	Lins 7
mrm a	Lins 15, 16	-
mrm b	Lins 9, 11, 12	-
er A	-	er B, C
er B	er A	-
er C	er A	-
er D	er E	-
er E	-	er D
er F	-	er G
er G	er F	-

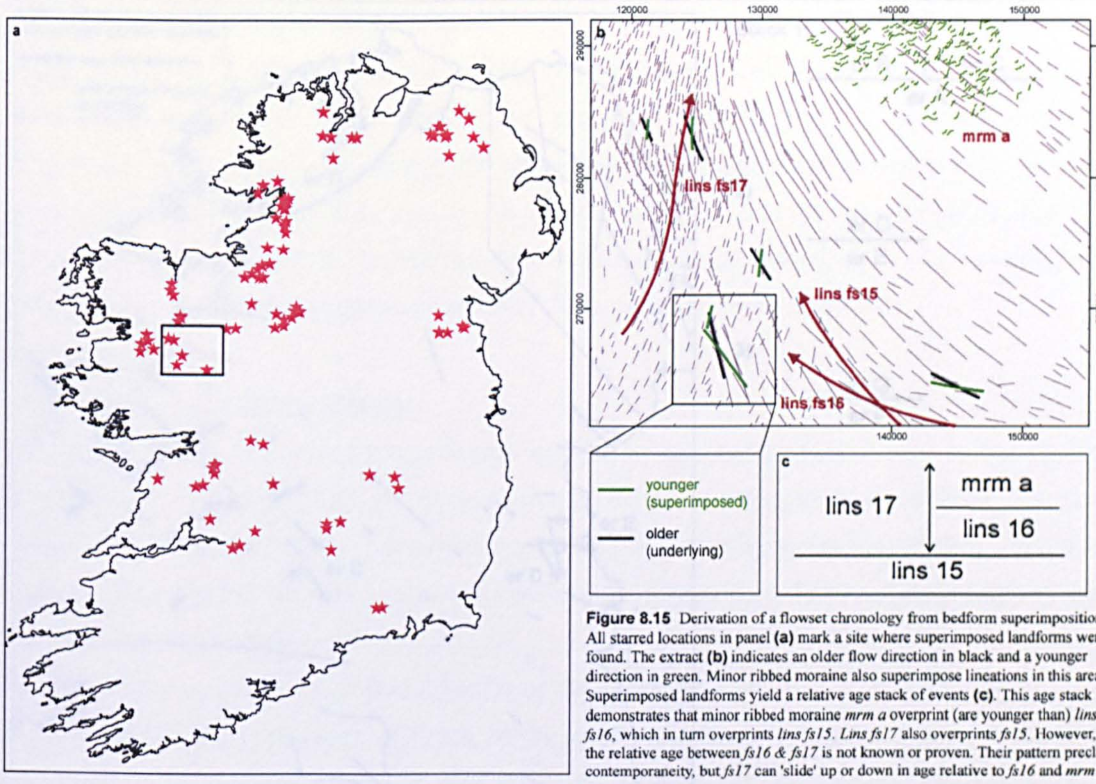


Figure 8.15 Derivation of a flowset chronology from bedform superimposition. All starred locations in panel **(a)** mark a site where superimposed landforms were found. The extract **(b)** indicates an older flow direction in black and a younger direction in green. Minor ribbed moraine also superimpose lineations in this area. Superimposed landforms yield a relative age stack of events **(c)**. This age stack demonstrates that minor ribbed moraine *mrm a* overprint (are younger than) *lins fs16*, which in turn overprints *lins fs15*. *Lins fs17* also overprints *fs15*. However, the relative age between *fs16* & *fs17* is not known or proven. Their pattern precludes contemporaneity, but *fs17* can 'slide' up or down in age relative to *fs16* and *mrm a*.

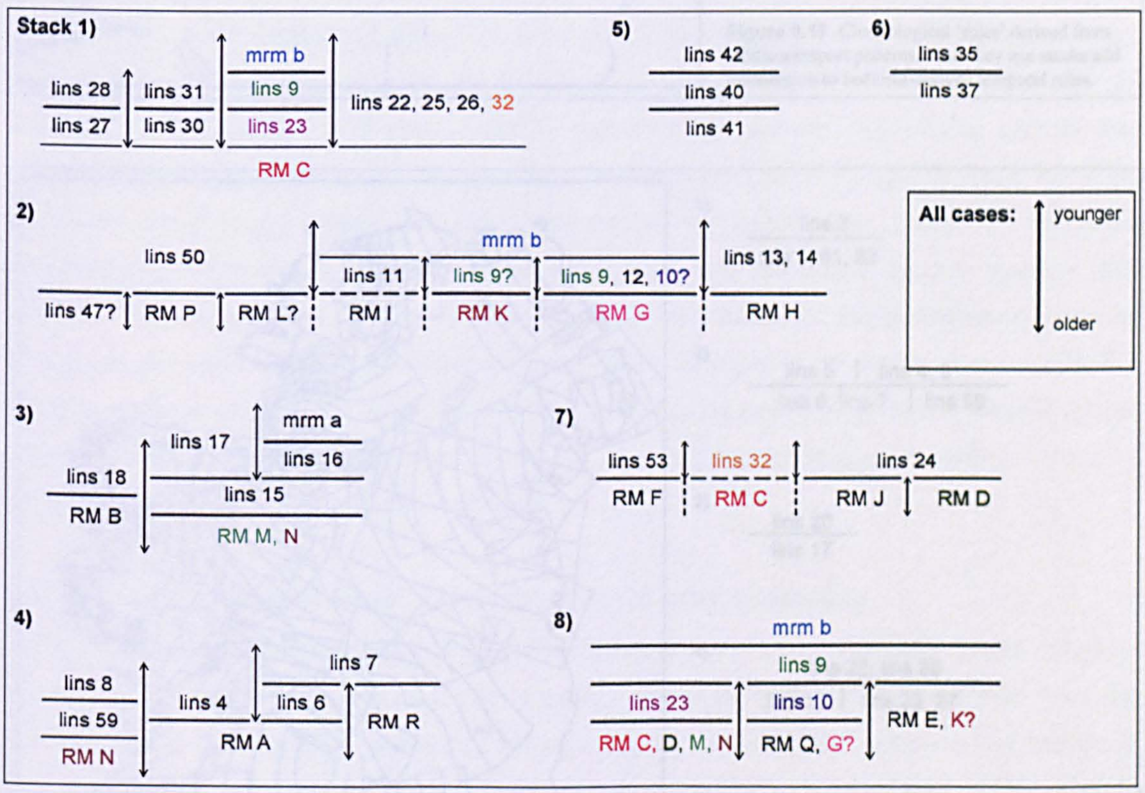


Figure 8.16 Relative age flowset stacks, derived from bedform superimposition information (see Table 8.4 for individual relationships). In each stack, a horizontal line denotes superimposition of flowsets, i.e. in stack 1 *lins fs28* overprints (is younger than) *lins fs27*, and *lins fs31* is younger than *fs30*. However, the relative age relationship between these two pairs is not known or not proven, so the pairs are divided by a vertical double arrow and each can 'slide' up or down in relative age. Commas do *not* imply contemporaneity, merely that both (or all) flowsets possess the same relative age relationship with an underlying or overlying flowset: in stack 1 *lins fs22, 25, 26 & 32* are all younger than *rm fsC* but no comment on the contemporaneity of the lineation flowsets is made. Dashed lines stylistically represent 'open doors' in the age stack: in stack 7, for example, *lins fs32* overprints *rm fsF, C & J*, but not *rm fsD*; *lins fs24*, meanwhile, overprints just *rm fsJ & D*. Note the complex interrelationships between bedform flowsets and the occurrence of single flowsets in multiple chronological stacks (colour coded to facilitate tracing across stacks).

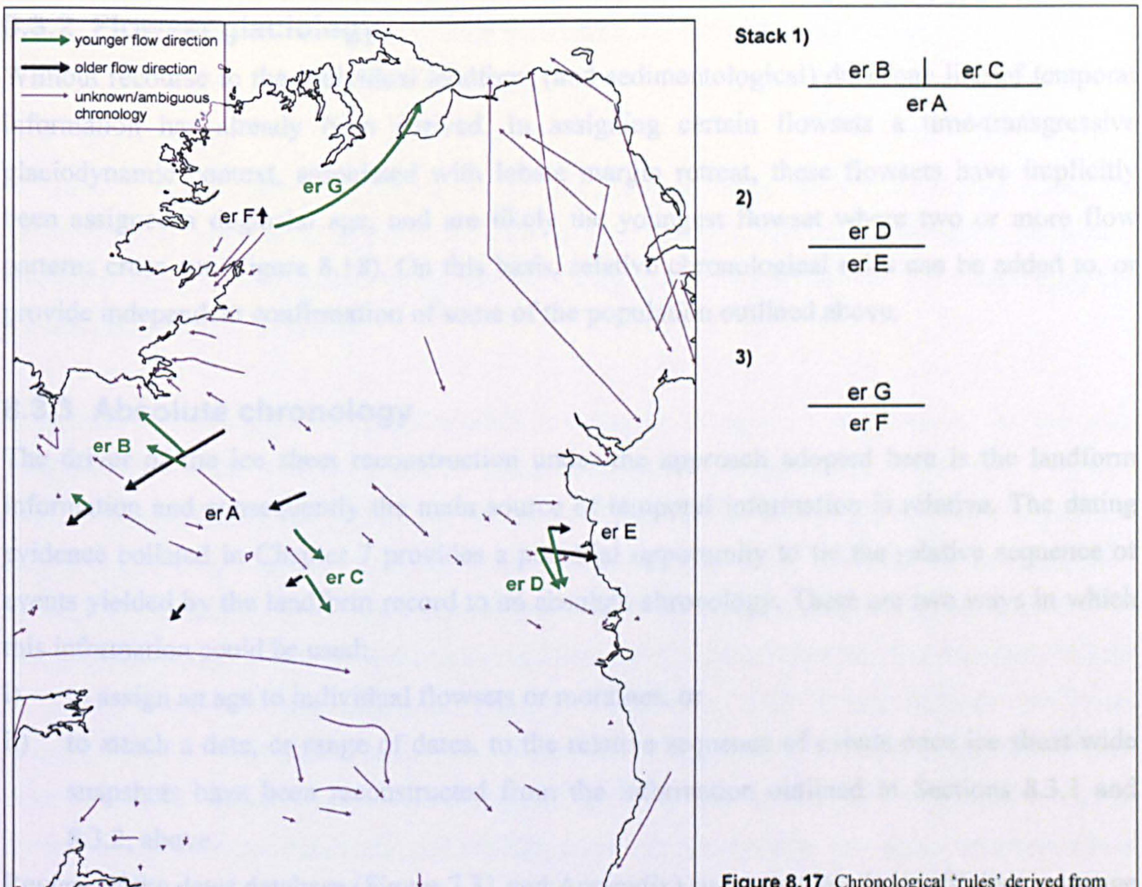


Figure 8.17 Chronological 'rules' derived from erratic transport patterns. Three key age stacks add information to bedform-derived temporal rules.

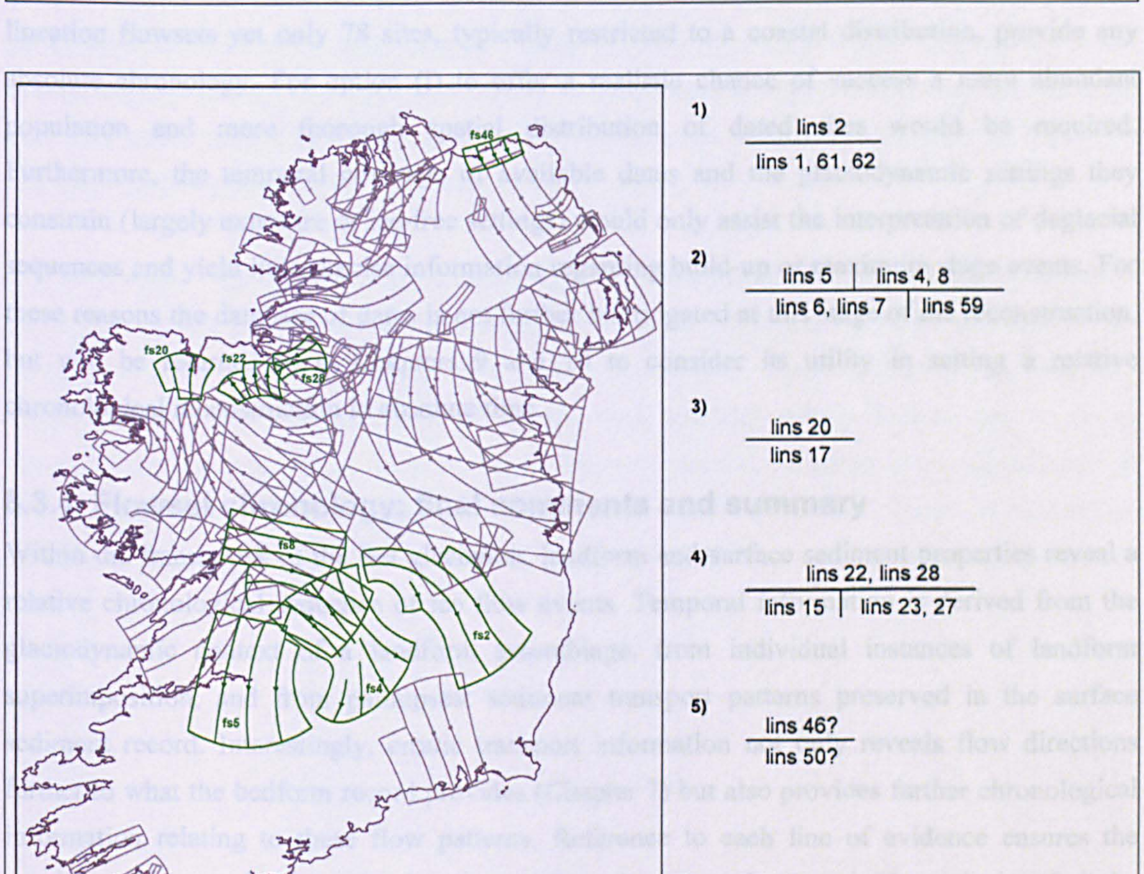


Figure 8.18 Flowsets assigned a time-transgressive, margin retreat glaciodynamic context (deglacial) confirm (Stacks 2 & 4) and add (Stacks 1, 3, 5) temporal information to the rules established from the bedform record.

8.3.2 Flowset glaciology

Without recourse to the individual landform (and sedimentological) data, one line of temporal information has already been derived. In assigning certain flowsets a time-transgressive glaciodynamic context, associated with lobate margin retreat, these flowsets have implicitly been assigned a deglacial age, and are likely the youngest flowset where two or more flow patterns cross-cut (Figure 8.18). On this basis, relative chronological rules can be added to, or provide independent confirmation of some of the population outlined above.

8.3.3 Absolute chronology

The driver of the ice sheet reconstruction under the approach adopted here is the landform information and consequently the main source of temporal information is relative. The dating evidence collated in Chapter 7 provides a potential opportunity to tie the relative sequence of events yielded by the landform record to an absolute chronology. There are two ways in which this information could be used:

i) to assign an age to individual flowsets or moraines, or
ii) to attach a date, or range of dates, to the relative sequence of events once ice sheet-wide snapshots have been reconstructed from the information outlined in Sections 8.3.1 and 8.3.2, above.

Review of the dates database (Figure 7.31 and Appendix) suggests there is insufficient coverage and consistency of information for the former to be a worthwhile approach. There are ~60 lineation flowsets yet only 78 sites, typically restricted to a coastal distribution, provide any absolute chronology. For option (i) to offer a realistic chance of success a more abundant population and more thorough spatial distribution of dated sites would be required. Furthermore, the temporal coverage of available dates and the glaciodynamic settings they constrain (largely exposure or ice-free settings) would only assist the interpretation of deglacial sequences and yield little precise information regarding build-up or maximum stage events. For these reasons the database of dates is not further interrogated at this stage of the reconstruction, but will be returned to in Chapters 9 and 10 to consider its utility in setting a relative chronological reconstruction in absolute time.

8.3.4 Flowset chronology: final comments and summary

Within the framework of the last glaciation, landform and surface sediment properties reveal a relative chronological sequence of ice flow events. Temporal information is derived from the glaciodynamic context of a landform assemblage, from individual instances of landform superimposition, and from palimpsest sediment transport patterns preserved in the surface sediment record. Interestingly, erratic transport information not only reveals flow directions further to what the bedform record provides (Chapter 7) but also provides further chronological information relating to these flow patterns. Reference to each line of evidence ensures the maximum amount of information is extracted from the composite record. The majority of all the information units which are input to a reconstruction (i.e. flowsets and ice flowlines) may consequently be positioned within a series of relative age-stacks. These age-stacks are the temporal rules which govern a time-space reconstruction of the Irish Ice Sheet.

8.4 Summary

In Chapter 7 the spatial properties of the Irish glacial record were synthesised. Here, the glaciodynamic and chronological information held by this record is extracted. Individual landform arrangements, spatial properties and topographic contexts are the key to revealing the palaeo-glaciology of a flowset.

A number of existing conceptual models, developed in light of observations of the Irish landform record, serve as templates for the glaciodynamic interpretation of flowsets. Two new models further clarify the glaciodynamic context revealed by a time-transgressive imprint. A fluctuating or migrating flowline whilst the bedforming process is continual better describes a number of 'smudged' landform assemblages within the Irish record, which enables a more comprehensive interpretation of the palaeo-glaciology of all Irish flowsets. Several insights may be drawn from their glaciodynamic context. There is a lack of key features which are characteristic of cold-based conditions. There is an abundance of time-transgressive flow imprints which record frequent reworking of the bed; this in turn has implications for the dynamism of ice sheet behaviour and configuration change. Finally, the spatial arrangement of flowsets of different glaciodynamic contexts has implications for the evolution of the ice sheet geometry. Isochronous flowsets are found mostly in the west recording flow offshore onto the continental shelf. Flowline migration and margin retreat imprints are more constrained to the present-day landmass. This spatial arrangement may indicate reorganisation of the ice sheet geometry and a change in its pattern of behaviour between the maximum period of glaciation and the deglacial phases of the ice sheet history.

The derivation of a flowset relative chronology is facilitated primarily by recourse to records of palimpsest landscapes, either geomorphological or sedimentological. A series of relative age-stacks have been built from interpretation of these landscapes. It is encouraging that these age-stacks can each link a number of different flowsets, and that certain flowsets can be traced through more than one stack; this complexity suggests there is sufficient temporal information to be able to tie flowsets together across both space and time. These chronological interpretations provide the primary set of 'rules' to which any ensuing reconstruction must adhere.

Chapter 9. Reconstruction of the last Irish Ice Sheet

9.1 Introduction

Reconstruction of an ice sheet should ideally provide us with the locations of ice divides, ice flow paths, ice sheet extent, its retreat patterns and a chronology for the attainments of and changes in each of these ice sheet elements. It should ideally account for the entire geological and geomorphological legacy of glaciation in a glaciologically plausible manner. It is the aim of this thesis to contribute towards these objectives.

Flowsets and their associated palaeo-glaciological interpretations form a series of analytical units each of which describes a particular state of the ice sheet in a particular location. The challenge of a reconstruction is to piece these units together geometrically and chronologically, i.e. to work out how and in what sequence they fit, such that a coherent picture of the ice sheet emerges at snapshots in a temporal sequence. Building a reconstruction can be likened to a jigsaw puzzle, except the jigsaw pieces (flowsets) must be put together in both space and in time. To build the jigsaw, we need a set of rules to play by.

9.2 Principles & procedure for building an ice sheet reconstruction

The primary suite of rules to which any reconstruction must adhere are the temporal relationships set out in Chapter 8. All relationships described in Table 8.4 and Figures 8.16-8.18 should be obeyed. Furthermore, flowsets must not only be grouped appropriately in space and time, but we wish to determine their requisite ice divide locations, margin positions and overall ice sheet configuration. To achieve this some additional interpretative guidelines are required.

9.2.1 Principles for ice sheet reconstruction

Flowsets are built into an ice sheet reconstruction with reference to a series of principles or assumptions describing an ice sheet's structure and behaviour. These are based on modern ice sheet analogues and current understanding of glaciological process, and govern how ice sheet properties (i.e. ice divides, ice extent, flow routes) are reconstructed from flow pattern imprints. The principles adopted are considered here.

1. Symmetry and structure. Ice sheets tend towards simple, roughly symmetrical structures. Modern ice sheets are characterised by main ice divides, passing approximately through the geometric centre of the ice sheet (i.e. they are ~symmetrical), with a branching, ordered structure of subsidiary divides (Figure 9.1). These sub-divides separate the ice sheet into individual catchments in the same way that fluvial catchments provide structure to a fluvial landscape. Ice emanates from all divides in an approximately radial fashion. This geometry describes an ice sheet which is stable and in steady state. Profile asymmetry can be induced by features or conditions which perturb the ice sheet from steady state, the most likely candidate for which would be ice streaming, with a lower basal shear stress and a more 'slippery' bed, causing drawdown of ice on one side of a divide only. Boulton and Clark (1990b) and Boulton *et al.* (2001) follow this model of ice sheet structure to reconstruct the Laurentide and Fennoscandian ice sheets, respectively.

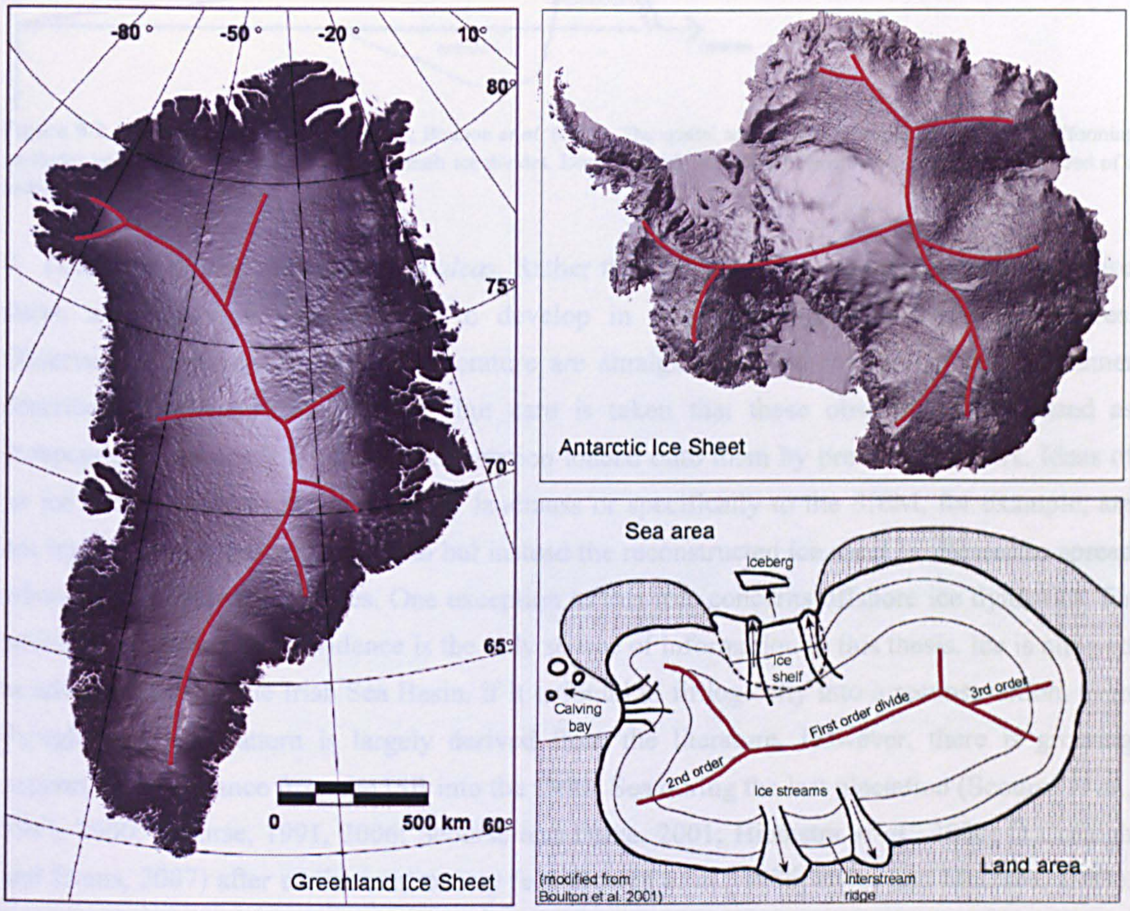


Figure 9.1 The ice divide structure of ice sheets. DEM images from Bamber (2006) and NSIDC.

2. *False divides.* Bedforming occurs a distance downstream of divides. Directly underneath an ice divide there is very little lateral ice flow and these regions are hypothesised to be zones of landscape preservation rather than landform generation (Figure 9.2). Divide positions should therefore be reconstructed some distance upstream of the head of a bedform imprint. Where separate bedform imprints diverge from within close proximity, it would be false to locate a divide between the two patterns. Rather, the migration of an ice divide across the region must be invoked. That is, two separate ice sheet configurations are required with the ice divide at different positions, between which time a divide migration is interpreted.

3. *Multi-temporal record.* Landforms in Ireland clearly display a multi-temporal record. Consequently, changes in ice sheet configuration are required for explanation of this record: the responsible flowlines alter and therefore the requisite divide locations and ice sheet extent are expected to change.

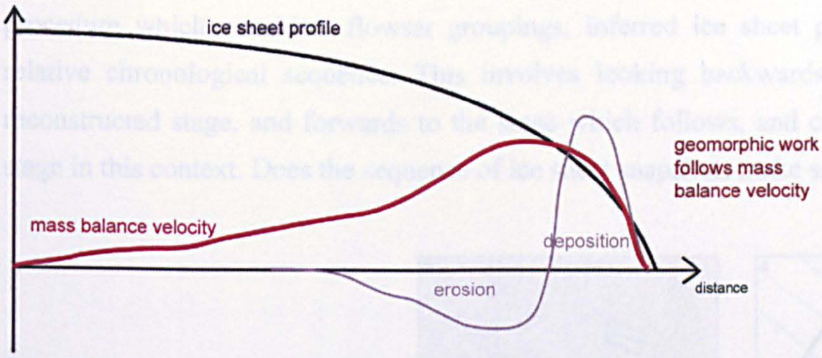


Figure 9.2 After Boulton and Clark (1990b); Boulton *et al.* (2001). The spatial arrangement of zones conducive to bedforming precludes landform genesis close to or underneath ice divides. Divides should therefore be positioned *upstream* of the head of a bedform imprint.

4. *Detachment from pre-conceived ideas.* Rather than impose pre-conceived models of the ice sheet, a reconstruction is allowed to develop in whichever way the evidence requires. Observations reported in previous literature are amalgamated and interpreted in the manner described in Chapters 6, 7 and 8, but care is taken that these observations are used as independently as possible of the interpretation loaded onto them by previous workers. Ideas of an ice sheet limited to the present-day landmass or specifically to the SIEM, for example, are not imposed upon the reconstruction but instead the reconstructed ice sheet is allowed to spread wherever the evidence requires. One exception to this rule concerns offshore ice dynamics, for which literature reported evidence is the only source of information to this thesis. Ice is allowed to advance through the Irish Sea Basin, if it is found to fit logically into a reconstruction, even though this flow pattern is largely derived from the literature. However, there is growing support for an advance from the ISB into the Celtic Sea during the last glaciation (Scourse *et al.*, 1991, 2000; Scourse, 1991, 2006; Scourse and Furze, 2001; Hiemstra *et al.*, 2006; Ó Cofaigh and Evans, 2007) after earlier controversy (e.g. Bowen *et al.*, 1986; Eyles and McCabe, 1989). No other flow patterns or ice sheet properties are imposed upon this reconstruction.

5. *Rule of minimum complexity.* Where uncertainty or alternative reconstruction options exist the principle of simplicity is adopted. Any reconstruction, at either a local, regional or ice sheet-scale, is no more convoluted than the evidence demands.

9.2.2 Procedure for ice sheet reconstruction

There are several conceptual stages of ice sheet reconstruction, which are iterative until a solution is found which meets all the principles set out above and the temporal rules established in Chapter 8. Some flowset groups tell coherent stories of the regional ice sheet history, which can be interpreted independently. For the integration of regionally coherent stories with the full flowset record in an ice sheet-wide reconstruction, groups of flowsets which could feasibly occur at the same time, and belong to the same ice sheet configuration, are sought (e.g. Figure 9.3). Two approaches may be followed. Either the lowermost flowsets should be isolated, ice sheets drawn, and work forwards in time. Alternatively, the deglacial or youngest envelope of flowsets should be extracted, a retreat pattern determined, and then with the remaining flowsets work backwards in time. In reality, elements of both strategies are adopted in an iterative procedure which considers flowset groupings, inferred ice sheet properties and a plausible relative chronological sequence. This involves looking backwards in time to the previous reconstructed stage, and forwards to the stage which follows, and considering the intervening stage in this context. Does the sequence of ice sheet snapshots make sense?

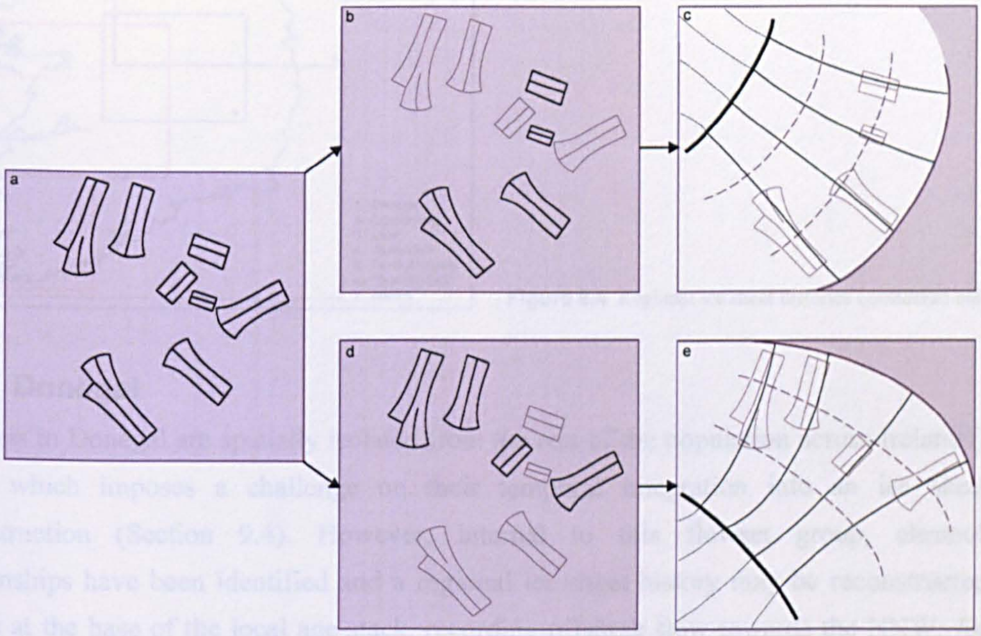


Figure 9.3 From an assemblage of flow patterns **(a)**, certain flowsets are aggregated into larger groups **(b,d)** which could feasibly represent a snapshot of the ice sheet **(c,e)**. Based on the properties of these flowsets, the ice divide location, margin position, flowlines and formlines may be inferred. A rule of minimum complexity always applies. See text below for further clarification of the reconstruction of ice sheet properties.

The procedure of drawing ice sheet properties invokes the principles set out in Section 9.2.1, above. Divides should be positioned upstream of a flowset, or group of flowsets; the ice sheet margin should be located downstream; flowlines should join the ice divide to the margin, passing parallel to each individual flowset; and an overall ice sheet configuration depicted which is roughly symmetrical and has an ordered divide structure. Ice sheet properties should be drawn in the simplest manner, with reference to broad-scale topography and application of a rule of minimum complexity (as for building individual flowsets). Margins, for example, are depicted as smooth, cartographically stylised lines, which is the simplest interpretation of spatially separate flowsets which could, alternatively, have formed behind a highly crenulated margin. In essence, the ice sheet configuration is the final stage of data reduction and consequently it must be a simplified representation of reality.

9.3 Regional ice sheet histories

Every region of landform evidence tells a story of its ice sheet history in its own right. Assessing what each regional group of flowsets reveals palaeo-glaciologically is an important step in deducing which groups plausibly fit with each other at an ice sheet-wide scale. In many cases, these regional histories reveal insights which are just as interesting (and interpretatively more secure) as the full ice sheet-wide reconstruction. A selection of regional histories are considered here (Figure 9.5), before their full integration into an ice sheet-wide reconstruction.

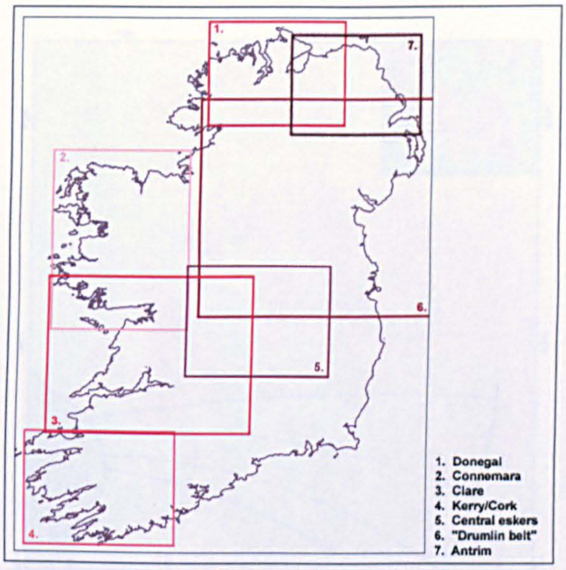


Figure 9.4 Regional ice sheet histories considered below.

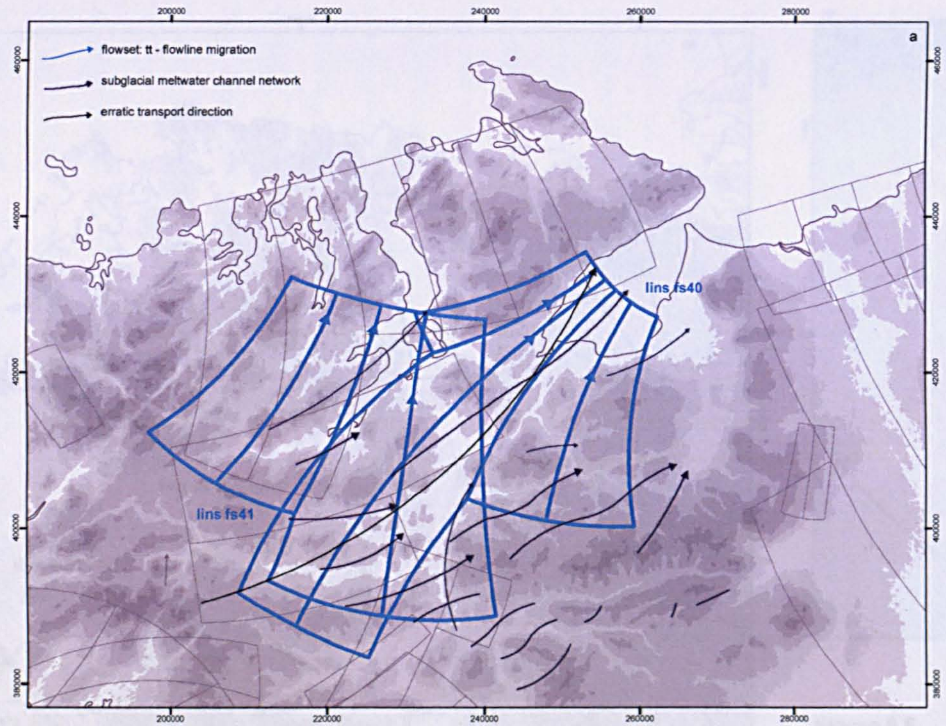
9.3.1 Donegal

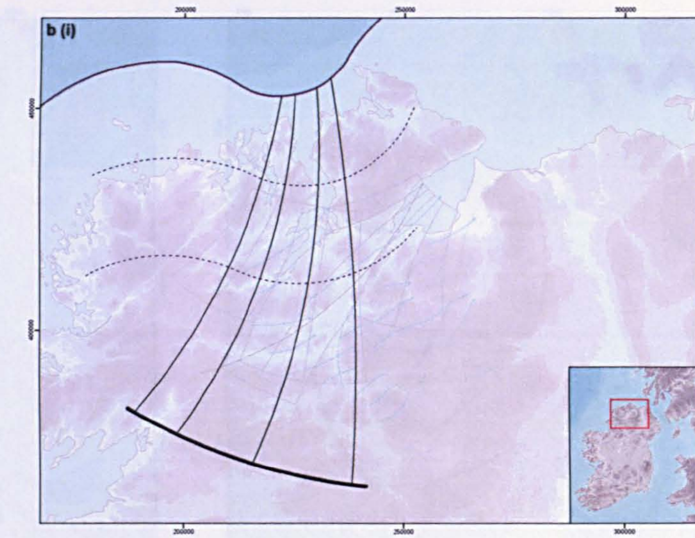
Flowsets in Donegal are spatially isolated from the rest of the population across Ireland (Figure 9.5a), which imposes a challenge on their temporal integration into an ice sheet-wide reconstruction (Section 9.4). However, internal to this flowset group, chronological relationships have been identified and a regional ice sheet history may be reconstructed. *Lins fs39* is at the base of the local age-stack, recording offshore flow towards the NNW; *lins fs42* postdates all other flow patterns and records late stage glaciation with a strong topographic control, i.e. valley constrained. The main 'story' of interest involves *lins fs40* and *fs41*, flowing approximately NE, and which occur (temporally) between these early and late bounding events. These flowsets display a spatial and directional coincidence with Charlesworth's (1924) Barnesmore granite dispersal, and with a large meltwater channel system identified by the present mapping and by Colhoun (1970), which penetrates the Sperrin Mountains, crossing them at an oblique angle via deeply incised channels in the valley floors.

To account for these ice flow patterns, an ice divide must be positioned at least as far south as the Bluestack Mountains. In Chapter 8, in which it was proposed that the glaciodynamic context of these flowsets fits a model of flowline migration in response to drawdown into calving bays. The available chronological information, deduced (speculatively, in this particular case) from landform superimposition relationships, suggests that *fs41* is first drawn into Lough Swilly and, subsequently, when Lough Foyle opens as a calving bay, flow is drawn through this new bay from its original outlet (*fs40*) (Figure 9.5b). This model infers a deglacial timing, when the Malin Shelf and North Channel reopened to marine water, creating successive calving environments in Loughs Swilly and Foyle, west and east of the upland Inishowen peninsula.

9.3.2 Connemara

The highlighted assemblage of ice flow information in Co. Mayo (Figure 9.6a) is similarly spatially isolated, at the western extremity of the onshore mapping programme. Some chronological information is available from landform superimposition: *lins fs17* clearly





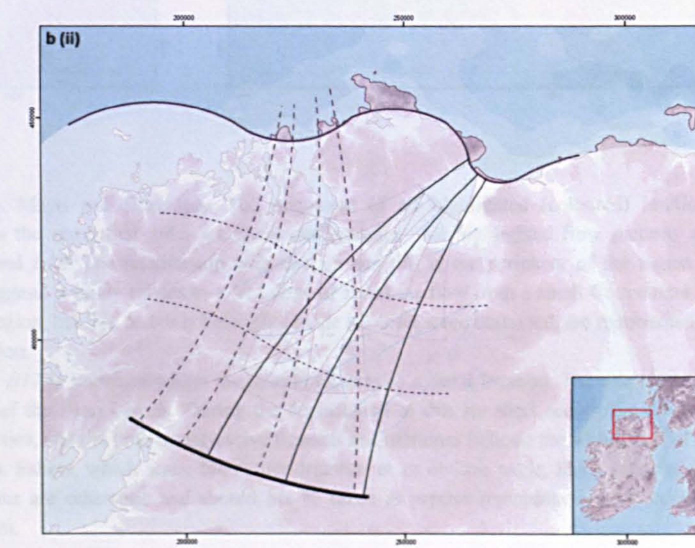
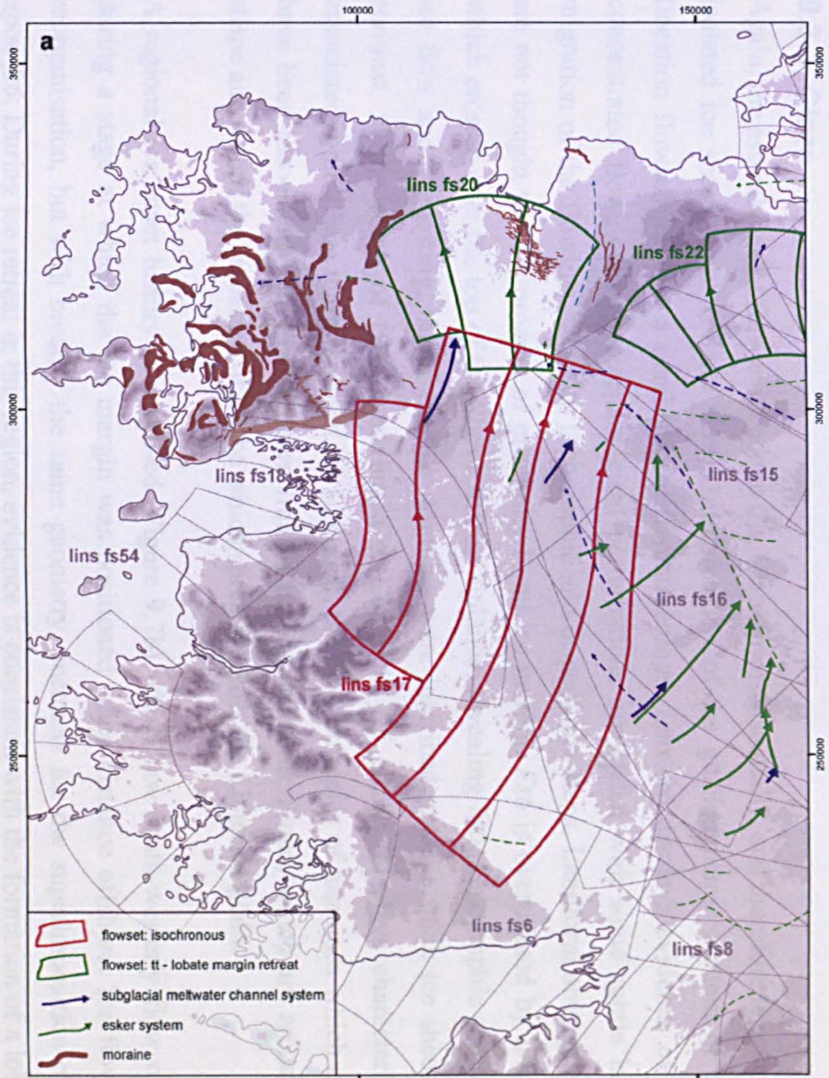


Figure 9.5

a) Landform evidence in Cos. Donegal and Londonderry. Flowsets are spatially isolated from the rest of Ireland but internal to the flowset group here there is identifiable chronological information. *Lins fs40* and *fs41* are aligned with erratic dispersal patterns and a large meltwater channel system. Flowsets which likely relate to other ice sheet phases are shown in grey. Scale: gridmarks at 20 km.

b) This landform assemblage can be captured by a model of drawdown into calving bays (Loughs Swilly and Foyle). As the ice margin retreats from the Malin Shelf towards the present-day coastline, calving bays develop in turn in these sea loughs, drawing ice flowlines to these discharge outlets. The ice divide must be located at least as far south as the Bluestack Mountains. (These reconstruction diagrams are schematic and should not be taken as precise representations of ice sheet properties.) Scale: gridmarks at 50 km.



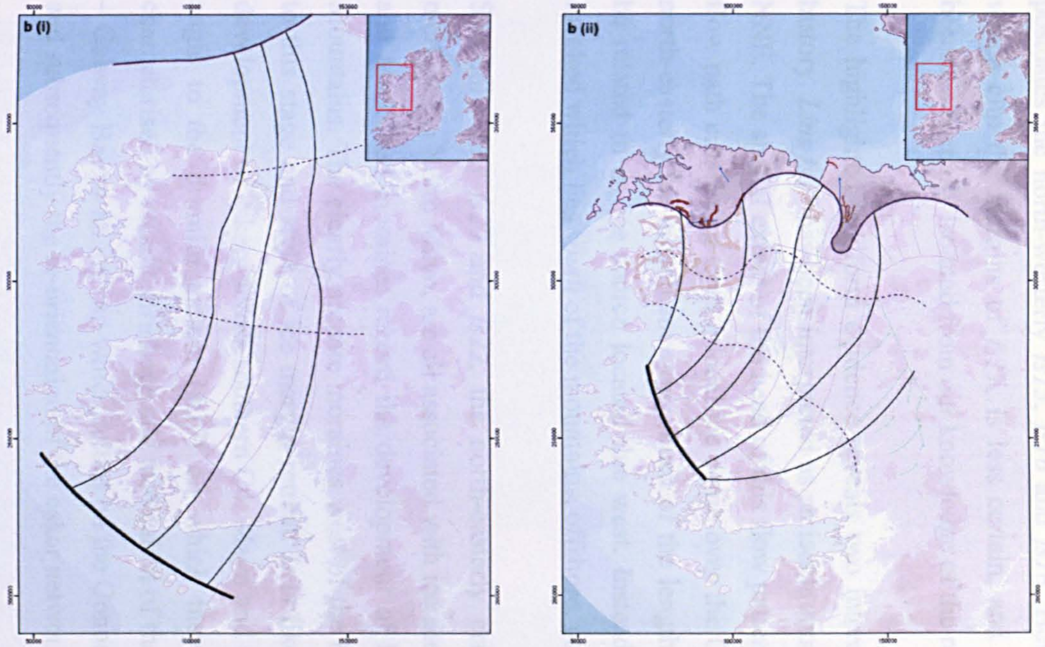


Figure 9.6

a) Landform assemblages in Co. Mayo and surrounds. The alignment of all highlighted (coloured) landform assemblages suggests they relate to the same first-order ice sheet configuration. All highlighted flow patterns and landforms postdate *lins fs15*, *fs16* and *fs18*. The relationship with *lins fs6* and *fs8*, at the periphery of the region, is unknown. The shape of *lins fs54* suggests it likely relates to a late stage of radial ice flow from a small Connemara ice cap. Meltwater systems within this region, but less certainly belonging to the ice sheet stage described, are represented by dashed lines. Scale: gridmarks at 50 km.

b) A model is interpreted in which *fs17* is inscribed whilst the margin remains in a distal location. The associated ice divide is positioned in the vicinity of the Aran Islands. During the deglaciation of this ice sheet sector, the divide is repositioned over the onshore mountains, and the time-transgressive flowsets and moraines indicate the withdrawal of the ice margin onshore in a lobate form. Eskers, which drape the earlier drumlins at an oblique angle, likely relate to this stage. (These reconstruction diagrams are schematic and should not be taken as precise representations of ice sheet properties.) Scale: gridmarks at 50 km.

postdates the north-westerly *fs15*, *fs16* and *fs18*. However, its relationship with *fs6* and *fs8*, which clip the margins of *fs17*, is less certain, and the 'story' in which *fs17* fits therefore becomes partially isolated from our knowledge of the rest of the ice sheet's history.

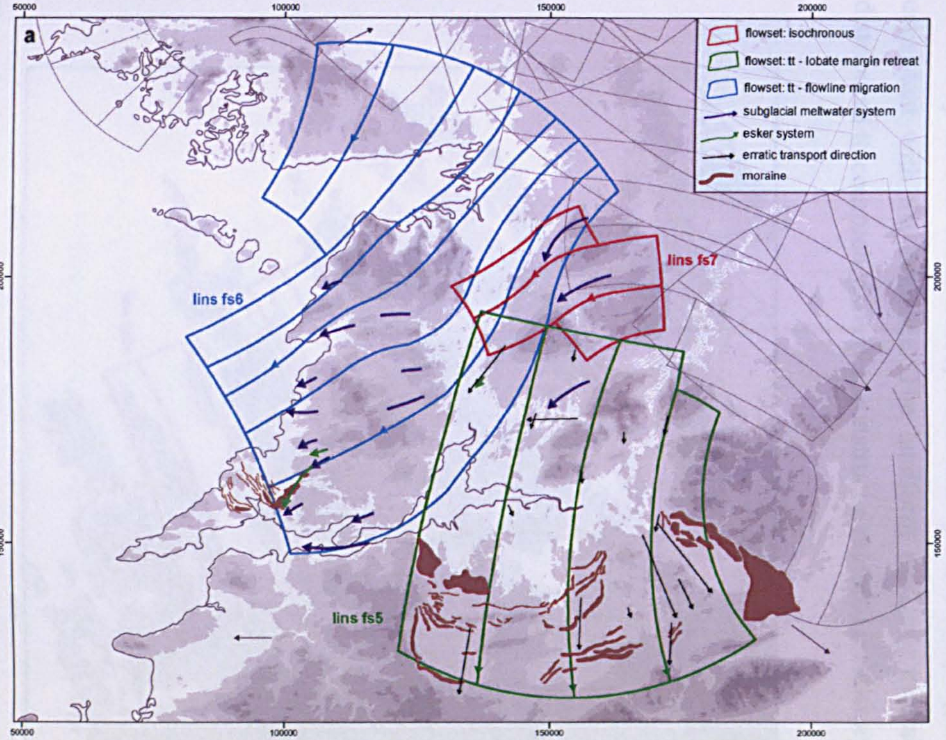
The highlighted landform evidence reveals two interesting elements of the regional ice sheet history. *Lins fs17* has been interpreted as an isochronous lineation flowset, flowing from SW to NNE. The spatial extent of the head of this flow pattern precludes the simple interpretation of a flow path emanating from a local ice dome over the Connemara mountains. Drumlins indicate north-easterly ice movement along much of the length of Lough Corrib, which cannot feasibly be related to an ice source located due west. Instead, a more substantial ice divide must be invoked which lies *south* of the mountains, offshore, potentially across or near the Aran Islands.

Secondly, *lins fs20* and *fs22*, the north-easterly oriented esker systems and the suites of moraines in North Mayo, are all associated with ice sheet retreat. The time-trangressive flowsets and associated moraines record the development of lobes in Killala Bay and around the Ox Mountains. The clearly arcuate moraines west of the Nephin Range could also feasibly belong to this stage and style of ice margin retreat. It is likely that this stage is responsible for the development of eskers across southern Co. Mayo and northern Galway, which lie at an oblique angle to the drumlin pattern (*fs17*) on which they are draped. A model of deglaciation characterised by steady shrinkage and movement of the earlier ice divide from the Aran Islands – Galway Bay to an ice cap which settles on the Connemara mountains would capture first *fs17* and subsequently the re-orientation of the esker network during margin retreat (Figure 9.6b).

9.3.3 Clare

Again, the assemblage of flow evidence in Co. Clare forms a spatially, and therefore temporally, isolated ice sheet sector (Figure 9.7a). Interpretation of the glaciodynamic context of these lineation flowsets reveals a number of different settings. *Lins fs6* displays evidence of fast, concentrated flow, with geomorphological perturbations associated with some subtle lateral migration of the flowline and with topographic and/or geologic steps. Landform arrangements are not thought to be a product of proximity to an ice margin. *Fs6* is overprinted by *lins fs7*, which crosses over the top of the Slieve Aughty uplands, revealing little topographic control of ice flow and suggesting, therefore, that drumlins were inscribed under a thick ice sheet. By contrast, in the south of Clare and into Co. Limerick, *fs5* clearly displays characteristics associated with lobate margin retreat. In Limerick, the best examples of moraines which could have been associated with the Southern Ireland End Moraine are found, which are arcuate in shape and record the recession of a lobe which spreads across the Limerick plain.

A regional ice sheet history is proposed (Figure 9.7b) which saw south-westerly flow of ice during a stage at which the ice margin was positioned some distance offshore. Ice flowline reorganisation, but with broadly the same geometry, accounts for the superimposition of *fs7* upon *fs6*. During ice retreat in this region, evidence is consistent with the formation of a lobe of



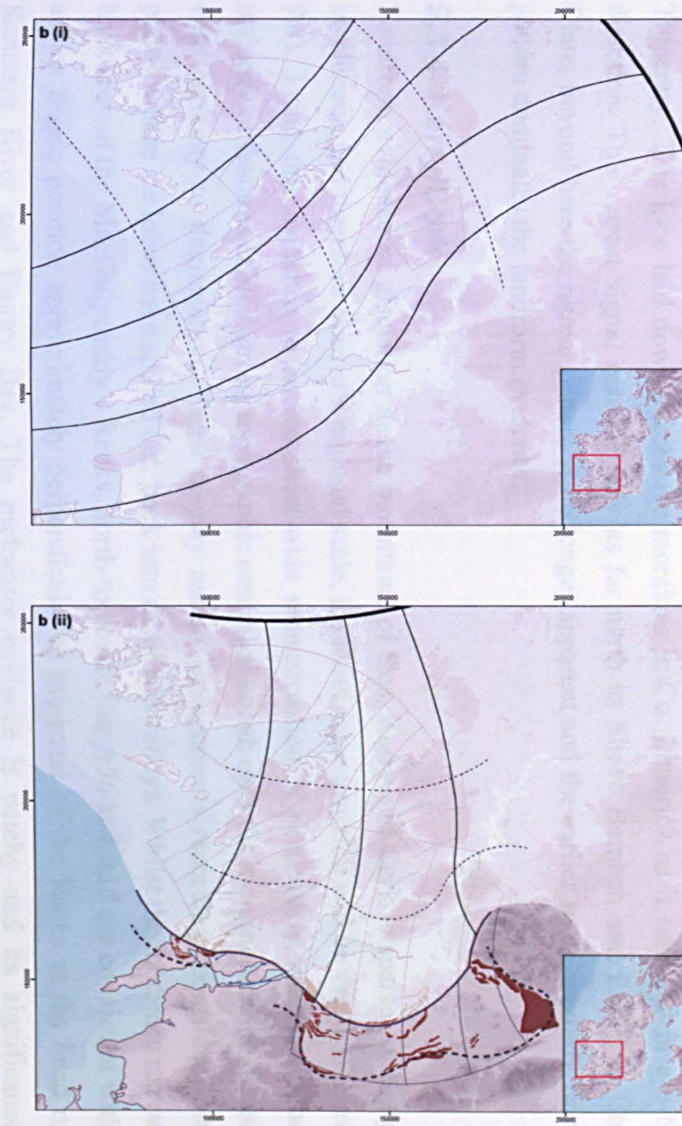


Figure 9.7

a) *Lins fs6* and *fs7*, and associated meltwater landforms, are interpreted as belonging to a separate time period to *fs5* and its associated moraines, which are interpreted as the final deglacial signature. Unrelated flowsets are in grey. The highlighted landform assemblages shown are underlain by ribbed moraine around Slieve Bernagh, recording an earlier ice flow perpendicular to those revealed here (south-eastwards); this field is not shown to preserve the clarity of the figure. Scale: gridmarks at 50 km.

b) Two distinct stages are interpreted. First, south-westerly ice flows to an offshore margin. The requisite ice divide for this flow pattern is located over the central lowlands of Ireland; it potentially extends in a N-S direction over Slieve Bloom to account for *lins fs7*. During the later retreat, the flow direction is more N-S aligned and the ice divide must be positioned in Mayo/Galway. The margin splays into lobes which successively deposit moraines during their retreat. (These reconstruction diagrams are schematic and should not be taken as precise representations of ice sheet properties.) Scale: gridmarks at 50 km.

ice across the Limerick plain, pinned between the high ground of Cos. Kerry, Cork and Tipperary. This lobe laid down successive moraines in Co. Limerick as it retreated in a S-N direction. This retreat signal extends only as far north as Slieve Bernagh and Ennis, in Co. Clare; beyond here the retreat pattern is no longer apparent and the earlier south-westerly flow pattern dominates the landform evidence.

9.3.4 Kerry/Cork

Landform evidence of glaciation in the mountains of Cos. Kerry and Cork is sparse, spatially incoherent, and therefore even at a regional scale, ice sheet reconstruction will be vague (Figure 9.8). Tying this evidence to an ice sheet-wide reconstruction is particularly uncertain. The majority of features exhibit strong topographic control although only the moraines can be linked with certainty to deglaciation. These display nested arrangements recording recession from plains, where ice lobes have spilled out, back into mountain valleys. Whilst the moraines retreat back around the MacGillycuddy's Reeks, north-to-south, *lins fs56* and *fs58* are consistent with an ice divide position approximately perpendicular to the trend of the Reeks at the head of Kenmare River and Bantry Bay. The meltwater evidence is patchy and its significance uncertain, but displays a strong east-west trend across the whole region. This region either displays a multi-temporal record, with several separate stages of ice sheet history, or several subsidiary ice sources operated, controlled by the underlying topography. Both options could be consistent with the evidence. The landform evidence available at this scale is too sparsely distributed to comprehensively reconstruct a regional ice history for the Kerry/Cork mountains.

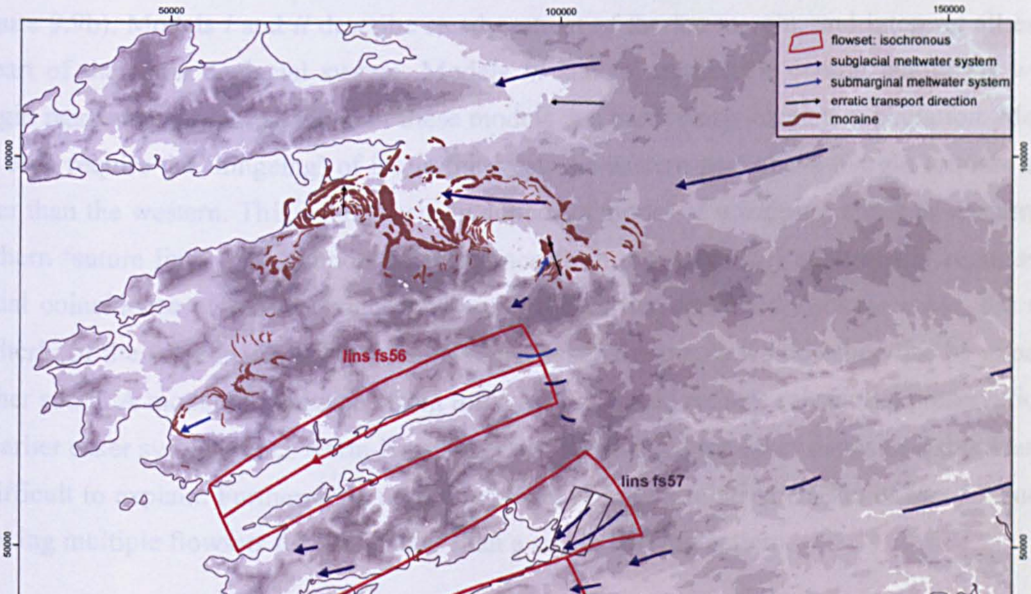


Figure 9.8 Landform evidence in Cos. Kerry and Cork. Flowsets and other landform information are sparsely distributed and spatially isolated from the rest of the ice sheet. Ice margin retreat on the Iveragh Peninsula can be relatively well reconstructed, in places, from moraines. However, the final ice dome configuration is likely different to that which generated *fs56* & *fs58*, which require an ice divide across the head of Kenmare River and Bantry Bay. Scale: gridmarks at 50 km.

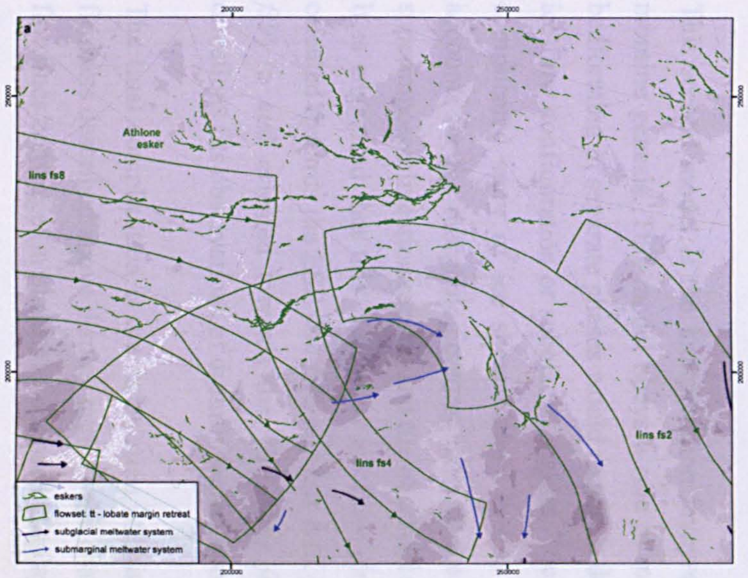
9.3.5 The central eskers

The central lowlands of Ireland are filled with a myriad of flow patterns which overprint and cross-cut each other, yielding an abundance of geometric, glaciodynamic and temporal information about the ice sheet history. It is the crux region of the whole ice sheet, where peripheral flow patterns meet at their headward extent. It also provides two regional stories of its own, revealed by the central esker system, and by the swathe of bedforms traditionally referred to as the 'drumlin belt'.

The region occupied by the central eskers yields retreat pattern information. Eskers provide deglacial information, and the bedform patterns with which they are most closely and clearly associated are interpreted as time-transgressive records of lobate margin retreat (Figure 9.9a). However, the retreat information held by these landform assemblages is not easily extracted; more than one model of retreat could provide an explanation for their disposition. The problem lies in the regional-scale interpretation of the eskers. Eskers are known to form dendritic networks, but those in central Ireland appear to be at the threshold of what may be considered a single, dendritic system. Confluences are sharp, to the extent that some junctions suggest a more trellised than dendritic arrangement, meeting almost at right angles. The most severe examples of this arrangement lie along the most northerly of the three main W-E eskers, the Athlone esker. Potentially more than one system and, consequently, more than one recorded phase of margin retreat, must be invoked.

Four models could account for the eskers and associated bedform flowsets in central Ireland (Figure 9.9b). Models *i* and *ii* describe steady retreat of the ice margin, and interpret all eskers as part of the same deglacial system. Models *iii* and *iv* capture the central landforms within margin readvance scenarios. None of these models is a particularly elegant explanation. Models *i-iii* each require the 'hingeing' of ice in the west: the eastern part of the margin retreats much faster than the western. This would seem to support a model of unzipping along an eastern and northern 'suture line' (*ii*). A model of readvance from the north (*iii*) additionally requires the spatial coincidence of the readvance limit with the earlier deposited Athlone esker, the most northerly of the three main W-E eskers. NW-SE esker fragments would otherwise be expected further south. A model of readvance from the west (*iv*) would require substantial preservation of an earlier esker system; since warm-based ice must be invoked for esker deposition this scenario is difficult to explain. Furthermore, model *iv* would require a reinterpretation of *lins fs2* and *fs4* invoking multiple flowsets for each rather than a single curving pattern.

Determining the plausibility of any of these models based purely on objective landform interpretation requires a greater understanding of esker genesis and palaeo-glaciological significance than is currently available. How far can an 'at-a-time' esker system penetrate into the ice sheet behind the margin? How sharp, i.e. how close to perpendicular, can a junction be between two tributary eskers of the same, synchronously operating system? The wider palaeo-glaciological context of these central Ireland landform assemblages is sought to better judge



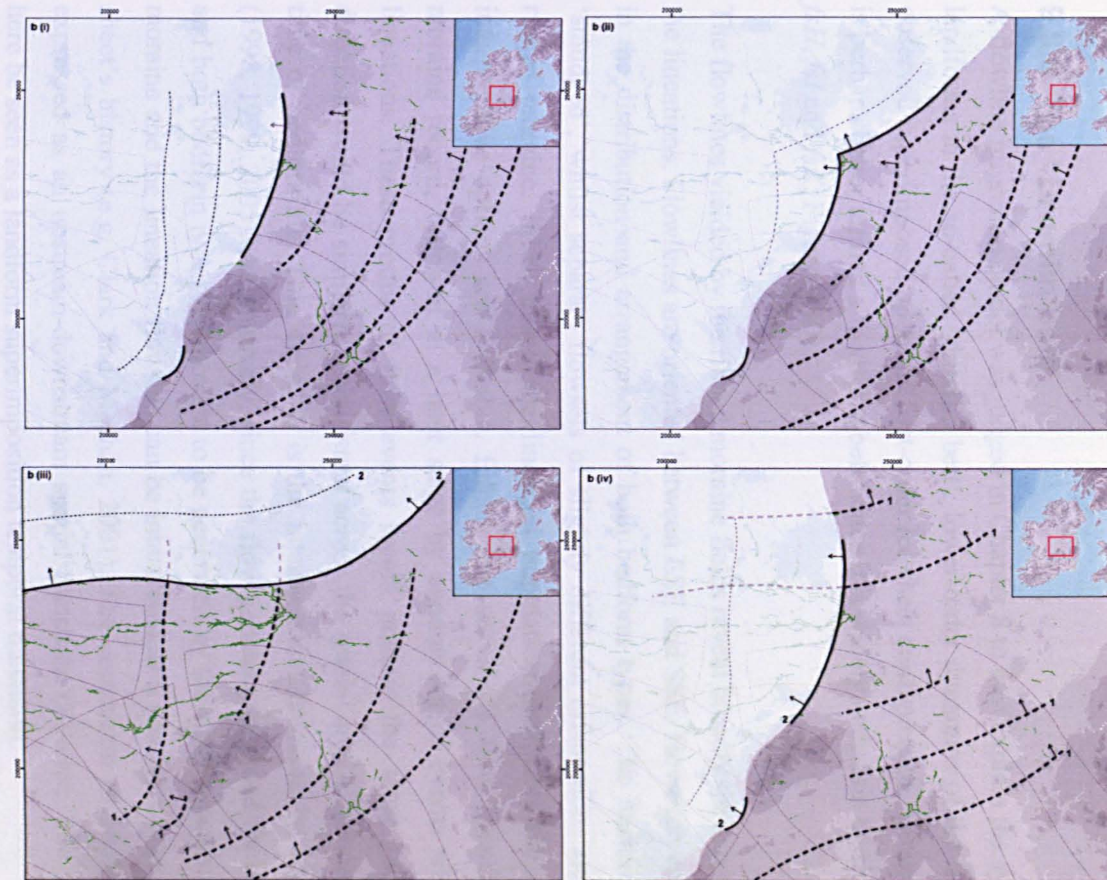


Figure 9.9

a) Eskers dominate the landform record in south-central Ireland (Cos. Galway – Offaly – Kildare). The major eskers are W-E oriented; elements either side flow more to the SSE. Along the line of the W-E Athlone esker, a NNW-SSE system joins at a sharp angle. Ice sheet history models depend on whether eskers of different orientations are interpreted as single or multiple systems. Scale: gridmarks at 50 km.

b) Four models of ice sheet retreat could apply to this region. (*i*) Eskers are interpreted as part of the same, single system. Margin retreat hinges south of the Slieve Bloom mountains and the orientation of the margin rotates from SW-NE to S-N as retreat progresses. (*ii*) As *i*, but sharp junctions of the most northerly eskers with the Athlone esker are interpreted as a signature of the development of two large ice lobes, unzipping along a suture line. (*iii*) Ice retreats first to the west, hingeing as in *i* and *ii* in the south of the region. The most northerly esker systems were deposited as a subsequent ice margin retreated following a readvance from a northern source to the Athlone esker. (*iv*) The first stage of margin retreat is to the north, followed by readvance from the west and with the subsequent retreat laying down most of the eskers. Solid black lines represent the margin position at the moment in each figure; heavy dashed lines indicate earlier margin positions (and are numbered for clarity for the readvance scenarios; dotted lines indicate future margin positions; arrows indicate direction of margin retreat. (These reconstruction diagrams are schematic and should not be taken as precise representations of ice sheet properties.) Scale: gridmarks at 50 km.

which model may best explain their disposition (Section 9.4).

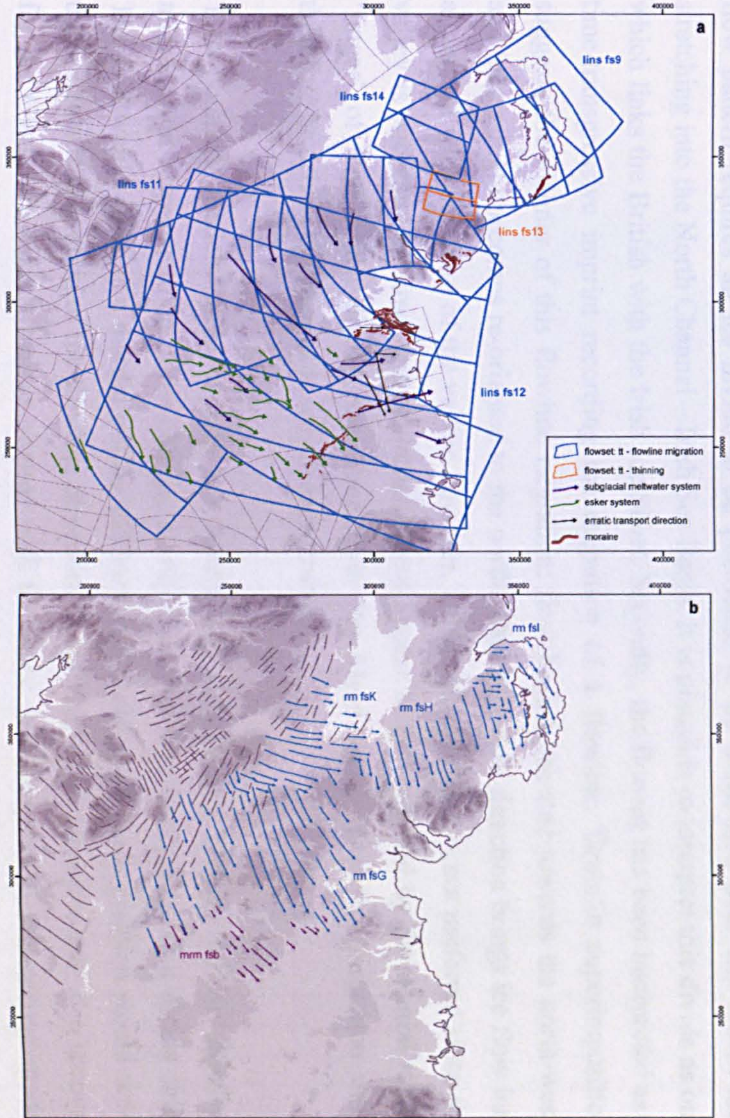
9.3.6 The "Drumlin belt"

A flowline migration model was judged in Chapter 8 to best explain the systematic smudging of landforms in the so-called 'drumlin belt': lower-order dynamics of the flowline direction were observed superimposed upon the first-order ice sheet configuration. However, the 'drumlin belt' is perhaps better termed a 'bedform belt' since it is widely underlain by ribbed moraine (*rm fsG, fsH, fsI* and *fsK*; Figure 9.10).

The flowlines yielded by the ribbed moraine fields reveal broadly the same ice flow geometry as the lineations. Flowlines are oriented between ESE and SSE. However, complexity is witnessed in the distribution and arrangement of both bedform types. The lineations are systematically 'smudged', whilst separate flowsets of slightly different orientations are interpreted from the ribbed moraine. In all cases, the lineation population overprints the ribbed moraine. Two interpretative options are available. Either, one set of ice flow events inscribes the ribbed moraine record, followed at a later stage by another set of events which generates glacial lineations. These groups of flow events would possess the same geometry, and the flow direction would be similarly inconsistent across the spatial area of concern and throughout the time of bedforming. This, broadly, is the interpretation favoured by McCabe and colleagues (1998, 1999, 2005). Alternatively, since the flow geometry required for their genesis is similar, and both bedform types are thought to be generated by the same process continuum, the ribbed moraine and the lineation flowsets can be interpreted as a product of the same phase in the ice sheet's history (e.g. Clark and Meehan, 2001). The continuum of bedforms which is usually expressed as an upstream-downstream spatial transition (Boulton, 1987; Menzies, 1987) can here be seen as a landform superimposition temporal transition.

This second model is the interpretation favoured here: drumlinisation shortly follows ribbed moraine genesis. This model obeys a rule of minimum complexity of interpretation, whereas bedforming in separate phases would require a deviation from, and then a return to, a particular ice flow configuration or subglacial regime. The latter scenario would present an unnecessarily complicated story of ice sheet history in this region. A model of flowline migration best accounts for the morphologic complexity in the ribbed moraine record, the 'smudging' of the superimposed lineation record, and the observed erratic transport history patterns (*erD* and *erE*). It is suggested that this change in ice flow direction, whilst continually bedforming, begins oriented towards the ESE (*rm fsK, fsI; lins fs12, fs14; erE*), turns through SE (*rm fsG, fsH; lins fs9*) to end oriented towards the SSE (*lins fs11; erD*). This relative chronology of flow directions fits observations of drumlin superimposition and palimpsest erratic dispersal patterns.

The final complication is the association of this bedform suite with deglacial landforms. The flowsets described above display none of the characteristics of retreat stage bedforming, indeed, flowlines converge (in places) as opposed to splaying. However, the disposition of moraines and



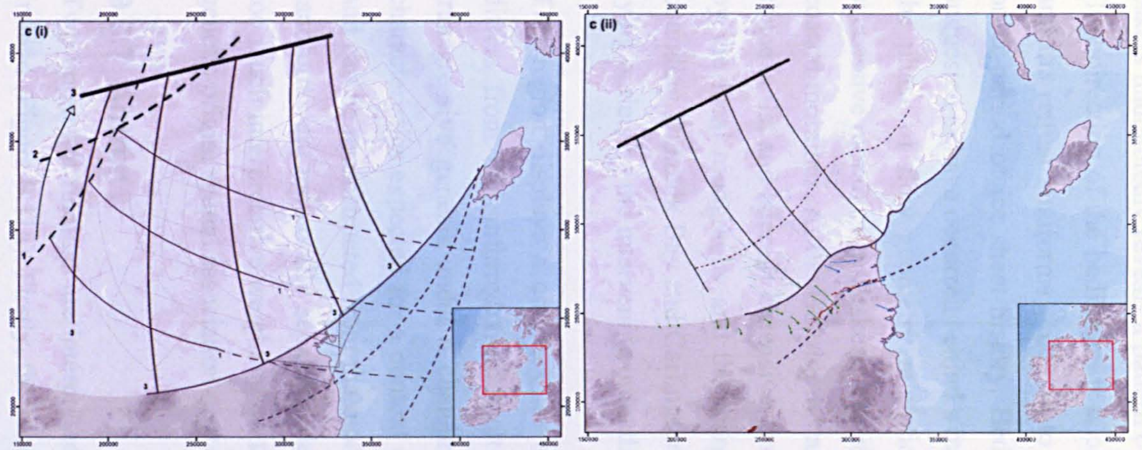


Figure 9.10

a, b) *Lins fs9, fs11, fs12, fs13* and *fs14* display ice flow directions ranging from ESE-SSE. These flowsets are aligned with *rm fsG, fsH, fsI, fsK* and *mrm fsb*, and with the suite of meltwater systems. Flow direction yielded by these assemblages is perpendicular to, but not bounded by groups of moraines. Flowsets relating to other interpreted ice sheet phases are in grey. Scale: gridmarks at 50 km.

c) A model is proposed in which the groups of bedforms and deglacial landforms are temporally distinct from each other. Bedforms are interpreted under a flowline migration model (*i*). The ice margin under this model is positioned initially in the middle of the Irish Sea Basin, with an ice divide over western counties (position 1). The divide moves and rotates to a more northerly position, possibly north of the Sperrin Mountains (position 3). Onshore withdrawal of the ice margin follows this stage, depositing eskers and moraines (*ii*). The margin splays into lobes which successively deposit moraines during their retreat. (These reconstruction diagrams are schematic and should not be taken as precise representations of ice sheet properties.) Scale: gridmarks at 50 km.

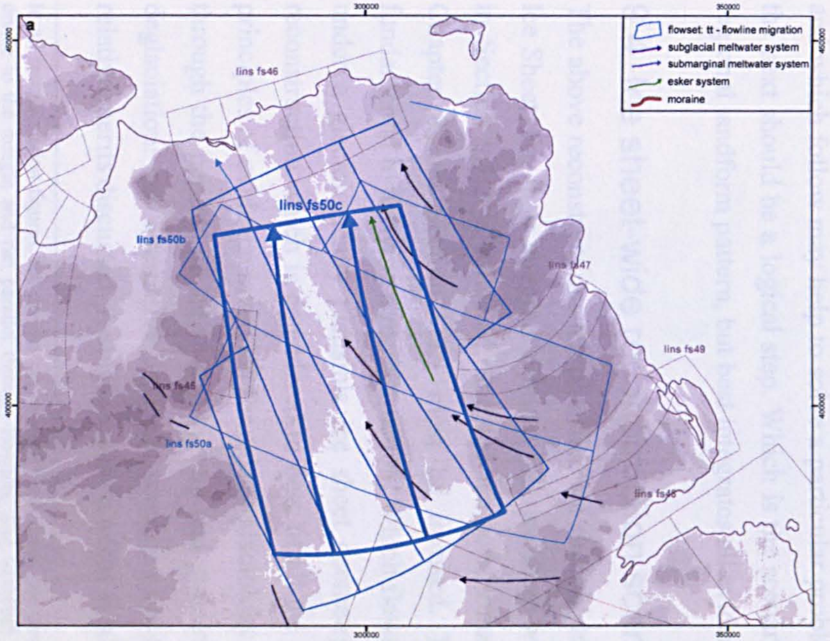
eskers undoubtedly reveals a pattern of retreat over this ground approximately aligned with the flow direction of the bedforms. It is proposed that the two suites of landforms – the bedforms and the retreat landforms – belong to slightly different temporal stages within the same first-order period of ice sheet history. Bedforming, and its associated changing flow geometry, is suggested to have occurred behind a margin located some distance offshore. Towards the end of the phase of flow geometry migration, the ice margin retreats back onshore and deposits successive moraines and eskers. The shape of this margin retreat is defined by the shape of the coastal moraines. At the Galtrim moraine, the most distal to a potential ice source, the moraine shape is flat and laterally extensive. As ice withdraws further, it becomes increaingly influenced by the local topography and the margin becomes lobate, revealed by the shape of moraines bounding Dundalk Bay and Carlingford Lough. It is likely lobes were funnelled into these low lying outlets by the intervening uplands.

This region displays a complex ice sheet history, in which the story revealed by bedforms differs from that inferred from meltwater and morainic landforms. Bedforms reveal time-transgressive genesis under a changing ice flow geometry, but reveal none of the lineation characteristics expected for a context of ice retreat. Retreat is, however, evident in this region and can be reconstructed from the moraines and eskers. It is suggested that these two groups of landforms are temporally separated despite their spatial coincidence. This alerts us to placing too much interpretative weighting on the spatial alignment of landforms which have a different genetic origin: spatial association may not necessarily imply temporal association.

9.3.7 Antrim

Two important findings are interpreted from the landform assemblages in this part of Northern Ireland (Figure 9.11a). Firstly, the drumlin flowset indicates a north-westward ice flow. Such a flow pattern requires an ice divide to be positioned to its south-east, over Co. Down and stretching into the North Channel – Irish Sea Basin. It is plausible to interpret this divide as one which links the British with the Irish Ice Sheet. Secondly, the flowset has been interpreted as a time-transgressive imprint recording the migration of a flowline. Drumlin superimposition suggests the manner of this flowline migration: flow begins oriented towards the north-west, and increasingly becomes re-oriented to the north. This later flow direction brings ice flow into alignment with the trend of the valley; however, a thinning signature is not preferred since the valley is wide and shallow, and drumlins do not appear to be perturbed by the central raised 'finger' of land which divides the Bann from the Main valley. Flowline migration must therefore be driven by changes in ice sheet geometry.

Two potential models could explain the Antrim landform record (Figure 9.11b): flowline migration in response to an outlet change, or flowline migration in response to a divide shift. The first would position a margin not far offshore, and a changing outlet position would drive the systematic migration of the flowline direction. A deglacial environment would also account for the Glarryford esker which is aligned with the latest drumlin pattern. The second model



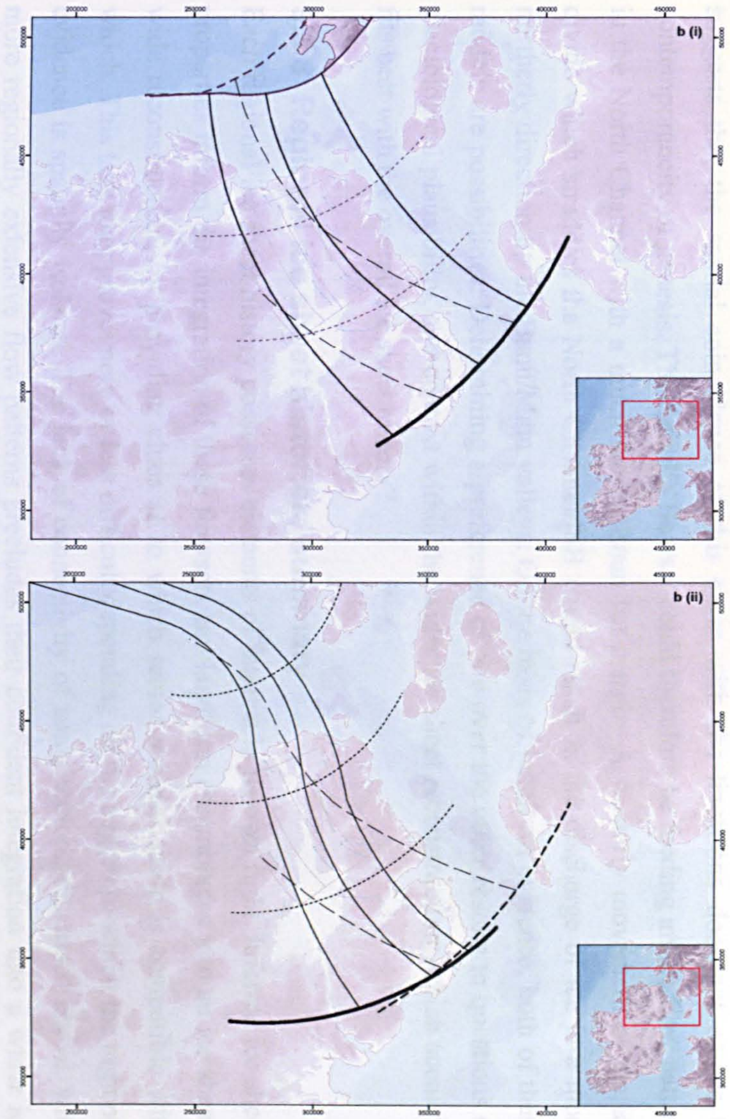


Figure 9.11

a) The main N/NW oriented flowset, *lins fs50*, has been interpreted as an imprint of a flowline migration. It is aligned with meltwater channels and one esker system. This landform assemblage postdates the valley constrained flowsets (*lins fs47 & fs48*) which flow onshore from the east, and likely predates the most northerly flowset which records flow *on*shore in a southwards movement (*lins fs46*). Unrelated flowsets are in grey. Scale: gridmarks at 50 km.

b) Two potential ice sheet models could explain this landform assemblage. One interprets a deglacial context on the basis of the meltwater landforms; the other does not equate spatial coincidence of different landform types with their temporal coincidence. In the first (*i*), flowline migration is accounted for by a change in outlet, associated with ice sheet retreat and the re-opening of the North Channel. The second model (*ii*) would position the bedform flowset earlier in the ice sheet's history, when the margin is more distant, and infers flowline migration due to the lateral movement of the ice divide. The margin splays into lobes which successively deposit moraines during their retreat. (These reconstruction diagrams are schematic and should not be taken as precise representations of ice sheet properties.) Scale: gridmarks at 50 km.

suggests that the spatial coincidence of this esker with the lineations does not equate to contemporaneity of genesis. The drumlin flowset could therefore be feeding an ice flow pattern in the North Channel with a much more distant ice margin. A westerly movement of the ice divide which straddles the North Channel/ISB would result in the discharge of ice in a more northerly direction up the Bann/Main valleys. On the basis of landform evidence, both of these models are possibilities. Determining a preference of one over the other resorts to questions of glaciological plausibility, and context within the wider ice sheet reconstruction: which scenario fits best with the overall ice sheet history?

9.3.8 Regional ice sheet histories: summary

Each regional ice sheet history possesses elements of interest in its own right. Inferred ice sheet properties inform the integration of these flowsets and landform assemblages into an ice sheet-wide reconstruction, by providing clues as to which sector reconstruction is compatible with which. This task may prove more or less difficult depending on the degree to which the regional evidence is spatially isolated. The lack of connectivity of some sectors, discussed above, with more regionally extensive flow patterns precludes their confident integration into a wider ice sheet reconstruction. Instead, we must call upon notions of glaciological plausibility, and what appears to be a logical progression of events. There is a similar requirement for the integration of sectors for which several palaeo-glaciological models could fit the evidence: which model is best suited given the wider reconstruction context? These issues underscore earlier comments on the iterative nature of the reconstruction process. The ice sheet configurations which precede and which follow may help to solve a particular problem, and the progression from one stage to the next should be a logical step. Which is the scenario which does not just explain an isolated regional landform pattern, but best integrates all evidence across the full scale of the ice sheet?

9.4 Ice sheet-wide reconstruction scenarios

The above reconstructions tell plausible ice sheet histories for individual sectors of the last Irish Ice Sheet. For their integration into a full, ice sheet-wide reconstruction, the procedure outlined in Section 9.2.2 is followed, and the temporal rules and inversion principles established in Chapter 8 and Section 9.2.1 must be invoked. The problem of flowset aggregation is fundamental to deriving a reconstruction. Which flowsets could feasibly occur at the same time, under a glaciologically plausible ice sheet geometry? The following sub-sections present a reconstruction which is considered to best fit all the available evidence, obeying all rules and principles of evidence inversion for palaeo-glaciology. This reconstruction follows a single path through the periods of ice sheet build-up and maximum glaciation. This path diverges during deglaciation: two alternative deglacial scenarios are presented, their differences described and relative merits discussed. A single scenario of the final decay of ice from Ireland is presented.

In all reconstruction figures, ice divides are in solid black lines, the outer line is the proposed ice sheet limit, flowlines join the divide to the margin and run parallel through flowsets, and formlines ('contours') help to define the shape of the ice sheet. Underneath the 'ice sheet' lineation flowsets are shown as boxes, ribbed moraine as flowlines, erratics as flowlines (arrows), meltwater channels, eskers and moraines as blue, green and brown lines respectively. Over Britain, the ice sheet is represented by dashed lines since the nature of the connection is unknown. These reconstruction diagrams are abstracted from detailed evidence and are necessarily smoothed and stylised at this scale. Projected on the Irish National Grid, with latitude – longitude markers.

9.4.1 Build-up

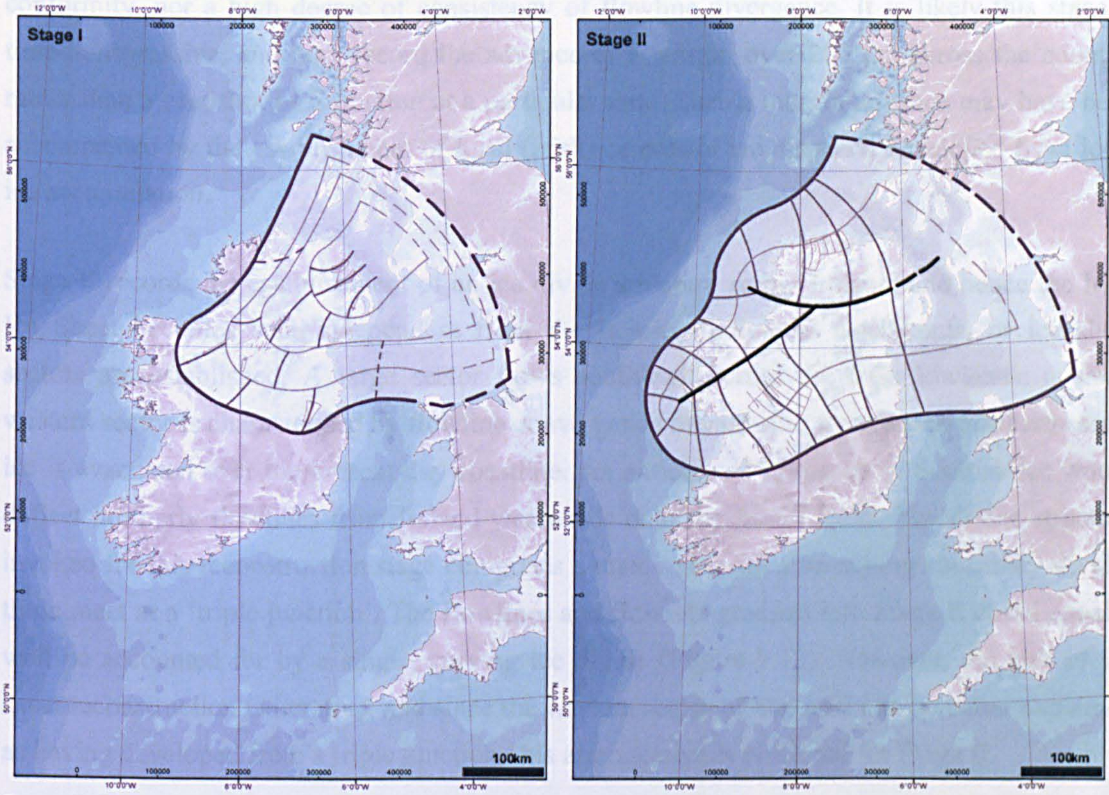


Figure 9.12 Reconstructed build-up stages of the last Irish Ice Sheet. Ice flow evidence is consistent with an early NE to SW flow geometry, followed by the establishment of a main ice divide across west and north Ireland. Evidence is fragmented and sparse, but each parcel of information occurs at the base of its local age-stack. See Table 9.1 for details of flowsets captured in these stages, and the security with which they have been allocated.

Table 9.1 Geomorphological and geological evidence captured in Stages I and II.

Stage I		Stage II	
Landform group	**Security of interpretation?**	**Landform group**	**Security of interpretation?**
lins fs47	Must occur when N. Ireland has limited ice cover. Topographically controlled so unlikely synchronous with flow patterns to the west.	*lins fs39*	Could fit in Stage IV??
lins fs48		*lins fs59*	Little temporal constraints but must occur as part of ice divide migration from Stage II-IIIb.
lins fs62	Very subtle (and speculative) flowset. Could not be incorporated elsewhere in reconstruction.	*lins fs61*	Must occur prior to Stage V.
lins fs60	Could possibly be squeezed into end of Stage V sequence (bedform belt flowsets), but the lineations which overprint must be at start of Stage V.	*rm fsA*	Must occur prior to Clare flowsets in Stage IV.
rm fsE		*rm fsN?*	Unknown ice flow direction, could also fit in Stage IIIa
rm fsD?		*er C*	Must follow Stage I. Too far west to be incorporated into Stage V.
er A	Strongest evidence of early ice incursion from NE.	*Galway granite dispersal?*	Also possible in Stage V. Dispersal likely a product of numerous stages.

9.4.1.1 Stages I & II: description

The build-up of the last Irish Ice Sheet is proposed to have been characterised by an early advance of ice from a British source (Figure 9.12). Fragments of ice flow information, each lying at the base of its local evidence age-stack, are distributed across much of northern and central Ireland and record ice flow from north-east to south-west. This information is not confined to one landform type but exists in several different groups of ice flow evidence: glacial lineations, ribbed moraine and erratic dispersal directions. The range of ice flow evidence consistent with this stage in the ice sheet's history displays neither a high degree of parallel conformity, nor a high degree of consistency of flowline divergence. It is likely this stage is time-transgressive, and may record the advance of a margin over 200 km across the country, rather than a snapshot of formation at a particular time. Such a margin advance may have been accompanied by the establishment of local (Irish) centres of ice dispersal developed from local ice accumulation.

Stage II records the establishment of an ice divide structure across Ireland, and hence the Irish Ice Sheet becomes semi-independent from the British. Individual catchments, or ice sheet sectors are established. A large sector flows south-east across the Irish lowlands; a small western sector is characterised by flowline convergence towards the west; in the northern sector ice is evacuated over the present-day coastline. An anticipated influence of Scottish ice would deflect northerly flowlines from Ireland westwards onto the Malin Shelf. The divide structure invoked for this reconstruction stage comprises a main axis with a branching subsidiary divide; these meet at a 'triple junction'. The flowlines and flowsets grouped into Stage II could equally well be accounted for by a single, curving ice divide (Figure 9.13). However, the task of ice sheet reconstruction is iterative, and since the western sector of Stage III can be better explained as having developed from a triple junction, this arrangement is preferred for Stage II.

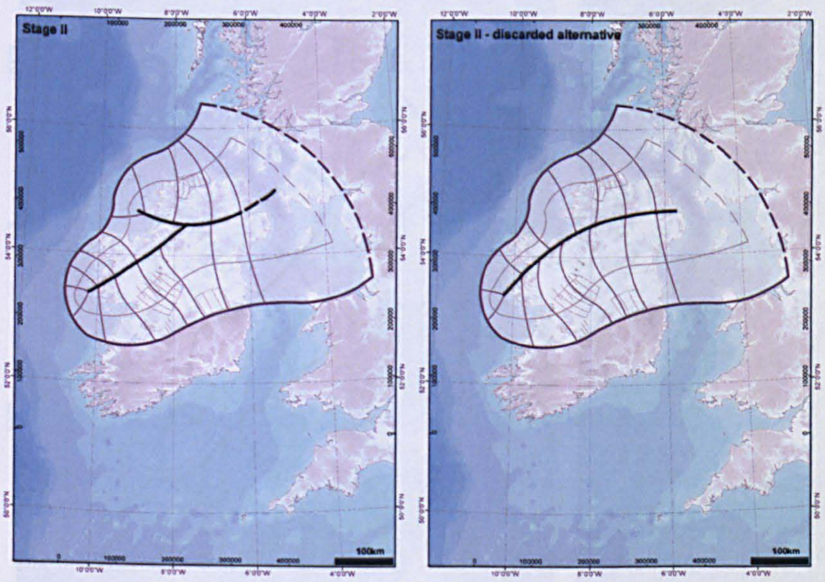


Figure 9.13 Either ice sheet geometry could account for the flowsets allocated to Stage II. However, the stage which follows develops better from a branching divide structure rather than a single axis. This scenario is consequently preferred

9.4.1.2 Stages I & II: palaeo-glaciological insights

Sediment dispersal. Whilst certain landform patterns captured in Stage I could possibly be squeezed into other reconstructed stages, erratic dispersal patterns provide strong evidence of an early incursion of ice from the north-east. This dispersal direction precedes all bedform patterns which overprint it. Prior to the bedforms assigned to Stages II and III there must be a substantial flow of ice from north-east to south-west. Few landforms from this flow geometry remain. Bedforms have therefore either been remoulded, and their imprint largely erased from the landscape, or the subglacial environment associated with this ice flow was not conducive to bedforming, merely sediment dispersal as a till sheet.

Scottish ice. A significant, early flow from the NE clearly indicates some role of British-sourced ice in assisting the establishment of an Irish ice sheet. The role of 'Scottish ice' has long been debated in the Irish literature: an earlier glaciation characterised by a substantial incursion of ice from Britain (Synge and Stephens, 1960; Stephens *et al.*, 1975), or an advance of British ice during the build-up stages of the last glaciation (McCabe *et al.*, 1999; Clark and Meehan, 2001)? This reconstruction favours the latter stance, although the former cannot be ruled out. This issue will be further discussed in Chapter 10.

Offshore extent. Stage II depicts an ice sheet which, even at this early stage in its evolution, extends onto the continental shelf. An offshore extent is a requirement, given the principles of symmetry set out in Section 9.2.1, of this ice sheet whose main ice divide is positioned across western Ireland. If the continental shelf experienced glaciation at this early stage in the last ice sheet's history, shelf glaciation may be expected during the period of maximum extent.

9.4.2 Maximum stages

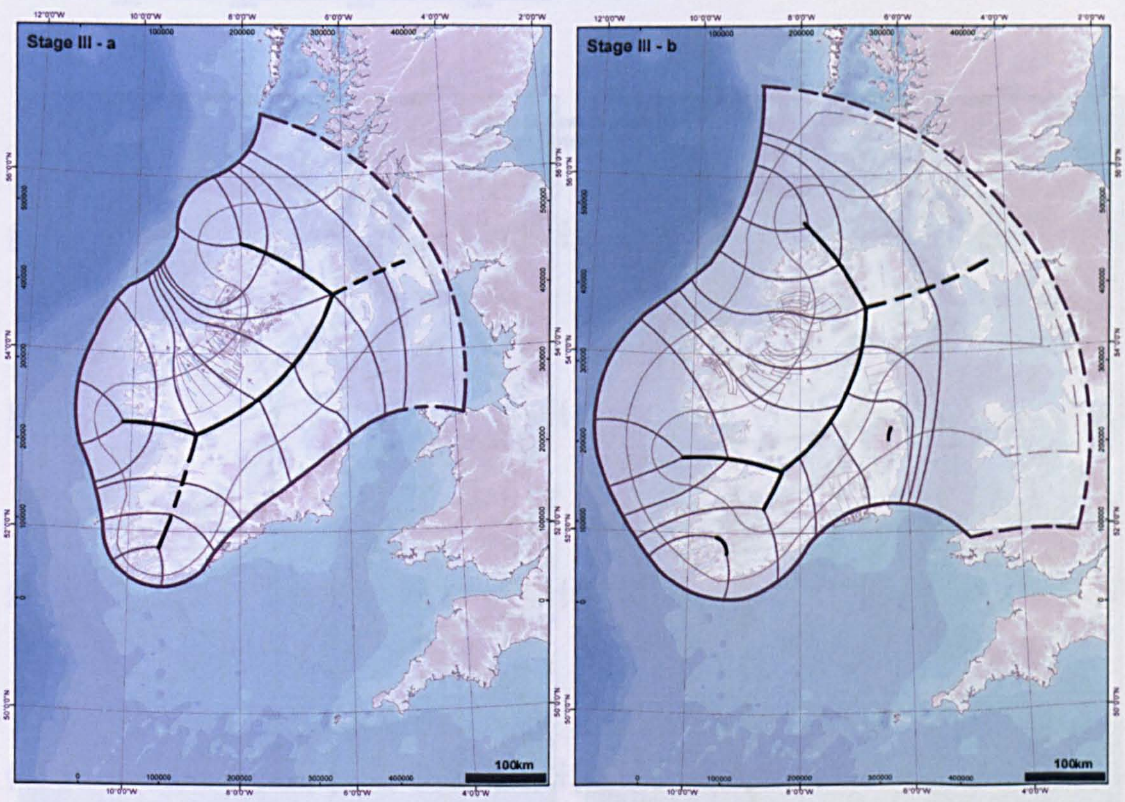


Figure 9.14a The reconstructed maximum period of glaciation is characterised by the development of a large western ice sheet sector. Fast flow is funnelled through the embayments of the west coast and may connect in the nearshore region to form an ice stream system. The ice divide rotates anti-clockwise between Stages IIIa-b, directing flow more obliquely over the initial landform imprint. See Table 9.2 for details of flowsets captured in these stages, and the security with which they have been allocated.

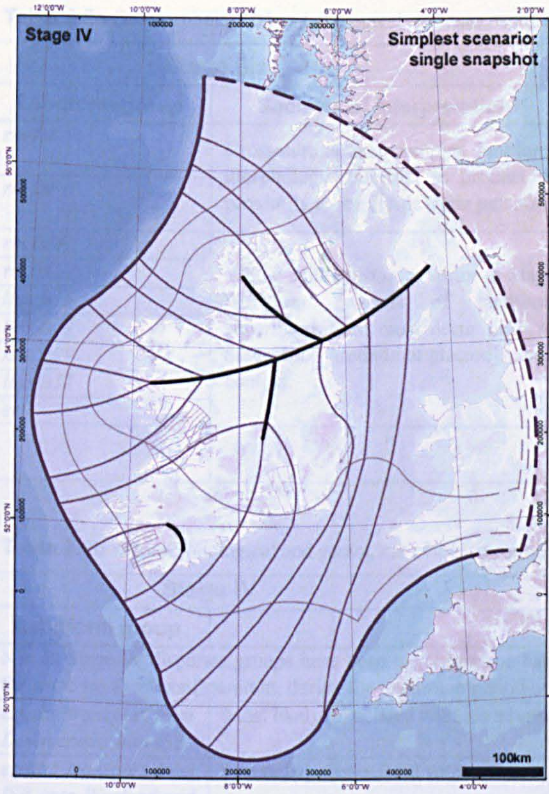


Figure 9.14b Three main flow pattern groups are thought to belong to the maximum period of glaciation: flowsets in Clare, Antrim, and erratic transport patterns through the ISB & Celtic Sea. Little information is available to decipher their chronology relative to one another. The simplest interpretation is to group them within a single ice flow geometry (left). However, if erratic transport paths ~southwards over Co. Down belong to the maximum period, they cannot be contemporaneous with ~northwards flow over Antrim. A maximum period ice sheet in which the divide over the North Channel – ISB fluctuated between a position further north and a position further south is required (Figure 9.14c, below). (Additional flow patterns in Kerry and Waterford may also belong here.)

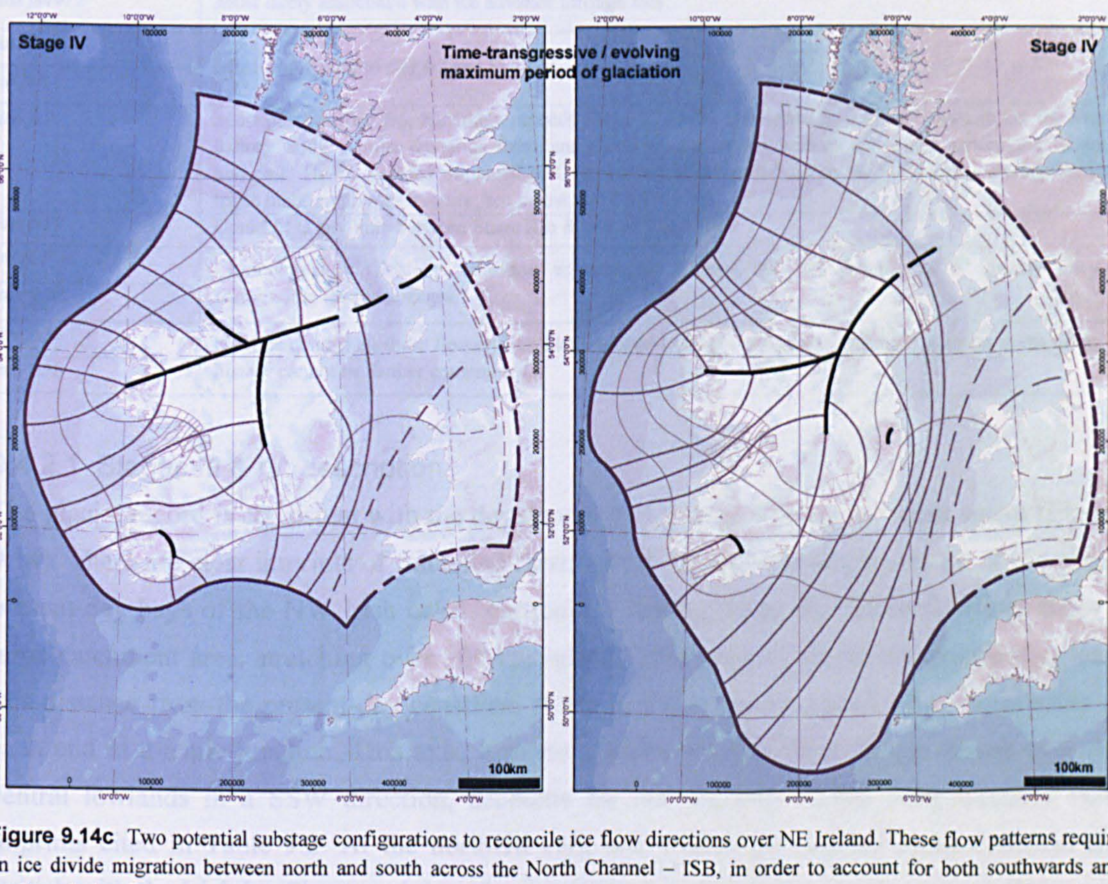


Figure 9.14c Two potential substage configurations to reconcile ice flow directions over NE Ireland. These flow patterns require an ice divide migration between north and south across the North Channel – ISB, in order to account for both southwards and northwards ice flow events. However, there is no relative chronological control on these 2 potential end members of ice divide fluctuation, and it is possible the divide repeatedly moved between north and southern positions. See Table 9.2 for details of flowsets captured in Stage IV, and the security with which they have been allocated.

Table 9.2a Geomorphological and geological evidence captured in Stage III.

Stage IIIa		Stage IIIb	
Landform group	**Security of interpretation?**	**Landform group**	**Security of interpretation?**
rm fsJ *rm fsF*	Cross-cutting and complex landform morphology. Interpret as product of proximity to ice divide triple junction.	*rm fsB* *lins fs18*	Most plausibly fits here. Could occur at start of Connemara regional history; would require considerable curvature of the flowline.
rm fsM *rm fsC* *lins fs15* *lins fs27* *lins fs29* *lins fs37* *erB*	Whole suite must occur prior to Stage IIIb on grounds of landform superimposition; must occur prior to Stage V on grounds of glaciodynamic context.	*lins fs16* *lins fs23* *lins fs32* *lins fs35* *mrm fsa*	Whole suite must postdate Stage IIIa on grounds of landform superimposition; must occur prior to Stage V on grounds of glaciodynamic context.
		rm fsQ?? *lins fs10??*	Too close to ice divide? Must occur prior to Stage V.
		lins fs1?	Could fit at any time between Stage IIIb & end of Stage IV.

Table 9.2b Geomorphological and geological evidence captured in Stage IV.

Stage IV	
Landform group	**Security of interpretation?**
NB. In Stage IV disparate groups have been aggregated on basis of a plausible ice sheet geometry. They likely fall within broadly the same ice sheet configuration, during the maximum period of glaciation, but may belong to separate substages within this period.	
erratic transport from Down coasts into ISB	Most likely associated with ice advance through ISB.
erratic transport from ISB onto Wexford and Waterford coasts	Can only be associated with ice advance through ISB.
lins fs49??	Most likely associated with ice advance through ISB.
lins fs6 *rm fsR*	Must occur prior to *lins fs7* and Stage V.
lins fs7	Must postdate *lins fs6*, but likely preceds Stage V. To be reassigned to a further stage in the ice sheet's history would require deviation from, and return to, a geometry with an ice source particularly far south and east. This is deemed implausible. Overprinting is accounted for by flow dynamics arising from the triple junction divide structure; see below and Ch.11.
lins fs1?	Could fit at any time between Stage IIIb & end of Stage IV.
rm fs P *lins fs50*	Chronologically 'floating' landform assemblage. Inserted here on grounds of a suitable fit with surrounding ice sheet stages.
lins fs56 *lins fs58*	No time control on these flowsets. Unlikely related to final deglaciation, but their position in the ice sheet history cannot be further constrained.

9.4.2.1 Stages III & IV: description

The glacial record is consistent with the development of a large western ice sheet sector (Figure 9.14). There are clear imprints of funnelled flow, with flowlines converging on all of the major present-day bays of the NW Irish coast, particularly during Stage III. These flowlines drain a large catchment area, stretching over 100 km inland. They require ice divide positions at least this distance from the present-day coastline. A main axis is reconstructed which terminates at each end in a triple junction. This axis, extending approximately from Lough Neagh over the central lowlands in a SSW direction, accounts for the majority of the north-westerly flow imprints cited in Table 9.2. At the northern end, one branch (or saddle) likely connects the British with the Irish Ice Sheet, and the other is required to discharge ice over Omagh Basin and through Donegal Bay. At the southern end, one branch likely connects to an ice dome over the Kerry/Cork mountains, whilst the other is required to maintain a north-westerly flow direction from central Ireland (rather than allowing a south-westerly escape).

The temporal rules established in Chapter 8 allow all of these flow patterns to be interpreted as a single, though evolving ice drainage system. Two sequential snapshots of this evolution are shown in Figure 9.14a (Stage III). In the first, Stage IIIa, ribbed moraine are inscribed, followed by drumlinisation in the same flow direction. Ice feeds into the offshore region via all three of the bays named above. These initial suites of landforms are all overprinted at oblique angles by later drumlin patterns. In the north, the Donegal Bay SW flowset is overprinted by one flowing in a more westerly direction; further south, the initial NW flowsets are succeeded by WNW flow directions. A model in which the main ice divide migrates can account for these flow arrangements. An ice divide is reconstructed which is hinged in the north, about the Lough Neagh region, but swings towards the east at its southern end (Stages IIIa – IIIb). This rotation of the ice divide effects new flow directions which overprint earlier imprints at oblique angles.

There are fewer onshore constraints on the ice sheet geometries reconstructed in Stage IV. Two main ice flow patterns are interpreted as belonging to a maximum stage ice sheet (or, at least, pre-deglacial): over Co. Clare, and the Irish Sea Basin. A third, the Antrim assemblage, also likely belongs to this period. Its regional interpretation offered both deglacial and maximum stage options, but the requirement of an ice divide over the North Channel – ISB corridor is not consistent with any other observed deglacial patterns (see below). The Antrim suite is therefore incorporated into the maximum phase. The ice divide structure in the preceding Stage III lends itself to the development of each of these sectors. The northern sector of the north triple junction (Stage III) could plausibly develop (expand south and west) to explain the Antrim flow history; the south-western sector of the southern triple junction could likewise develop (migrate and expand to the north) to account for the Clare regional history. Flowlines discharged from the main axis in Stage III inevitably converge in the ISB due to the funnelling effect between the Irish and Welsh lateral boundaries to the basin. This provides a context under which an advance of Irish Sea ice to a southern maximum limit past the Scilly Isles could have occurred.

Whilst each sector can easily develop on an individual basis from the preceding ice sheet stage, it is less clear as to how they all fit together. The temporal constraints on these ice sheet sectors are few and we must turn to notions of likelihood and glaciological plausibility to piece them together. The simplest option, i.e. following a rule of minimum complexity, would group all relevant flowsets into a single ice sheet configuration (Figure 9.14b). The main ice divide would trend ENE-WSW across Ireland, with possible branching sub-divides. This divide would have a maximum height at its eastern end in order to discharge ice in south-west and north-westerly directions along the North Channel and ISB. This configuration, however, poses a problem. There is overlap where Antrim and ISB patterns meet at their headward extent, which violates a false divide principle of an inversion model for ice sheet reconstruction (Section 9.2.1). The evidence requires a migration of the saddle between a more northerly position (to account for the ISB flow event) and a more southerly position (to account for the Antrim flowsets). Perhaps a better representation of the broad configuration of Stage IV is as multiple evolving sub-stages. Two such potential ice configurations are shown in Figure 9.14c, in which the ISB route is the more dominant in one sub-stage whilst the North Channel route dominates the other. The order in which such phases may have developed is not clear and it is perhaps likely that the ice sheet geometry fluctuated between such configurations. The North Channel sector appears to develop from an early stage (Stage II) of the ice sheet history. Potentially this is the long-standing ice flow route, and a rapid and short-lived advance of Irish Sea ice ends the maximum period of glaciation. A resultant collapse of the North Channel – ISB saddle may then be responsible for the flowline migration recorded in Antrim landform assemblage (Section 9.3.7).

The Clare sector of the ice sheet is clearly separate from the North Channel – ISB history, and its relative position may again only be judged upon its geometric and glaciological plausibility. It, also, reveals time-transgressive behaviour and migration of the main flowline direction (Section 9.3.3). The smudged character of *lins fs6* and its overprinting by *lins fs7* may be accounted by the subtle evolution of the south-western ice sheet sector throughout Stage IV.

9.4.2.2 Stages III & IV: palaeo-glaciological insights

Landform 'smudging' and an unstable ice flow geometry. Most sectors of the ice sheet are characterised by time-transgressive imprints in the landform record. In Clare and in Antrim (Stage IV), flowsets are explicitly interpreted as smudged imprints likely arising from a lateral fluctuation of the flowline direction. In the Western Bays ice sheet sector (Stage III), we find flowsets similarly interpreted as a product of flowline migration, and other more discrete flowsets which overprint each other obliquely. Such landform arrangements clearly point to an inherently unstable flow geometry, which underwent continual fluctuations in ice flow direction. The 'snapshots' of ice sheet history presented in Figure 9.14 therefore summarise an evolving system. Dynamic behaviour is likely a response to marine-terminating margins and to the presence of ice streams in most ice sheet sectors. These would impact the stability of both the ice flow outlet and the ice divide.

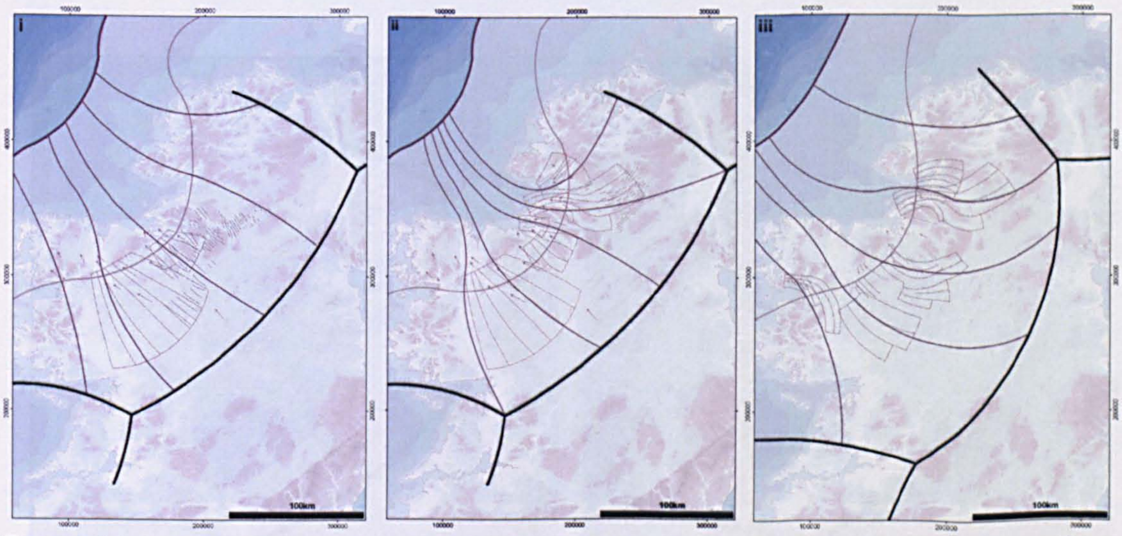


Figure 9.15 An evolving sequence of events can be reconstructed from flowsets feeding the western embayments. Flowsets become increasingly funnelled **(i-ii)**, drawing ice flowlines into the western bays. All flowsets are later overprinted by ice flowing obliquely to the initial funnelled flow direction **(iii)**. Even when split into three sub-stages, there are still local and smudged flowline deflections below the scale of the ice sheet-wide flowline which record the development of this phase of ice sheet history and its local interactions with the subglacial topography.

There is an inherent cartographic problem in representing evolving behaviour as two-dimensional, snapshot diagrams and there are likely further sub-stages in which subtly different flowset directions would reside. Figure 9.15 illustrates how Stages IIIa-b may be further split in time; Figure 9.14c has already demonstrated possible configurations which may better represent the Stage IV summary shown in Figure 9.14b. To arrive at a manageable reconstruction of the first-order history of the ice sheet one or two snapshots must capture the essence of the ice sheet behaviour during this period. It is possible, however, to infer or to determine the manner of ice sector evolution and transitions in the geometry of the ice sheet within these broad stages of its history.

Ice streams. Ice streaming is a key element of the maximum period of glaciation reconstructed in Stages III and IV. It characterises a number of ice sheet sectors, and can be speculated to act as a driver of the ice sheet dynamics witnessed during this period. The sector for which evidence of streaming is strongest is the western sector of Stage III. The funnelled flow, converging flowlines and, in places, lineations interpreted as MSGL are all indicative of flow acceleration towards and through the western embayments. This system is interpreted as a network of ice stream tributaries which converge in the nearshore area. Clearly, there is no evidence available which suggests the nature and geometry of this convergence once ice flow has passed offshore. One large ice stream may form from all the tributaries; alternatively, the system could retain the appearance of a 'network' and individual stream segments could bifurcate (Figure 9.16). There is no significant trough apparent in the offshore bathymetry, which might have pointed to convergence into a single, large ice stream. Nonetheless, the geometry of this ice margin is conducive to ice streaming. The shape of the continental shelf break is concave in a seaward direction, and a margin positioned here will therefore always encourage ice flowline convergence and enhanced flow velocities out of the western bays. The absence of a trough is not a conclusive argument against this scenario. This region should be a priority for offshore mapping once high resolution seabed data has become available.

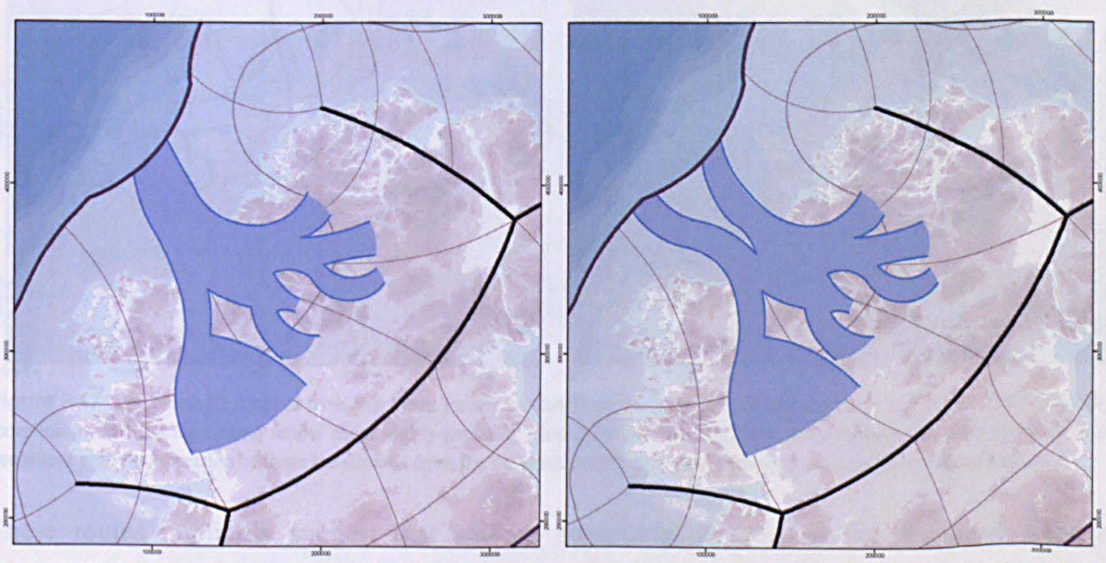


Figure 9.16 Potential ice stream networks in the Western Bays sector of ice sheet Stages IIIa – IIIb. Only tributaries and onset zones are observed in the onshore record, where fast ice flow is funnelled through the coastal region topography. Conclusive evidence of ice streaming should be sought in the trunk region, offshore.

Ironically, the sectors for which there is least evidence to support an inference of ice streaming are those which are the most likely candidates for large ice streams on purely theoretical grounds (Figure 9.17). For a number of reasons, it is hard to imagine that the North Channel and the Irish Sea Basin could *not* have funnelled ice streams to the ice sheet margin. The North Channel feeds the Malin Shelf, which, in turn, terminates in the largest of all the glacial fans on the continental margin of the British Isles. Far larger than the Sula Sgeir Fan, the Rona or Foula Wedge, each of which has been proposed to have been fed by ice streams or concentrated flow routes (Nielsen *et al.*, 2005; Stoker and Bradwell, 2005; Stoker *et al.*, 2006b; Bradwell *et al.*, 2007) the Barra Fan must have received material from a considerable discharge of ice and sediment over a considerable length of time. The most likely candidates for the routes of this discharge, based on the shelf bathymetry, are the North Channel, the Little Minch, and the Firth of Lorn. The North Channel, likely receiving ice both from British and Irish sources, is highly likely to have deflected flowlines along its axis, and their convergence along this funnelled route would have encouraged ice acceleration. A similar situation arises in the Irish Sea Basin. Although there is no tell-tale glacial fan at the terminus of the ISB, the considerable extent to which Irish Sea ice is believed to have advanced in a short-lived event is an indicator of the speed with which ice must have flowed. Again, flow convergence from both Britain and Ireland, the topographic funnelling, and the soft, deformable marine sediments lying on the ISB bed produce a context highly conducive to ice streaming.

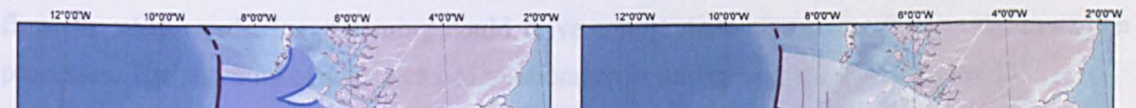


Figure 9.17 The North Channel & Irish Sea Basin funnel ice flowlines from both the British and Irish Ice Sheets. Their geometry, morphology and marine setting render them highly probably candidates for ice streaming. Reconstructed ice flow geometries are consistent with the operation of these ice streams from the same ice divide, or saddle, during the maximum period of glaciation.

These routes implicitly suggest that any ice streaming occurred at the *maximum* stage of glaciation, since streaming is invoked in order to explain the delivery of material, both sediment and ice, to its most advanced position in western and southern sectors. Stage IV is therefore the most appropriate stage in which these flow events should be housed. Combined with the stream system previously described from the western sector in Stage III, this reconstruction paints a picture of a maximum stage ice sheet dominated by streaming around most of its margins.

Ice divide migrations. Stages II - IV are characterised by considerable movement of the main ice divide. From Stage II to IIIa, the main axis undergoes an eastwards migration, and a further 'swing' of this axis is reconstructed from Stage IIIa to IIIb. Stage IV sees a pivot of the axis and the start of a shift back towards the north and west. In previously published reconstructions of the last Irish Ice Sheet, each of these stages has been grouped together as one, and 'false divides' reconstructed in positions of flow divergence. Applying the principles of reconstruction established earlier in this chapter, such positions are recognised as false locations, which could not generate subglacial bedforms so close to the divide. Divide migration is therefore required.

Given that these stages are characterised both by ice streaming and considerable ice divide migration, we can speculate there is a causal relationship. Arteries of ice flowing orders of magnitude faster than surrounding ice, and responsible for up to 90% of an ice sheet's discharge (Bamber *et al.*, 2000), may be hypothesised to exert a considerable control upon the stability and structure of the ice sheet. In a fast-flowing ice sheet sector, if discharge rates slow then the catchment would be expected to accumulate ice; its profile would grow. If ice discharge rates cannot be balanced by accumulation then the catchment must enlarge to sustain the rate of ice flow. In other words, ice streaming could drive a migration of the ice divide via drawdown processes. The potential of such a causal relationship is further examined in Chapter 11.

Ice divide structure. Rather than a single axis (e.g. Hull, 1878; McCabe, 1985), or multiple discrete domes (e.g. Close, 1867; Warren and Ashley, 1994), an ice divide structure is reconstructed for the maximum period consisting of a main axis, branching subsidiary divides and triple junctions. This structure of divides is necessary to account for the convergence of flowlines, particularly in the Western Bays sector of the Stage III ice sheet, where flow converges into the bay area from Co. Donegal, to the north-east, and from the central lowlands in the south-east. In the area downstream of a triple junction, one could expect bedform evidence of flow convergence. Omagh Basin, in this reconstruction, lies in such a position. Bedforms here possess complex and unusual morphologies, and display a range of landform arrangements. In Chapter 7 it was suggested that four possible flowsets could have been interpreted over Omagh Basin; a two flowset option was eventually selected as the preferred, simplest, landform summary. It is proposed that such morphological complexity could be a signature of contemporaneous ice flow influences from multiple directions, consistent with its position in relation to an ice divide triple junction. The significance of ice divide structure for subglacial bedform generation and landform arrangement is returned to in Chapter 11.

Variable presence / absence of geological evidence. During the reconstructed stages describing the maximum period of glaciation, different sectors reveal evidence of palaeo-ice flow at different times. Their disposition with respect to each other precludes integration into fewer stages: the Western Bays and Clare sectors, for example, have different requisite ice divide positions and configurations. Furthermore, certain reconstructed sectors lack ice flow evidence – they are invoked on the basis of the principles of symmetry and likelihood. Two explanations for the absence of evidence could be put forward: either bedforms once inscribed have since been erased or remoulded; or the subglacial environment was not conducive to bedforming during this ice sheet phase – these regions acted as landscape preservation zones rather than zones of landform generation. During Stage III, for example, there is an apparent lack of flow evidence on the eastern side of the reconstructed main ice divide. Flow patterns exist in this region in Ireland, but their disposition in relation to the reconstructed divide for Stage III bars their integration at this stage. Their inclusion would violate the second principle of palaeo-glaciological inversion outlined in Section 9.2.1, lying too close to the divide to expect any significant geomorphic activity. Landform evidence to the east of the main divide which is reconstructed in Stages III and IV likely lies offshore or, if once present on land, has since been erased or remoulded by later stages of bedforming.

Kerry/Cork ice divide. In these maximum phases of the last Irish Ice Sheet, the connection of the main ice divide structure to the Kerry/Cork region is uncertain. This area has traditionally been thought (by all proponents of the various models) to have supported an independent ice 'cap' or 'dome'. Landform evidence gathered at the scale of research employed in this thesis refutes an entirely isolated ice cap. There is a strong east-to-west trend of meltwater channels throughout Co. Cork, which may relate to a period of glaciation controlled primarily by the 'main ice sheet' rather than a local cap. However, evidence has proven inadequate to more precisely reconstruct the style of glaciation experienced in the Kerry/Cork mountains. The nature of the connection of this region with the main ice sheet can only be speculated. Such speculation proposes the southern sub-divide in Stages III and IV could connect to, or control ice flow around a local dome.

Ice sheet extent: an asynchronous 'Last Glacial Maximum'. This reconstruction suggests that the ice sheet attained its maximum extent during different stages for different sectors of the margin. The western limit is reached first, during Stage III, whilst the advance to the southern limit occurs in Stage IV, driven by flow convergence in the ISB. This pattern of margin advance is both a logical outcome of flowset analysis, and consistent with chronologies emerging from the published literature. Furthermore, the western ice sheet limit is a nearer one to attain than the southern, in relation to the landmasses from where the ice is sourced. The reconstruction presented above reveals an ice divide migration which begins closer to the western margin, and moves towards the east and south, promoting an advance of the southern ice sheet sectors. This spatial pattern of the differential growth to maximum limits fits the available chronological evidence from the literature. It has been suggested that the ice sheet maintained a maximum position on the western continental shelf for several thousand years, beginning from approximately 26 ^{14}C ka (~30 cal ka; Knutz *et al.*, 2001), whilst the advance of ISB ice onto the

Celtic Shelf is constrained to a time period at approximately 20 ^{14}C ka (~24 cal ka; Ó Cofaigh and Evans, 2007). Flowset analysis and the dating record are therefore consistent with asynchronous behaviour of different ice sheet sectors with respect to their attainment of a maximum extent. Use of the term 'Last Glacial Maximum' could be misleading where the maximum for different sectors of the same ice sheet occurs at different times. For that reason, Stages III and IV are described collectively as the maximum stages of glaciation, rather than a singular period with a specific chronological significance.

9.4.3 Deglaciation: two scenarios

Following Stage IV, there are two possible deglaciation trajectories which may be interpreted from the landform legacy. Scenario A describes steady retreat of the ice margin and fragmentation of the ice sheet into component domes. Scenario B describes broadly the same pattern, but an altogether different style of deglaciation: large-scale retreat and readvance.

9.4.3.1 Deglacial Scenario A: steady retreat and fragmentation into ice caps

Table 9.3 Geomorphological and geological evidence captured in Stage V. Note that these stages describe a time-transgressive sequence of events, rather than discrete snapshots of the ice sheet's geometry. Individual flowsets are also time-transgressive. Flowsets therefore may 'slide' between one stage and the next.

Stage Va	
Landform group	**Security of interpretation?**
lins fs2	Time-transgressive flowsets with similar geometry; most plausibly fit the same time period.
lins fs4	
lins fs5	
Kildare/Carlow eskers	Associated with *lins fs2*, likely fits here.
Limerick moraines	Associated with *lins fs5*, likely fits here.
rm fsK	Disposition consistent with pattern of retreat to the south. An alternative explanation of the Offaly/Westmeath esker systems would attribute these flowsets to a readvance postdating the southern margin retreat: Scenario B.
rm fsI	
lins fs12	
lins fs14	

Stage Vb	
Landform group *as Stage 5a, plus:*	**Security of interpretation?**
lins fs8	Time-transgressive flowset, likely successor to *lins fs2* & *fs4*.
Offaly/Westmeath eskers	Aligned with *lins fs8* therefore most likely occur here. Two models of esker interpretation underpin two deglacial scenarios.
lins fs9	Follows bedform belt flowsets assigned to Stage Va as part of time-transgressive (flowline migration) landform assemblage. Contemporaneity with southern flowsets depends upon model for Offaly/ Westmeath eskers (i.e. Scenario A vs B).
rm fsG	
rm fsH	
erE	
mrm fsb	
lins fs13	As above; signature of ice thinning. Must occur as part of bedform belt sequence of events.
Galtrim moraine	Associated with retreat of bedform belt flowsets: Stage Vb-Vc.

Stage Vc	
Landform group *as Stage 5b, plus:*	**Security of interpretation?**
lins fs11	Must occur as part of bedform belt sequence of events: Scenario A vs B.
erD	
Louth/Down moraines	
lins fs28	Topographically controlled, must postdate Stage III.
lins fs30	
lins fs17	The integration of the Connemara regional history with the full ice sheet has little direct temporal constraints, but fits most plausibly here.
lins fs20	
lins fs22	
Roscommon eskers	
Killala Bay moraines	
W. Mayo moraines?	Could fit here or in Stage VI.

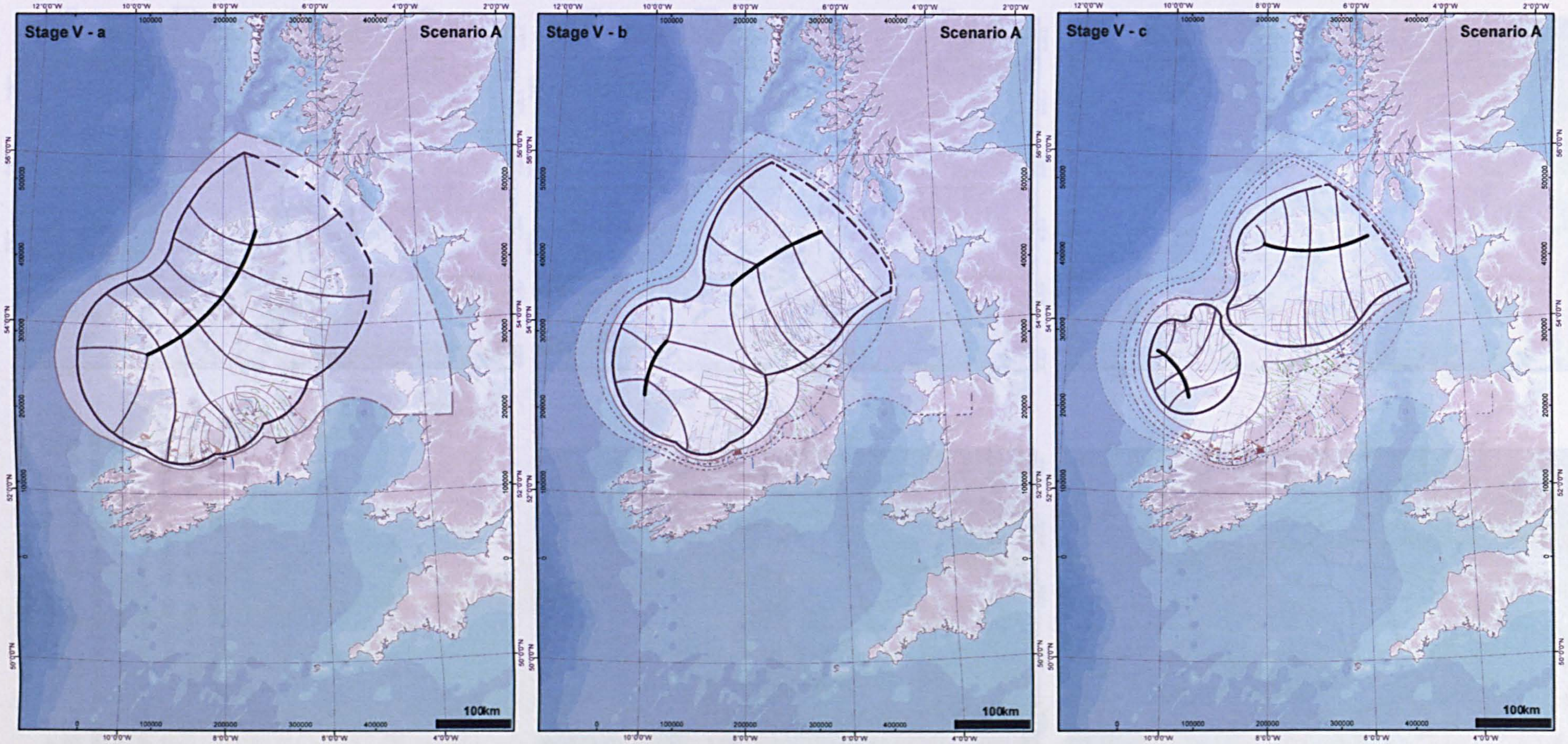


Figure 9.18 Deglacial Scenario A. Central-southern Ireland landform assemblages, the 'bedform belt' group and the Connemara regional history fit a model of steady margin retreat and ice sheet uncoupling into two domes. The eastern margin first retreats in a north-westwards direction, hinged over Co. Limerick. Two separate 'domes' begin to uncouple along a suture line from Co. Sligo to the central eskers. Ice is subsequently drawn into the uncoupled zone, and remnant ice divides migrate away from each other. These patterns of behaviour are revealed by time-transgressive flowsets and esker systems, which are by their very nature incrementally formed. There is an inherent problem in representing time-transgressive behaviour as a sequence of snapshots. To aid the clarity of these reconstructions, the sequence of events is illustrated in a number of sub-stages. The margin positions indicated in each previous stage are carried forward to the next as dotted lines to clarify the geometry of the sequence. See Table 9.3 for details of flowsets captured in these stages, and the security with which they have been allocated.

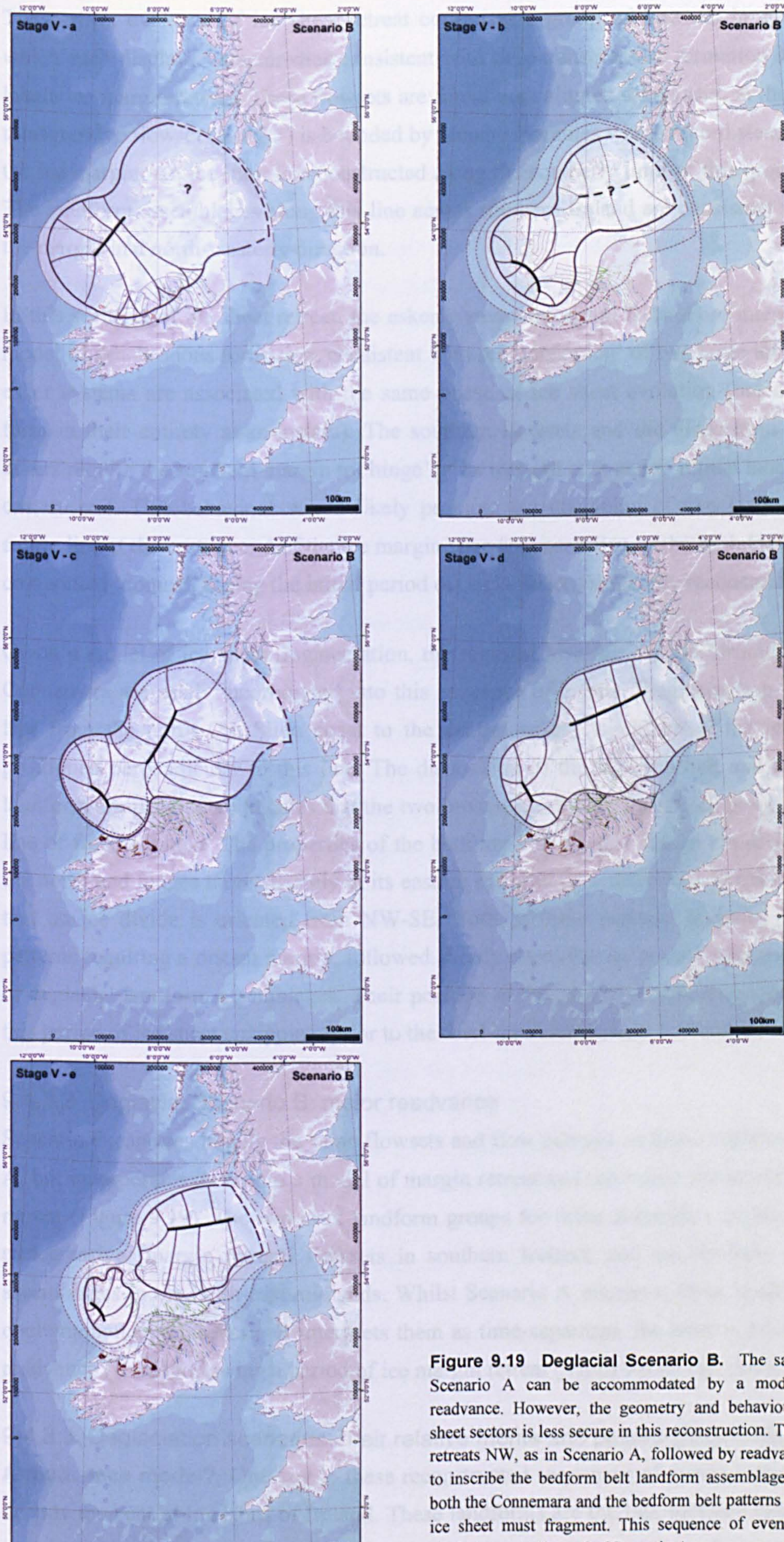


Figure 9.19 Deglacial Scenario B. The same flowsets as in Scenario A can be accommodated by a model of retreat and readvance. However, the geometry and behaviour of different ice sheet sectors is less secure in this reconstruction. The southern margin retreats NW, as in Scenario A, followed by readvance from the north to inscribe the bedform belt landform assemblage. To accommodate both the Connemara and the bedform belt patterns in this scenario the ice sheet must fragment. This sequence of events culminates in a similar stage to the end of Scenario A.

The earliest evidence of ice sheet retreat comprises a group of flowsets in southern Ireland which each display characteristics consistent with time-transgressive formation in a context of lobate ice margin retreat. These flowsets are found with aligned eskers and, in the west, a time-transgressive flowset (*lins fs5*) is bounded by arcuate moraines which record steady recession of the ice margin. An ice limit is reconstructed along the southerly limit of this group of flowsets. The landform assemblages along this line across southern Ireland are consistent with retreat of the margin in a north-westerly direction.

In this scenario of ice sheet retreat, the esker systems in central Ireland are interpreted under a model of synchronous formation, consistent with the 'unzipping' of two large lobes. That is, *all* esker systems are associated with the same phase of ice sheet evolution (but not required to form in their entirety at-an-instant). The southern flowsets and the disposition of the central eskers require the southern margin to 'hinge' at its western end, and to retreat more rapidly at its eastern end. This behaviour would likely promote the unzipping of two large lobes along a suture line at the eastern end of the ice margin. The fragmentation of the Irish Ice Sheet into two component 'domes', during the initial period of deglaciation, is thereby reconstructed.

Given a model of ice sheet fragmentation, the regional histories for the 'drumlin belt' and for Connemara are easily incorporated into this sequence of events. Fragmentation along a suture line from the north Co. Sligo coast to the central eskers would break the ice divide once positioned perpendicular to this line. The disposition of the bedform belt and the Connemara landform arrangements indicates that the two broken ice divides must both pivot away from the line of fragmentation. The properties of the bedform belt require that an ice divide migrates to the north and hinges more strongly at its eastern end; the flow directions in Connemara require that an ice divide is oriented from NW-SE. Both of these regional histories comprise flow patterns requiring a distant margin, followed shortly thereafter by margin retreat and deposition of deglacial landform assemblages. Their position in the overall ice sheet history at the end of this period of ice sheet unzipping, prior to the final ice sheet demise, is therefore most suitable.

9.4.3.2 Deglacial Scenario B: major readvance

Scenario B captures largely the same flowsets and flow patterns as those explained by Scenario A, but incorporates them into a model of margin retreat and readvance instead of one of steady retreat (Figure 9.19). The two crux landform groups for these alternative models are the time-transgressive (margin retreat) flowsets in southern Ireland, and the bedform belt landform assemblages in the north-east midlands. Whilst Scenario A interprets these landform groups as contemporaneous, Scenario B interprets them as time-separated, the latter a product of margin readvance (Vc-d) following a period of ice margin retreat (Va-b) which laid down the former.

9.4.3.3 Deglaciation scenarios: their relative merits and palaeo-glaciological insights

A readvance model? One key to these reconstructed sequences of events is the eskers which occupy the central lowlands of Ireland. These landforms are the link between two spatially and behaviourally disparate landform groups: the time-transgressive southern flowsets which record ice margin retreat first to the north and subsequently to the west; and the 'bedform belt' flowsets which record flowline migration unrelated to margin retreat, and a flow direction which becomes *more* north-south oriented with time rather than less so. In Section 9.3.5, above, four possible options were presented to explain the central eskers. The two deglacial scenarios now considered reduce these options to two, in light of the broader scale of reconstruction and the requirement of a model not only to explain the esker configuration but to tie in the wider landform groups. Given this requirement the earlier models *i* and *iv* are not considered plausible. Models *ii* (Scenario A: a single esker system with major tributaries) and *iii* (Scenario B: the 'tributaries' from the N/NW are in fact part of a separate deposition regime; these eskers are the deglacial product of a margin readvance) remain viable.

The question of scale is fundamental to weighing up these two options. What scale of readvance requires us to abandon an overriding model of steady retreat, which could be punctuated by minor margin oscillations, and adopt a scenario of ice sheet-wide retreat and major readvance? Scenario B links the northern, 'tributary' system of eskers with bedform assemblages to the north-east which possess a similar flow direction. On this basis, the whole bedform belt is interpreted in a readvance context. From one or two specific sites which suggest diachroneity of two esker systems, a readvance model is spatially extended in a lateral direction to incorporate an entire ice sheet sector, and scaled-up longitudinally from <50km to ~80km to account for the full length of the 'drumlin belt'. In one specific locality, i.e. the region of esker system confluence, a local readvance could be viewed as a local dynamic within an otherwise steadily retreating ice sheet. However, by scaling-up across a whole ice sheet sector, a more substantial readvance model is required for the explanation of the glacial landform record.

The development of Scenario B has been somewhat driven by ideas previously presented in the Irish literature, namely the long-standing interpretation of a 'drumlin readvance' (Synge, 1969) and its development into a Heinrich event model (McCabe *et al.*, 1998, 2005). These links with the literature will be fully discussed in Chapter 10 and the basis for a readvance model will be more fully evaluated. It will, however, be noted here that the sequence of flowsets and pattern of events between Scenarios A and B are largely the same; it is their behavioural interpretation which differs. There is therefore little in the landform record which explicitly differentiates between the two potential models of deglaciation. Scenario A, as it is strictly drawn, is perhaps unrealistic: margin oscillations are to be expected and a strict model of steady retreat is rather implausible. Scenario B, a large-scale readvance, can be accommodated but is not *necessary* to explain the landform record of the bedform belt, as has so frequently been postulated (Synge, 1970; McCabe and Clark, 1998; McCabe *et al.*, 1998). The regional scenario presented in Section 9.3.6 (flowline migration) is the preferred explanation of the bedform belt assemblage.

Not only does the landform evidence not require a readvance scenario, such a model produces a more convoluted solution. The same flowsets, and the same regional stories, must be inserted into more stages than would be the case under a steady retreat model. As a result, there are several periods during which it is unknown what is occurring in one ice sheet sector whilst all the activity occurs in the other. The position of the Connemara regional history is less secure in Scenario B than in A: it could be inserted anywhere from Stage Vb to Vd-e. Scenario A presents a neater, more elegant solution. It obeys the reconstruction principle of minimum complexity to satisfactorily explain the available evidence.

A potential 'esker readvance' must, however, still be accommodated. Scenarios A and B should perhaps be seen as end members rather than strict either/or alternatives. The true manner of margin retreat potentially lies somewhere in between, with a model which allows local margin oscillations of different magnitudes, and which allows variability in margin behaviour across and within sectors of the ice sheet. This would be consistent with insights from the literature (see Chapter 10) which have identified from terrestrial sequences repeated margin oscillations during retreat (McCabe *et al.*, 2007b; Thomas *et al.*, 2004; Thomas and Chiverrell, 2007; Evans and Ó Cofaigh, 2003), and pulsing of the ice sheet revealed in offshore cores (Knutz *et al.*, 2001, 2007; Peck *et al.*, 2006). This model would reconcile the simplicity and elegance of Scenario A's solution with evidence in the literature for margin oscillations, without needing to invoke a more unwieldy model of large-scale retreat and readvance which is not strictly required by the landform evidence for its explanation.

Palaeo-glaciological insights. Whichever deglacial scenario is preferred, the evidence of deglaciation in Ireland is consistent with the fragmentation of the ice sheet into two component 'domes'. Scenario A explicitly interprets ice sheet uncoupling to explain the disposition of the central esker system. Scenario B implicitly produces an uncoupled ice sheet because retreat in one direction is followed by readvance from another. The alternative – migration of a single, coherent axis, without ice sheet fragmentation – cannot be invoked without neglecting the landform assemblages in Co. Mayo, the Connemara regional history. To explain both the bedform belt and the Connemara assemblages, the ice sheet must disintegrate into a western and a northern ice mass. It must fragment and cannot decay as a single, coherent ice sheet.

There are two final by-products of the reconstructed patterns of deglaciation which deserve brief consideration. Retreat from the south of Ireland is characterised by a margin movement which is hinged, or pinned over Cos. Clare and Limerick. Whichever deglacial scenario is preferred, the western end of the southern margin must be pinned here in order to account for the shape of *lins fs2*, *fs4* and *fs8*. However, a landform signature of this pinning is unclear. Moraine evidence points to a steady margin recession northwards from Co. Limerick across the Shannon, although the timescale of recession is unknown. Potentially, the margin may have been pinned at these moraines whilst eastern Ireland deglaciated. Standstill in the west during margin retreat further east could explain the absence of moraines but the abundance of eskers in eastern Ireland.

Secondly, between the 'start point' of deglaciation in both scenarios and the events reconstructed in the preceding Stage IV, there is an apparent hiatus in the landform record. The ice sheet has undergone a considerable period of retreat following its maximum extent onto the Malin and Celtic shelves, to a margin position well onshore, pinned along the line of southern upland regions. However, in doing so the ice sheet has left little landform legacy of its geometry or behaviour. In this time *lins fs1* and associated erratic transport patterns may have been inscribed over the Waterford coast, but the temporal control on this flowset is limited; it plausibly fits at any time from Stage IIIb to this period between IV and V. Reconstructions from the literature may fill this gap, and this anomaly is returned to for discussion in thesis Section D. The variable inscription and preservation of landform evidence is an observation which has arisen time and again in this interpretation of the Irish landform record and this ice sheet reconstruction. This theme will also be addressed in later discussion.

9.4.4 Final decay

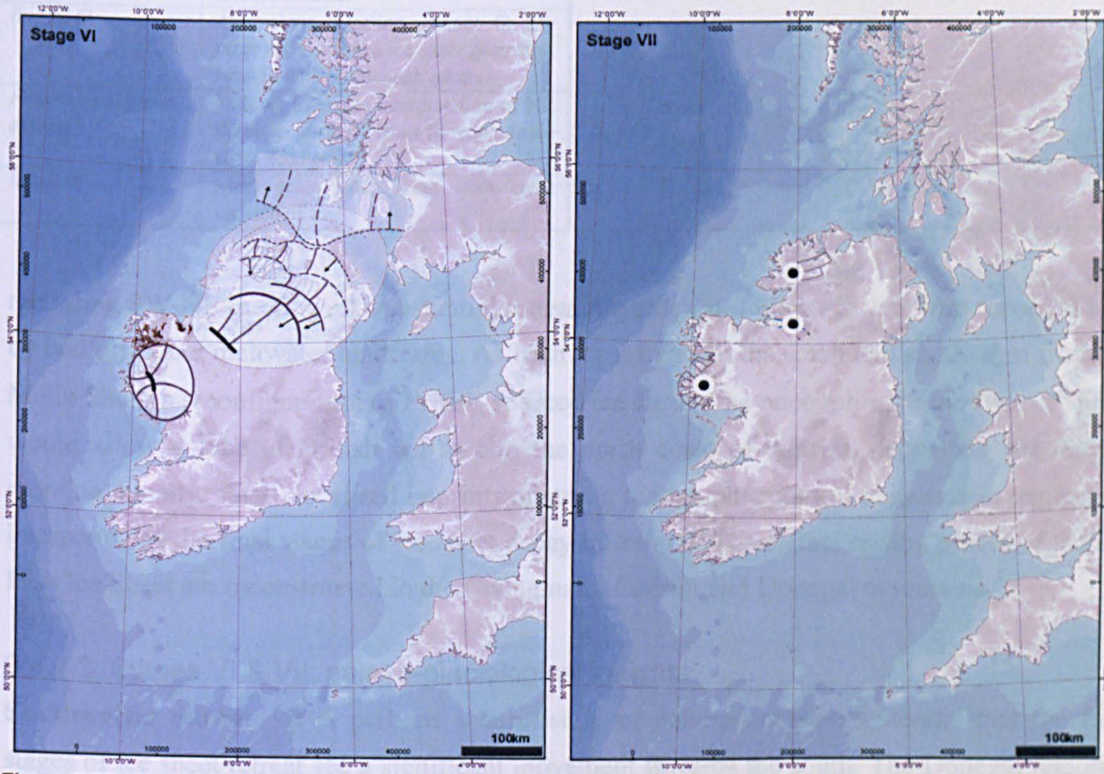


Figure 9.20 Final stages of decay are characterised by retreat to centres over the Leitrim, Donegal and Connemara mountain groups. Stage VI describes the migration of the ice divide and associated ice margin retreat from Co. Donegal towards the SW. See Table 9.4 for details of flowsets captured in these stages, and the security with which they have been allocated.

9.4.4.1 Stages VI & VII: description

Following divergence of the reconstructed ice sheet history into two scenarios for initial deglaciation, these scenarios reconvene in a single reconstruction of the final stages of ice sheet decay. The only major remaining flowset group to explain is that located in Cos. Donegal and Londonderry, described earlier in Section 9.3.1. These flowsets were interpreted under a model of flowline migration responding to the opening of calving bays in Loughs Swilly and Foyle, either side of the Inishowen upland disposition requires an ice divide position over the south of County Donegal and Fermanagh, which suggests a final migration of the main axis of the northern dome back towards the south. This is consistent with esker systems in Omagh Basin and the Clogher Valley which, although not displaying any morphological indicators of palaeo-flow direction (e.g. dendritic network forms), have been interpreted (e.g. Knight, 2003a,b) as

Table 9.4 Geomorphological and geological evidence captured in Stages VI and VII.

Stage VI		Stage VII	
Landform group	**Security of interpretation?**	**Landform group**	**Security of interpretation?**
lins fs41		*lins fs42*	Strong topographic control on very small flowset – likely late-stage mountain glaciation
lins fs40	Glaciodynamic context precludes assignment to any other period of ice sheet history.	*lins fs54*	Radial outflow from mountain ice cap; cannot fit any other reconstructed ice sheet geometry.
erG			
lins fs45??	Cannot fit any other reconstructed ice sheet geometry.		
rm fsL??	Direction not always secure. If SW rather than NE, fs could be associated with *rm fsE*, in Stage I. Little temporal control due to uncertainty and complexity in interpreting cross-cutting ribbed moraine.		
lins fs24?	Anomalous direction, cannot fit any other reconstructed ice sheet geometry. May fit with Fermanagh eskers.		
Fermanagh/Tyrone eskers	Follows literature interpretation of NE flowing (see text). Must fit with this ice sheet geometry.		
lins fs46	Must occur after north Irish coast vacated of ice.		

recording SW-NE ice flow. A substantial retreat towards Co. Leitrim is therefore recorded both by bedforms and meltwater landforms. As Irish ice retreats to the south and south-west from the Malin Shelf, a reconfiguration of British-sourced ice during the uncoupling of the two ice sheets would allow a lobe of British ice to clip the north coast of Antrim, depositing the Armoy moraine. Finally, small, localised imprints of strong topographic control in mountain regions are interpreted as the final stages of ice sheet decay in Ireland. Three final resting places of the last Irish Ice Sheet are reconstructed in the Connemara, Leitrim and Donegal mountains.

9.4.4.2 Stages VI & VII: palaeo-glaciological insights

Southwards retreat. It is perhaps a surprising, or counter-intuitive outcome that the final stages of ice sheet retreat see a significant movement towards the south. The Donegal region is reconstructed as a final site of ice sheet decay, but a considerable margin retreat occurs towards Co. Leitrim from all over Northern Ireland. This is most clearly displayed in the meltwater landform record, both in esker systems and meltwater channels.

Absence of deglacial bedforming. It is also an interesting outcome to find that there is so little evidence of late-stage bedforming. In almost all contexts throughout Ireland, the explicitly deglacial pattern (i.e. the eskers) either differs in flow direction information from the bedform record, or is found in isolation from other landform types. This is in stark contrast to other ice sheet beds where eskers and lineations align and bedforms can be linked widely to deglacial patterns (e.g. Prest *et al.*, 1968; Prest, 1969; Boulton *et al.*, 1985). In Ireland, the bedforms appear to record the maximum and early deglacial stages of ice sheet history, whilst reconstruction of the pattern of ice sheet retreat is more strongly influenced by the esker record. This points to a lack of ability of the ice sheet in its final stages to deform its bed and mould subglacial landforms.

Asymmetry of evolution. This reconstruction presents an asymmetric ice sheet evolution. Stage I was dominated by ice flow from the north-east, but deglaciation is not characterised by the 'return' of ice to its original source. Rather, the last vestiges of the Irish Ice Sheet retreat to western mountain locations. An asymmetric pattern of evolution perhaps relates to asymmetry in the forcing of glaciation during the stages of ice sheet initiation and ice sheet decay.

9.4.5 Ice sheet retreat pattern

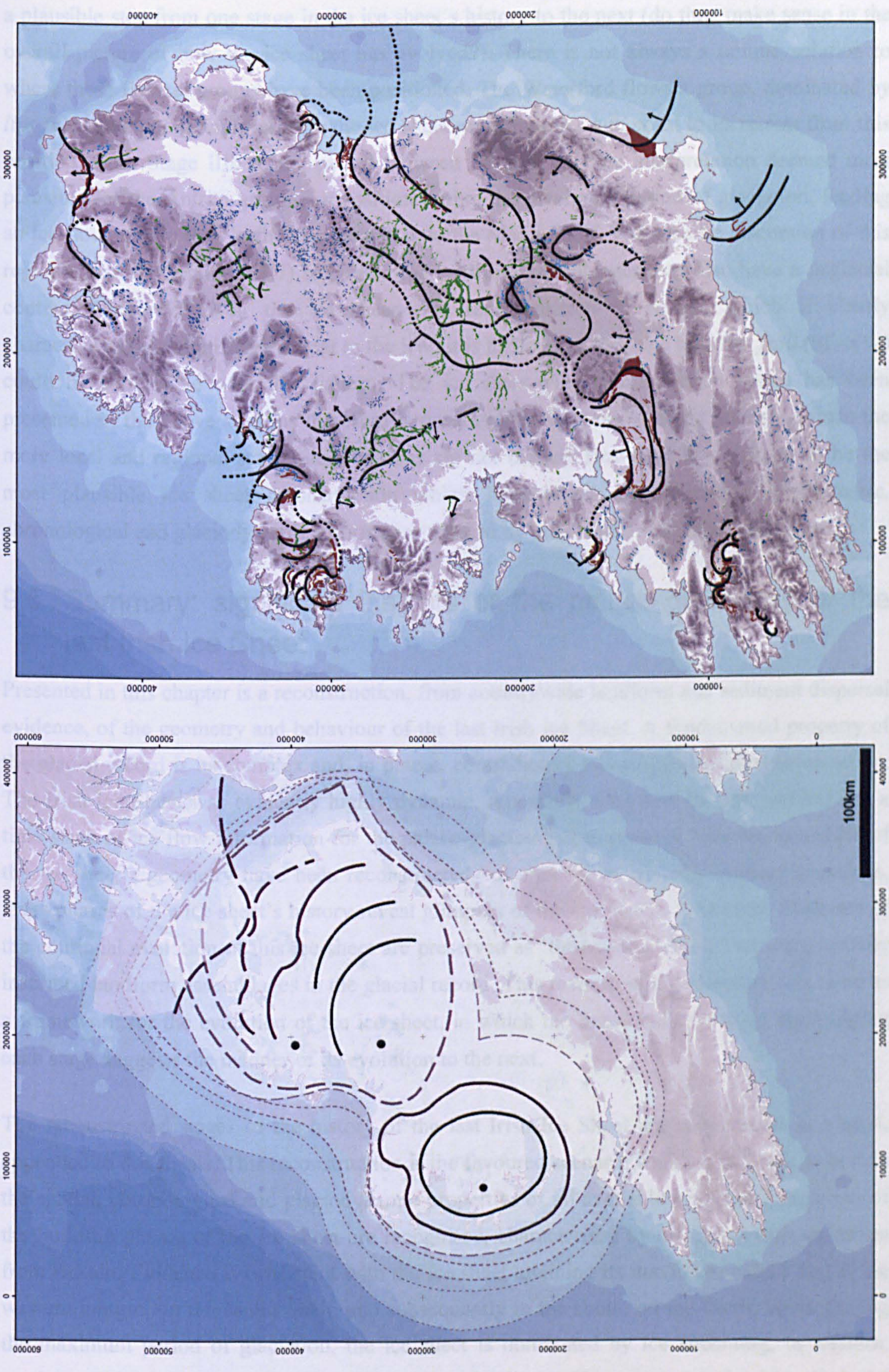
Subglacial bedforms are the traditionally the drivers of ice sheet-wide inversion approaches to palaeo-glaciological reconstruction (Boulton and Clark, 1990a,b; Kleman *et al.*, 1997; Clark *et al.*, 2000; De Angelis and Kleman, 2007). In Ireland, however, it has been observed that deglacial landforms tell a different story to the bedform flowsets (see comment above). It has therefore been essential to thoroughly incorporate the information imparted by deglacial indicators into the ice sheet reconstruction presented in the above sections. As a result, a retreat pattern has implicitly been derived, and the reconstructed margin positions for the periods of deglaciation can be overlain to produce a margin retreat map for the ice sheet (Figure 9.21a). There are strong similarities with a retreat pattern derived solely from deglacial landforms (Figure 9.21b). Nothing in the subglacial bedform record requires a deviation from the pattern reconstructed purely from eskers, moraines and lateral meltwater channels.

9.4.6 Floating stages and residual flowsets

There are, perhaps inevitably, some residual flowsets which have not been assigned to any of these reconstructed stages. These are typically the very small flowsets, which comprise only a handful of landforms, whose requisite ice flow direction is not always known and whose glaciodynamic context could not be interpreted for the same reasons. It is possible that these may fit into the late stages of ice sheet retreat, a period not observed to be widely characterised by bedforming, but a few sparsely distributed patches of bedforms may have been inscribed. This position could account for *lins fs26, fs31, fs43, fs44, fs51, fs52, fs53* and *fs57. Lins fs25* could potentially fit this scenario; alternatively it could have formed in Stage III. However, most flowsets formed in Stage III are very well-defined, unlike *lins fs25. Lins fs38* groups all those glacial lineations flowing offshore from west Co. Donegal. This landscape is drift-poor, the flowset is characterised by streamlined bedrock and isolated drumlins upon a bedrock surface, and its geometry is consistent with most of the reconstructed phases of the last Irish Ice Sheet. Clearly, this region was one which rarely provided an environment conducive to bedforming.

A number of flowset groups evident in Ireland are chronologically 'floating'. Internally, a regional ice sheet history may be relatively well-constrained for these groups. However, their connection to wider ice sheet events is less secure. Such flowset groups are typically peripheral to the present-day landmass: Donegal, Antrim, Connemara, Clare and Waterford. Most of these sectors have been discussed above, in Section 9.3, in terms of their regional ice sheet history.

Figure 9.21 (next page) a) Retreat sequence of ice limits invoked in Stages I – VII based upon the whole landform assemblage. **b)** Retreat pattern derived solely from deglacial landforms. Solid margins are placed at moraines and in front of eskers. Dashed lines speculate how margin positions link together. The strong similarity of **a** & **b** lends support to the bedform driven reconstruction and emphasises the importance of incorporating deglacial landform assemblages with bedforms in an holistic process of reconstruction.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These sectors have been built into the above reconstruction on the basis of their broad glaciodynamic context (i.e. must they occur early or late in the glaciation?), and on the basis of a plausible step from one stage in the ice sheet's history to the next (do they make sense in the overall picture of how the ice sheet has evolved?). There is not always a unique solution to where these flowset groups have been positioned. The Waterford flowset group, dominated by *lins fs1*, could occur anytime from the ice sheet reaching the south coast to its retreat from this position: from Stage IIIb to the period between IV and Va. The interpretation deemed most plausible for the Antrim group is a position during the maximum period of glaciation, feeding an ice flow path in the North Channel and onto the Malin Shelf. The specific discussion of this region's history (Section 9.3.7) suggested the landform assemblages may also have a deglacial context. However, given the ice sheet-wide reconstruction of retreat, which is clearly characterised by a significant retreat to the SW, it is difficult to envisage how *lins fs50* (SE-NW) could be compatible with this pattern. The ice sheet-wide reconstruction which has been presented in the above sections therefore is not a unique solution. It could not be so since the more local and regional-scale interpretations are not unique. However, it is thought to be the most plausible ice sheet reconstruction which incorporates all the available geometric, chronological and glaciodynamic information yielded by the countrywide landform record.

9.5 Summary: significant insights of the palaeo-glaciology of the last Irish Ice Sheet

Presented in this chapter is a reconstruction, from countrywide landform and sediment dispersal evidence, of the geometry and behaviour of the last Irish Ice Sheet. A fundamental property of the glacial record is its complex and, in places, contradictory palaeo-glaciological information. The Irish Ice Sheet was evidently highly dynamic, repeatedly reworked its bed, and has left a time-stack of ice flow information for the palaeo-glaciologist to unravel. Discrete snapshots of the ice sheet's geometry have been reconstructed but, more than just at-a-moment snapshots, these phases of the ice sheet's history reveal glimpses of the ice sheet's behaviour. Elements of the continual evolution of this ice sheet are preserved as 'time-transgressive', or incrementally inscribed landform assemblages in the glacial record. This reconstruction therefore acts more as a framework for the evolution of the ice sheet, in which the behaviour of the ice sheet during each stage suggests the manner of its evolution to the next.

The reconstructed stages of the history of the last Irish Ice Sheet are summarised in Map 4, appended to this thesis. This reconstruction is the favoured scenario which is believed to best fit the spatial, chronological and glaciodynamic properties of all available evidence. Fragments of the build-up phases of the ice sheet are recognised, characterised by an early incursion of ice from Britain. Evidence is consistent with the ice sheet attaining its maximum extent first at the western margin, on the Malin Shelf, and subsequently in the south, on the Celtic Shelf. During the maximum period of glaciation, the ice sheet is dominated by ice streaming, in western, northern and southern sectors. There is a hiatus in the landform record before the deglacial signature becomes apparent. Two potential scenarios for initial deglaciation have been presented: a model of steady retreat and one of a large-scale retreat and readvance. These potentially represent end member scenarios, and the ice sheet likely experience repeated margin oscillations during decay (see Chapter 10). Uncoupling, or fragmentation of the Irish Ice Sheet into two component 'domes', characterises deglaciation. The final period of decay sees margin retreat of ice from the north coast of Ireland to the Leitrim mountains, and the last vestiges of the ice sheet disintegrate over Connemara, Co. Leitrim and Co. Donegal.

A number of significant geometric and glaciological properties of the ice sheet have been revealed by the above reconstruction. These can be summarised as follows:

- **British ice** plays a role in the build-up of the Irish Ice Sheet. A record of flow from the north-east across much of Northern Ireland and the central Irish lowlands suggests that a lobe from Scotland was instrumental in driving the build-up of the Irish Ice Sheet. It is unlikely the whole NE-SW flow imprint can be accounted for by a single, snapshot flowline stretching from Scotland to central-western Ireland. A model of incremental advance, concurrent with local ice cap build-up and convergence, is more plausible.
- **Continental shelf glaciation** is required by the landform evidence. Even during early stages of the ice sheet, whilst still growing, an ice divide position over western Ireland demands continental shelf glaciation in order to maintain ice sheet symmetry.
- **Ice streams** dominate the maximum stages of glaciation. However, apart from one well-developed network of ice stream tributaries in the western sector of the ice sheet, onshore evidence of these ice streams is lacking. They are invoked largely on strong theoretical grounds. Given the convergence of ice flow from large areas of both Britain and Ireland, the soft underlying marine sediments, and to account for the considerable size of the Barra Fan and the considerable extent of margin advance onto the Celtic Shelf, it is hard to imagine that the North Channel and the Irish Sea Basin did not channel fast flowing ice streams.
- **Ice divide migrations** are reconstructed throughout the ice sheet history. From the early stages to the maximum, a main ice axis migrates from west to east up to 140 km (>⅓ of the ice sheet span). During the initial phases of deglaciation, it migrates back along a similar path, before fragmenting when the ice sheet unzips into two domes. It is hypothesised that some of these ice divide migrations are driven by the drawdown effect of ice streaming; this hypothesis is returned to for further examination and discussion in Chapter 11.
- **The ice divide structure** comprises neither 'domes' (as Warren and Ashley, 1994; Close, 1867) nor a single axis (as McCabe, 1985; Hull, 1878) for the full duration of the ice sheet. The configuration of flowsets in Ireland through its maximum period requires a more complex ice divide structure, consisting of a main axis, branching subsidiary divides and triple junctions. Such a configuration resembles those of modern-day ice sheets.
- **Two scenarios for deglaciation** can be accommodated by the landform evidence: steady margin retreat versus large-scale retreat and readvance. The development of the latter model is partly driven by literature models of ice sheet readvance. Such a scenario can be incorporated by the landform evidence does not explicitly require it.
- During deglaciation, the whole **ice sheet fragments** into separate, component entities. At

some stage, possibly driven by ice streaming in both the North Channel and Irish Sea, the saddle between the British and Irish Ice Sheets must collapse. The two ice sheets undergo independent subsequent deglaciation and the Irish Ice Sheet fragments further as northern and western 'domes' unzip. Fragmentation must occur under either deglacial scenario.

- **Three final sites of ice sheet disintegration** are proposed: over the Connemara mountains, over Co. Leitrim and Co. Donegal.

9.6 Section C: summary

The spatial and temporal coverage of subglacial bedforms in Ireland renders them the most suitable tool to drive a reconstruction of ice sheet dynamics. A flowset approach, used with success for other palaeo-ice sheets (e.g. Clark *et al.*, 2000; Kleman *et al.*, 1997; De Angelis and Kleman, 2007), has been developed and applied to the Irish case. Spatial, temporal and glaciodynamic information has been extracted from the full glacial landform record, using eskers and moraines to peel off the final layer of deglacial information from the underlying bedform record. Using a set of rules and assumptions, flowsets can be arranged in time and space, and their requisite ice sheet properties extracted, such that a glaciologically plausible evolution of the last Irish Ice Sheet can be described at regional and ice sheet-wide scales.

Snapshots of the history of the last Irish Ice Sheet are presented in the sections above and in Map 4. These provide a first-order framework of ice sheet evolution. Additionally, lower order ice dynamics are interpreted within this overall context. An abundance of time-transgressive, or incrementally inscribed flowsets are recognised from different palaeo-glaciological contexts, and reveal more subtle changes in ice flow behaviour during stages of the glaciation. A new model of the last Irish Ice Sheet is proposed which comprises an early, Scottish influence on ice sheet build-up; maximum stages of glaciation in which ice extends onto the continental shelf, and ice streams operate in most ice sheet sectors; and a pattern of ice sheet retreat characterised by the uncoupling of separate, component domes of the ice sheet. Asymmetric evolution of the ice sheet has been reconstructed, which begins with a strong north-easterly influence, and ends with ice sheet decay towards the west.

Objectives 1-3 of this thesis have now been largely addressed: the glacial geomorphology of Ireland has been systematically mapped, all relevant ancillary information pertinent to the reconstruction of the ice sheet has been gathered and analysed and, using both of these lines of information, a palaeo-glaciological reconstruction of the last Irish Ice Sheet has been deduced. Section D now discusses the new ice sheet model in detail. First it is important to examine the relationships between the model presented here, and those ideas of Irish glacial history which have previously been proposed in the literature. Inevitably there are areas of agreement, contradiction, and mutual assistance in enhancing understanding of palaeo-glacial behaviour in Ireland. Secondly, a number of interesting geometric and palaeo-glaciological insights have been drawn from this reconstruction. Some implications of this ice sheet reconstruction for glacial geomorphology, for drivers of ice sheet dynamics and for the interaction between the Irish Ice Sheet and the wider Earth system are explored and discussed.