The last British Ice Sheet: a reconstruction based on glacial landforms

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Abstract

The last British Ice Sheet has been a focus of research for over a century, and yet we have only a generalised picture of its extent and internal geometry. This is a remarkable situation compared to knowledge of the larger former ice sheets of North America and Fennoscandia. The central tenet of this thesis is that the glacial landform record has been neglected as a source of spatial information, hindering our attempts to reconstruct the characteristics of the ice sheet. This motivated systematic mapping of glacial landforms (subglacial bedforms, moraines, eskers, and meltwater channels) for the whole of Britain, yielding the first consistent and countrywide glacial maps. Mapping was achieved primarily using a high resolution (5 m horizontal) digital elevation model to visualise the landscape. Over 60,000 features were identified and mapped, greatly expanding the known distribution and pattern of glacial landforms. Analysis of the landform data permitted a country-wide reconstruction of the pattern of ice sheet retreat. A database of just over 400 dates, compiled from the literature, was used to arrange the pattern of retreat in time. This exercise highlighted various incompatibilities between the presently available dates. Examination of landform patterns enabled the elucidation of some pre-deglacial configurations of ice divides and flow geometry, including ice streams. This revealed the existence of both transient (migrating) and persistent ice divides. In contrast to other and larger palaeo-ice sheets, the majority of flow evidence in Britain exhibits a particularly close association with topography, indicative of an ice sheet thickness comparable with the amplitude of subglacial relief. The retreat pattern, flow geometries and divide configurations that have been identified from this research provide a set of evidence-based constraints at ice sheet scale for future numerical ice sheet modelling experiments.

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This thesis has depended on a number of digital data sources. NEXTMap Britain elevation data, from Intermap Technologies, Landsat TM data, 1:625,000 and 1:50,000 digital geological maps, and drift thickness model data was provided by BGS. Offshore bathymetric data was obtained from the GEBCO One Minute Grid via the British Oceanographic Data Centre. Digital Ordnance Survey maps, place names gazetteer and the LANDFORM PANORAMA DEM were obtained via EDINA. The Archaeology Data Service was kind enough to supply the whole of their online database of British radiocarbon dates. I thank Peter Bragg for making available some 500+ GB to store the above datasets and the large volume of additional image data I generated during this project. He has also been the port of call for numerous computer and server problems.

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The culmination of this PhD project marks the end of almost a decade (on and off) of living in and around Sheffield. Thanks to all the people and places (too numerous to mention) that have made my time here, and in Hathersage, so special.

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Introduction

1.1 Introduction and rationale

The last (Late Devensian/Weichselian) British Ice Sheet has been a focus of research for over a century, and yet we have only a generalised picture of its extent and internal geometry. This is problematic for understanding the role of the ice sheet in, and/or its response to, the climate changes of the last glacial cycle. The underlying thesis of this work is that the glacial landform record of Britain has been underused in attempts to reconstruct the characteristics of the ice sheet. The research presented directly addresses the consequent lack of a spatial framework in two ways:

- Systematic countrywide mapping of glacial landforms to produce the first consistent glacial map of England, Scotland and Wales.
- Extraction of key characteristics of the last British Ice Sheet (retreat pattern and glimpses of flow pattern configuration) from the glacial map employing clearly stated assumptions of landform production, preservation, and destruction to interpret the distribution and pattern of landforms.

1.1.1 The significance of ice sheets

Ice sheets are significant components of the global climate system affecting atmospheric and oceanic circulation systems, planetary albedo and the hydrological cycle (Clark and Mix, 2002). The present day ice sheets of Antarctica and Greenland together contain 27 x 10^6 km^3 of ice, which is equivalent to 63.9 m of global sea level (Marshall, 2005; Lemke et al., 2007). The response of the polar ice sheets to rising global temperatures is presently uncertain because we do not have an adequate understanding of ice sheet dynamics (Lemke et al., 2007).

Marine sediment and ice core records have demonstrated that the Late Quaternary climate has been highly unstable with abrupt climatic and oceanic shifts a characteristic feature of the last glacial period (Sarnthein et al., 2000; Hinnov et al., 2002) (figure 1.1). Significant demonstrations of this instability are the abrupt and periodic (approximately every 7,000 years) increases in the volume of ice-rafted debris (IRD) in North Atlantic marine sediments (Heinrich Events). The associated volume of meltwater released to the ocean during these events may have been enough to cause a shut down of the thermo-haline circulation, further suppressing North Atlantic temperatures. Heinrich Events are indicative of rapid, closely linked changes in the hydrosphere, atmosphere and cryosphere (Hemming, 2004). The ultimate cause of Heinrich events remains elusive (Hinnov et al., 2002). On shorter timescales (1,000-1,500 years), but possibly related to Heinrich Events (Bond et al., 1997), air temperatures also fluctuated during the last glacial cycle. These Dansgaard-Oescheger Events are characterised by abrupt increases in temperature succeeded by gradual cooling over 1,000-1,500 years (Broecker, 1994).

Elucidating the histories of former ice sheets, which we know operated under dramatic shifts in temperature, is one means by which we can investigate the response and/or role of ice sheets in climatic change. Numerical climate models are increasingly used to reconstruct the past, and predict future, climate change. The successful application of numerical climate models depends on accurate parametisation of the cryosphere, including the dynamics and extent of former ice sheets. Reconstructing former ice sheets and their dynamics also provides insights into the behaviour of the present day ice sheets in Greenland and Antarctica and may potentially help to determine how they will respond to future climate change.

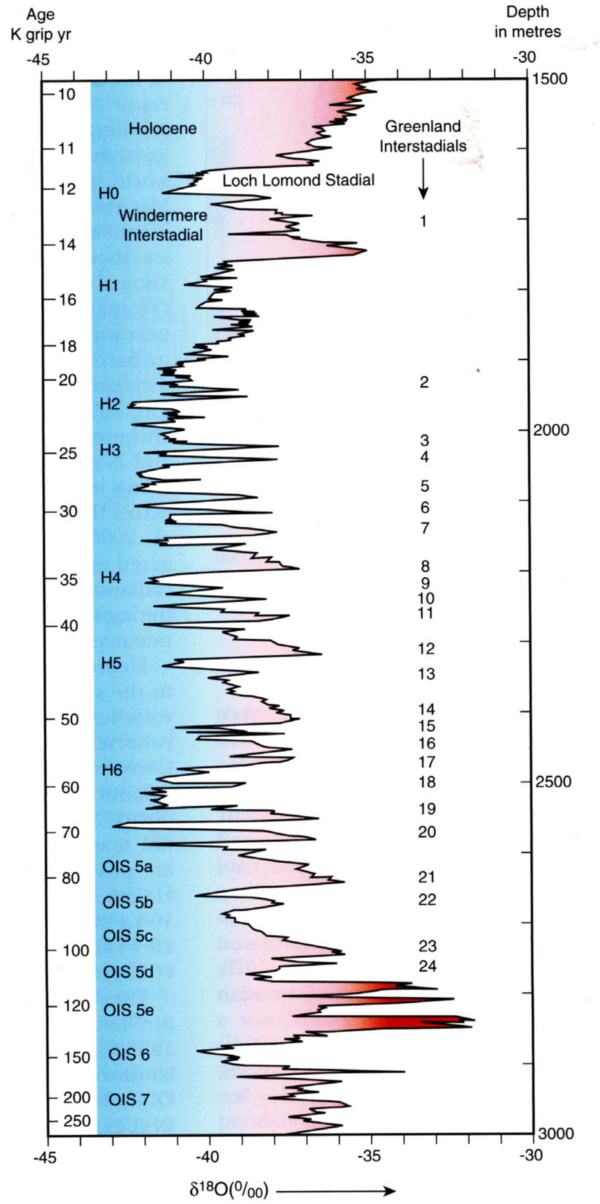
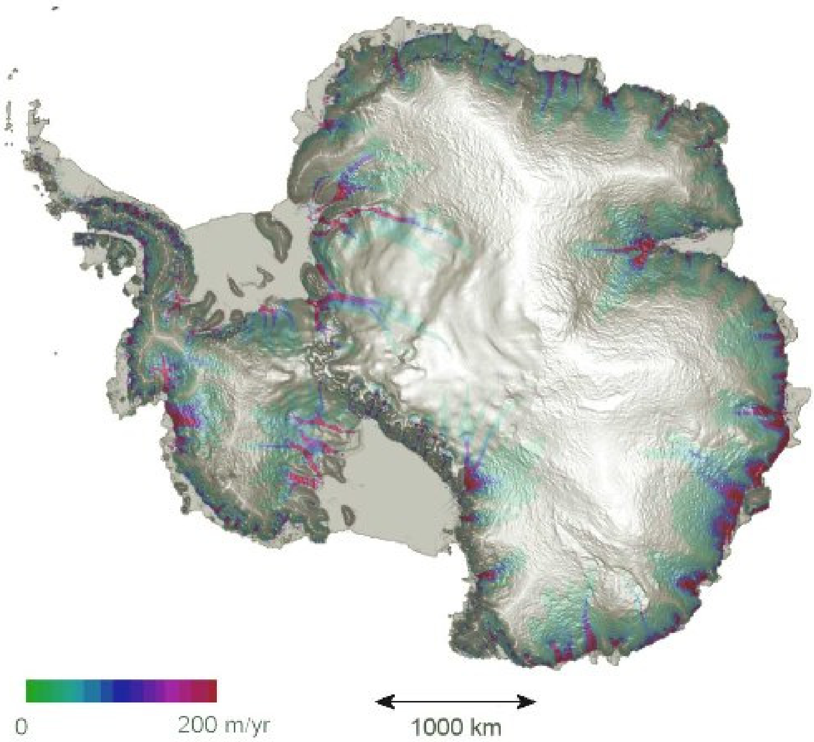


Figure 1.1 Abrupt temperature changes occurred during the last glacial cycle. Graph shows the Greenland (GRIP summit) oxygen isotope record (after Dansgaard et al. 1993), which is a proxy for North Atlantic air temperature. The timing of peaks in ice rafted debris (Heinrich Events: H0-H6) are placed after Bond et al. (1993). Reproduced from Merritt et al. (2003).

1.1.2 Approaches to ice sheet reconstruction

Ice sheets, as exemplified by the present day ice sheets on Antarctica and Greenland, consist of one or more ice domes or divides from which ice flows out towards the margins. The flow configuration, or geometry, of the ice sheet is thus determined by the location of the ice divides. Figure 1.2 shows the key features of the Antarctic Ice Sheet. A central objective of Quaternary science is to reconstruct the extent, volume, dynamics and temporal evolution of former ice sheets (Andrews, 1982). Determination of the ice configuration and dynamics of former ice sheets can provide insight into the location of iceberg seed points, ice discharge history and information on the scale of ice sheet oscillations (McCabe et al., 1998). The location of iceberg initiation points can be used to assess the provenance of IRD using iceberg trajectory modelling (Bigg and Wadley, 2001). Determining the source of IRD in Heinrich Events is an increasingly important area of research for understanding the relationships between climate and ice sheets. The reconstruction of former ice sheets can provide the initial boundary condition information for climate models or can be used to test the accuracy of climate model outputs (Mix et al., 2001).

There are three main approaches to ice sheet reconstruction: numerical modelling based on physical principles of behaviour derived from observations of present day ice sheets; isostatic modelling of the rate of crustal deformation due to ice loading; and inversion of the glacial geomorphological record using assumptions about glacial landform genesis (Andrews, 1982). The present understanding of glaciological and isostatic processes does not permit the development of an ice sheet model that is completely compatible with the geological evidence (Hagdorn, 2003). For this reason it is necessary to use all three approaches to make up for the limitations and restrictions of each. All three approaches have been used in attempts to elucidate the history of the British Ice Sheet. This thesis is concerned with the glacial geomorphological approach to ice sheet reconstruction (e.g. figures 1.3 and 1.4). Glacial geomorphology and geology are the most direct lines of evidence for the reconstruction of former ice masses (Kleman et al., 1997). Evidence based reconstructions of former ice sheets from glacial geology and geomorphology can be used to constrain ice sheet models or validate their outputs (Mix et al., 2001). Therefore, ice sheet reconstructions based on evidence can form an independent check on the ability of such models to simulate the three-dimensional behaviour of ice sheets (Boulton et al., 2001) and lead to refinement of the model and our understanding of glacial processes. Furthermore, the spatial distribution of glacial deposits and landforms is important information for land-use planning, the construction, engineering and water resources industries, agriculture, mineral resource exploitation, tourism, conservation and education (McMillan, 2002).



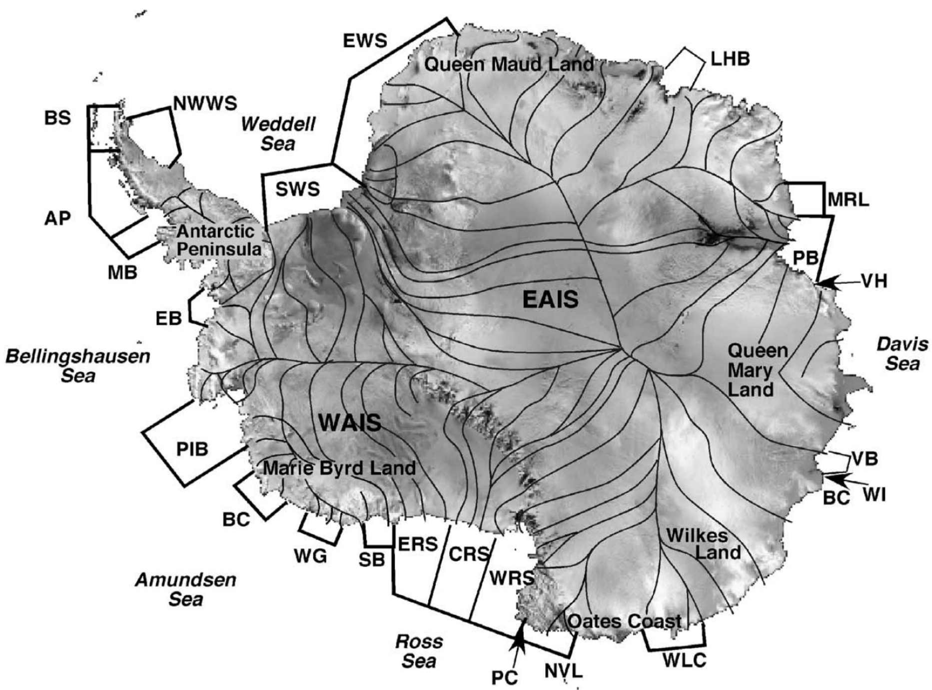


Figure 1.2 Ice sheets typically comprise a number of interconnected ice divides from which ice flows out towards the ice margin. Ice streams (anomalously fast rivers of ice within the main ice sheet) are most common at the ice sheet margin but their tributaries may extend into the interior of the ice sheet. The highest points coincide with the ice divide positions. Top image: Surface topography and steady-state flow rates for the Antarctic ice sheet. Reproduced from Bamber et al. (2000). Lower image: Flow configuration of the Antarctic Ice Sheet. Lines show ice divides and flow patterns. Reproduced from Anderson et al. (2002).

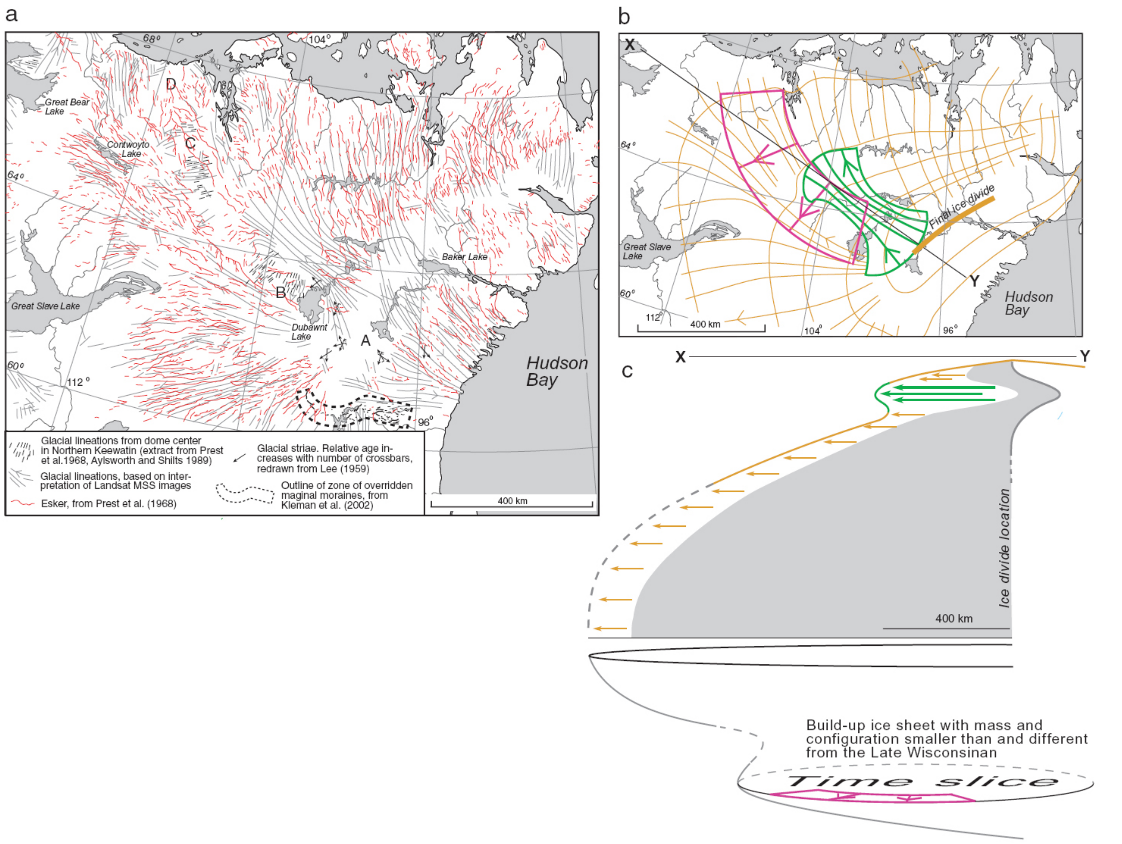


Figure 1.3 Example of the inversion of the glacial landscape to reconstruct the evolution of the Keewatin sector of the Laurentide Ice Sheet: a) Glacial Map detailing the distribution and pattern of landforms over the area of interest; b) Generalisations of evidence contained within the glacial map in terms of ice flow and retreat pattern. Deglacial information from eskers and aligned lineations in yellow, earlier ice flow patterns in pink and green; c) time-distance diagram across transect X-Y. Relative chronology derived from landform superimposition of the three discrete events identified constrains order within the diagram. Ice sheet geometry (divide locations and margin positions) extrapolated from the spatial arrangement of the generalisations. Reproduced from Kleman et al. (2006).

1.1.3 The last British Ice Sheet

Britain occupies a climatically sensitive position on the edge of the NE Atlantic (Map 1). Therefore it is reasonable to expect that the former British Ice Sheet (BIS) was highly dynamic. Studies into the delivery of ice–rafted debris to the Barra Fan off NW Scotland have supported this, indicating that the BIS may have fluctuated on 1,500 year cycles during the last glacial (Knutz et al., 2001). A more detailed understanding of the evolution of the last BIS could provide insights into the nature of abrupt climate changes and the dynamics of small maritime ice sheets. A number of provenance studies have demonstrated that there is a European component to Heinrich Events and that a distinct European-Laurentide-European phasing occurs (Scourse et al., 2000). This lack of synchronicity in the response of the ice sheets may reflect different response times to external climate forcing due to ice sheet size. It has been further postulated that the British Ice Sheet is responding to the 1,500 year climate cycle of Dansgaard-Oescheger Events in contrast to the approximate 7,000 year Heinrich cycle characteristic of the Laurentide Ice Sheet (Knutz et al., 2001). This new marine evidence places greater demands on the terrestrial record (Bowen, 1999a).

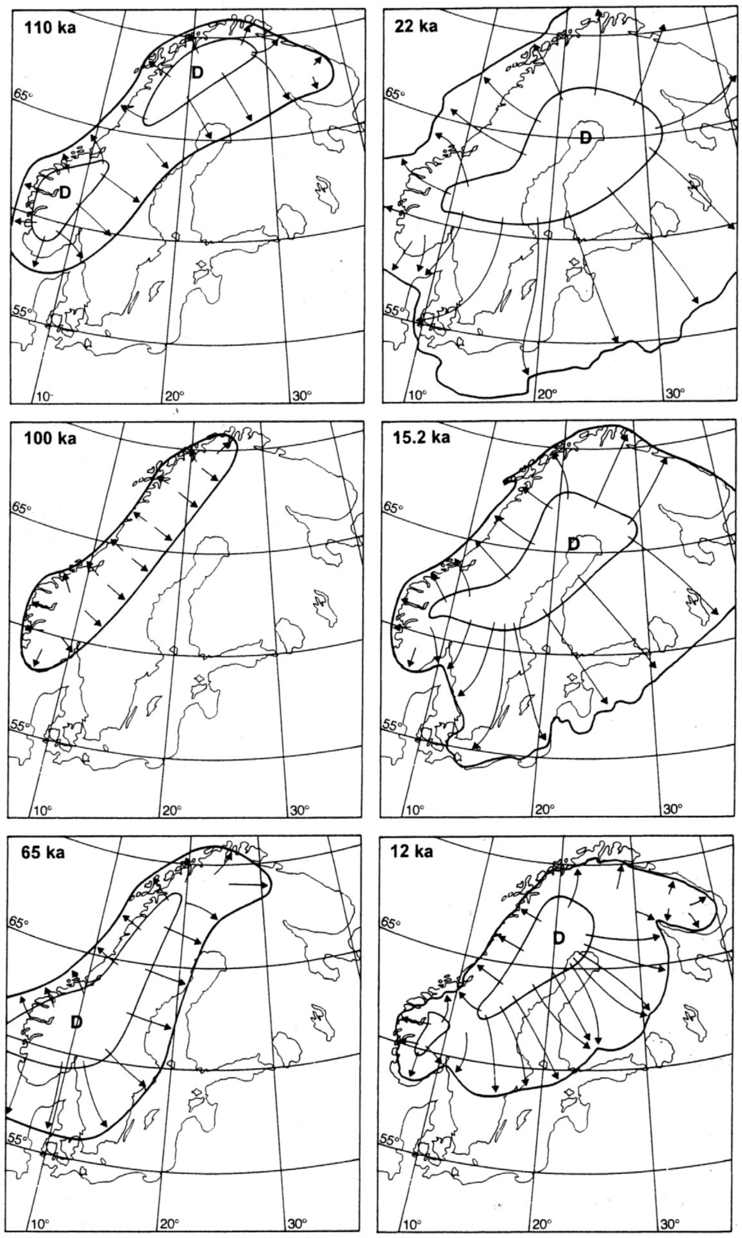


Figure 1.4 Evolution of the last Fennoscandian Ice Sheet interpreted from an inversion of the glacial landscape. Reproduced from Kleman et al. (1997).

The British landscape has been sculpted by numerous glaciations and glacial landforms and deposits cover a significant proportion of the country (Warren and Horton, 1991). There is terrestrial evidence for up to six glacial episodes although the deposits and landforms of the last (Late Devensian) ice sheet are the best preserved and most widespread (Bowen et al., 1986). Despite over a century of research and interest in the former glaciations of the British Isles there is very little information on the flow configuration, other than a 'generalised flow distribution' (for example see Ballantyne, 1998), the vertical extent, ice divide and ice stream locations and the retreat pattern of the BIS. This is in marked contrast to the information available for other northern hemisphere palaeo-ice sheets (e.g. figures 1.3 and 1.4). The majority of research into the BIS has involved field mapping of landforms and investigation of stratigraphic sections (for example see Merritt et al., 1995). Investigations have been on a local to regional scale meaning that synthesis has been difficult and conclusions are limited in scope due to the lack of a coherent dataset on which to base ice sheet scale reconstructions. Defining the maximum extent of the Late Devensian ice sheet has been the main focus of research, however this may not be the most useful information for understanding ice sheet behaviour and relationships with climate (Clark et al., 2004a). Numerical and isostatic modelling have been used to investigate the last BIS (Boulton et al., 1977; Boulton et al., 1985; Lambeck, 1991; Peltier et al., 2002; Shennan et al., 2006b; Boulton and Hagdorn, 2006). Models disagree on the vertical and spatial extent of ice and the number and location of ice dispersal centres. Many aspects of the ice sheet remain unresolved and controversial, for example the style of glaciation in the Irish Sea (Eyles and McCabe, 1989; McCarroll, 2001), a connection with the Scandinavian Ice Sheet across the North Sea (Boulton et al., 2001) and the extent of ice in northeast Scotland, (Merritt et al., 2003).

The BRITICE collaboration between British Geological Survey (BGS) and some university academics collated 150 years of published information on the landforms of the last BIS in a Geographic Information System (GIS) and produced the first Glacial Map of Britain (Clark et al., 2004b; Evans et al., 2005) (figure 1.5). The project identified inconsistencies in the published record, for example differences in mapping styles and scales between observers and restricted spatial coverage. In addition, during 150 years of research, our understanding of the genesis of glacial landforms has developed considerably leading to changes in terminology and classification schemes (Clark et al., 2004b). A systematic mapping program of British glacial geomorphology is therefore necessary before our understanding of the last BIS can attempt to approach that of the other Northern hemisphere ice sheets (Evans et al., 2005). This PhD builds upon the results of the BRITICE project to produce a comprehensive database of British glacial landforms to facilitate a glaciologically plausible reconstruction of the last BIS.

The main obstacles to a detailed understanding of the history of the last BIS are the lack of a consistent glacial geomorphological map and a reliable chronology. A comprehensive database of the glacial geomorphology of Britain would provide data to constrain models and enable a more rigorous assessment of their results. Due to the time and logistical constraints of fieldwork, studies based on glacial geomorphology and sedimentology are often limited to producing local and regional reconstructions. Understanding the dynamics of a former ice sheet is best achieved by a systematic synthesis of information from the whole area covered by the ice sheet, as local-scale studies will inevitably reconstruct small scale features of the ice sheet system (Clark et al., 2004a). It is not supposed that the (local) detail is incorrect, just that it becomes impossible to reconstruct the whole ice sheet from such data; a classic case of ‘not seeing the wood for the trees’. This is a classic example of the problem of reductionism in the earth sciences (Harrison, 2001). The focus on process-form studies and individual sites in

Britain, and the consequent lack of a geomorphological framework on which to base ice sheet scale models and provide a context for sedimentological information, has led to controversy over the dynamics and form of the last BIS.

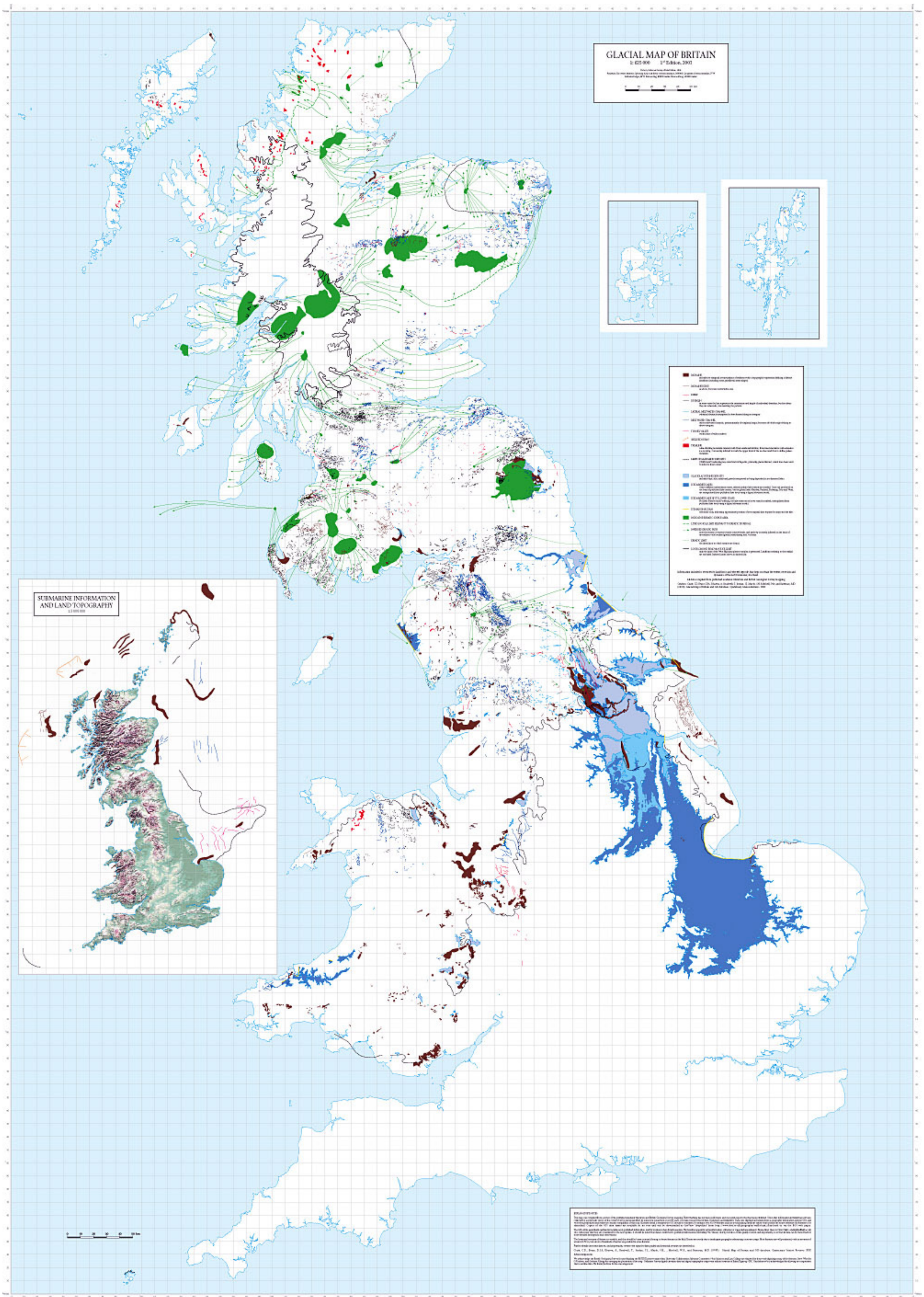


Figure 1.5 Glacial Map of Britain (Clark et al. 2004b). Map was compiled from over 150 years of published mapping including, journal articles, PhD theses and British Geological Survey map sheets and memoirs. Full details of compilation procedure are described in Clark et al. (2004b). The BRITICE assimilation demonstrated the wealth of information available for the last British Ice Sheet but also that the existing information suffers from inconsistencies and gaps in the record.

1.2 Aims and objectives

This thesis addresses the research problem of the last British Ice Sheet by improving the spatial coverage, detail, and consistency of the British glacial landform record by conducting a systematic countrywide mapping program. Using a range of assumptions and inferences about the genesis of glacial landforms, the geomorphological record provides the basis for deriving glimpses of ice sheet behaviour through time from which we can build a reconstruction of ice sheet evolution, and move away from locally specific reconstructions and towards explaining the palaeoglaciology of the last BIS.

The aim of this thesis is to produce a palaeoglaciological reconstruction of key aspects of the BIS based on existing and newly acquired geomorphological evidence. This aim is achieved through attainment of the following objectives:

1. *Countrywide mapping of glacial landforms of the England, Scotland and Wales to produce comprehensive and coherent maps of glacial geomorphology*. The first step is the production of a consistent glacial map of Britain to provide the basis for a reconstruction of key aspects of the BIS that remain unresolved, i.e. the retreat pattern, the location of ice divides and ice streams, flow configuration, and evolution over time. Individual GIS layers of the following glacial landforms will be produced: bedforms (drumlins and ribbed moraine), meltwater channels (subglacial and marginal), moraines, eskers, and bedrock streamlining (e.g. crag and tails, scoured bedrock). The aim of mapping is to produce a database which will be useful for a reconstruction at the scale of the ice sheet.
2. *Produce a GIS database of glacial geomorphology for Britain.* Primary data, from countrywide mapping of glacial landforms (objective 1), is used to augment the BRITICE dataset of published information. Secondary data published after the BRITICE census date of 2002 will be added to the BRITICE database as it is published.
3. *Reduce the information contained in the glacial map to a manageable number of units of glaciological information using the principles set out by Kleman and Borgström (1996).* The information contained in the glacial map is reduced to flowsets (distinct phases of ice flow) and margin positions. Inspection of cross cutting patterns is used to set up a relative chronology of ice sheet flow pattern events. These units of glaciological information form the ingredients for the reconstruction (objectives 4 and 5).
4. *Reconstruct the flow patterns, ice divide and ice stream locations of the last BIS and their evolution.* The reconstruction produced is the most appropriate explanation of the geomorphological record following the principles of Occam's Razor (i.e. the simplest). Where the conflicting sources of evidence or data gaps preclude a single unequivocal reconstruction a number of different scenarios are presented.
5. *Reconstruct the pattern of retreat of the last BIS.*
6. *Collate a database of absolute dates and to constrain the build up and retreat of the last BIS in absolute time.*

1.3 Thesis outline

This thesis consists of eleven chapters which can be broadly organised into four thematic sections. The first section includes the introductory chapters (1-3) that detail the motivation and philosophical approach. This chapter (1) introduces the topic and outlines the structure of the thesis, highlighting the main themes as well as listing the aims and objectives. Chapter 2 sets out the research problem through an examination of what we currently know about the last British Ice Sheet and what still remains elusive or controversial. Chapter 2 also explores the failure of British based glaciologists to maintain a tradition of glacial landform mapping as a possible reason for why key features of the ice sheet remain poorly constrained in contrast to what we know about other palaeo-ice sheets. Expansion and refinement of the Glacial Map of Britain (Clark et al., 2004b) is a major motivation for this research. The philosophical approach to ice sheet reconstruction employed is described in detail in chapter 3.

Section two details the research results (chapters 4-6). Chapter 4 describes the methods and datasets used to conduct countrywide glacial geomorphological mapping for Britain (objective 1) and chapter 5 details the resulting glacial maps and the GIS database on which all further interpretation is based (objective 2). Chapter 6 describes the first level of interpretation of the glacial maps into generalised summaries or nuggets of glaciological information and details the resulting flowsets and margin positions (objective 3).

Section three describes the interpretations that have been gleaned from the results (chapters 7-10). Chapter 7 develops the concepts outlined in chapter 3 and sets up the procedure for reconstructing ice sheet elements from the building blocks presented in chapters 5 and 6. Chapter 8 shows how the flowsets have been organised into glaciologically plausible ice sheet evolution reconstructions at the regional level (objective 4). Chapter 9 presents the reconstructed retreat pattern (objective 5). Chapter 10 attempts to attach a chronology to the retreat pattern (objective 6). The fourth and final section comprises the discussion and conclusions (chapter 11). Chapter 11 examines the implications of the reconstruction, describes avenues for further research and presents the thesis conclusions.

The thesis is accompanied by five maps enclosed unbound for ease of use. Maps 2 and 3 are split into north and south sheets. Map 1 is a location map listing all of the sites, place names and geographic features mentioned in the text. Maps 2 and 3 record the results of the countrywide systematic mapping. The interpreted flowsets are shown in Map 4 and Map 5 shows the reconstructed pattern of retreat. The appendix contains the collated table of published dates relating to the last British Ice Sheet.

Chapter 2

The last British Ice Sheet: a review

2.1 Introduction

It is beyond the scope of this thesis to review, in detail, all of the published research papers that concern the last British Ice Sheet (BIS). The literature on this topic is vast and expansive reflecting nearly two centuries of fascination with the elusive glacial history of England, Scotland and Wales. A synthesis of the mapping of glacial geomorphology that has amassed over this time, contained in published academic journals, maps, PhD theses, and British Geological Survey map sheets and associated memoirs, has already been conducted by Clark et al. (2004b) and the research literature contained therein is reviewed by Evans et al. (2005). As such, the purpose of this chapter is to briefly examine using illustrative examples what we currently know about the major characteristics of the ice sheet, focussing on identifying what is confidently constrained, what is yet to be elucidated, and what aspects remain controversial. This review draws heavily upon review papers, book chapters, Quaternary Research Association Field Guides and British Geological Survey Memoirs that collectively summarise in much more detail the state of knowledge and development of ideas (e.g. Charlesworth, 1957; Price, 1983; Sutherland, 1984; Boulton et al., 1991; Ehlers et al., 1991; Gordon and Sutherland, 1993; Benn, 1997; Gordon, 1997; Delaney, 2003; Ehlers and Gibbard, 2004; Lewis and Richards, 2005; Sejrup et al., 2005; Catt et al. 2006; Catt, 2007). These reviews summarise a wealth of research undertaken by generations of glaciologists, geomorphologists, and sedimentologists too numerous to mention specifically here. The final part of the chapter will examine some of the obstacles that have prevented an evidence based *ice sheet scale* reconstruction. First, it is useful to define what characteristics need to be determined in order to reconstruct a former ice sheet. This PhD project is concerned with the glacial record of Britain (England, Scotland and Wales); for an up to date review of the literature on the Irish Ice Sheet see Greenwood (2008).

2.2 What do we want to know about ice sheets?

There are four principal elements of a former ice sheet of interest to palaeoglaciologists – size, form, evolution, and timing (Clark et al., 2006). We want to know:

- How big was the ice sheet? - spatial and vertical extents, ice volume.
- What shape was the ice sheet? - flow pattern configuration, ice divide locations, ice stream locations.
- How did the ice sheet evolve? - nucleation centres, configuration changes, retreat pattern.
- When did the ice sheet exist and how long did it take to build up and retreat?

The answers to these questions allow us to calculate how much water was locked up in the ice sheet in terms of relative sea levels, and to determine how much of the country was affected by glacial processes. The vertical extent of the ice sheet will determine whether it had any effect on the atmospheric circulation. Establishing the location of former ice streams helps to identify the major discharge points for iceberg calving and thus model the effect of the last BIS on the ocean circulation (e.g. Bigg and Wadley, 2001). Knowledge of how the ice sheet evolved during the climate changes of the last glacial cycle would further our understanding of ice sheet dynamics and ice-climate interaction. Finally, we want to fix the operation of the ice sheet in time and therefore require an absolute chronology to constrain the evolution of the ice sheet.

2.3 Spatial extent

Determining the maximum extent of the last (Devensian/Weichselian) BIS has been a major focus of debate and controversy. A detailed discussion of the evolution of opinion is given in Clark et al. (2004a). Proposed maximum limits have ranged from complete shelf-edge glaciation coalescent with Scandinavian ice in the North Sea to a more restricted ice sheet with peripheral ice free enclaves in Scotland and no connection to Scandinavian ice. Figure 2.1 shows some of the various limits that have been suggested. Note that the maximum limit is frequently presumed to be equivalent to the Last Glacial Maximum (LGM) limit. The LGM defined as the global glacial ice volume peak at 23-21 ka BP (Clark and Mix, 2002). However, it has been suggested that the maximum limits of the last BIS were reached earlier than this (Bowen et al., 2002).

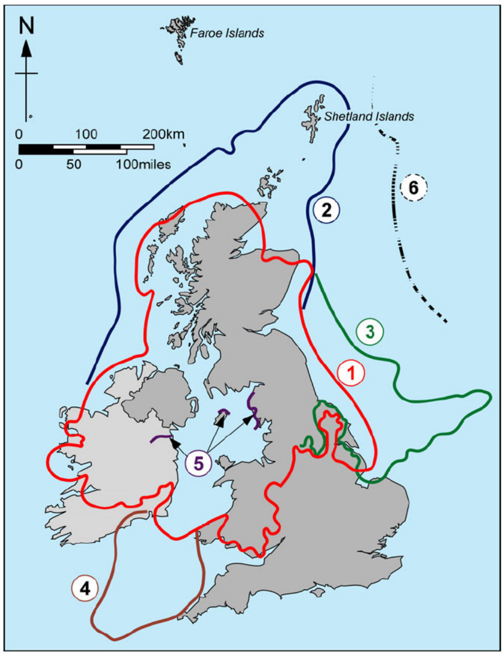


Figure 2.1 Some of the limits proposed for the last British Ice Sheet. 1 = Bowen et al (2002), 2 = Hall (1997), 3 = Balson and Jeffrey (1991), 4 = Scourse and Furze (2001), 5 = proposed readvance limits in the Irish Sea Basin (Isle of Man – Dackombe and Thomas (1991), Cumbria – Huddart (1991)), 6 = possible western margin of the Scandinavian ice sheet at the LGM (Hall, 1997). Reproduced from Boulton and Hagdorn (2006).

Most of the maximum terrestrial limits of the last BIS are not marked by significant end moraines (Evans et al., 2005) and so the former extent of ice has traditionally been defined by the spatial extent of glacial deposits (figure 2.2), and the 'freshness' of glacial landforms (Bowen et al., 2002). For example, the compilation of Charlesworth (1957) summarised the results of much of this research defining the limit of what he referred to as 'newer drift'. Where this limit has been difficult to find because of little or no geomorphological expression, patchy or thin till deposits, or if successive generations of glacial deposits have been derived from the same source area and therefore have similar lithological characteristics, there has been debate over the precise position of the limit. For example, the 'Wolverhampton Line' marking the maximum extent in Cheshire and Shropshire has been placed with a disparity of up to 10 km by different field workers (Worsley, 2005).

Suggested limits for the Welsh section of the limit vary by as much as 50 km depending on the evidence used (Clark et al., 2004a) (figure 2.3). The South Wales End Moraine was first delimited by Charlesworth (1929) on the basis of overflow channels, discontinuous moraines and postulated ice dammed lake boundaries. Re-examination of the limit based on lithostratigraphy now places it further south (Bowen, 1981). The position of the limit in Pembrokeshire is based on the occurrence of Irish Sea till (Hambrey et al., 2001).

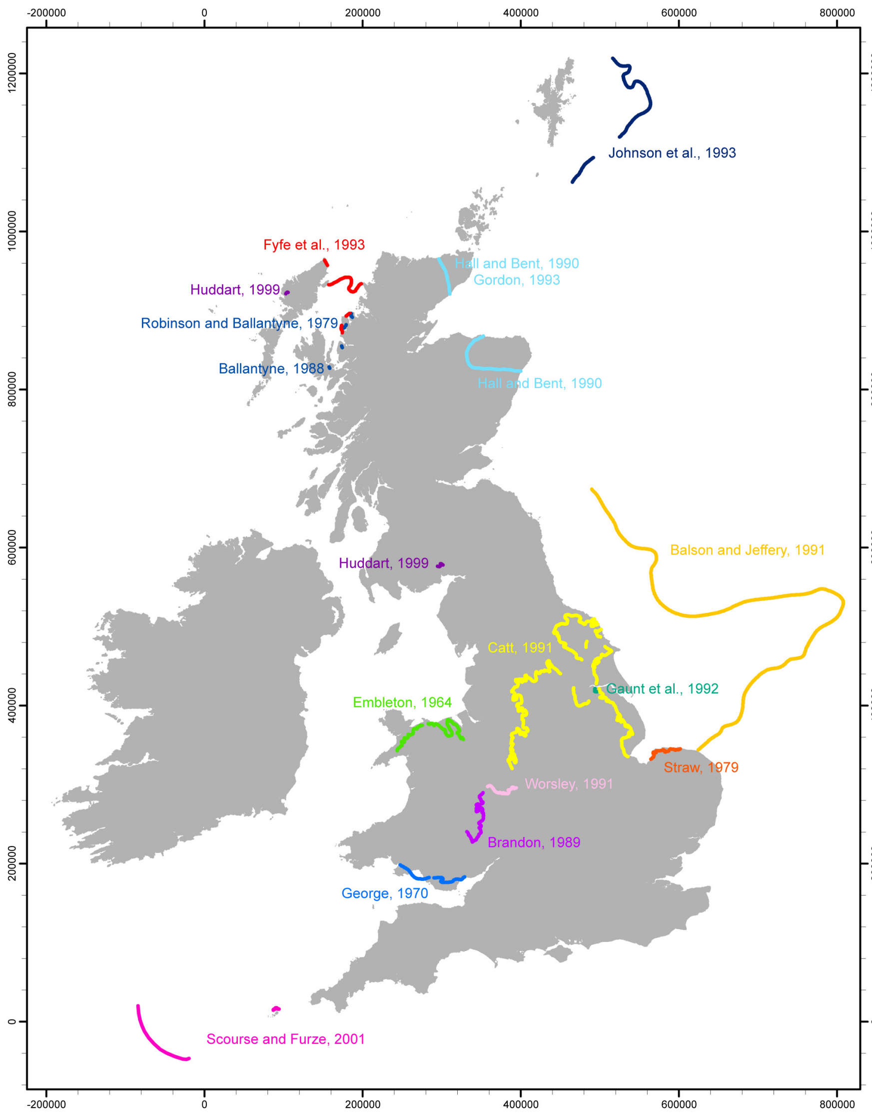


Figure 2.2 Drift limits related to the last British Ice Sheet. Reproduced from the Glacial Map of Britain and BRITICE GIS database. Drift limits in NE Scotland and Lewis have been used to support the existence of ice free enclaves during the last glaciation. In Caithness the limit of shelly till is now recognised as representing the junction between mainland sourced and Moray Firth sourced ice (Evans et al. 2005).

Several positions have been suggested for the limit in the Vale of York (Straw, 2002). Charlesworth (1957) places the limit of newer drift at the Escrick Moraine, but other research based on sedimentary evidence places the maximum limit south of these moraines, at Wroot, invoking surge behaviour of the Vale of York ice lobe into Glacial Lake Humber (Gaunt, 1976; Catt, 1991). The limit of onshore flow on the east coast is set at the Horkstow Moraine marking the westernmost limit of Skipsea till (Evans et al. 2005) or the feather edge of the Skipsea Till on the Wolds dip slope (Catt, 2007). The most southerly limit of ice in the east is marked in NW Norfolk by the limit of Hunstanton Till (Hart and Boulton, 1991). The Hunstanton Till is correlated with Devensian till found in the southern North Sea, the limit of which is placed at the Dogger Bank (Balson and Jeffery, 1991). The limits along the southern margin are thought to have dammed several proglacial lakes, e.g. Lake Teifi in Cardiganshire (Etienne et al., 2006) and Lake Sparks in Cambridgeshire (West, 1993).

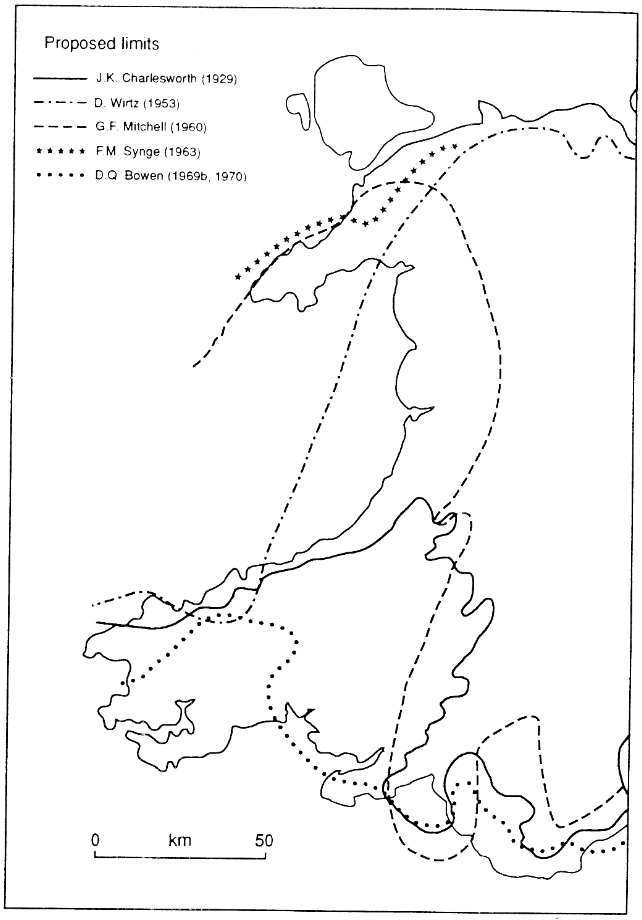


Figure 2.3 Conflicting ice limits suggested for Wales. Today ice is recognised to have covered all of Wales except Pembrokeshire (following the Bowen 1970 line). Reproduced from Jones and Keen (1993).

The southern terrestrial limit in England is well established and is reproduced repeatedly in the literature without much debate, although, minor revisions of the order of kilometres continue to be made to the limit (e.g. Brand et al., 2002). It is suggested that it is known to a precision of 40 km although at several points the limit is necessarily interpolated where there is no direct field evidence available (Clark et al., 2004a). The accepted limit forms an inverted V shape across the country (figures 2.1 and 2.2).

The southernmost offshore limit in the Irish Sea Basin has been subject to controversy (Hiemstra et al., 2006). Scourse et al. (1991) first produced evidence for a drift limit on the Northern Scilly Isles, which has been since augmented with morainic evidence (Hiemstra et al., 2006) and dates (Scourse, 2006). Scourse and Furze (2001) examined cores from the Celtic Sea and suggested that till extends into the Celtic Sea, placing the terminus of the Irish Sea ice lobe at about 49°N, much further south than suggested by other studies (Hiemstra et al., 2006) (figure 2.2). Scourse and Furze (2001) infer that this is a grounded ice sheet margin as IRD beyond the limit contains material that could only have been incorporated from the northern Celtic Sea. There is ongoing debate as to the age of the glacial evidence on the Isles of Scilly but the 'balance of evidence' suggests an MIS 2 age (Hiemstra et al., 2006). The consensus view is that the Celtic Sea limit represents a short lived margin position possibly as the result of a surge or ice stream event. The placement of the southern ice limit this far south has implications for the glacial outcrops on the north coast of southwest England presently viewed as Anglian or Elsterian (Scourse and Furze, 2001).

Views of the extent of ice over Scotland and the continental shelf have fluctuated from two polarised positions; a restricted ice sheet model with limited offshore expression (Sutherland, 1984; Bowen et al., 2002), and continental shelf edge glaciation favoured by those investigating the offshore record (Stoker et al., 1993; Sejrup et al., 2005). The restricted glaciation model suggests that some parts of Scotland were never overwhelmed by ice, Shetland and Orkney were not affected by the mainland ice sheet, there was no connection with Scandinavian ice, and ice terminated at the Wee Bankie Moraine offshore of Aberdeenshire, and just west of the Outer Hebrides. This model was widely accepted until relatively recently, advocated by Sutherland (1984), and later by Bowen et al. (2002), and seemingly verified by the isostatic modelling of Lambeck (1991).

The existence of ice free enclaves in NW Scotland and the Hebrides is the key motivation for the restricted glaciation hypothesis. Ice-free enclaves were initially inferred from the apparent lack of glacial deposits of Devensian age in these areas, e.g. 'moraineless Buchan' (Charlesworth, 1957). Recently derived thermoluminescence dates on glaciofluvial sands overlying till ranging from 116 to 72 ka BP also appear to support the ice free hypothesis (Gemmell et al., 2008). The restricted glaciation model has been strongly criticised from both the terrestrial and offshore points of view. Non-glacial conditions in Buchan during the last glaciation are unlikely on the basis of a large integrated network of subglacial meltwater channels identified in the region (Clapperton and Sugden, 1975; Merritt et al., 2003). The meltwater channels are accompanied by other deglacial features which strongly indicates full glaciation of Scotland during the last glacial (Merritt et al., 2003). New cosmogenic dates in the same area suggest ice free conditions commencing at c. 18 ka BP in conflict with the thermoluminescence dates (Phillips et al., 2008).

The restricted glaciation view also fails to account for the significant moraine complexes and glacial sediments on the Hebridean and West Shetland shelves (Stoker and Holmes, 1991). These are defined, on the basis of marine stratigraphy, to be of Late Devensian age, which precludes the presence of low-lying ice free enclaves throughout the glaciation (Evans et al., 2005). The four major glacial fans; the Barra Fan, Sula Sgeir Fan, and Rona and Foula Wedges, also suggest that shelf edge glaciation is likely to have occurred during each main glaciation (Sejrup et al., 2005) (figure 2.4). Seismic and borehole evidence suggests that the ice sheet also reached the continental shelf south of the Hebrides (Davies et al., 1984). Examination of multi-beam seismic data from the continental shelf around northern Scotland has led to the discovery of a multitude of morainic features (Bradwell et al., 2008b). The clear expression of these features on the surface of the present day seabed implies that the moraine ridges are the product of the most recent phase of glaciation.

The extent of ice in Scotland is closely tied to debates about glaciation of the North Sea. A variety of Late Devensian ice sheet limits have been proposed for the North Sea based on various criteria (Carr et al., 2006) (figure 2.5). One of the key questions in the history of research on the BIS has been to determine whether the British and Scandinavian Ice Sheets (SIS) were coalescent in the North Sea during the last glaciation and the issue continues to be somewhat contentious (Evans et al., 2005). The view of an extensive ice sheet was originally postulated by Valentin (1957) on the basis of acoustic profiling. Using the new technique, Valentin suggested that the BIS and SIS were confluent at the location of Dogger Bank. Jansen (1976) suggested that the central and southern North Sea was ice free but coalescence occurred at the latitude of Shetland and Orkney. Ehlers and Wingfield (1991) used the distribution of deep channel like incisions evidenced from seismic profiling to determine the offshore limit.

Sedimentological investigations have been used to support both scenarios. In his 1984 review, Sutherland described that till extended 20 km offshore to the Wee Bankie Moraine but not beyond and, coupled with the concept of ice-free enclaves in Scotland, concluded that the ice sheets were never confluent. Cameron et al. (1987) place the eastern boundary of British till at approximately 100 km offshore, and state that Scandinavian till does not extend beyond the Norwegian trench, thus establishing an ice free corridor between the two ice sheets.

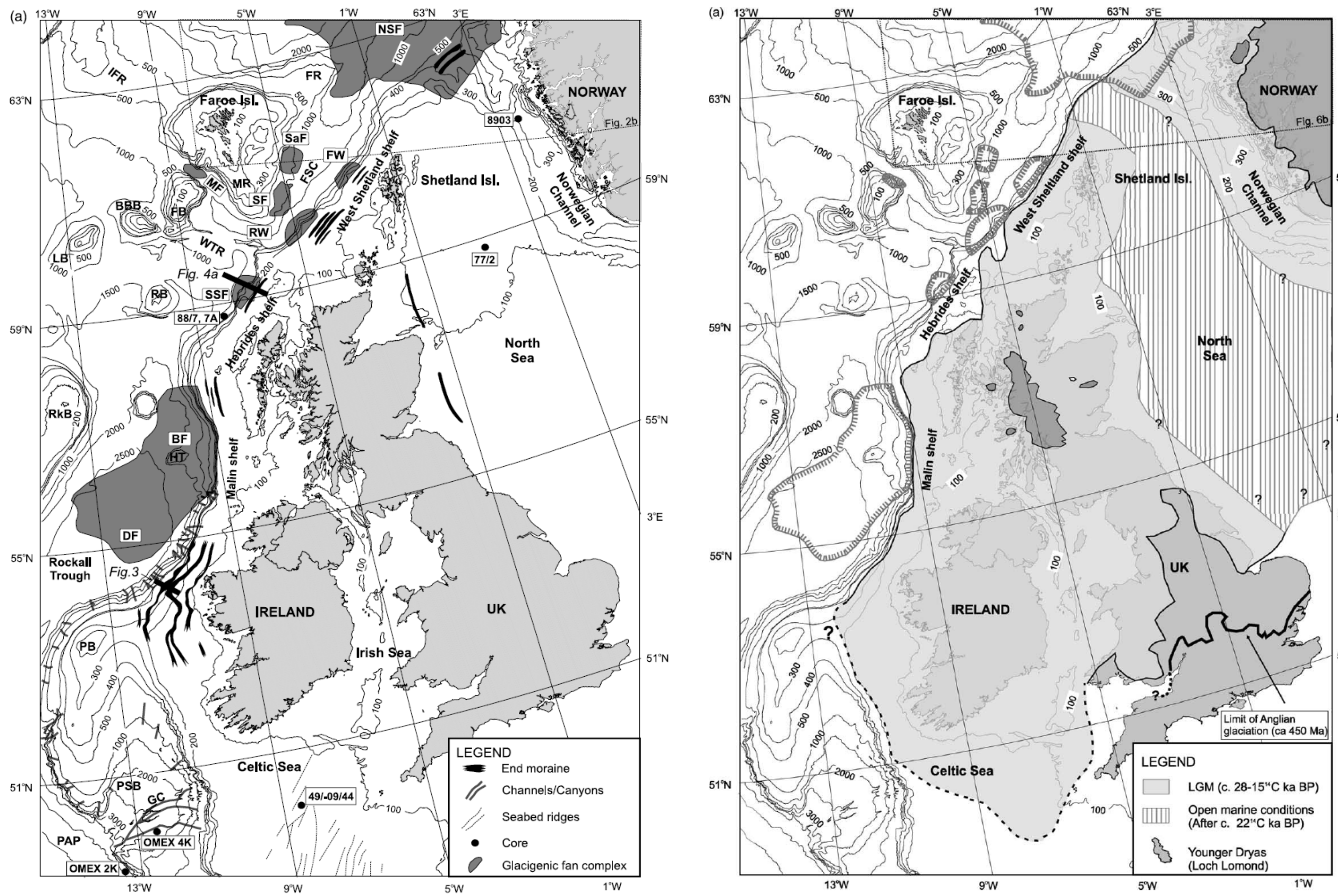


Figure 2.4 Offshore evidence, moraines and trough mouth fans, supports the view of the ice sheet reaching the continental shelf edge during the last glaciation: a) bathymetry of the continental margin and offshore moraine locations from Stoker and Holmes (1991), King et al. (1998b), Bulat and Long (2001), and Sejrup et al. (2003). BBB: Bill Bailey's Bank; BF: Barra Fan; DF: Donegal Fan; FB: Faroe Bank; FW: Foula Wedge; FR: Fugloy Ridge; FSC: Faroe-Shetland Channel; GC: Gollum Channel; HT: Hebrides Terrace Seamount; IFR: Iceland-Faroe Ridge; LB: Lousy Bank; MR: Munkagrunnur Ridge; MF: Mykines Fan; NSF: North Sea Fan; PAP: Porcupine Abbysal Plain; PB: Porcupine Bank; PSB: Porcupine Seabight; RW: Rona Wedge; RB: Rosemary Bank Seamount; RkB:Rockall Bank; SaF: Sandoy Fan; SF: Suderoy Fan; SSF: Sula Sgeir Fan; WTR: Wyllie-Thomson Ridge. (b) the emerging consensus view of limit for the last British Ice Sheet at the Last Glacial Maximum. Younger Dryas (Loch Lomond Stadial) limit is also shown. Reproduced from Sejrup et al. (2005).

The Bosies Bank and Wee Bankie Moraines mark the offshore limit of till and the glaciomarine sediments of the Marr Bank Formation beyond have been used to support their status as end moraines (Evans et al., 2005). Hall and Bent (1990) and later Hall et al. (2003) reject the concept of ice free enclaves in Scotland but accept that there was no connection with the Scandinavian Ice Sheet (SIS) in the North Sea at the LGM on the basis of the offshore stratigraphy. Their model suggests that the BIS extended as far as the Bosies Bank and Wee Bankie Moraines, overwhelmed Shetland and Orkney forming the Otter Bank moraines north of Shetland, and deposited the moraine banks to the west of St. Kilda. Others have accepted the terrestrial limits in Buchan and on Caithness and accommodated them with the positions of offshore 'end moraines' and other evidence for extension of the ice sheet into the North Sea (Ehlers and Wingfield, 1991). Carr (1999) conducted a detailed examination of the micromorphological properties of sediments from cores from the central North Sea and advocated a subglacial origin of these sediments thereby supporting a more extensive easterly limit. The Boulders Bank Formation and/or the Dogger Bank is usually taken as the limit in the southern North Sea (Clark et al., 2004a).

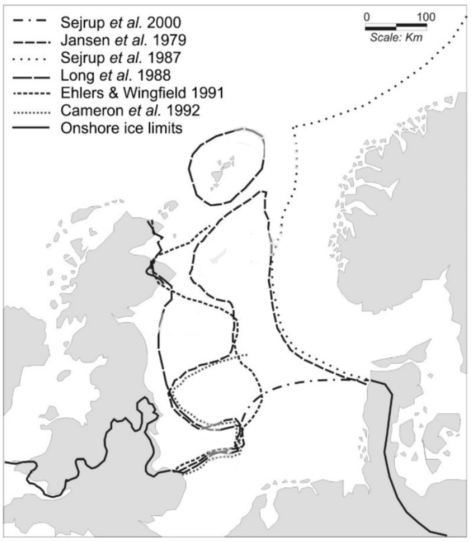


Figure 2.5 Some of the proposed ice limits for the North Sea The difference in opinion reflects the challenge of defining limits from coastal sections and limited marine core and seismic evidence. Reproduced from Carr et al. (2006).

Sejrup et al. (1994) conducted sedimentological analysis and radiocarbon dating of three cores from Fladen Ground in the central North Sea and found that full glaciation in the North Sea occurred prior to the global LGM (23-21 ka BP). They conceive a two-stage glaciation model with pre-LGM glaciation of the North Sea followed by retreat and a subsequent but more limited readvance of the BIS to correspond with the well constrained Tampen readvance of the Scandinavian ice sheet. The concept of a two-stage model for the North Sea has been accepted and refined by subsequent researchers (Merritt et al., 2003; Carr, 2004; Carr et al., 2006). The two-stage model is consistent with conflicting evidence between the terrestrial and offshore records, especially in terms of timing, and the complicated nature of the glacial sediments (Carr, 2004) (figure 2.6). In this scenario, the Bolders Bank and Wee Bankie moraines off the east coast of Scotland become retreat features. Recent work using a 3-D seismic dataset from the

Witch Ground area east of the moraines has identified mega-scale glacial lineations running broadly NNW-SSE. These lineations rest on top of the Weichselian stratigraphic unit and thus imply grounded ice in the North Sea at this time (Graham et al., 2007). Therefore the Scandinavian and British Ice Sheets must have been confluent.

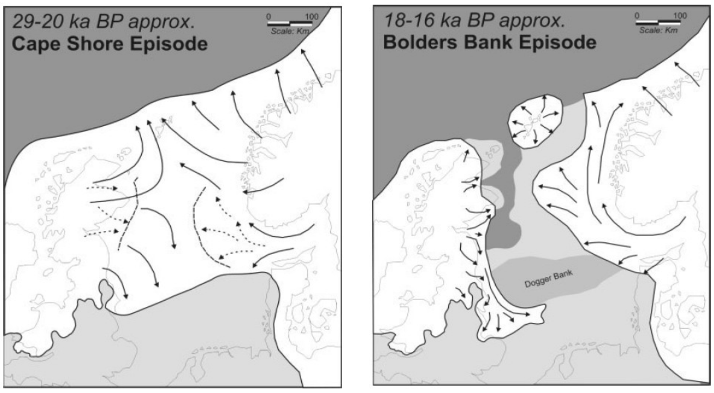


Figure 2.6 Schematic of a version of the two-stage model of glaciation of the North Sea. The British and Scandinavian Ice Sheets are confluent during an early part of the last glacial (Cape Shore Episode; left image). This is followed by retreat to the vicinity of the Wee Bankie and Bolders Bank moraines (dashed lines) and a second stage of advance into the North Sea with a lobe of ice emanating out of northern England and Scotland (Bolders Bank Episode; right image). Limits are based on correlation of tills in the North Sea. The Bolders Bank Episode model adopts some of the previously suggested terrestrial limits for a less extensive ice sheet in Scotland at the LGM. The two stage model of the North Sea is supported by dates from the northern North Sea suggesting deglaciation after 25 cal. ka BP and dates for ice incursion on the eastern English coast after 21 cal. ka BP. Dates on the figure are uncalibrated radiocarbon ages. Reproduced from Carr et al. (2006).

The emerging consensus view of an extensive ice sheet reaching the continental shelf edge and confluent with the Scandinavian ice sheet for at least the early part of the last glacial represents a return to the picture we had at the turn of the century (Geikie, 1894). The main areas of controversy in determination of the spatial extent of the last BIS have been the southernmost limit in Wales; terrestrial and offshore limits in and around Scotland; confluence of ice in the North Sea; and the offshore limits southern Irish and Celtic Seas. Only the southernmost limit in England has persisted relatively unquestioned in the literature with only minor modifications being made over time.

2.4 Vertical extent

Numerical and isostatic models of the last BIS have produced disparate values for the altitude of the ice surface (figure 2.7). Differences between the models are largely a function of the different boundary conditions used; for example, the assumed lateral extent and characteristics of the bed can have significant implications for the height of ice surface. Boulton et al.'s (1977) model postulated heights of 1800 m and 1200 m for central Scotland and North Wales respectively. They assumed extensive lateral extent of ice with coalescence in the North Sea and a rigid bed. Later models have predicted lower maximum altitudes of 1000 m in central Scotland and 500 m in Wales (Boulton et al., 1985; Boulton et al., 1991) assuming a bed of deformable sediments and with a more restricted view of maximum lateral extent. There is approximately 50% difference in height between the maximum model of Boulton et al. (1977)

and the minimum model of Boulton et al. (1985) in NW Scotland (Ballantyne, 1998). A new, and arguably more objective model (driven by climate and changes in subglacial parameters), published by Boulton and Hagdorn (2006) suggests maximum ice surface heights ranging from 2,250-1,500 m depending on the boundary conditions. Relevant to the following discussion of periglacial trim-lines (see below) they found it difficult to satisfy the required ice sheet surface using 'sensible' flow parameters.

Figure 2.7 Models of the last British Ice Sheet at its maximum extent. The range of modelled ice surface heights is 1800-1000 m. A. Boulton et al. (1977); B. Boulton et al. (1985); C. Boulton et al. (1991); D. Lambeck (1993). Surface contours are in metres. Reproduced from Lowe and Walker (1997).

Isostatic models have not produced consistent estimates for the height of the ice surface either. Lambeck's (1991, 1995) models suggested a maximum height of 1,100 m and 1,500 m respectively, but his most recent model suggests a maximum height of just 1000 m (Johnston and Lambeck, 2000). Peltier et al.'s (2002) ICE4G model suggests a height of 2,500 m whereas Shennan's model of the same year suggests 1,125 m (Shennan et al., 2002). Models also disagree on the location of the greatest vertical extent of ice, for example Lambeck's (1991) model centred the maximum height in the northern Irish Sea. A new isostatic inversion model that adheres to the view of confluence of ice in the North Sea suggests a maximum height of between 875-1,000 m centred on the Midland Valley and Kintyre (Shennan et al., 2006a) (figure 2.8).

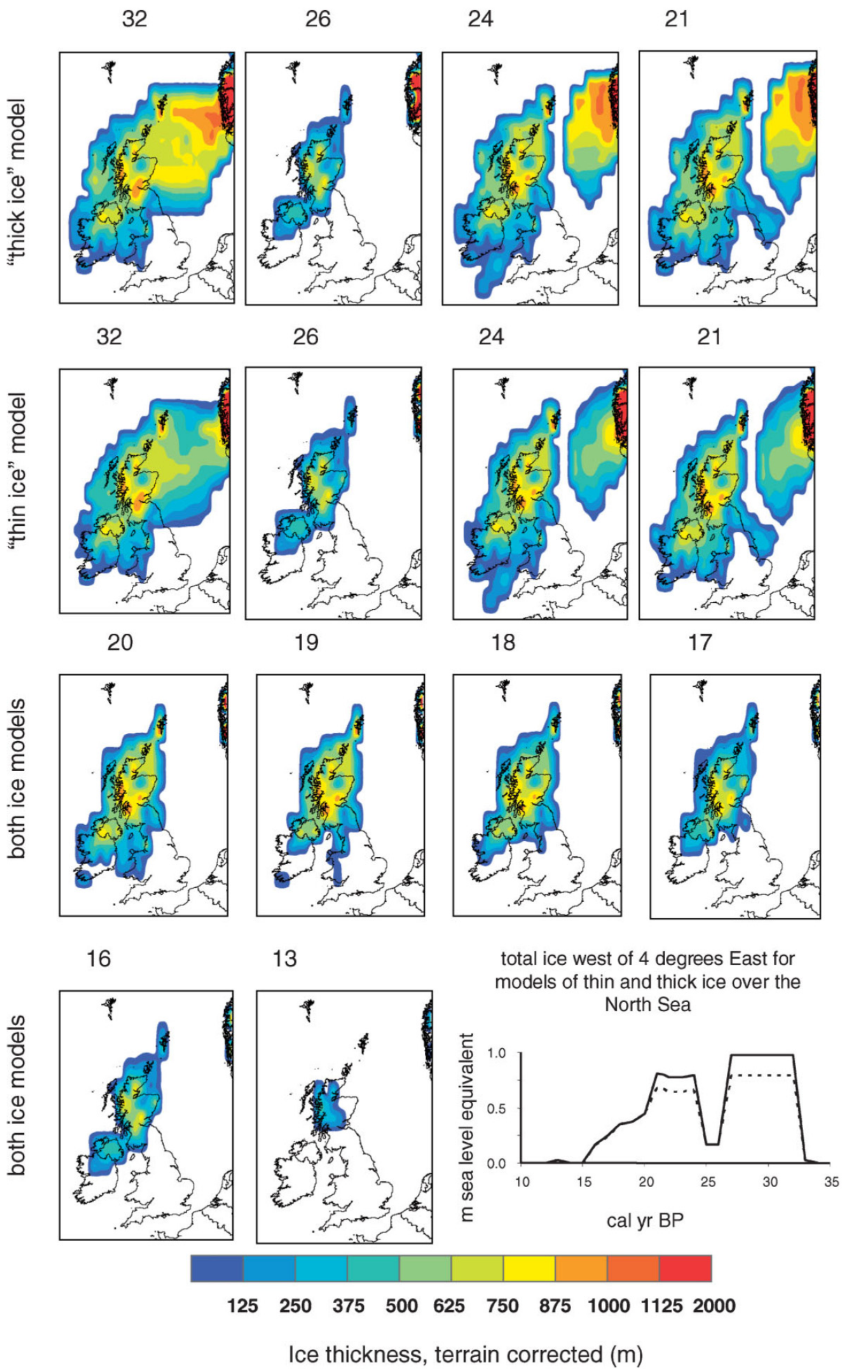


Figure 2.8 Terrain corrected isostatic model of the British Ice Sheet, 35-10 ka BP. 'Thick' and 'thin' ice models differ 33-21 ka BP in the amount of ice over the North Sea and the continental shelf west of Scotland and Ireland. Note that the pattern and extent of ice cover is an input to this type of model, and not a result. Reproduced from Shennan et al. (2006a).

A series of recent publications summarise work, led by C.K. Ballantyne, identifying palaeo-nunataks of the last BIS on the basis of periglacial trim-lines (Ballantyne and McCarroll, 1995; McCarroll et al., 1995; Dahl et al., 1996; Ballantyne and McCarroll, 1997; Ballantyne et al., 1997; Ballantyne et al., 1998c; Ballantyne et al., 1998b; Ballantyne, 1999; McCarroll and Ballantyne, 2000; Ballantyne and Hallam, 2001). This develops earlier work of J. Geikie in NW Scotland and the Hebrides. The papers reassess the possibility of reconstructing the maximum possible height of the ice surface and other aspects of ice sheet configuration by mapping the altitude of periglacial weathering limits or trim-lines. It is suggested that the trim-line altitudes represent the maximum altitude of the ice surface and hence delimit locations of palaeo-nunataks. Periglacial trim-lines have been identified in NW Scotland and on the Inner and Outer Hebrides (figure 2.9) (McCarroll and Ballantyne, 2000), Snowdonia (Lamb and Ballantyne, 1998) and the Lake District (Ballantyne, 1997).

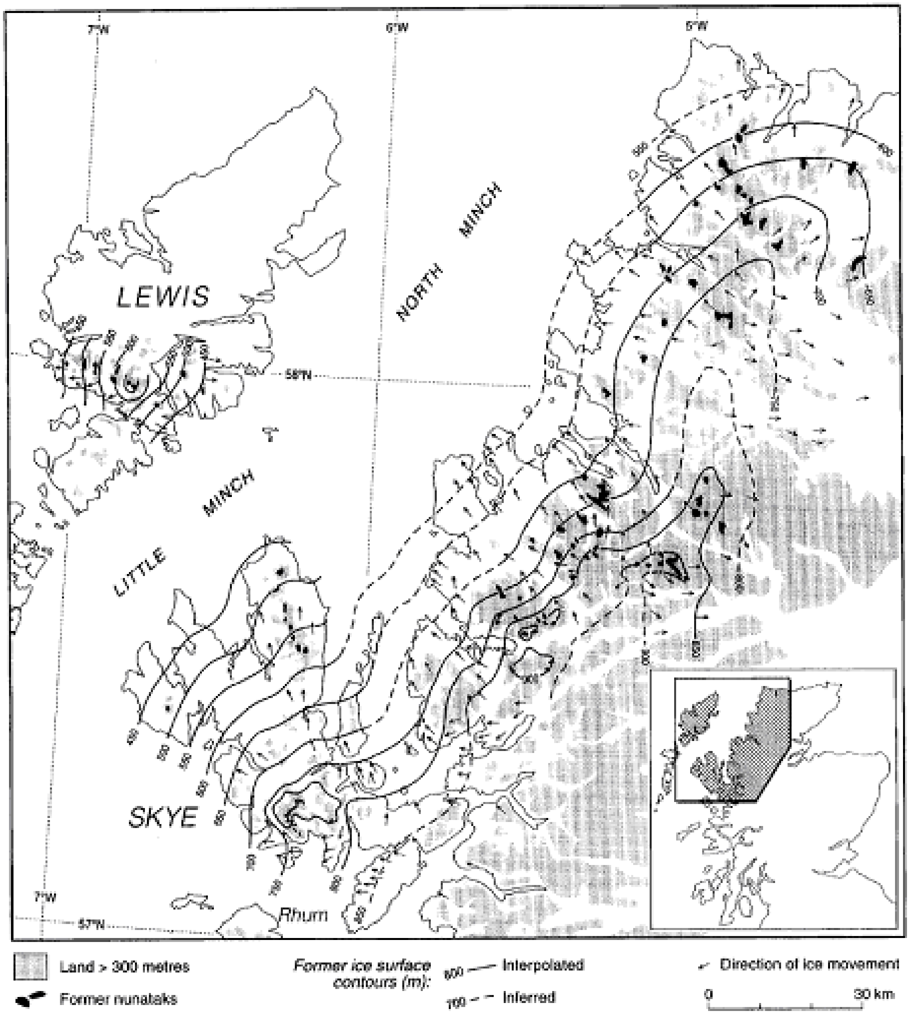


Figure 2.9 Periglacial trim-line locations identified in NW Scotland and the Outer Hebrides (black). Contours show the projected ice surface profiles that satisfy the trim-line heights. Arrows show direction of ice flow. Reproduced from Ballantyne et al. (1998c).

Ice surface reconstructions from regional assemblages of trim-lines suggest that the maximum altitude of the last ice sheet was 900 m in NW Scotland, 700 m over the Outer Hebrides, 850 m in Snowdonia, and 870 m and 800 m in the eastern and western Lake District respectively.

Using the periglacial trim-line evidence to create parabolic profiles of the ice surface the lateral extent in NW Scotland is projected 7-10 km west of the coast of Lewis (Ballantyne et al. 1997). This is more restricted than suggested by the offshore record of glacial moraines (Ballantyne and McCarroll, 1995). This conflict lends support to the alternative interpretation of periglacial trim-lines as marking the location of an englacial thermal boundary (Ballantyne et al. 1998b). None of the criteria used to identify periglacial trim-lines rule out the possibility that the difference in erosion above and below the trim-line was the result of a transition from erosive warm based ice at lower elevations to protective cold based ice at higher elevations. Ballantyne et al. (1998b) argued against this interpretation on the basis that an englacial thermal boundary would not exhibit an even decline in altitude from inland to the coast, as observed in NW Scotland. However, the identification of periglacial trim-line evidence from summits in northern Scotland that must have been subsumed by ice at the LGM indicate it is impossible to unequivocally use trim-lines to identify palaeo-nunatak locations, (Ballantyne and Hall, 2008). A further problem for the palaeo-nunatak interpretation is the inability of the most recent numerical modelling experiments to reproduce the vertical limits suggested by the trim-line altitudes (Boulton and Hagdorn, 2007). The vertical extent of the ice sheet is still debated and the existence of nunataks remains controversial. It is likely that all summits in the central part of the ice sheet were submerged although it is possible that nunataks existed in peripheral regions of the ice sheet.

2.5 Ice sheet configuration

2.5.1 Flow patterns

Ice flow patterns have been established on the basis of straie, erratic paths and till lithological properties, as well as streamlined bedrock features, subglacial bedform patterns, and till fabric analysis (Evans et al., 2005). The main flow patterns of the last BIS have been known since the turn of the twentieth century (figure 2.10) (Geikie, 1894). Charlesworth's (1957) synthesis of flow pattern information derived from erratic transport paths and glacially streamlined landforms is remarkably similar to the summary produced by Geikie (1894), except in East Anglia. The basic flow pattern for the last BIS in Scotland has only been modified slightly since the map produced by A. Geikie in 1865 and 1901 (Price, 1983; Hall, 1997) (figure 2.11). The key changes are the interpretation of flow patterns over the Outer Hebrides and Shetland. The generally accepted pattern is of radial ice flow out of a number of ice centres distributed N-S along the western side of the country. Ice in Scotland is drawn down into the topographic depressions presented by the major troughs such as the Firth of Forth. Ice from Scotland is deflected to the west and south around Ireland and to the north and south in the North Sea. This deflection of ice is usually invoked to support coalescence of British and Scandinavian ice. Southward ice flow in the Irish Sea is deflected around Wales to enter the Cheshire Plain and flow SW over Anglesey.

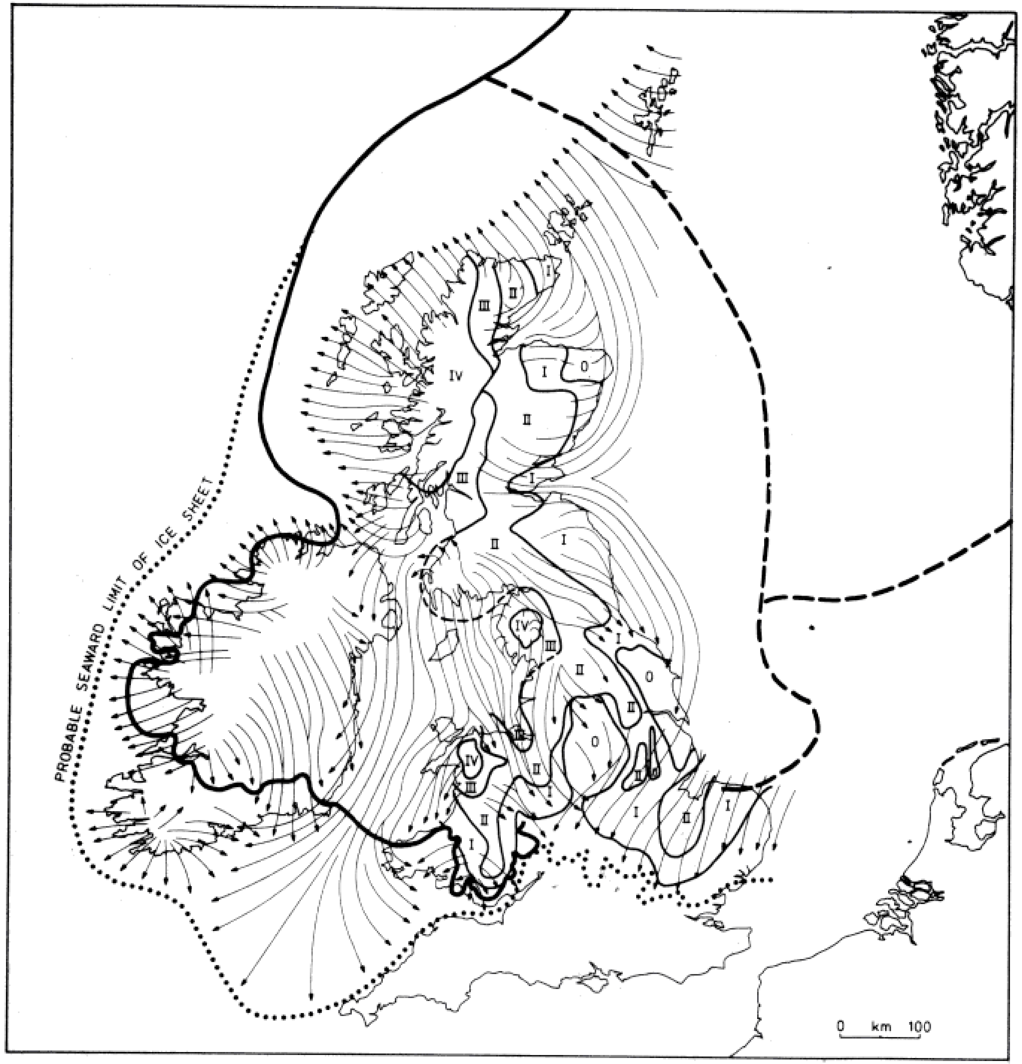


Figure 2.10 Generalised maps of flow patterns for the last British Ice Sheet at its maximum extent; J. Geikie (1894) (left image) and Charlesworth (1957) redrawn by Boulton et al. (1977) (right image). The later synthesis of Charlesworth reproduces virtually the same flow patterns as Geikie's map of 50 years earlier.

Offshore pathways have been inferred from the till lithology of coastal sections and the distribution of sediment packages on the continental shelf (Holmes, 1997). Concentrated delivery of sediment has led to the development of a number of shelf edge fans around the UK which imply directed flow of ice throughout numerous glaciations in well defined flow paths (Nielsen et al., 2005). Till fabrics from tills containing Scottish erratics record NNE-SSW ice flow on the Holderness coast and have been invoked to suggest an ice flow path skimming the east coast (Catt, 2007) (figure 2.12).

There are some problems using erratic indicators of flow paths as there is significant potential for reworking of material in subsequent glaciations (Evans et al., 2005). Field mapping of streamlined landforms, till stratigraphies and straie has led to detailed reconstructions of flow patterns in several localities. However, there has not been a systematic accumulation of evidence and so the detail of reconstructed flow directions varies widely between areas (Evans et al. 2005). Mapping of drumlin distribution and orientation in northern England has refined models of flow directions derived from erratic trains (Mitchell and Riley, 2006) suggesting that a similar approach should be adopted elsewhere (figure 2.13). To date, the drumlin population of the British Isles has been underused in reconstruction of flow patterns of the last BIS and several major drumlin fields have not been mapped in detail (Evans et al. 2005).

Greater variability in flow directions is evident at the local scale which is suppressed in the national summaries of generalised ice flow directions. Furthermore, the national summaries do not take into account the dynamic nature of the ice sheet; all flow pattern evidence is shoehorned into a single time period, usually taken to be the LGM. It is apparent that the evidence is multi-temporal as in some locations opposing flow direction information occurs which cannot have existed contemporaneously (figure 2.14).

2.5.2 Ice divides

Principal and minor ice divide locations have been established on the basis of divergent erratic transport paths and inferred from reconstructed flow patterns. For example the pattern of Rannoch granodiorite erratics suggests radial flow out from Rannoch Moor (figure 2.15) (Evans et al., 2005), confirming its status as a major ice accumulation centre as also suggested by the organisation of glacial troughs surrounding the plateau. Detailed examination of the distribution of straie and erratics in the Grampians has further refined the structure of the 'Rannoch' ice centre as three connected ice domes located on the high ground surrounding the plateau (Thorp, 1987).

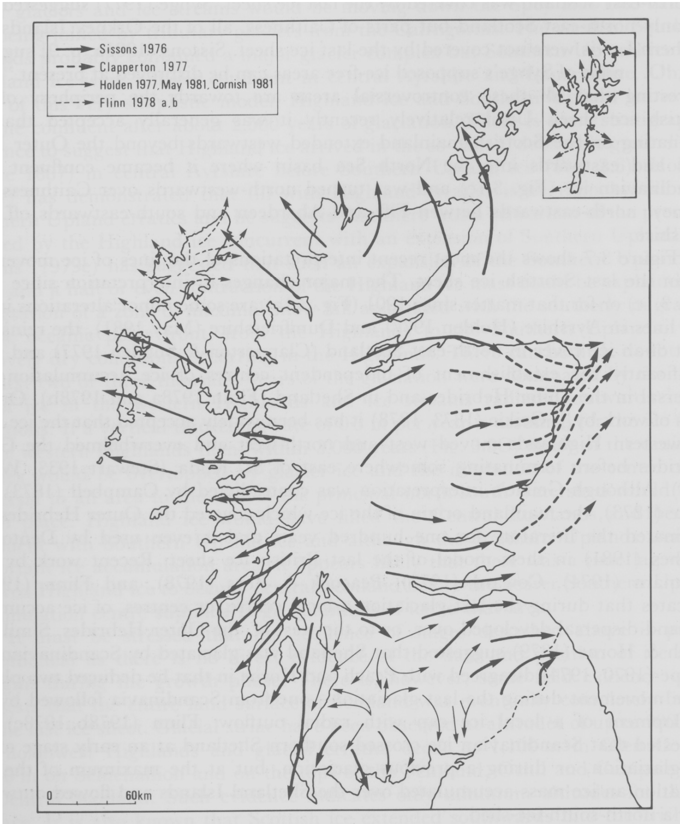


Figure 2.11 The general pattern of ice flow in Scotland has remained relatively unchanged over time except on the Outer Hebrides and Shetland. Reproduced from Price (1983).

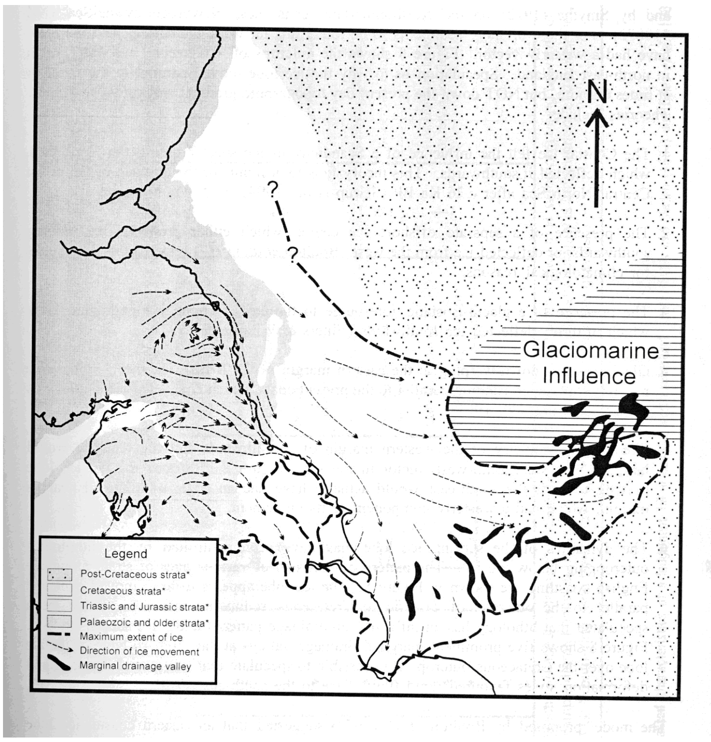


Figure 2.12 An ice lobe down the eastern coast of England has been invoked to explain the presence of erratics from Scotland and northern England on the east coast in the absence of coalescence of ice in the North Sea. Reproduced from Teasdale and Hughes (1999).

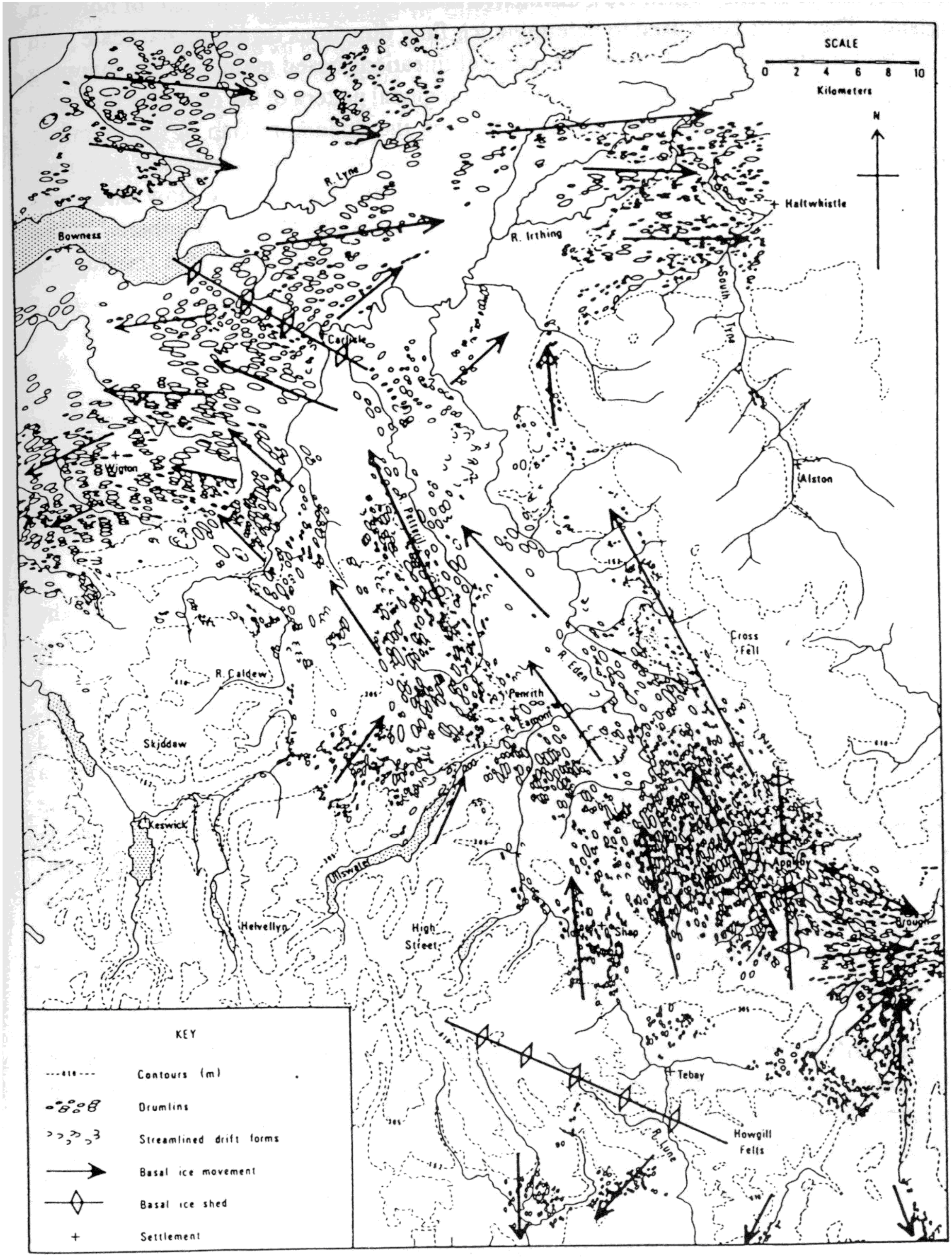


Figure 2.13 Geomorphological map of the Vale of Eden and Solway lowlands. Interpreted ice flow patterns and ice divide locations are shown. Original diagram by Hollingworth (1931) redrawn by Letzer (1978).

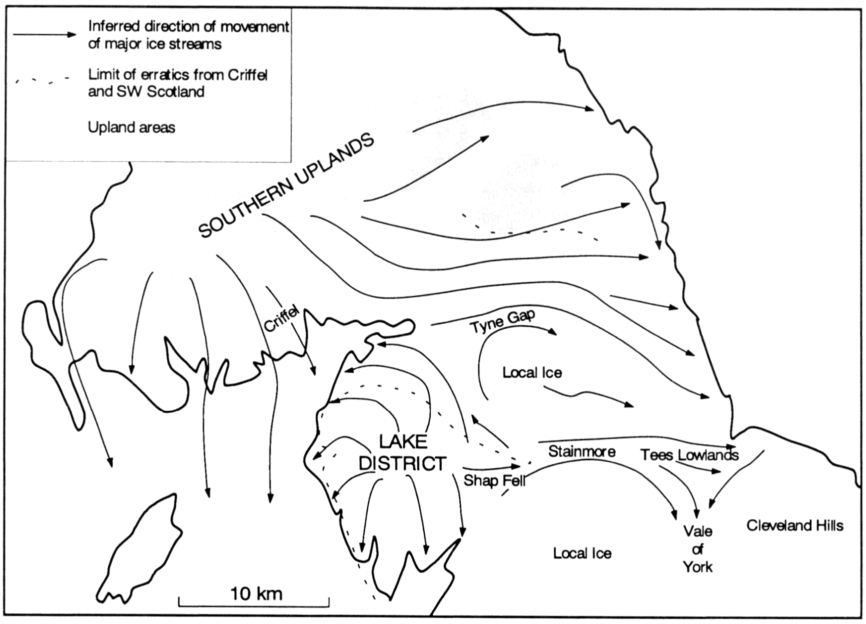


Figure 2.14 Generalised flow patterns for northern England and southern Scotland. The opposing flow directions in the Solway lowlands are glaciologically implausible suggesting that they occurred during two distinct ice flow geometries. Reproduced from Boardman and Walden (Boardman and Walden, 1994).

The main ice divides are located in the north and west upland regions, i.e. the Scottish Highlands, Lake District and Wales (Clark et al., 2004a) (figure 2.10). The principle ice divide stretches down through NW and W Highlands from Sutherland to Rannoch (Hall, 1997). Secondary divides have been identified in the Southern Uplands, Cairngorms, Southeast Grampians, Cheviots, Outer Hebrides, Shetland, Inner Hebridean islands of Mull, Skye and Arran, Lake District, Yorkshire Dales and Snowdonia (Evans et al., 2005). Ice flow from more dominant ice centres in Scotland appears to have been deflected around secondary ice domes centred on the Lake District, Pennines, Wales and the Cheviots. The lack of 'foreign' erratics in these regions has been used to suggest that these areas supported independent ice caps and were never over-run by ice from elsewhere. For example, limited radial flow of erratics out of the Cheviots in combination with the evidence for west-east ice flow clockwise around the massif in the Tweed suggests that this was a subsidiary ice centre (Clapperton, 1970). These smaller ice divides are located predominantly on high ground at the periphery of the ice sheet. There has been considerable debate as to whether Shetland and the Outer Hebrides sustained independent ice domes or where overwhelmed by North Sea or mainland ice respectively (Evans et al., 2005) (figure 2.11). Opinion about the ice flow configuration over Shetland has fluctuated in tune with debates about the confluence of ice in the North Sea (overwhelmed by ice from the SE vs. an independent ice cap) (Peach and Horne, 1879; Sutherland, 1991b; Golledge et al., 2008).

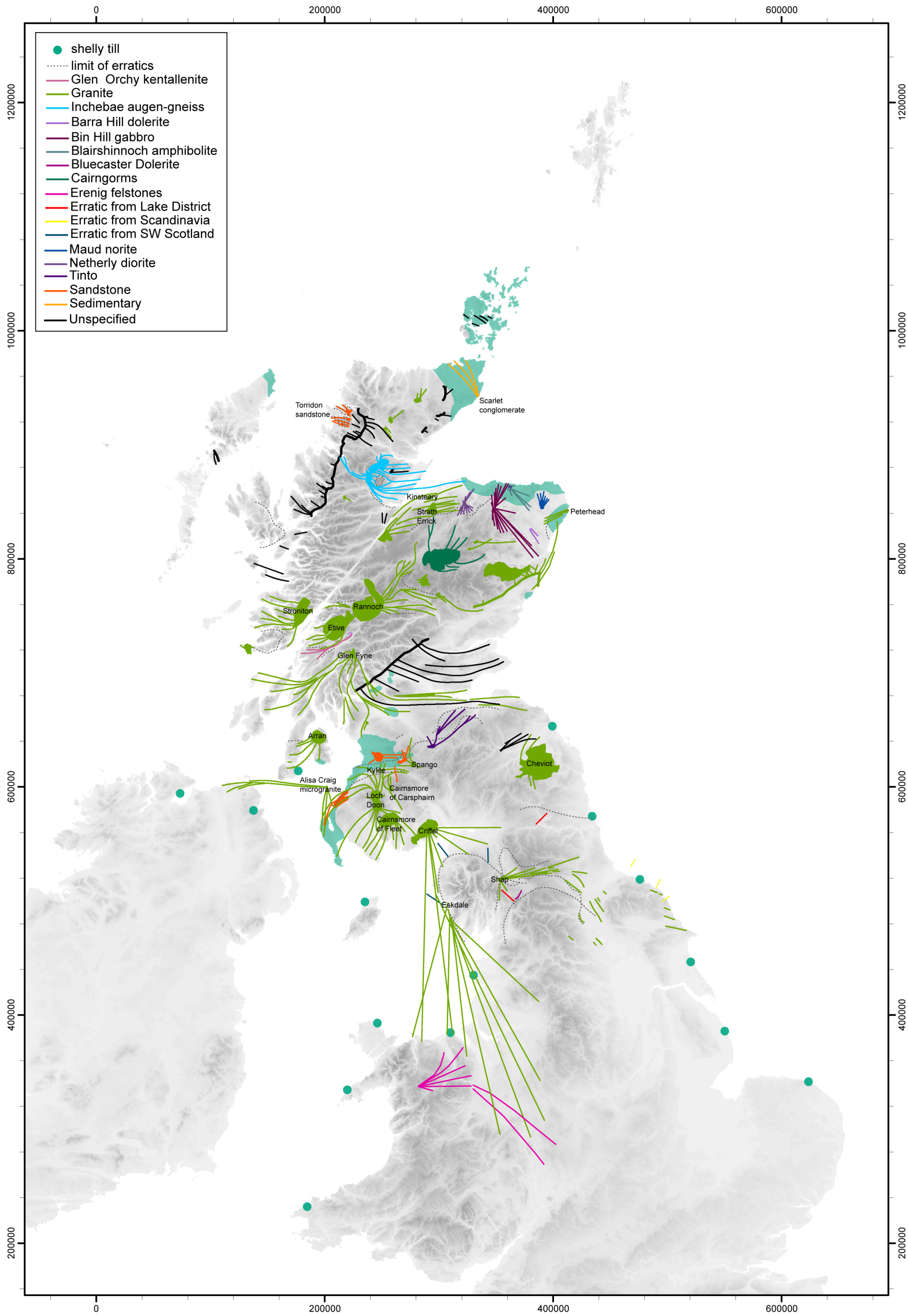


Figure 2.15 Erratics have been used to define centres of ice dispersal in the NW Highlands, Cairngorms, Cheviots, western Southern Uplands, Lake District and North Wales. Erratic sources and transport paths and shelly till locations. Erratics taken from BRITICE GIS database with additions from Mackintosh (1879). Shelly till locations taken from Charlesworth (1957) and Sissons (1976). Granite outcrops are labelled with location.

Most of the ice divides have remained relatively uncontroversial (like the generalised flow patterns) since the earliest reconstructions of the configuration of the ice sheet, with their location remaining relatively unchallenged (Price, 1983). Numerical and isostatic models collectively support ice divide locations in the NW Highlands, southwest Southern Uplands, Cumbria and Wales. Only minor changes have been made, for example debates on the relative importance of a Snowdonian versus Menrioneith centred ice divide in North Wales (McCarroll and Ballantyne, 2000). What remains to be elucidated is how and whether these ice divides moved over time. It is possible that some local and regional centres of ice dispersal have yet to be identified, especially if they were transitory features. Thorough mapping of drumlins in the western Pennines and Lake District indicates an ice divide stretching from Cumbria over the Howgill Fells to the western Pennines (figure 2.12) modifying the reconstruction of an ice dome centred on the Lake District suggested by the erratic evidence. Offshore ice divides have also been postulated, for example Merritt et al. (2003) postulate the existence of an ice dome in the central North Sea during confluence of Scandinavian and British ice.

2.5.3 Ice streams

Ice streams are zones or 'rivers' of anomalously rapid ice flow within an ice sheet. It is thought that they exert a fundamental control on ice sheet dynamics and appear to be an intrinsic feature of ice sheet geometry (Marshall, 2005). At present it is not known what factor is ultimately responsible for ice stream location (Winsborrow, 2007) and behaviour although it has been shown that ice streams produce distinctive landform signatures that permit palaeo-ice streams to be identified (Dyke and Morris, 1988; Stokes and Clark, 1999). A number of ice streams have been suggested for the last BIS based on evidence of varied quality. Postulated palaeo-ice streams include the Irish Sea, the Minch, Vale of York, Vale of Eden, Wensleydale, Tweed, and Strathmore Ice Streams (Evans et al., 2005) (figure 2.16 and table 2.1).

There is good evidence in the form of mega-scale glacial lineations (MSGL) observed from multi-beam seismic images of the seafloor and detailed onshore field mapping of large elongate subparallel landforms termed 'mega-grooves' (Bradwell, 2005) to support the existence of a palaeo-ice stream in the Minch (Stoker and Bradwell, 2005). This ice stream appears to have reached the shelf edge and would have fed the Sula Sgeir shelf edge fan system. Stoker and Bradwell (2005) suggest that the ice stream was a feature of repeated glaciations and dominated the configuration of the NW Sector of the last BIS. They estimate that it would have drained an area of approximately 15,000 km^2 if the ice stream existed at the maximum extent of the glaciation. Elongate streamlined landforms on the coastal fringes of the Minch suggest that the ice stream had up to nine tributaries (Bradwell et al., 2007).

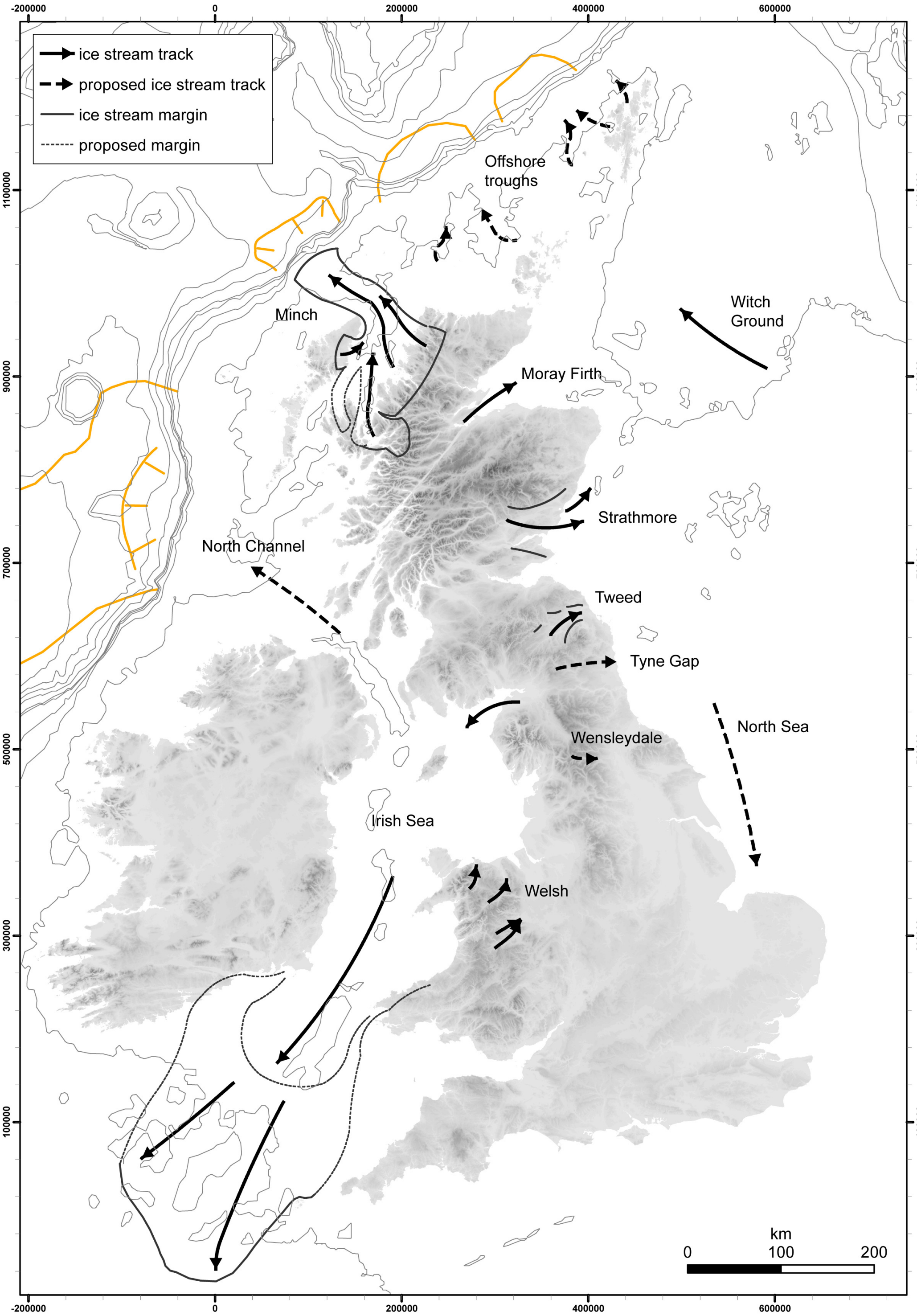


Figure 2.16 Proposed ice streams of the last British Ice Sheet. Direction of ice flow is shown by arrow. Trough mouth fans are outlined in orange. Compiled from various sources, see table 2.1.

Observations from high resolution remotely sensed imagery has led to the identification of palaeo-ice stream tracks in the Tweed and Strathmore basins (Clapperton, 1970; Everest et al., 2005; Golledge and Stoker, 2006). Other hypothesised ice streams are less well grounded in geomorphological and sedimentological evidence. In the case of the Irish Sea Glacier, the main evidence cited to support its status as an ice stream are the converging flow patterns along the Irish Sea coasts from Britain and Ireland, typical of ice stream onset zones (Evans and O

Cofaigh, 2003), and sediments found in the Celtic Sea that indicate it was a major discharge route of the last BIS. Fluctuations in the calving rate are inferred from changes in the deposition of ice-rafted debris (Scourse et al., 2000). Moraines on Anglesey and the Lleyn Peninsula have some of the characteristics of a lateral shear moraine (Thomas and Chiverrell, 2007).

Mitchell (1994) describes the possibility of an ice stream in Wensleydale. Thorough field mapping of drumlins indicates that drumlin length increases to >400 m in central Wensleydale and drumlin orientations converge at the head of the valley. Flow convergence identified from detailed mapping of drumlins has also been used to postulate an ice stream in Stainmore (Letzer, 1987). Mapping of moraines of the Otter Bank sequence using boreholes and seismic stratigraphy indicates that there were preferential pathways for ice flow in the Faroe-Shetland channel supplying the shelf-edge fans and it is speculated that these could be the route of small ice streams (Bulat and Long, 2005; Stoker et al., 2006). However, the current data does not allow for any other of the characteristic criteria for palaeo-ice streams to be identified. The existence of ice streams emanating from western Scotland and Ireland supplying the Barra Fan sediment system has been speculated but, at present, there is no evidence to support such features. Merritt et al. (1995) suggest that there was a major tidewater glacier in the Moray Firth, but unequivocal evidence to support ice streaming has not been provided. Surge behaviour has been invoked to explain the presence of Devensian age glacial deposits along the North Norfolk coast (Eyles et al., 1994). This may have been achieved by an ice stream flowing offshore parallel with the east coast. Support for this comes from the identification of mega-scale glacial lineations in the Tweed, which may have been the inception area of the ice stream (Everest et al., 2005). Jansson and Glasser (2004) suggested, on the basis of mapped streamlined bedforms in the North Welsh valleys, that Wales experienced ice streams during deglaciation.

The most recently published numerical model of the last BIS is able to simulate fast ice flow in the Irish Sea, Tweed and a North Sea ice lobe (Boulton and Hagdorn, 2006). The extension of ice to the Scilly Isles could be achieved maintaining the position of the southern most limit in England. Furthermore, the model required topographically constrained or static ice streams in order to generate reasonable ice sheet surface profiles.

Ice stream research is a major driver of new geomorphological mapping in Britain. Several ice streams have been suggested for the last BIS but the evidence to support these features is variable and in some cases very sparse. Detailed mapping of glacial geomorphology is required to distinguish between landform assemblages created by ice stream rather than sheet flow to support claims of ice streaming (e.g. Stokes and Clark, 2001). It is likely that the most convincing evidence for ice streams in Britain will come from the offshore record in the form of high resolution 3-D seismic bathymetry (e.g. Ottesen et al., 2005). There is almost no information for the timing and duration of ice streaming in the UK. Preliminary numerical modelling suggests that ice streams were an intrinsic feature of the last BIS. Determining the behaviour of ice streams of the last BIS is critical to unravelling interactions with oceans and climate.

Table 2.1 Postulated ice streams of the last British Ice Sheet. Margins and dimensions of palaeo ice streams have only been suggested for a selection of the proposed ice streams.

Ice stream	Dimensions	Evidence	Reference
Minch	200 km long 50 km wide	Bedform elongation ratios (L/W) >70:1 in Minch, >20:1 onshore. Convergent ice flow in up to 9 tributaries along coastal fringes of Minch.	Stoker and Bradwell (2005) Bradwell et al. (2007)
Strathmore	100 km long 45 km wide	High elongation ratios <38:1. Convergent ice flow. Abrupt margins. Possibly two periods of operation, later stage topography of the bed influences ice flow.	Golledge and Stoker (2006)
Tweed	65 km long (onshore) 40-20 km wide	Elongation ratios <23:1. Convergent ice flow, topographically constrained. Abrupt margins.	Everest et al (2006) Clapperton (1970)
Irish Sea	c. 600 km long 190 km wide at snout	Ice flow patterns converge into the Irish Sea from Solway, Scotland and Ireland. Ice limit at Scilly's likely to be the result of short lived expansion of the ice front. Sedimentary evidence for possible lateral shear margin on Lleyn Peninsula (Thomas and Chiverrell, 2007).	McCabe et al. (1998) Evans and O Cofaigh (2003)
Offshore troughs	-	Speculated on the basis of trough mouth fans and bathymetric troughs.	Stoker et al. (2006) Nielsen et al. (2005)
North Sea	-	Invoked to explain ice flow pattern skimming eastern English coastline. Possible surge.	Eyles et al (1994)
Wensleydale	70 km long 10 km wide	Convergent ice flow into valley. Elongate drumlins and streamlining.	Mitchell (1994)
Welsh	Conwy: 31 km long, 15-5 km wide Bala: 36 km long, 7.5-4 km wide Four Crosses: 32 km long,14 km wide Severn:50 km long, 18-4 km wide	Convergent topographically constrained ice flow along major valleys. Sharp lateral boundaries, high parallel conformity between lineations, elongation ratios 10-15:1.	Jansson and Glasser (2004)
Tyne Gap	-	-	Beaumont (1971) c.f. Everest et al. (2006)
Witch Ground	>90 km long >30-50 km wide	Highly attenuated bedforms. High elongation ratios and parallel conformity.	Graham et al. (2007)
Moray Firth	-	Convergent ice flow into the Moray Firth. Calving front during deglaciation.	Merritt et al. (1995)

2.6 Ice Sheet Evolution

2.6.1 Ice sheet initiation

There is very little evidence for the pattern of build up of the last ice sheet, as most evidence seems to have been removed or remodelled during deglaciation (Clark et al., 2004a). It is highly likely that initiation of the ice sheet occurred in the highlands of Scotland and Wales (Seigert, 2001). Some authors have suggested that the Loch Lomond Stadial ice cap can be used as an analogue for the early stages of ice sheet growth (Price, 1983). Numerical modelling will probably be the best method to investigate the build up of the last BIS. In the model simulations of Boulton and Hagdorn (2006) the ice sheet initiates and grows out of the NW Highlands, there are no other sites of ice sheet nucleation. Section 2.9 considers the timing of the last BIS.

2.6.2 Flow configuration evolution

The last BIS was a polycentric ice sheet with numerous sites of ice accumulation, and it is generally accepted that the dominance of different ice divides varied over time as the ice sheet configuration responded to climate events (Sutherland, 1984). The flow patterns between the two main ice divides in the southern Uplands and Rannoch is particularly complex, reflecting the changing dominance of the two ice centres. Superimposed, variable size distributions and cross-cutting drumlin patterns which are exhibited by many of the country's drumlin fields are also indicative of changes in the configuration of the ice sheet (Rose and Letzer, 1977; Mitchell, 1994) (figure 2.13). Conflicting flow pattern information is derived from adjacent drumlin fields, e.g. drumlin orientation in the Solway Firth lowlands suggests opposing flow directions which is glaciologically unlikely (figure 2.14). Erratics suggest that ice flowed up the Vale of Eden and through the Stainmore Gap, whereas drumlins and straie record ice flow in the opposite direction down the vale into the Irish Sea (Evans et al., 2005). These ice flow patterns must have occurred under different ice sheet configurations.

Lithological variations within till stratigraphies have been used to propose differential ice sources. For example on the coast of Holderness the lower Skipsea till containing Southern Upland erratics is overlain by the Withernsea till containing erratics from the Lake District (Evans et al., 2005) indicating an increase in dominance of the more southerly ice centres as glaciation progressed. Changes in till fabrics between superimposed tills also indicate variations in ice flow patterns (e.g. Kirby, 1969) and in some locations used to reconstruct a detailed picture of ice flow variation. In NE Scotland detailed sedimentological and geomorphological mapping has revealed interaction between a Grampian ice mass and lobes from the Moray Firth and Strathmore (Peacock and Merritt, 2000; Merritt et al., 2003). Detailed mapping of drumlins in the Pennines and Cumbria reveals changes in the position of ice divides in the Yorkshire Dales throughout the glacial (Mitchell, 1994). In Wales, mapping of streamlined bedrock from satellite imagery suggests at least two phases of ice flow: an early topographically unconstrained Welsh ice sheet, followed by ice surface lowering and topographically constrained ice flow along major valleys (Jansson and Glasser, 2004) (figure 2.17). Mapping in Caithness indicates that local ice became more dominant after the retreat of the Moray Firth glacier (Evans et al., 2005).

Although it is known that the ice divides were spatially and temporally variable there is no overall picture of the evolution of ice sheet configuration. Specifically we do not know how changes in one part of the ice sheet were reflected elsewhere. Detailed histories of flow pattern changes exist at the local to regional scales only. A systematic map of bedform patterns would facilitate interpretation of the complex assemblage of information and provide valuable insights into flow evolution which cannot be gained from erratic transport paths (Evans et al. 2005). Detailed mapping of the drumlin fields of the Marchars of Galloway highlights the complexity of information (and potential for determining the detailed flow pattern history of the ice sheet); ten different flow phases were identified on the basis of differences in drumlin orientation, proximity and size (Salt and Evans, 2005).

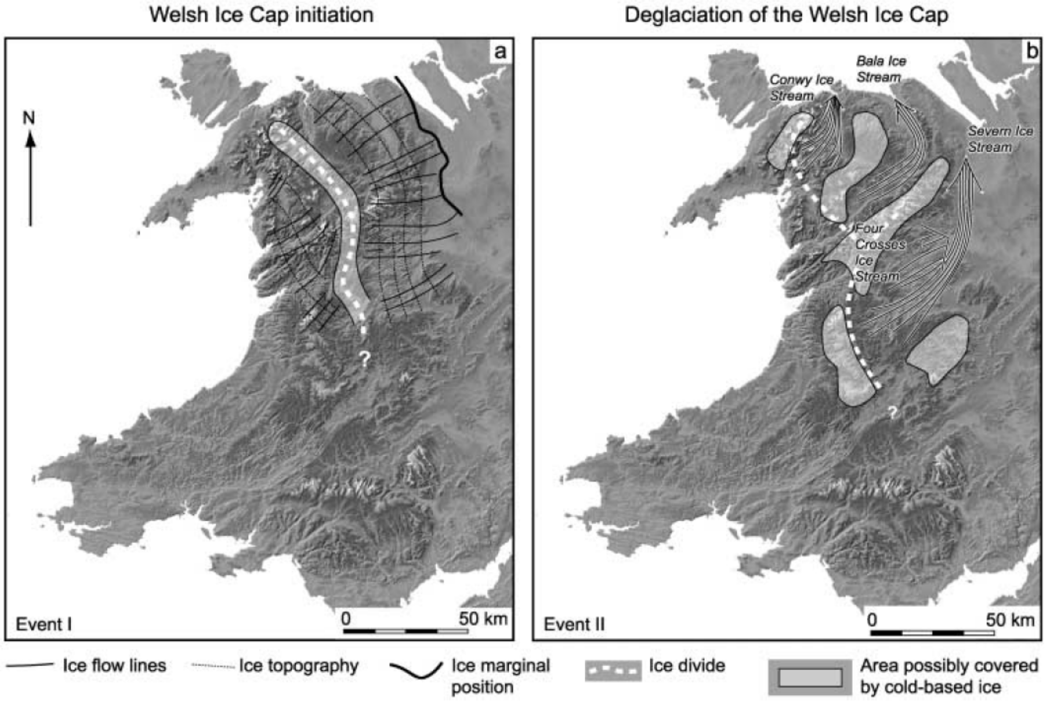


Figure 2.17 Ice flow configuration evolution in Northern Wales reconstructed from streamlined lineations mapped from satellite imagery: (a) Ice flow configuration prior to confluence with Irish Sea ice and (b) ice flow configuration following separation from Irish Sea ice and the development of topographically controlled ice streams. Locations of cold-based ice are inferred from ice sheet configuration. Reproduced from Jansson and Glasser (2004).

2.6.3 Ice sheet retreat pattern

The pattern of retreat has been reconstructed in detail for many parts of the ice sheet from individual valleys to larger areas incorporating several km^2. For example, Embleton (1961) reconstructed the retreat of ice in the Vale of Conwy from geomorphological and sedimentological mapping. Detailed field mapping of the Fortrose area has produced a comprehensive deglacial history of the Moray Firth and provided key information on the dynamics of the ice lobe (figure 2.18) (Merritt et al., 1995). Evans et al. (2005) review and describe in detail the numerous moraines, drift limits, ice contact landforms, meltwater channels and lake deposits that have been used to reconstruct the retreat of regional and local sections of the last BIS. For other sectors of the ice sheet, the significance in terms of the deglacial pattern of moraines and other ice contact features has yet to be resolved. For example, recessional moraines have been reported on the islands of the Inner and Outer Hebrides but have yet to be understood in terms of regional retreat of ice.

To my knowledge there are only a few published reconstructions of the ice sheet scale retreat pattern and most of these are based on numerical and isostatic modelling. A notable exception being the highly intricate reconstructions of Charlesworth (1926; 1957) based on a synthesis of geomorphological mapping but which are limited to Scotland. Lambeck (1993) used isostatic modelling to reconstruct a time-slice retreat pattern of the last BIS. Ice was found to retreat back to centres in the NW Highlands, Southern Uplands and Wales. More recent isostatic models concur with this general pattern (figure 2.8) (Shennan et al., 2002; Shennan et al., 2006a). The numerical model of Boulton and Hagdorn (2006) reconstructs ice retreat to the NW Highlands in a correlative manner to modelled ice sheet build up. Andersen (1981) used radiocarbon dates and the positions of large moraines to reconstruct isochrones of retreat. The ice sheet is shown retreating back to Wales, the Lake District, the Highlands of Scotland, Lewis and Shetland (figure 2.19). Boulton et al. (1991) reconstructed retreat in Scotland to ice centres in the westernmost Southern Uplands, Lewis and the Northwest Highlands by inferring the direction of retreat from drumlins, eskers and striation directions (figure 2.20a). In the south, the reconstructed pattern of retreat using the same approach is towards the Lake District and Wales (Boulton, 1992) (figure 2.20b). This approach presumes that these landforms relate to the most recent phase of ice flow and therefore record flow directions immediately behind the retreating margin (Boulton et al., 1985). The interpretation of drumlin patterns in this way is now viewed as only partially correct (Clark, 1999) and so the retreat patterns should be regarded as circumspect.

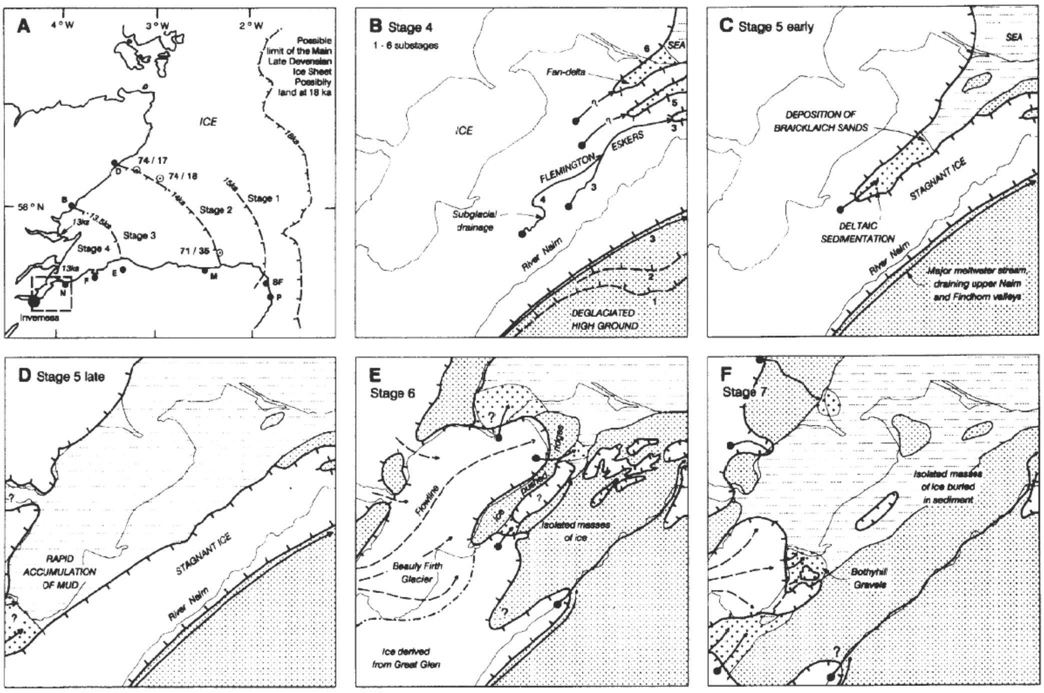


Figure 2.18 Stages of deglaciation of the Moray Firth reconstructed from detailed geomorphological and sedimentological fieldwork. Reproduced from Merritt et al. (1995).

Lateral meltwater channels can be used to reconstruct the three dimensional retreat of ice, for example the Forth glacier can be reconstructed from the series of lateral meltwater channels in the Ochill Hills (Evans et al., 2005). However, despite the ubiquitous nature of meltwater channels in the Scottish landscape only a small percentage have been mapped and there is considerable scope for gaining a greater understanding of the retreat of the last BIS using meltwater channels (Greenwood et al., 2007). Greenwood et al. (2007) employed the meltwater channel record contained within the Glacial Map of Britain (Clark et al., 2004b) to reconstruct the pattern of retreat (figure 2.21).

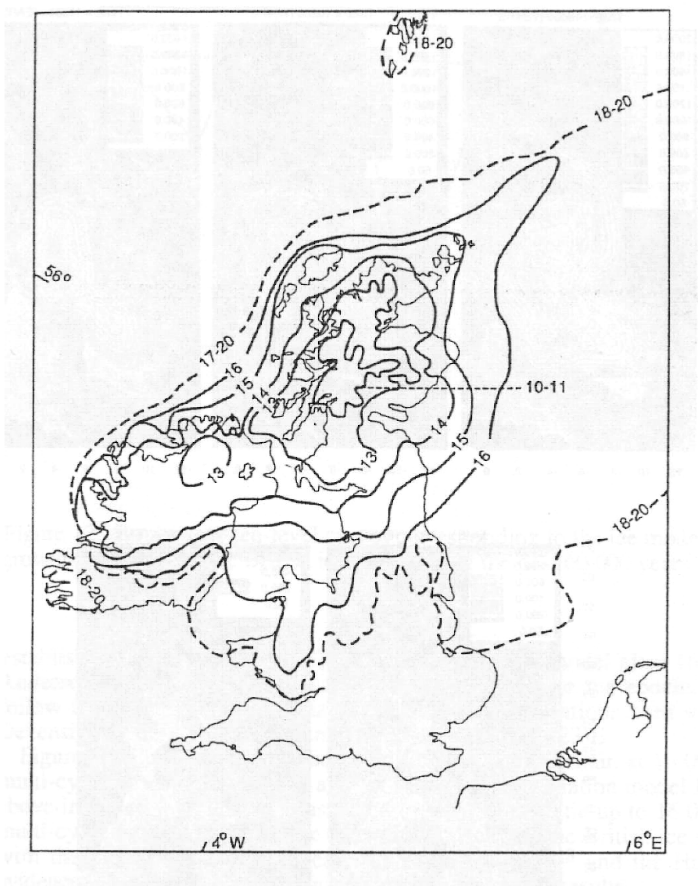


Figure 2.19 Isochrones of retreat of the last British Ice Sheet reconstructed from radiocarbon dates by Andersen (1981). Reproduced from Lambeck (1991)

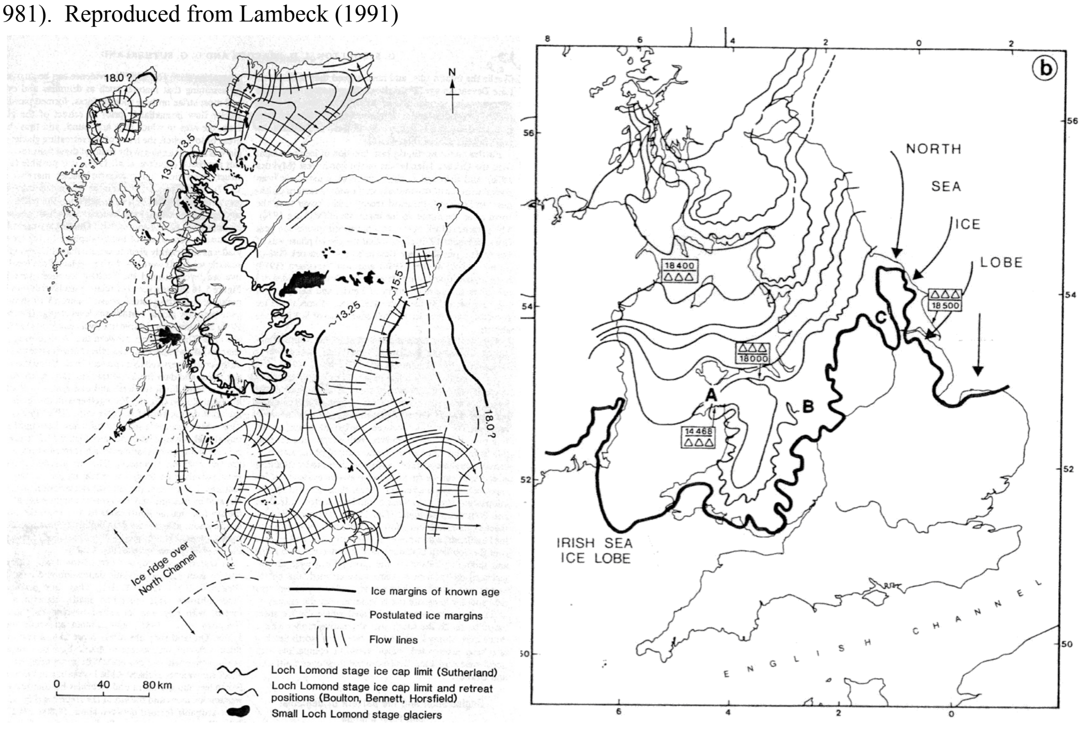


Figure 2.20 Reconstructed retreat pattern for Scotland (left image) and England (right image). Pattern of retreat is based on assumption that flow patterns represent most recent ice flow direction. Ages are attached to ice margin positions where possible. Reproduced from Boulton et al. (1991) and Boulton (1990).

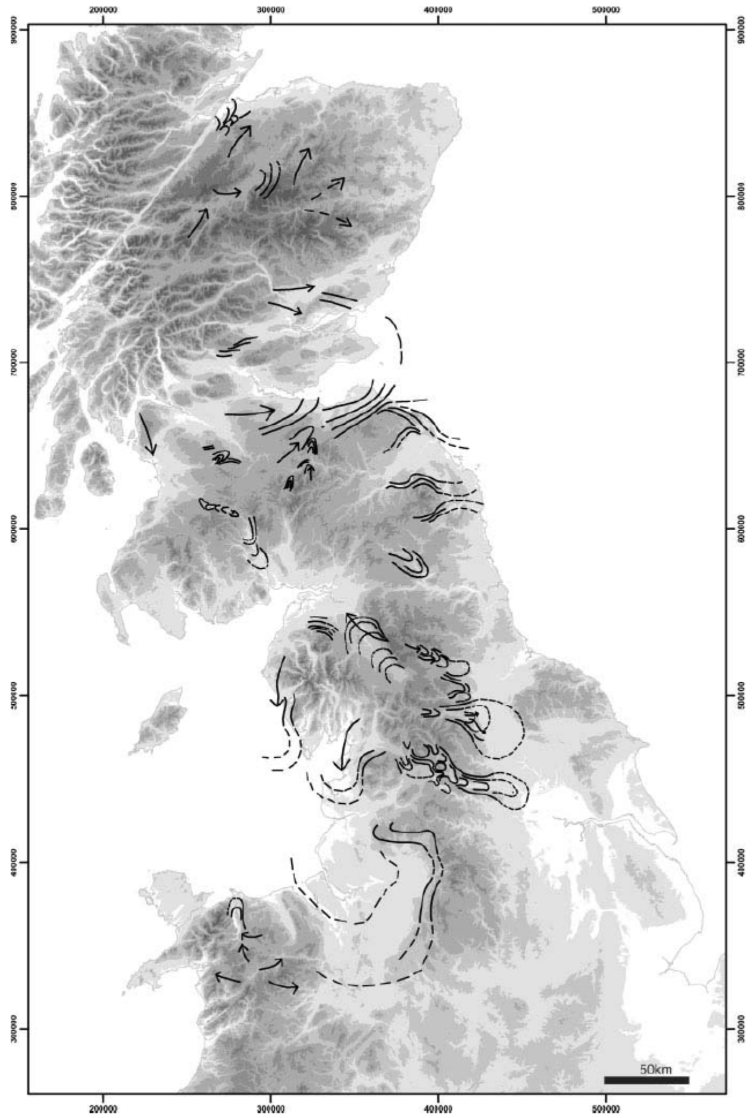


Figure 2.21 Reconstructed pattern of retreat from lateral meltwater channels contained within the BRITICE database. Solid lines indicate palaeomargins delineated with confidence, dashed lines represent margins inferred on the basis of topographic context and/or moraine positions contained within BRITICE, and arrows indicate flow directions close to the ice terminus. Reproduced from Greenwood et al. (2007).

Despite incomplete coverage of mapping across the country several major findings emerged (Greenwood et al. 2007):

- Evidence records a general direction of retreat from the eastern side of the country to the west indicating that ice centres were located in the west during deglaciation.
- The initial direction of retreat was not always towards the nearest high ground. For example, the ice lobe occupying the Cheshire Plain retreated to the north into the Irish Sea rather than west into North Wales.
- Deglaciation proceeded by thinning of the ice sheet, so that topography had a major influence on the retreat of major ice lobes.
- Ice retreated to several independent centres which varied in dominance during retreat; North Wales, the Howgill Fells, Pennines, westernmost Southern Uplands and Rannoch Plateau.
- Some of the reconstructed retreat patterns are incompatible suggesting more than one phase of retreat in some areas.

As demonstrated above, detailed retreat patterns have been reconstructed for individual locations by thorough field mapping of geomorphology and stratigraphy but as yet this information has not been combined to produce a comprehensive retreat pattern for the whole ice sheet. The prevailing consensus view of the maximum and LGM extent of ice has also had a major effect on the interpretation of retreat evidence. If the extensive glaciation view is favoured then offshore moraines in the North Sea such as the Wee Bankie and Bosies Bank Moraines become retreat features. The terrestrial limits of the restricted glaciation hypothesis similarly must therefore represent retreat margins. There have also been polarised opinions on the style of deglaciation.

2.6.3.1 Deglaciation of Irish Sea Basin

The nature and dynamics of the deglaciation of the Irish Sea has been a subject of ongoing controversy between those who favour a retreat in a glaciomarine setting as a result of isostatically raised sea levels (Eyles and McCabe, 1989) and those who favour retreat of a grounded terrestrial lobe (McCarroll, 2001). Disagreement about the characteristics and nature of deglaciation of the ice lobe remains a critical obstacle to understanding the dynamics of the last BIS. The majority of investigations based on evidence from the eastern margin of the Irish Sea basin do not support retreat in a glaciomarine setting (Harris, 1991; Crimes et al., 1992; Harris et al., 1997; Glasser et al., 2001; Hambrey et al., 2001; Scourse and Furze, 2001; Hiemstra et al., 2005; Roberts et al., 2006).

2.6.3.2 Ice sheet readvances

As with the maximum extent of the former BIS, the nature of deglaciation has been subject to fashions within the literature. Views have flickered between active retreat of ice accompanied by numerous readvances and still-stands, and *in situ* wastage of ice. Re-advances interrupting deglaciation were suggested primarily on the basis of extensive moraine systems, on the assumption that these were not formed by still-stands but by readvances of the ice margin (Evans et al., 2005) (figure 2.22).

The Lammermuir-Stranraer readvance was proposed by Charlesworth (1926) to account for the extensive belt of glaciofluvial landforms around the Lammermuir and Pentland Hills and extending to Stranraer and Galloway. Parts of this grand ‘kame-moraine’ have now been reinterpreted as the result of uncoupling of highland and southern upland ice and margin still-stands during retreat (Evans et al., 2005). In the Aberdeen area, spreads of glaciofluvial sands and gravels were used to propose both the Aberdeen-Lammermuir and Dinnet readvances (Synge, 1956). The same deposits were interpreted as ice stagnation features in the 1970s (Clapperton and Sugden, 1972; Murdoch, 1975; Sugden and Clapperton, 1975; Clapperton and Sugden, 1977). Most recently the deposits have been reinterpreted as ice marginal supraglacial moraines (Brown, 1993). In the Tay region the association of ice marginal glaciofluvial landforms with a prominent raised shoreline was used to propose the Perth readvance (Simpson, 1933) but this was rejected by Paterson (1974) and also Sissons (1981) who initially supported its status (Sissons, 1963a,b). The debate concerning regional scale readvances of the ice margin has been reawakened by the publication of new radiocarbon dates from eastern Scotland (McCabe et al., 2007). McCabe et al. (2007) support the Perth readvance and propose an additional earlier readvance based on stratigraphic observations at Lunan Bay on the eastern coast. This new readvance evidence is contested by Peacock et al. (2007). The only regional scale readvance in Scotland that persists in the literature today is the Wester Ross readvance (Robinson and Ballantyne, 1979) A major ice margin position is recorded at the mouths of Lochs Torridon, Gairloch and Ewe by a series of moraine ridges, drift limits and eskers. The readvance status of this moraine system is based solely on its clear morphological expression and cross cutting striae either side of the moraine at Redpoint. In the absence of stratigraphic evidence the moraine could just represent a still-stand of the ice margin. The age of the 'readvance' position has recently been confirmed by cosmogenic dating as c. 16.5 ka BP (Everest et al., 2006). Glaciotectonised outwash at St Bees on the Cumbrian coast and correlation of the St Bees moraine with the Bride moraine on the Isle of Man has been used to suggest two phases of readvance of Scottish sourced ice in the Irish Sea and Solway lowlands: the 'Gosforth Oscillation' (Merritt and Auton, 2000) and the 'Scottish Readvance' (Huddart, 1991) (line 5 on figure 2.1). Readvances in the Solway lowlands were suggested as early as 1929 (Trotter). The 'Scottish Readvance' remains controversial and is grounded in interpretation of the stratigraphy of the Solway lowlands (Boardman and Walden, 1994).

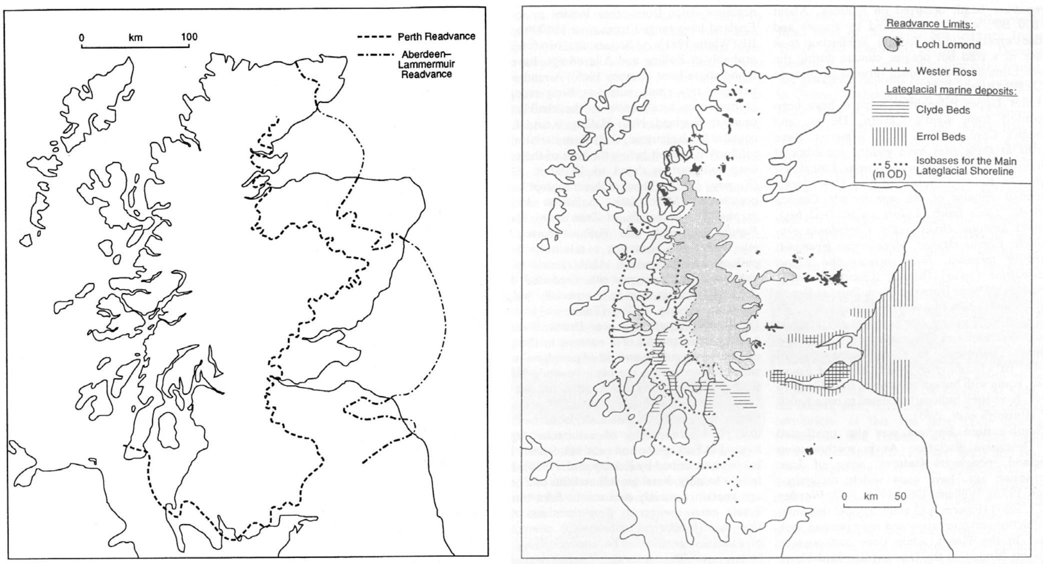


Figure 2.22 Readvance positions postulated in Scotland. Reproduced from Jones and Keen (1993).

There is evidence for local oscillations of the ice margin during retreat. Glaciotectonised sediments within the Ardesier Moraine close to Inverness indicate it is a push moraine formed by an advance of the Moray Firth ice lobe (Ardesier Oscillation) (Merritt et al., 1995).

Proglacial lake development and ice margin oscillations have been described during recession of ice in the Cairngorms (Brazier et al., 1998; Golledge, 2002). Oscillations of the Irish Sea glacier during retreat are suggested from sedimentological observations from a number of locations around the basin. Several phases of ice marginal oscillation during retreat are invoked to explain the off lapping stratigraphy of glacial diamicts on the northern Isle of Man (Thomas, 1984; Thomas et al., 2004). Sedimentological and stratigraphical evidence from NW and NE Wales documents oscillations during the uncoupling of Welsh and Irish Sea ice (Thomas, 1985, 1989) and up to 20 oscillations and 11 readvances of the Irish Sea ice front are proposed on the basis of new mapping of the moraines and ice contact sediments of Anglesey and the Lleyn Peninsula (Thomas and Chiverrell, 2007). Harris et al (1997) identified glaciotectonic structures on the North Wales coast and suggested that these sediments represented the remnants of a push moraine created during localised advance of the Irish Sea glacier. Landforms close to Loch Ryan are described as resembling those of a surge landsystem by Salt (2001).

Still-stands during retreat are also postulated. Topographically controlled still-stands occurred during retreat of ice in the Dee (Brown, 1993). The Otter Ferry Stage is thought to be a period of widespread ice marginal stabilisation and is used to explain sea level fluctuations in the Firth of Clyde (Sutherland, 1984, 1991a) and Ford-Kilmartin region (Gray and Sutherland, 1977). The Oban-Ford Moraine mapped and termed as such by Synge (1966) is thought to represent a still-stand but Gray and Sutherland (Gray and Sutherland, 1977) claim that the moraine is not isochronous. Benn (1997) supports a widespread stabilisation of the ice margin on the Western Islands of Scotland, and dynamic deglaciation with possible localised readvances on Mull, Skye and Raasay after retreat of the mainland Scottish ice sheet.

2.7 Thermal regime

Very few statements are made on the nature of the bed conditions of the BIS. The nature of the bed has significant implications for the thickness of the ice sheet and in terms of its behaviour. Numerical modelling suggests that the distribution of cold and warm based ice of the last BIS is complex reflecting the varied topography of the bed (Boulton and Hagdorn, 2006). The presence of well preserved tors in the Cairngorms suggest cover by sluggish cold based ice during the last glacial (Sugden, 1968) and the preservation of preglacial landscapes in Buchan can also be explained by a cover of cold-based ice (Hall and Sugden, 1987). The preservation of chemically weathered bedrock in the Cheviots suggests that the massif may have supported a cold-based ice dome (Mitchell, 2008). Parts of the Welsh ice mass are also thought to have supported cold-based ice and deflected ice flow from further afield ice sources (Jansson and Glasser, 2004, 2008) (figure 2.17). Periglacial trim-lines identified in Scotland, Wales and the Lake District may represent pockets of cold based ice on the high ground in these regions (see earlier discussion on vertical extent).

2.8 Relationship to climate

Even at its largest extent, the last BIS was a relatively small ice sheet compared to the Scandinavian Ice Sheet and the Laurentide Ice Sheet (LIS) of North America. It has been suggested from provenance studies of ice-rafted debris contained in deep ocean sediments that the BIS responded on shorter timescales than the larger LIS (Peck et al., 2006). During the last glacial cycle the LIS experienced major calving events approximately every 7000 years discharging large volumes of meltwater and debris into the North Atlantic, (Heinrich Events) (Hemming, 2004). At present it is not known whether these events are caused by an internal ice sheet mechanism or by external climatic forcing. One suggestion is that a small sea level rise caused by melting of the European ice sheets causes instability in the LIS which leads to calving. This is supported by the evidence for European 'pre-cursor' events – ice rafted debris (IRD) preceding the Heinrich Event 2 debris layer has been traced to the BIS (Scourse et al., 2000). The IRD record from the Barra Fan is testament to persistent instability of the last BIS, and is indicative of continual readjustment of the ice sheet (Peck et al., 2006). Peaks in the IRD in the Barra Fan occur at 16.9 ka BP and 24.1 ka BP (Wilson et al., 2002; Peck et al., 2006). This is broadly coincident with the timing of Heinrich Events 1 and 2. These IRD peaks coincide with low $\delta^{18}O$ values indicating that they represent major meltwater discharge events. The last BIS is emerging as a highly dynamic ice sheet that may never have achieved steady-state conditions.

2.9 Chronology

Unfortunately, due to a lack of appropriate material for radiocarbon dating the number of reliable dates for the build up and retreat of the last BIS is low (Benn, 1997). Support for a dynamic ice sheet and for the timing of major ice sheet discharges has come from IRD contained in shelf edge sediments. Development of methods of dating bedrock and boulder surfaces with cosmogenic isotopes is starting to provide a partial solution to this problem. In the last four years there has been a dramatic increase in the number of cosmogenic date determinations for the last BIS (e.g. Ballantyne et al., 1998a; Everest et al., 2006; Everest and Kubik, 2006; Phillips et al., 2006 ; Golledge et al.; Bradwell et al., 2008a; Phillips et al., 2008). The available dates relating to the last BIS will be discussed further in chapter 10.

At present there is not a clear picture of the volume of ice present on the British Isles immediately after the last full interglacial (MIS 5e). Ice rafted debris records from the Barra Fan and Celtic margin suggest an ice mass at sea level during MIS 3 and at the continental shelf edge by 30 ka BP (Wilson et al., 2002). However, radiocarbon dates from sites across Scotland indicate ice free conditions until at least 32 ka BP (Whittington and Hall, 2002). In opposition to these dates, Bowen et al. (2002) proposed (largely on the basis of amino acid dating and dates from Ireland) that the last BIS was most extensive during MIS 3 and was limited in extent at the

LGM. Evans et al. (2005) lists the nine most significant dates that constrain the maximum limits of the last BIS. The dates range between 30-17.5 ka BP and are of insufficient density to correlate maximum limit positions. The timing of retreat of the last BIS is largely speculative due to a lack of age information with which to correlate between margin positions inferred from geomorphological evidence. Unfortunately there is very little direct dating of margin positions. With the development of cosmogenic dating techniques there is now scope for a direct dating of moraines and this promises the possibility of reconstructing a detailed pattern of retreat. A recurrent debate is whether Scotland was fully deglaciated prior to the Loch Lomond (Younger Dryas) readvance or whether an ice mass persisted during the Windermere interstadial. Recently published cosmogenic dates from NW Scotland lend support to the latter position (Bradwell et al., 2008a). Attempts to link readvance evidence with climatic changes of the last glacial cycle remain largely speculative due to the inadequacies of constraining both the retreat pattern and the Heinrich Events of the North Atlantic.

2.10 Why do we not know more?

What we know about the last BIS is not comparable with what we know about the Laurentide and Scandinavian Ice Sheets. This state of affairs seems remarkable considering the long history of research and the relative size of the ice sheet. Clark et al. (2006) identify eight obstacles that contribute to the current situation:

- the large volume of information,
- the fragmented nature of evidence and reconstructions, with no means to resolve contradictions between study sites,
- 'theory-laden' evidence and its propagation,
- the (false) assumption of contemporaneity of evidence,
- the lack of firm dating control,
- incomplete mapping,
- the need to eliminate reconstructions that are glaciologically implausible based on numerical modelling and/or appeal to modern analogues,
- the need to clearly define reconstruction methodologies, including clear statements of assumptions.

The majority of research into the last BIS has involved field mapping of landforms and striations, identification of erratic transport paths, and investigation of stratigraphic sections. Investigations have generally been on a local to regional scale meaning that synthesis has been difficult to achieve due to the differences in methodologies between researchers and the lack of a coherent dataset on which to base whole ice sheet reconstructions. The ice sheet is frequently divided into components which are investigated independently, for example McCarroll and Ballantyne (2000) reconstruct the 'last ice sheet on Snowdonia' and numerous authors refer to just the 'Scottish Ice Sheet'. Some sites have been revisited many times, whereas others remain *terra incognita*. As observations are spatially fragmented and inconsistent, inferences about the evolution and dynamics of the ice sheet are restricted in scope. This is problematic when attempting to investigate relationships with the climate changes of the last glacial cycle in the North Atlantic. Attempts at correlation within and between regions have been conducted, most comprehensively on the basis of till stratigraphies (Bowen et al., 1986; Bowen, 1999b). However, this information provides only point data which has to be interpolated over large areas. The lithostratigraphic approach of correlation is difficult when there is considerable variability in till characteristics even on a local scale (Harris and Donnelly, 1991) and regional or local nomenclature can make a synthesis daunting. In many areas of Britain debates have arisen due to the equivocal nature of the record of glaciation. The glacial histories of the Irish Sea Basin and North Sea have been particularly controversial (Eyles and McCabe, 1989; Balson and Jeffery, 1991).

2.10.1 History of glacial landform mapping in Britain

Arguably, the major stumbling block to reconstructing the ice sheet scale attributes of the last BIS and synthesising the wealth of information derived from over 150 years of research is the lack of a geomorphological framework. The glacial geomorphological record provides the spatial context in which to set point information such as dates and sedimentological observations. The glacial record is by nature complex and incomplete and therefore we require consistent glacial maps that cover the whole of the former bed of the ice sheet. A glacial map is a key part of our toolkit for ice sheet reconstruction. For example, the Glacial Map of Canada (Prest et al., 1968) produced from landform mapping from aerial photography is still used as a starting point for reconstructions of the flow configuration evolution and retreat pattern of the Laurentide Ice Sheet today (Dyke and Prest, 1987; Dyke and Dredge, 2003; Jansson et al., 2003). We do not have a similar glacial map for Britain (i.e. one based on systematic mapping).

Consideration of the history of landform mapping in Britain presents a possible explanation for this. Since Agassiz's seminal paper (Agassiz, 1841) glacial research has been actively undertaken by British based academics, amateur researchers and officers of the British Geological Survey. A simple tally of the number of mapping papers produced in each decade (based on the information contained within the BRITICE database) reveals the following trends. Early work focused on mapping and recording striations and erratics (e.g. Tiddeman, 1872; Goodchild, 1875) (figure 2.23). Later the focus switched to landform mapping with the central aim of much of this work being to determine ice limits and document the results of geological surveys (e.g. Charlesworth, 1929; Trotter, 1929; Raistrick, 1933) (figure 2.24). Much detailed information was revealed and recorded in this way but the approach was piecemeal and conducted with variable enthusiasm.

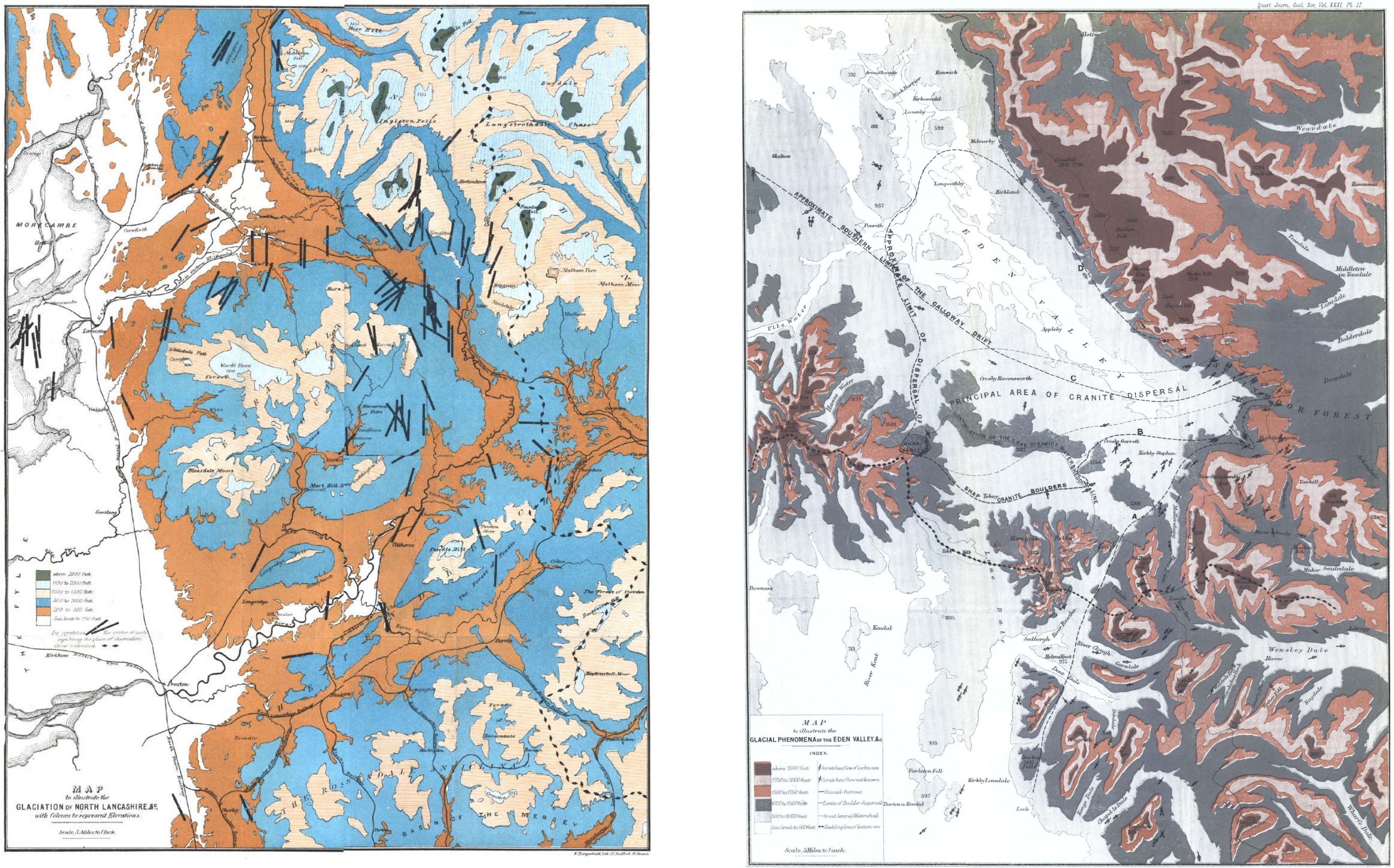


Figure 2.23 Examples of maps of striations in the Forest of Bowland (left) and erratic transport paths in the Vale of Eden (right) produced in the early phase of glacial research in Britain. Reproduced from Tiddeman (1872) and Goodchild (1875).

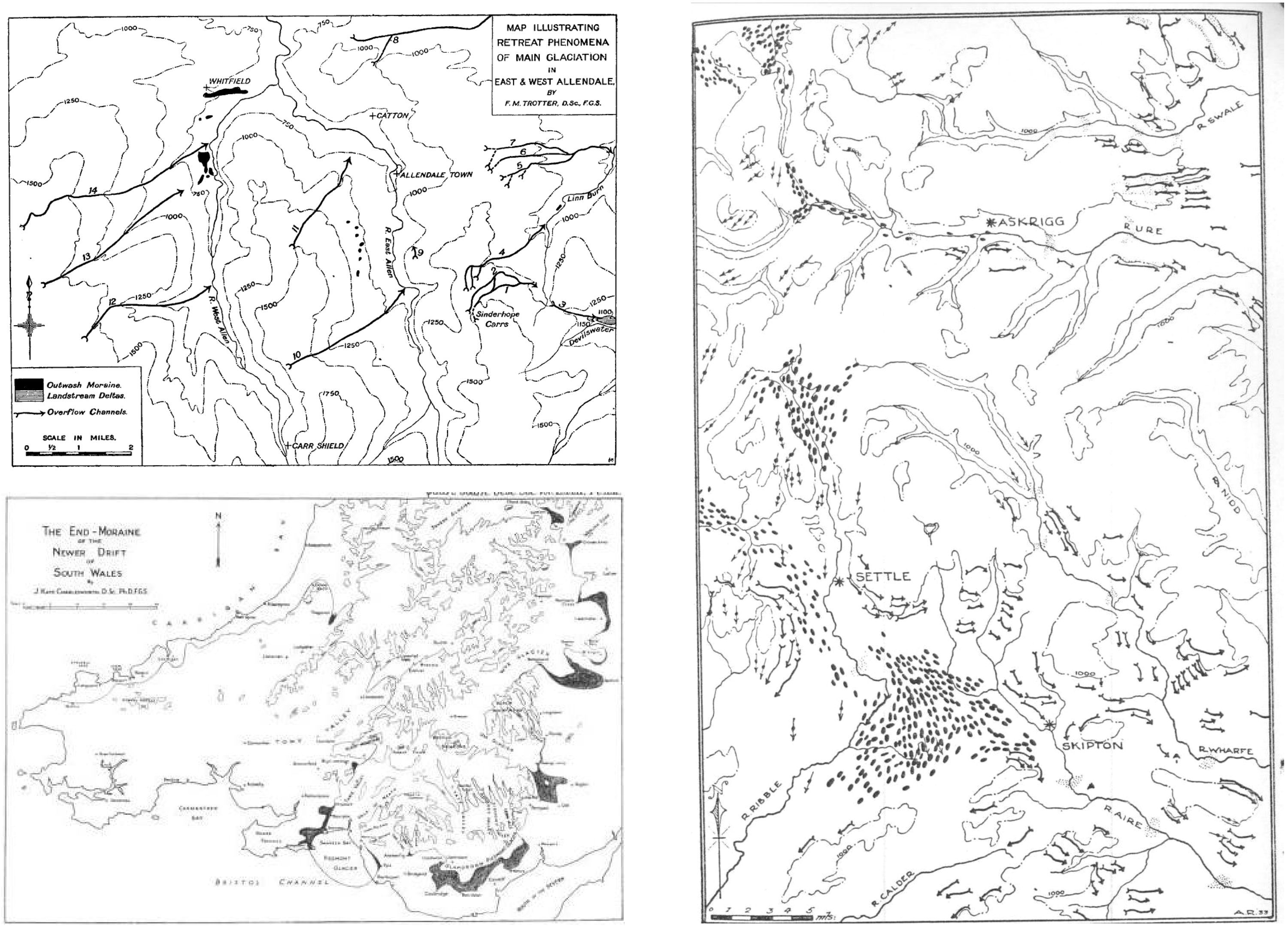


Figure 2.24 Examples of glacial geomorphological maps produced in the 1920s and 1930s. Reproduced from (clockwise from upper left) Trotter (1929 (meltwater channels and moraines in Allandale), Raistrick (1933) (drumlins, meltwater channels and striations in the Yorkshire Dales) and Charlesworth (1929) (South Wales end moraine).

There was a noticeable peak in map output in the 1970s with a plethora of detailed maps published that summarised the results of meticulous fieldwork (e.g. Sissons, 1963c; Clapperton, 1970; Day, 1970) (figure 2.25). After this point the number of published maps declined. There are several possible reasons why mapping did not keep pace: switch in focus to sedimentological and process studies, the rising cost of publication and journal size constraints and the inaccessibility of aerial photography amongst others, or maybe it just became unfashionable in a period when the emphasis was on quantification and reductionism. The effect of journal size limits is not insignificant as it leads to the reduction of information to generalised summaries often merged with interpretations, meaning that observations fail to stand the test of time in light of changing paradigms and theories of landform genesis.

2.10.2 Glacial Map of Britain and BRITICE GIS database

The BRITICE collaboration brought together 150 years of published information on the landforms of the BIS to create a glacial map for England, Scotland and Wales (Clark et al., 2004b) (figure 1.5). Landform mapping from British Geological Survey map sheets and memoirs, journal articles, books and PhD theses was collated and entered into a Geographic Information System (GIS) as thematic layers. The map was published as north and south sheets at 1: 625, 000 scale and the GIS layers made available online (http://www.shef.ac.uk/geography/staff/clark_chris /britice.html). The evidence contained in the BRITICE database is reviewed by Evans et al. (2005). Full details and caveats are given in Clark et al. (2004b). BRITICE represents the first attempt to draw together the published research on the BIS into a coherent synthesis. The synthesis provided a major service to the Quaternary community as now all the data is summarised in one place and it is clear where the gaps lie. The completion of the collaborative project also highlighted problems beyond simple incompleteness. Because of the large number of 'contributors' to the map there are inevitably inconsistencies in mapping methods, styles, scales and terminology between areas. Resolution of these issues was a major motivation for this PhD project.

2.11 Summary

This chapter has briefly outlined the state of knowledge of the last British Ice Sheet with a focus on what is confidently known what remains to be elucidated and what is controversial.

- The maximum spatial extent of the last BIS has been a major focus of research. The spatial limits of the ice sheet are broadly known but the quality of supporting evidence varies between areas and some contentions remain. From an ice sheet modelling perspective, the position of contemporaneous palaeomargins is more important information than the maximum extent of ice (Clark et al., 2004a).

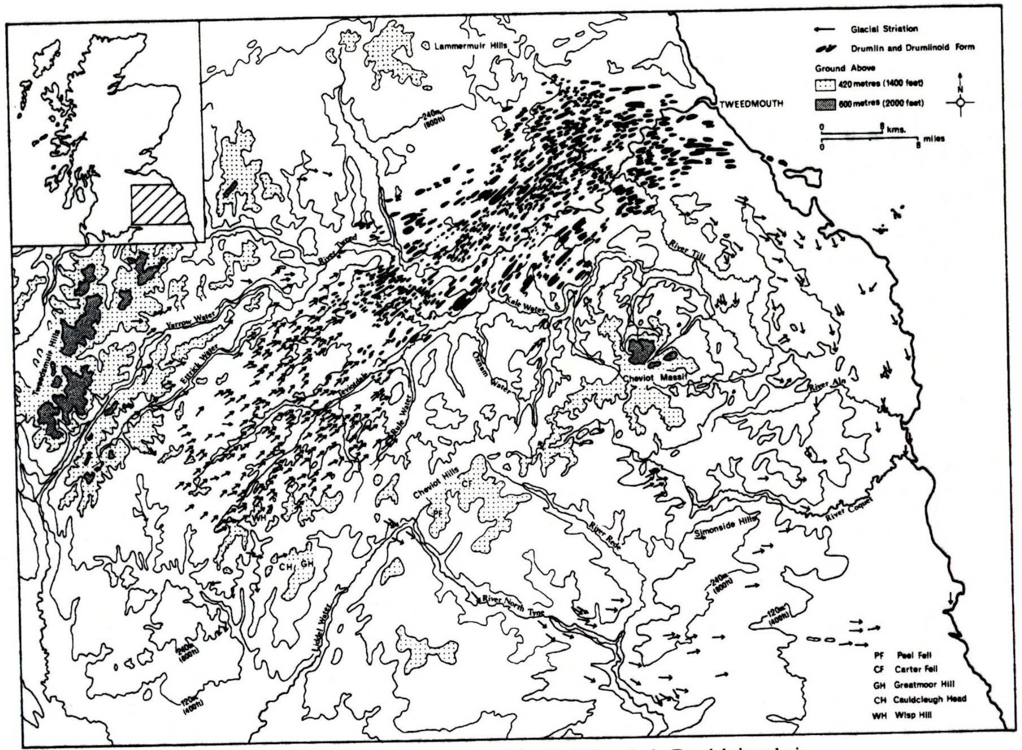


FIGURE 1. Glacial striations, drumlins and drumlinoid forms in the Tweed drainage basin

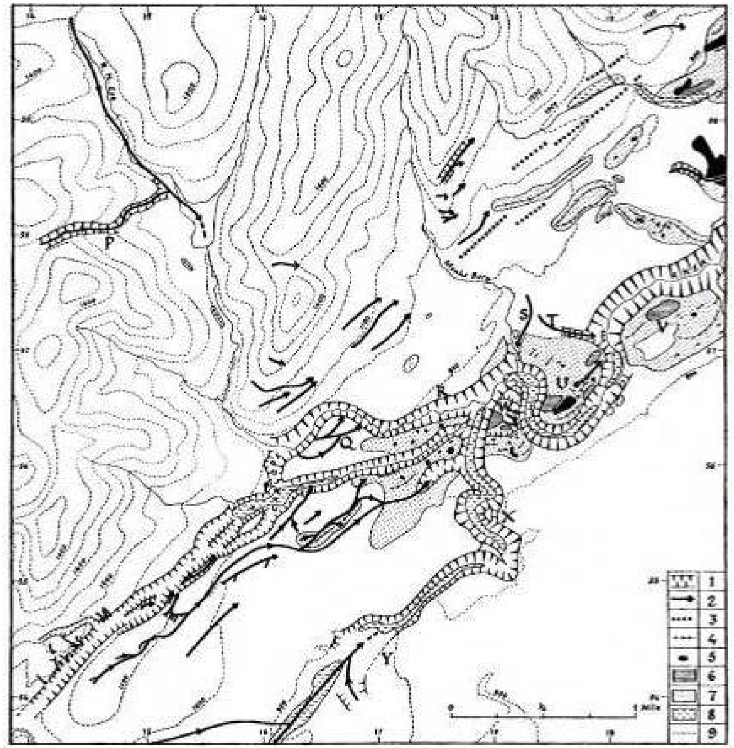


Figure 2.25 Examples of maps produced at the peak of glacial geomorphological research in Britain. Left image shows drumlins in the Tweed basin mapped by Clapperton (1970) and the right image shows the Carlops meltwater channel system mapped by Sissons (1963).

The offshore limits of the last BIS have remained elusive for many years partly due to the lack of appropriate technology and surveying techniques necessary for a detailed investigation of the geomorphology and sediments of the sea bed. Increasing coverage of the North Sea basin by geophysical survey techniques and detailed sedimentological studies are starting to produce a more coherent picture of the offshore limits in the North Sea (Carr et al., 2000), and also on the western continental shelves (Davison, 2004; Stoker et al., 2006).

- The broad-scale flow patterns and main ice divide locations of the have been known since the turn of the twentieth century. There is evidence for changing flow pattern geometries during the last glacial as ice centres competed for primacy. However, this only exists at a local-regional scale and so we do not know how different sectors of the ice sheet interacted.

- In the last decade a number of ice streams have been proposed. These are supported by evidence of variable quality and some may be purely examples of focused ice flow paths rather than true ice streams. The lack of information on ice sheet scale flow configuration hampers attempts to understand the role and timing of these ice streams.

- There is a vast amount of recorded evidence for former ice margin positions. However the evidence is yet to be synthesised into an overall reconstruction of the retreat pattern of the ice sheet. Debate has focused on the recognition and/or dismissal of re-advance stages rather than developing a pattern of retreat.

- The ice-rafted debris record from marine cores surrounding the last BIS indicates that the ice sheet was sensitive to climate and may never have reached steady-state conditions.

- The currently available chronology for ice build up and retreat is inadequate.

We do not have an evidence-based ice sheet scale reconstruction of the last BIS comparable with those for other palaeo-ice sheets. Over 100 years of research and interest in the former glaciations of has produced a wealth of information on the ice sheet extent, form and evolution but as yet this has not been incorporated into a reconstruction of the ice sheet wide retreat pattern and flow configuration evolution. Arguably, the explanation for this failure is the lack of a spatial framework in the form of a 'Glacial Map' equivalent to that available for Canada (Evans et al., 2005).

Chapter 3
Approach

3.1 Introduction

The previous chapter reviewed the state of knowledge of the last British Ice Sheet and examined potential explanations for our failure, to date, to produce an evidence-based ice sheet reconstruction from glacial geomorphology similar to those available for other palaeo-ice sheets (e.g. Kleman et al., 1997; Clark et al., 2000; Dyke et al., 2002). This chapter outlines the philosophical approach that underpins the ice sheet reconstruction I will present. Methodological procedures and their implementation will be described in the following chapters 4-10, steadily building towards the final reconstructions.

3.2 Ice sheet reconstruction

Reconstruction of palaeo-ice sheets ideally requires a systematic synthesis of geomorphological and geological information from the whole area covered by a former ice sheet (Clark, 1997). Attempts to use the geomorphological record in ice sheet reconstruction can be split into two broad categories; 'bottom up' and 'top down' (Clark and Meehan, 2001).

The 'bottom-up' approach occurs by the incremental accumulation of observations over time. This piecemeal approach is often problematic when attempting to reconstruct at the ice sheet scale (Clark and Meehan, 2001). It takes a long time to build up sufficient evidence to attempt a synthesis during which time interpretative paradigms will have evolved considerably (Clark, 1997).The spatially fragmented evidence amassed may be incompatible due to differences in the mapping methodologies of different observers (McMillan, 2002). The volume of information produced is daunting for any researcher attempting a synthesis, especially as there are likely to be discrepancies between areas as local-scale studies will inevitably reconstruct local-scale features of the ice sheet system (Clark et al., 2004b). All this is exemplified in the current situation of evidence-based reconstructions of the last British Ice Sheet (chapter 2). Despite over 150 years of research key characteristics of the last BIS remain unresolved (Evans et al., 2005). Arguably this is, in part, due to the failure to approach the interpretation of the record from the perspective of the ice sheet as whole (see Clark et al., 2006). Couple this with sporadic interest in glacial landform mapping and we are left with an incomplete record. This was compiled into a glacial map by Clark et al. (2004b) and Evans et al. (2005), revealing many blank areas. Although the existing geomorphological record has been synthesised by the BRITICE map there is no spatial framework in which to set sedimentological and chronological information and so it is difficult connect these point observations across space to make meaningful statements about the ice sheet as a whole. The situation also precludes productive comparison of numerical model outputs with real-world data stalling our understanding of the dynamics of the ice sheet (Shennan et al., 2006a; Boulton and Hagdorn, 2006).

In order to reconstruct the small scale characteristics of the ice sheet a non-reductionist or 'top-down' approach is adopted, where the scale of investigation matches the scale of the ice sheet system (Clark and Meehan, 2001). Rather than building a reconstruction from numerous local scale studies, this requires widespread mapping of critical glacial landforms (those that provide information on flow patterns and margin positions) and clearly defined method and interpretative rules. This type of approach has been variously described as palaeoglaciology (Boulton et al., 2001) and glaciological inversion modelling (Kleman et al., 2006). This type of reconstruction has never been attempted before for Britain (England, Scotland, and Wales).

3.3 Interpretative approach

3.3.1 The glacial inversion concept

Much geomorphological research is concerned with the genetic problem: determination of the formative process involved in the creation of a glacial landscape or individual landform. In ice sheet reconstruction, we are concerned with the problem of inversion: the application of genetic explanations to the glacial landform assemblage in order to determine form and dynamics of the ice sheet (figure 3.1). Kleman and Borgström (1996) set out a formal procedure for decoding glaciological information from the fragmentary and complex landform record left behind by the former mid latitude ice sheets. This inversion model is a genetically based classification scheme which aims to derive glaciological inferences from the landform record (Kleman et al., 2006). The purpose of the scheme is to formalise the method of building ice sheet reconstructions, i.e. to clearly state the assumptions and interpretative stages involved in converting the pattern and distribution of glacial landforms documented in a glacial map into ice sheet configurations (Clark, 1999; De Angelis, 2007a).

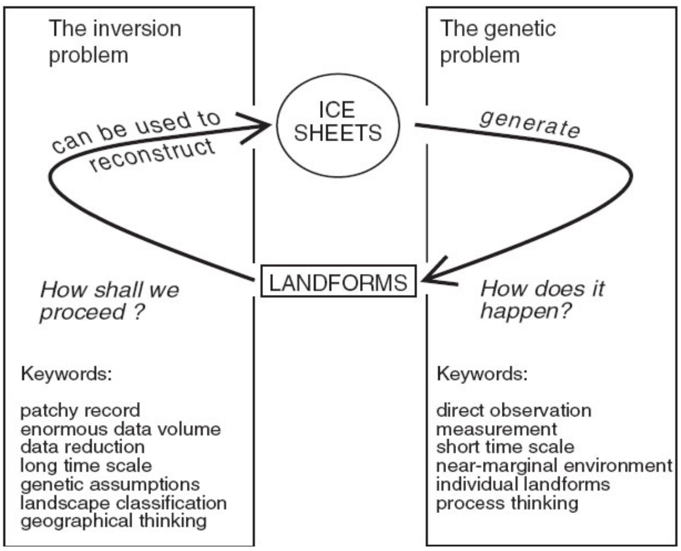


Figure 3.1 The conceptual differences between the genetic and inversion problems in glacial geomorphology and associated methodological issues. Ice sheet reconstruction is concerned with the inversion of the glacial landscape. Critical are the assumptions based in theories of the formative conditions for landform production, destruction, and preservation. Reproduced from Kleman et al (2006) and Kleman and Borgström (1996).

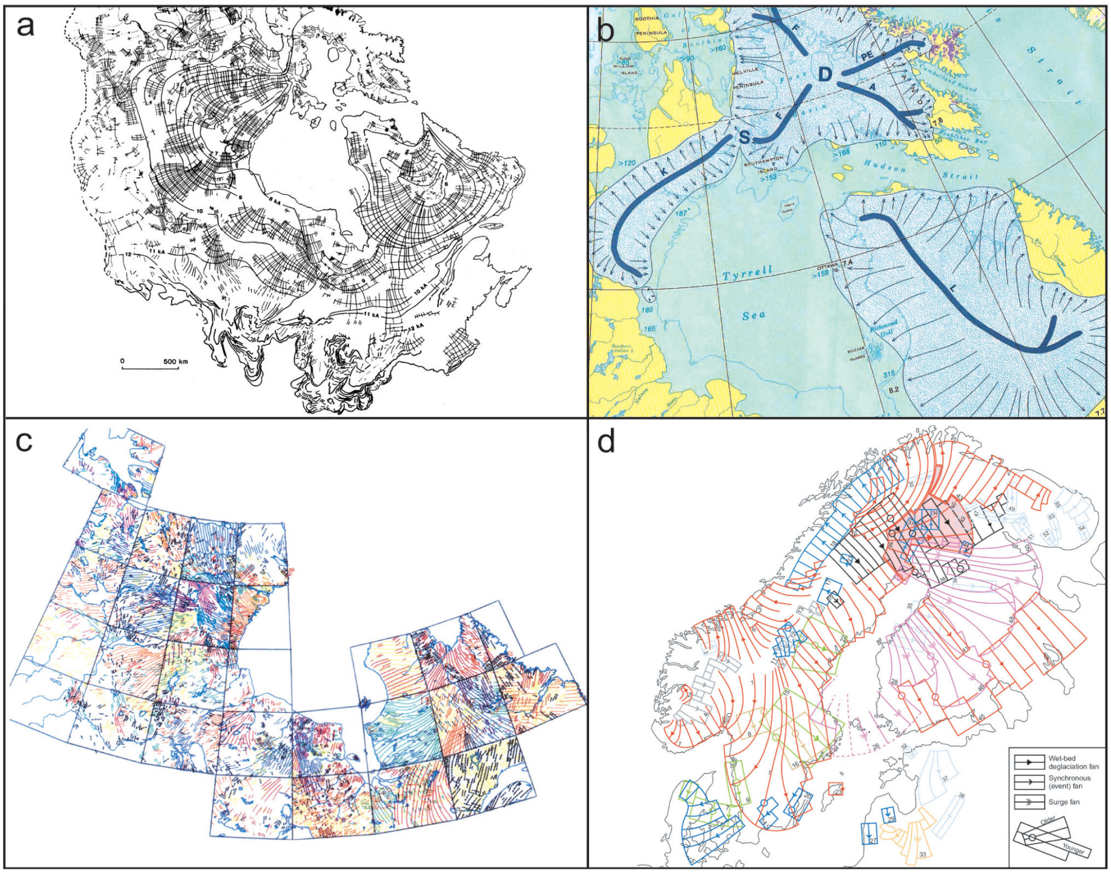


Figure 3.2 Four examples of ice sheet scale reconstructions using inversion protocols: a) Boulton et al. (1985); b) Dyke and Prest (1987a); c) Boulton and Clark (1990a, b); d) Kleman et al. (1997). Reproduced from Kleman et al. (2006).

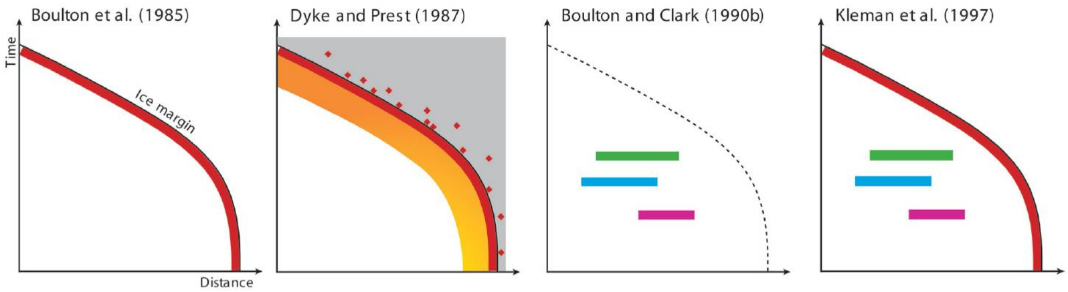


Figure 3.3 Differences between the four examples of ice sheet scale reconstruction shown in figure 3.3 expressed as a time-distance graph through a transect from the ice sheet centre to the margin. Differences in the genetic assumptions of each model lead to dramatic differences in the ice sheet reconstructions. Boulton et al. (1985) assumed that all lineations are formed close to the ice sheet margin. Dyke and Prest (1987) used published dates and lineation patterns to reconstruct the Laurentide Ice Sheet. Boulton and Clark (1990) used lineation patterns to reconstruct changes in ice divide locations. Kleman et al (1997) separated out event and deglacial flow patterns to reconstruct configuration changes and retreat pattern respectively. Reproduced from Kleman et al (2006).

The inversion approach outlined by Kleman and Borgström (1996) formalised and developed methodological approaches taken by Boulton and Clark (1990a, b) and Kleman (1990, 1992, 1994) (figure 3.2). The approach has been applied in a number of contexts, and refined and developed in recognition of recent observations from present day ice sheets (Clark, 1999; Stokes and Clark, 1999; Kleman et al., 2006; Kleman and Glasser, 2007). It is now a well established technique exemplified in reconstructions of the Laurentide, Scandinavian, and Irish Ice Sheets (e.g. Boulton and Clark, 1990a,b; Kleman et al., 1997; Clark et al., 2000; Clark and Meehan, 2001; Jansson et al., 2002; Kleman et al., 2002; Jansson et al., 2003; De Angelis and

Kleman, 2005) (figure 3.2). Two main schools of thought have embraced the inversion technique resulting in minor differences in the genetic assumptions used and procedural steps undertaken. Here, these are informally referred to as the Stockholm and Sheffield schools and are exemplified in papers by DeAngelis and Kleman (2005) and Clark and Meehan (2001) respectively. The main differences between the two schools are terminological and there is a high level of cross-pollination and shared ideas between the two groups. The method of the Stockholm School is clearly described in Kleman et al. (2006) and DeAngelis (2007a).

3.3.2 Assumptions

In philosophical terms, the inversion approach is a process of abduction (Baker, 1996). As such, any inversion is highly dependent on the genetic assumptions used (figures 3.2 and 3.3). Assumptions or rules are derived from glaciological theory and empirical observations. For example, the inversion model is grounded in theoretical explanations for the genesis and subsequent preservation of glacial landforms. No creation, modification, and by implication preservation, of existing landforms will occur at points of low basal velocity (ice divides) or under frozen bed conditions (Clark, 1999). Therefore, the distribution of subglacial bedforms defines the zones of the ice sheet bed that were warm-based at least once during the lifetime of the ice sheet. Successful application of the inversion methodology depends upon a clear understanding and definition of the glaciological contexts and processes of landform genesis (Clark, 1999).

Kleman and Borgström (1996) Kleman et al. (1997), and Kleman et al. (2006) set out the following eight assumptions:

1. The primary control on landform creation, preservation, and destruction is the location of the phase boundary between water and ice at or under the ice sheet base, i.e. the basal temperature.
2. Basal sliding requires a thawed bed.
3. Lineations can only form when basal sliding occurs.
4. Lineations (drumlins, flutes, straie) are created in alignment with local flow and perpendicular to ice surface contours at time of creation.
5. Frozen bed conditions inhibit rearrangement of the subglacial landscape.
6. Regional deglaciation is accompanied by the creation of a spatially coherent but metachronous meltwater features, e.g. channels, eskers, and lake shorelines.
7. Eskers form in a time transgressive fashion behind a retreating ice front.
8. Lateral meltwater channels will form the major landform record during frozen bed deglaciation; eskers are typically lacking in these situations.

3.3.3 Implementation/Procedural steps

Implementation of the inversion model proceeds in a series of interrelated stages:

1. Glacial Map

The starting point for any inversion model is a representative glacial map of the former bed of the ice sheet in question. The landforms required by the model, and therefore selected for inclusion on the maps presented in chapter 5, are listed in table 3.1. The former beds of palaeo-ice sheets typically cover large areas, incorporating both present day terrestrial and submarine landscapes. Ideally, the map will be a consistent representation of the distribution and pattern of glacial landforms over the entire bed. The map can be derived from existing work (e.g. Kleman et al., 1997) or freshly produced to capture the landscape in a consistent or more appropriate style (e.g. Clark and Meehan, 2001). Mapping of glacial landforms can be conducted in two main ways: fieldwork and from remotely sensed imagery (e.g. figure 3.4). There are several advantages to using remotely sensed data when considering large areas (Clark, 1997) and this is the methodological approach adopted by this project in order to produce a consistent basis for reconstruction (chapter 4).

Table 3.1 Palaeoglaciological information provided by the five primary landform types to be mapped. Some landforms have uncertain genesis (marked with an *) or are polygenetic. This is an important consideration in the palaeoglaciological interpretation of landforms.

Landform type		Palaeoglaciological significance
Subglacial bedforms	Drumlins	Ice flow direction at time of formation (stoss-end points upstream). Form under warm-based ice. Genesis disputed.
	Mega-scale glacial lineations, MSGL	Ice flow direction at time of formation. Form under warm-based ice. One of the key criteria for the identification of ice streams (table 3.3).
	Ribbed moraine	Form transverse to ice flow. Genesis uncertain. Stockholm school take the distribution to reflect the transition from warm to cold-based ice. Sheffield school presume that generated under warm-based conditions, because of the uncertain genesis.
Meltwater channels		Ice marginal channels (lateral and proglacial) record margin positions. Subglacial channel networks suggest surface slope close to the margin.
Moraine		Lateral or terminal ice margin position.
Eskers*		Orientated parallel to overall ice flow direction. Form behind margin of retreating warm-based glacier.
Streamlined bedrock		Ice flow directions. Possibly formed over several glacial cycles. Warm-based ice.

2. Generalisation and classification

The second stage of the inversion scheme proceeds by summarising the complex distribution of landforms contained in the glacial map into landscape scale pieces of glaciological information. For clarity, this process is explained as a series of steps, but in reality it is not a stepwise process but an iterative one.

- FLOWSETS AND SUMMARY ARROWS

The basic premise of the inversion scheme is that distinct ice flow phases can be recognised in the geomorphological record and used to determine flow behaviour at times during the evolution of the ice sheet (Clark and Meehan, 2001). The glacial map will contain a vast number of individual landforms. By nature, the glacial geomorphological record is complex, fragmentary, and multi-temporal reflecting the cumulative effect of ice sheet erosion, deposition, and preservation processes. The first stage of the inversion procedure is thus to reduce the volume of information into a manageable number of units of glaciological information via a process of logical reduction or cartographic generalisation. For example, ice flow traces (drumlins and other lineations) are grouped into *flowsets* (called swarms or fans by the Stockholm School) (figure 3.5). A *flowset* is defined as coherent group of geomorphological lineations that reflect a systematic pattern related to a distinct phase of ice flow (Clark and Meehan, 2001). Identification of *flowsets* is completed by subjective visual inspection of the mapped distribution of lineations, based on a collection of rules including parallel conformity, proximity, morphology and spatial arrangement (Clark, 1999) (figure 3.6). Resemblance to a glaciologically plausible pattern of ice flow and spatial continuity are also considered (e.g. De Angelis, 2007a). Delineation of flowsets is essentially via pattern recognition and conceptual models of possible flow patterns are used as an aid to this process (figure 3.7). For example, Clark (1997) suggested three possible glaciological contexts to explain cross cutting lineations (figure 3.8).

Figure 3.4 Summarised flow patterns of the Laurentide Ice Sheet interpreted from (a) map of Prest et al (1968) derived from inspection of aerial photographs and (b) map of lineations mapped from Landsat imagery by Clark (1990). The wide area view and resolution of Landsat imagery facilitated recognition of large scale patterns of lineations and cross-cutting. Reproduced from Clark (1993).

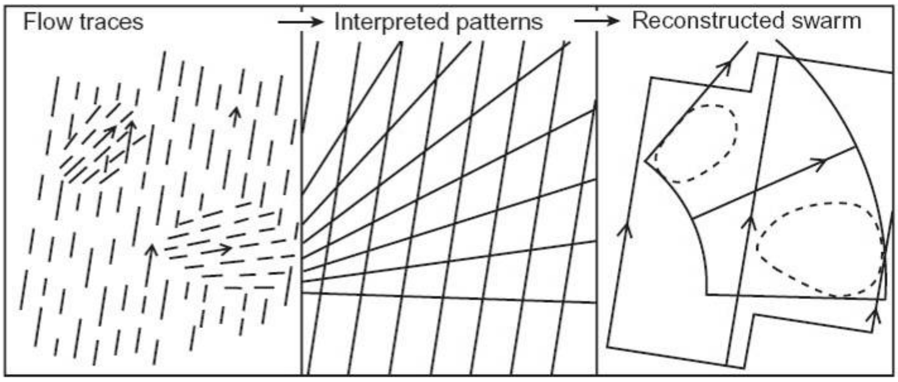


Figure 3.5 Transformation of flow traces (drumlins, lineations, etc) into landscape level flowsets via interpretation of flow patterns. Boundaries are drawn aligned or transverse to flow traces. Outline bounds limit of flow traces relating to particular fan (flowset). Arrows show interpreted direction of ice flow. Reproduced from Kleman and Borgström (1996).

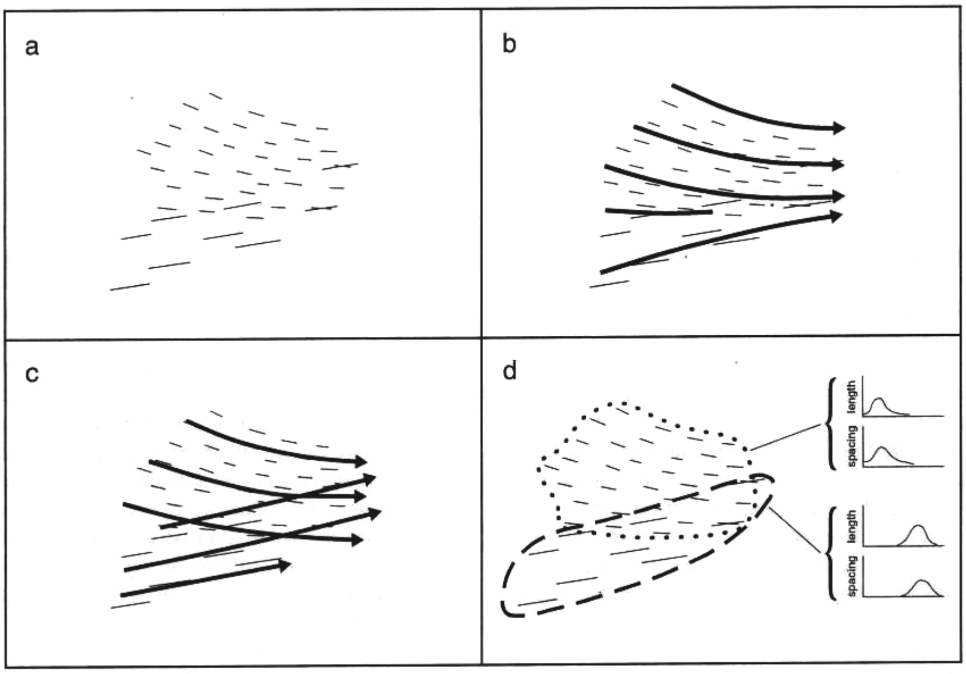


Figure 3.6 Schematic diagram to show how mapped lineations are summarised as flow patterns and organised into flowsets: a) hypothetical lineation pattern; b) and c) alternative flow pattern summaries. In b) all lineations assumed to be the same age and are grouped into a single flow pattern, in c) two separate flow patterns are identified; d) lineation morphometry statistics aids discrimination of flow patterns. In this case, the lineations form two populations on the basis of length and spacing and so the interpreted flow pattern c) is selected. The inherent assumption is that lineations formed under the same flow event will have similar morphometric characteristics. Such morphometric considerations aid flowset discriminations and are a useful additional tool to that of discrimination by cross-cutting landforms. In this case they also indicate c) as the preferred outcome. Reproduced from Clark (1997).

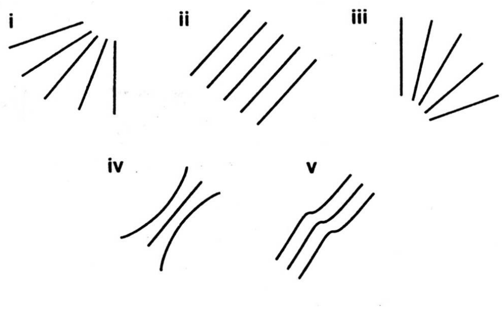


Figure 3.7 Conceptual models of possible flow patterns are used as tool to aid identification of flowsets in the glacial map. Coherent flow patterns exhibited by lineations of the Laurentide Ice Sheet: i = divergent, ii = parallel, iii = convergent, iv = 'Venturi', v = kinked. Reproduced from Clark (1994).

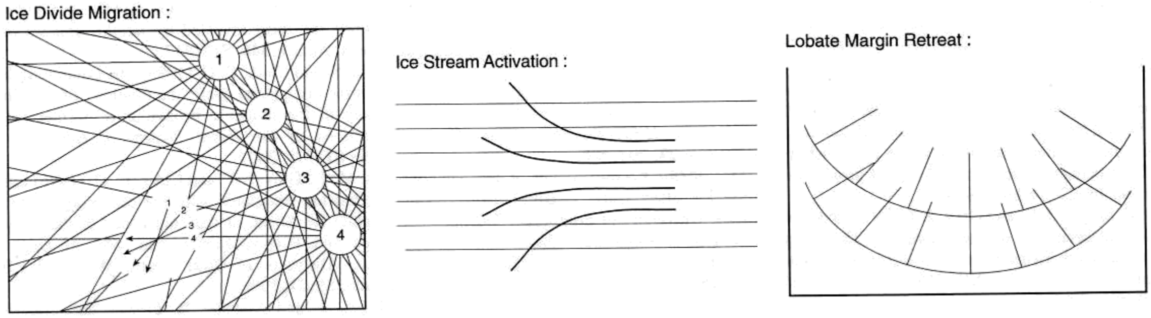


Figure 3.8 Scenarios where cross-cutting lineations (drumlins, etc.) might be expected to occur. These concepts are useful in the interpretation of cross-cutting flow patterns. One further explanation for cross-cutting is that of landforms from separate glaciations. Reproduced from Clark (1997).

Fields of ribbed moraine are also translated into a second set of flowsets defining phases of ice flow. This is achieved in a similar manner to lineation flowsets by summarising ribbed moraine by lines transverse to the orientation of ridges. The debate on ribbed moraine genesis is ongoing and so ridges are solely used to infer ice flow direction, and not to identify the transition zone between cold and warm-based ice (Hättestrand and Kleman, 1999). Esker systems are summarised by grouping similarly arranged and adjacent eskers into a cartographically simpler unit represented by arrows pointing in the interpreted direction of ice flow. Flights of lateral meltwater channels and networks of subglacial channels, with reference to topographic context, are summarised as arrows in the general direction of meltwater flow (after Hättestrand and Clark, 2006a). Ice margin positions are derived from the distribution of moraines using topographic setting where appropriate. Streamlined bedrock is summarised by summary arrows in the interpreted direction of ice flow. Flowsets and the other cartographic summaries are the first level of abstraction from the geomorphological record (De Angelis, 2007a). Figure 3.9 shows the change in detail of information that occurs at this stage. The process of flowset identification, including methodological procedure, will be explored in depth in chapter 6.

- FLOWSET CLASSIFICATION

Once flowsets have been established a critical stage of the reconstruction is to determine the temporal context of formation, i.e. whether the flowset developed over time or was formed 'at an instant'. It is essential to assess the internal synchronicity of flowsets as this has specific implications for interpretation of flowsets in terms of ice sheet evolution (Clark et al., 2000). The simplest interpretation is that the group of landforms represented by each flowset was generated at the same time by a single ice flow event. It follows that the flow pattern delineated by the flowset forms part of the ice flow geometry within a single time slice and thus reflects actual palaeo-flow lines of the former ice sheet. The alternative, that the composite landforms were generated in a *time-transgressive* fashion, implies that the flowset delineates an amalgam of ice flow at more than one point in time. Figure 3.10 illustrates the implications of this distinction.

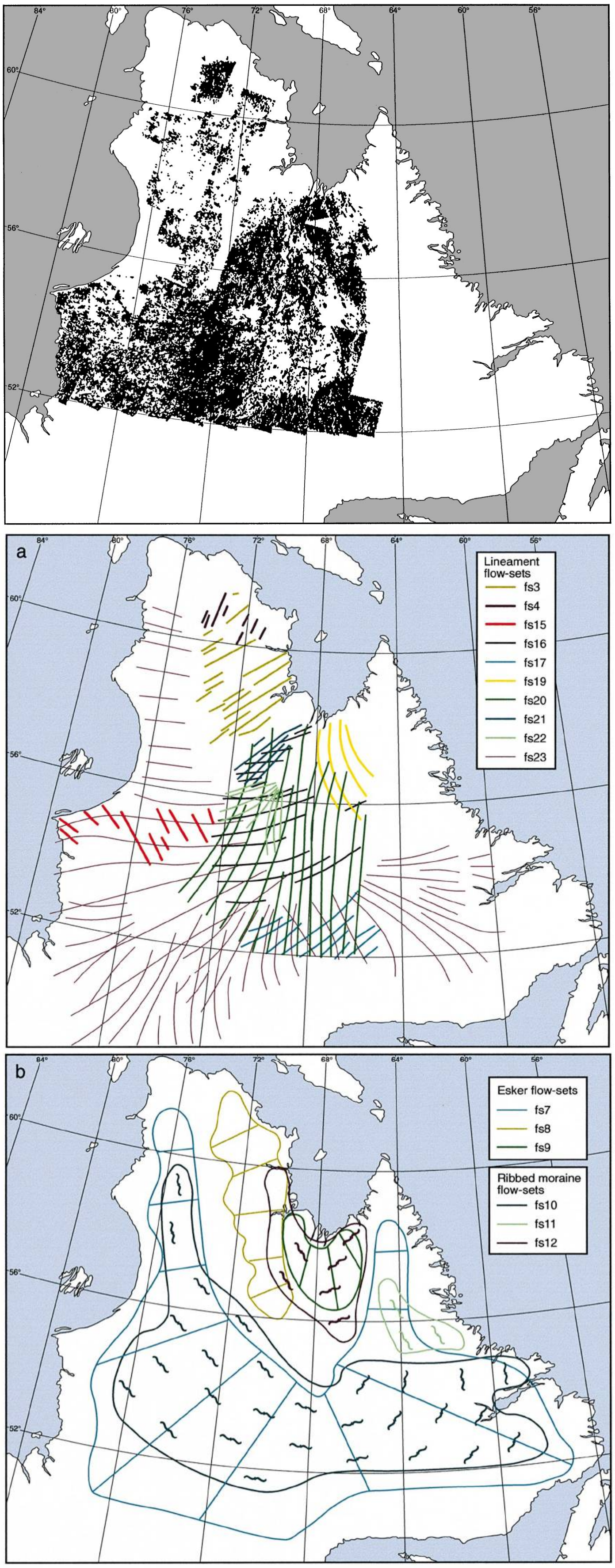


Figure 3.9 Glacial lineations mapped by visual interpretation of satellite images of Quebec, Canada (top image); Flowsets derived from the distribution of (a) lineations, (b) eskers and ribbed moraine. Reproduced from Clark et al. (2000).

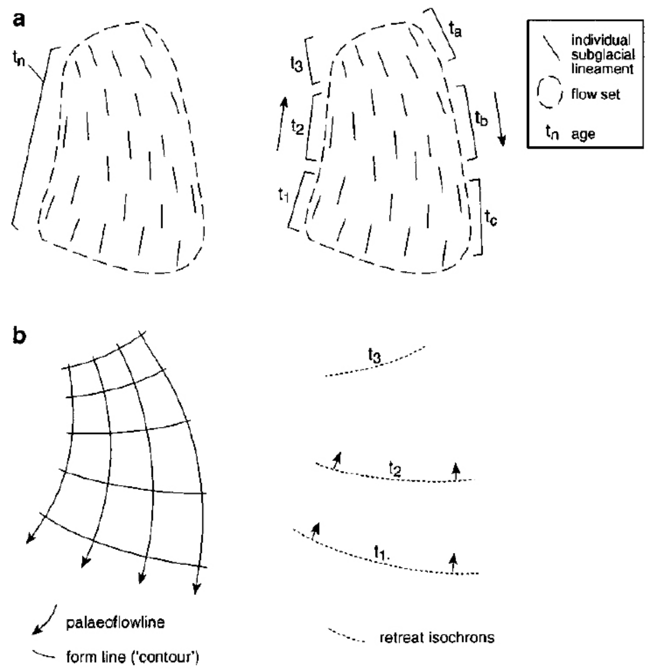


Figure 3.10 Determination of the internal synchronicity of flowsets is critical to the reliability of the ice sheet reconstruction. This is because time-transgressive and isochronous flowsets should be interpreted in different ways. Schematic shows implications of designation as isochronous (left) or a type of time-transgressive (right) a) On the left lineations are interpreted as formed near instantaneously at a time t_n. On the right lineations are interpreted to have formed incrementally over three time periods t_1 to t_3 (or the reverse t_a-t_c); b) In the case of the isochronous flowset it is assumed that the flow pattern represented reflects an actual palaeo-flow line of the ice sheet. In the case of the time-transgressive interpretation, the flowset is an amalgamation of several palaeo-flow lines operating at different stages of ice sheet geometry. In this case, the time-transgressive nature of the flowset is thought to be a result of retreat of the ice margin and so the flowset is interpreted in terms of margin positions. Reproduced from Clark (1999).

By consideration of the possible glaciodynamic contexts of lineation generation and preservation, and the patterns of lineations that would arise (figure 3.11), Clark (1999) presented a series of conceptual tools to aid discrimination of isochronous and time-transgressive flowsets (table 3.2). In essence, it is expected that a flowset generated isochronously will have a 'rubber stamped' appearance. Lineations comprising the flowset will have a high degree of parallel conformity, any changes in morphometry will be gradual along the interpreted flow line, and there will be no instances of cross cutting. In contrast, lineations comprising a time-transgressive flowset will have a 'smudged' appearance, exhibiting low parallel conformity, instances of cross cutting, and abrupt changes in morphometry along the flow line. Spatial coincidence with other landforms can be used as an additional means to determine internal synchronicity. Esker 'flowsets' will always be time-transgressive, if we accept the genetic assumption that eskers are only formed behind a retreating ice margin (table 3.1). Therefore, alignment with esker systems supports time-transgressive interpretation of the lineation flowset (figure 3.12).

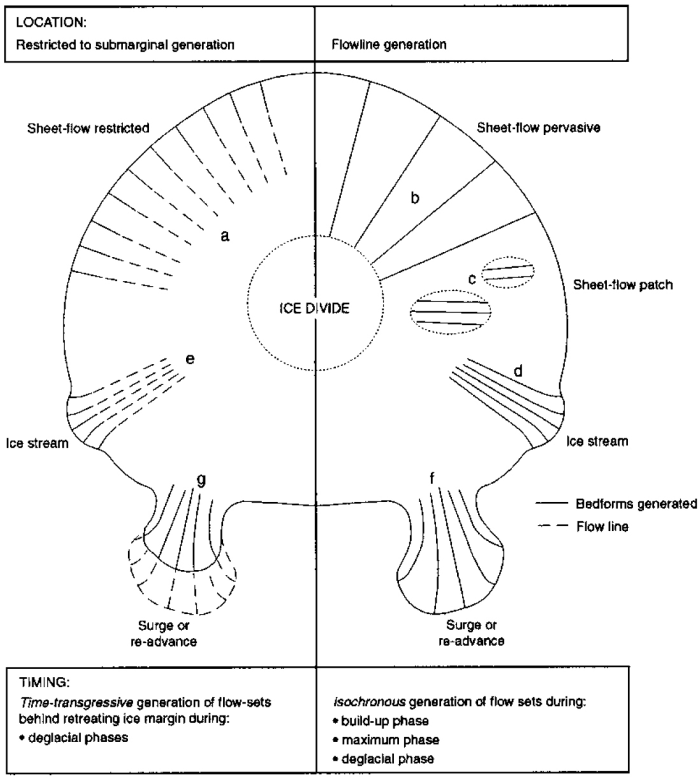


Figure 3.11 A hypothetical ice sheet to illustrate some of the glaciodynamic contexts of glacial lineation formation. Time-transgressive cases on left and isochronous on right: Reproduced from Clark (1999).

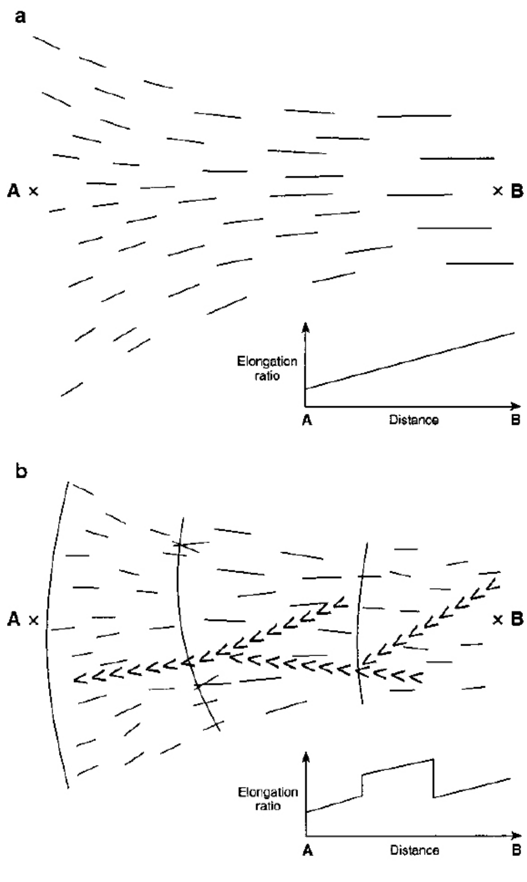


Figure 3.12 Predicted characteristics of isochronous (a) and time-transgressive (b) flowsets. Isochronous flowset comprise lineations with high parallel conformity, no cross cuts and gradual variations in morphometry. Time-transgressive flowsets will exhibit low parallel conformity, cross-cuts and abrupt discontinuities in morphometry. Moraines and eskers aligned with the flowset support time-transgressive interpretation. Reproduced from Clark (1999).

Table 3.2 Predicted characteristics that will arise from time-transgressive or isochronous flowset generation. Reproduced from Clark et al. (2000) and Clark (1999). Figure 3.12 is a schematic showing these characteristics.

Internal synchrony of flowset	Glaciodynamic context	Predicted flowset characteristics
Time-transgressive ⇒ Flowset built up incrementally	Formed close to ice margins: ▪ Thin ice ▪ Lobate margin patterns ▪ Rapidly varying flow directions	▪ Predominately lobate or splaying flow patterns ▪ Flow pattern correspondence to local topography ▪ Low parallel conformity between lineations ▪ Spatial variation in lineation morphometry will contain abrupt discontinuities ▪ Probable landform association with eskers and/or end moraines
Isochronous ⇒ Flowset generated rapidly, 'at an instant'	Formed away from ice margins: ▪ Range of ice thickness' ▪ Conforms to internal rather than marginal flow patterns ▪ Greater stability of flow directions	▪ Predominately parallel flow patterns ▪ Little or no flow pattern correspondence to local topography ▪ No cross-cutting lineations within flow sets ▪ High parallel conformity between lineations ▪ Spatial variation in lineation morphometry will be gradual ▪ No landform association with moraines ▪ No landform association with eskers

▪ ICE STREAMS

Ice streams are now recognised as an intrinsic element of ice sheet configuration and are thought to play a disproportionate role in ice sheet dynamics relative to their size (Bennett, 2003). The identification of palaeo-ice stream tracks is thus an important part of any ice sheet reconstruction. Scrutiny of the former beds of palaeo-ice sheets, principally the Laurentide, and bolstered by observations from the Antarctic continental shelf in front of present day ice streams (Shipp et al., 1999), have led to a set of diagnostic criteria for the discrimination of palaeo-ice stream tracks (Stokes and Clark, 2001; Stokes, 2002; Stokes and Clark, 2002; Clark and Stokes, 2003) (table 3.3). Application of these criteria enables us to identify flowsets that represent tracks of palaeo-ice streams. 'Ice stream' or 'non-ice stream' is therefore an additional classification for each flowset in order to flag their 'special' status in the ice sheet reconstruction. An ice stream flowset may be time-transgressive or isochronous (figure 3.13).

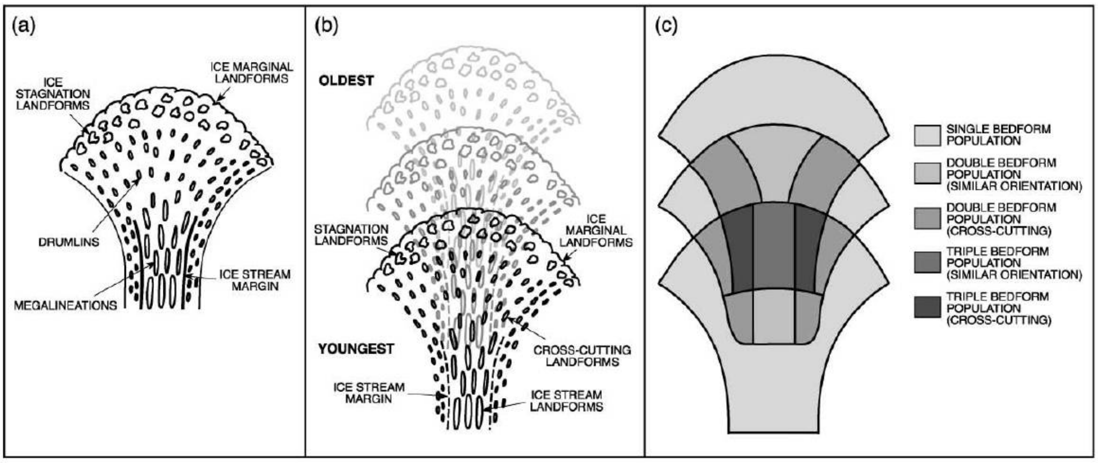


Figure 3.13 Schematic palaeo ice stream bed and diagnostic landforms. (a) Rubber stamped imprint. Pattern remains unaltered if ice stream switched off and ice retreated without remoulding the landforms. (b) Smudged imprint. Ice streaming continued during retreat of the margin. Continual generation of bedforms leaves behind a complex assemblage of landforms which may be characterised by instances of cross-cutting. (c) Interpreted flowsets relating to successive stages of bedform generation as ice stream retreats.

Table 3.3 Geomorphological criteria for identifying former ice streams. Reproduced from Stokes and Clark (1999; 2001).

Contemporary ice stream characteristics	Geomorphological signature
Characteristic shape and dimensions	▪ Characteristic shape and dimensions (>20km wide and >150km long) of distinct flow pattern ▪ Highly convergent flow patterns leading to a trunk
Rapid velocity	▪ Bedform signature of fast flow; mega-scale glacial lineations (MSGL) and highly attenuated drumlins (length:width >10:1, 100:1) ▪ Boothia-type erratic dispersal trains
Distinct velocity field (plug flow, downstream variation in velocity)	▪ Expected spatial variation in MSGL and drumlin elongation ratios ▪ Boothia-type erratic dispersal trains
Sharply delineated shear margin	▪ Abrupt lateral margins (<2km) ▪ Ice stream shear margin moraines
Spatially focused sediment delivery	▪ Submarine till delta or sediment fan

A key departure of the implementation procedure of the Sheffield school from the Stockholm group is to keep landform types separate at the generalisation stage (figure 3.14). Isochronous flowsets are broadly equivalent to the 'event' fans of Kleman et al. (2006). However, the 'deglacial envelope' of Kleman et al. (2006) is analogous to considering the time-transgressive flowsets (of the type that delimit continual landform generation behind a retreating ice margin), esker 'flowsets', lateral meltwater channel 'flowsets' and moraine margin positions collectively. Identification of ice stream flowsets (swarms) is achieved in the same way by both groups.

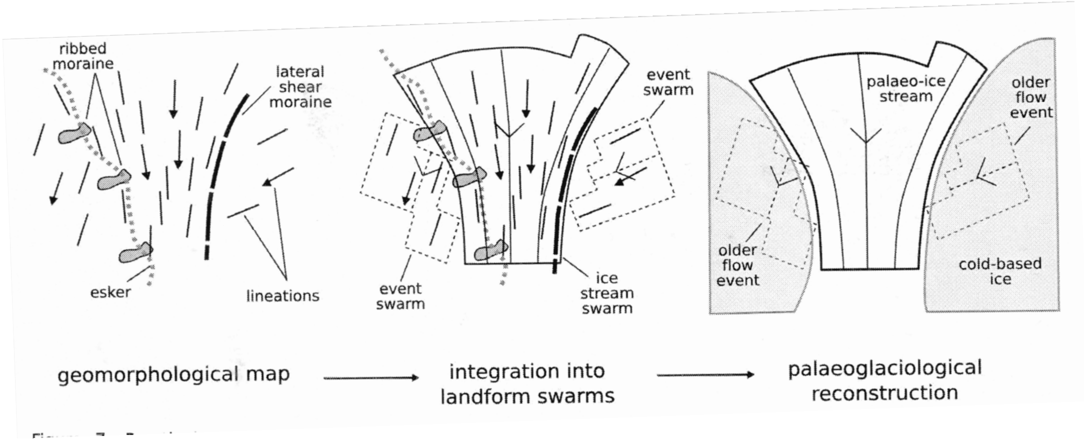


Figure 3.14 Practical steps of the inversion scheme as described in Kleman et al (2006) and exemplified in DeAngelis (2007). The 'Stockholm School' use the whole landform assemblage in order to delineate swarms (flowsets) and use preservation of older flow patterns to reconstruct areas of cold based ice. Reproduced from DeAngelis (2007).

▪ RELATIVE CHRONOLOGY

Integral to the inversion scheme is the observation that the lineations can survive beneath subsequent (conflicting) ice flow phases (Clark, 1993) (figure 3.15). The situation enables cross-cutting patterns to be used to determine the relative chronology of ice flow phases. Where interpreted flowsets overlap, the landform record is investigated for instances of landform cross cutting so that flowsets can be placed in a relative age stack. This is a crucial ingredient in order to group flowsets into contemporary ice flow geometries and reconstruct the evolution of the ice sheet. A key difference between the two schools of thought is the glaciological interpretation of palimpsest landscapes. The Stockholm school hold stringently to the idea that preservation of landforms will only occur under frozen bed conditions and that warm-based conditions will inevitably lead to remoulding of the subglacial landscape. This is taken to the logical extreme to identify locations of cold-based ice (figure 3.14). The Sheffield School differs from this in that additional glaciological possibilities for the preservation of landforms are recognised as it is thought unlikely that cold-based ice can explain all of the observed instances of preservation (Clark, 1993; Clark, 1994; Clark, 1999).

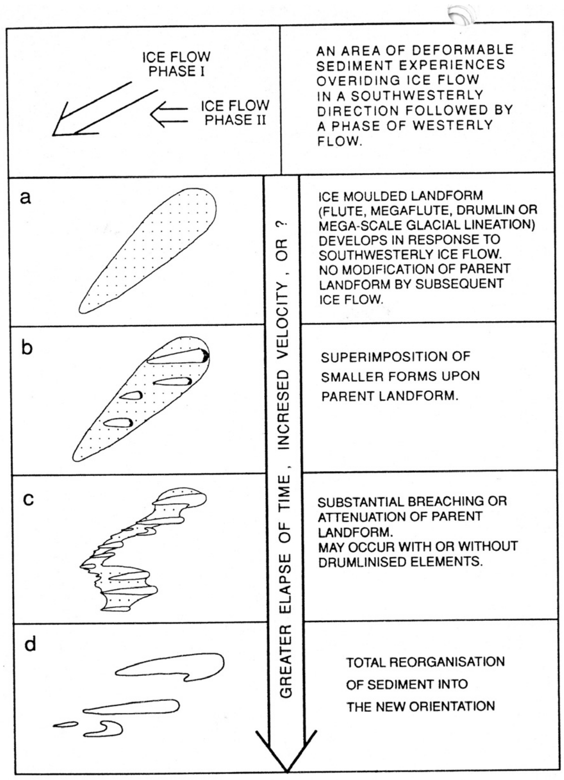


Figure 3.15 A possible explanation for the presence of palimpsest landscapes is incomplete remoulding by subsequent ice flow. Theoretical continuum of subglacial modification (a-d) of a lineation experiencing over-riding ice flow from another direction. Cross cutting or superimposition can occur by changes in ice sheet geometry and/or reflect multiple glaciations. Clear cross cutting as opposed to gradual changes in lineation orientation suggests that ice flow phases are either separated by a period of cold-based ice at the location or reorganisations of ice sheet geometry occur rapidly. Both cases preventing generation of subglacial lineations. Reproduced from Clark (1994) and Clark (1993).

3. Reconstruction

Classified flowsets, generalised arrows and the relative age stack provide the ingredients, or analytical components, of the ice sheet reconstruction. The next stage of the inversion model is to organise the ingredients, in combination with any reference data, to define the major components of the ice sheet, i.e. flow patterns, retreat pattern and the location of ice divides and ice streams, and document the evolution of these components through time. This is the second level of abstraction from the geomorphological record (DeAngelis, 2007). Reference data are any additional sources of information that are used. For example, elevation data from digital elevation models can be used to understand the topographic setting of flowsets and meltwater channels. Absolute chronological information from published dates is a valuable source of reference data. The reconstruction process is analogous to numerical modelling, in that a set of rules and assumptions are engaged in order to translate inputs (flowsets and mapping generalisations) into a glaciologically plausible ice sheet reconstruction. It is expected that there will be conflicting results from different lines of evidence and gaps in the record. In such cases, it is necessary to present a number of different scenarios and highlight areas of disagreement for future research. Flowsets are organised into plausible scenarios of ice sheet geometry based on relative chronology and spatial conformability, following the least complex solution. Generalisations of esker, lateral meltwater channel, and moraine distribution in addition to any time-transgressive flowsets that represent a retreating margin, are used to reconstruct successive margin positions (figure 3.17). Relative age information is used to organise changes in ice sheet geometry over time (figure 3.18). Dates are used to set the relative ice sheet geometry evolution in an absolute chronological order (figure 3.19). The reconstruction process and interpretative rules employed in this thesis is based on the principles outlined in this chapter with the addition of some necessary innovations more fully described in chapter 7.

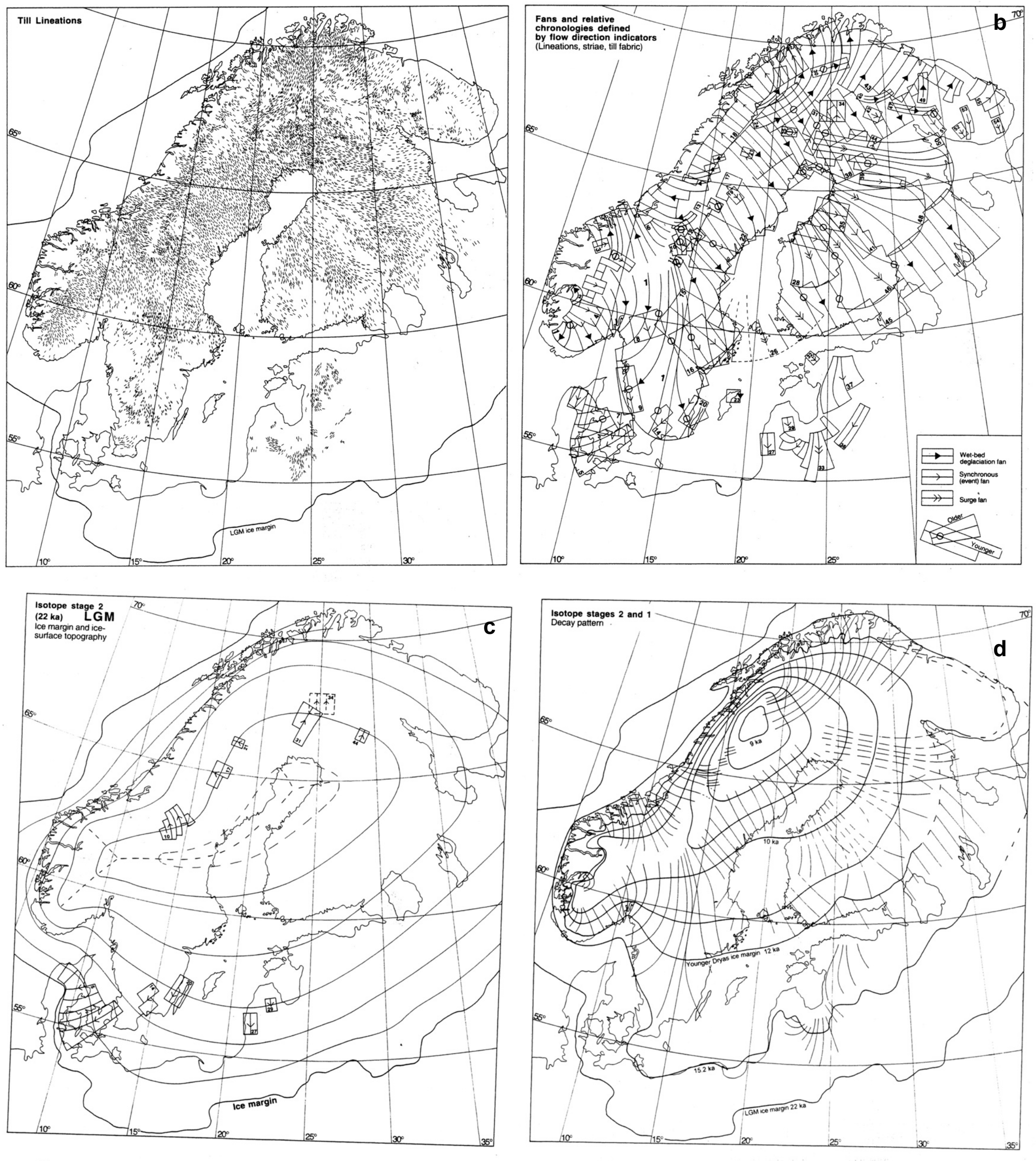


Figure 3.16 Example of steps involved ice sheet reconstruction using a glacial inversion model. a) Lineations of the Fennoscandian Ice Sheet compiled from various published sources by Kleman et al. (1997); b) Fans (flowsets) derived from examination of the spatial pattern and distribution of lineations in a) and striae and till fabric data. Fans delimited as deglacial or non-deglacial (synchronous) by the presence or absence of aligned glaciofluvial meltwater landforms. Relative chronologies based on striae and air photo interpretation; c) Fans grouped into the same ice sheet configuration. Ice sheet margins and interpolated from extrapolation of the flow geometry necessary to incorporate the flow pattern record by the fan; d) Retreat pattern inferred from arrangement of deglacial fans. Reproduced from Kleman et al. (1997).

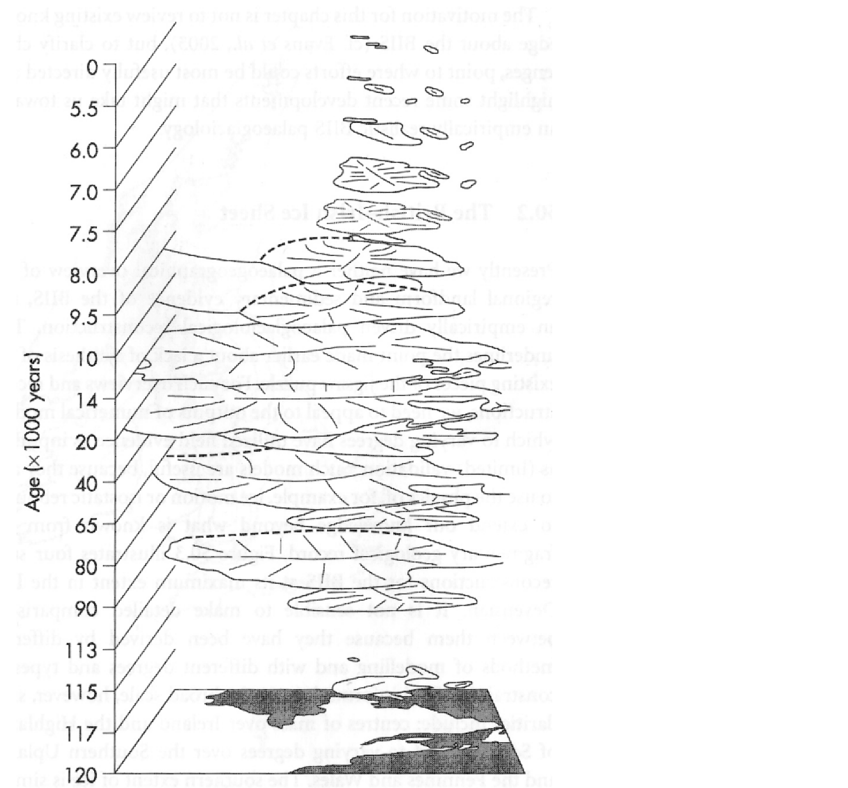


Figure 3.17 Ice sheet geometries are inferred via grouping of flowsets into contemporaneous groups and interpolating locations of ice divides necessary to generate such flowsets. Relative chronology is used to organise ice sheet geometries into time-slice envelope of ice sheet evolution. In this example ice sheet reconstruction derived from an inversion model of part of the Laurentide Ice Sheet. Spatial axes, x and y, and time shown on the z axis. Figure reproduced from Clark et al. (2006).

3.4 Summary

This chapter has described the conceptual/philosophical basis of the glacial inversion scheme used in this thesis. The steps involved in the reconstruction presented in this thesis are shown as a flow diagram in figure 3.18. The following chapters will describe the implementation of the scheme:

1. Glacial Map (chapters 4 and 5),
2. Generalisation (chapter 6),
3. Reconstruction (chapters 7-10).

This is the first time a glacial geomorphological inversion model has been applied to Britain as a whole. A few recent studies have reconstructed flowsets for sectors of the ice sheet but have not produced a full inversion model (Jansson and Glasser, 2004; Golledge and Stoker, 2006).

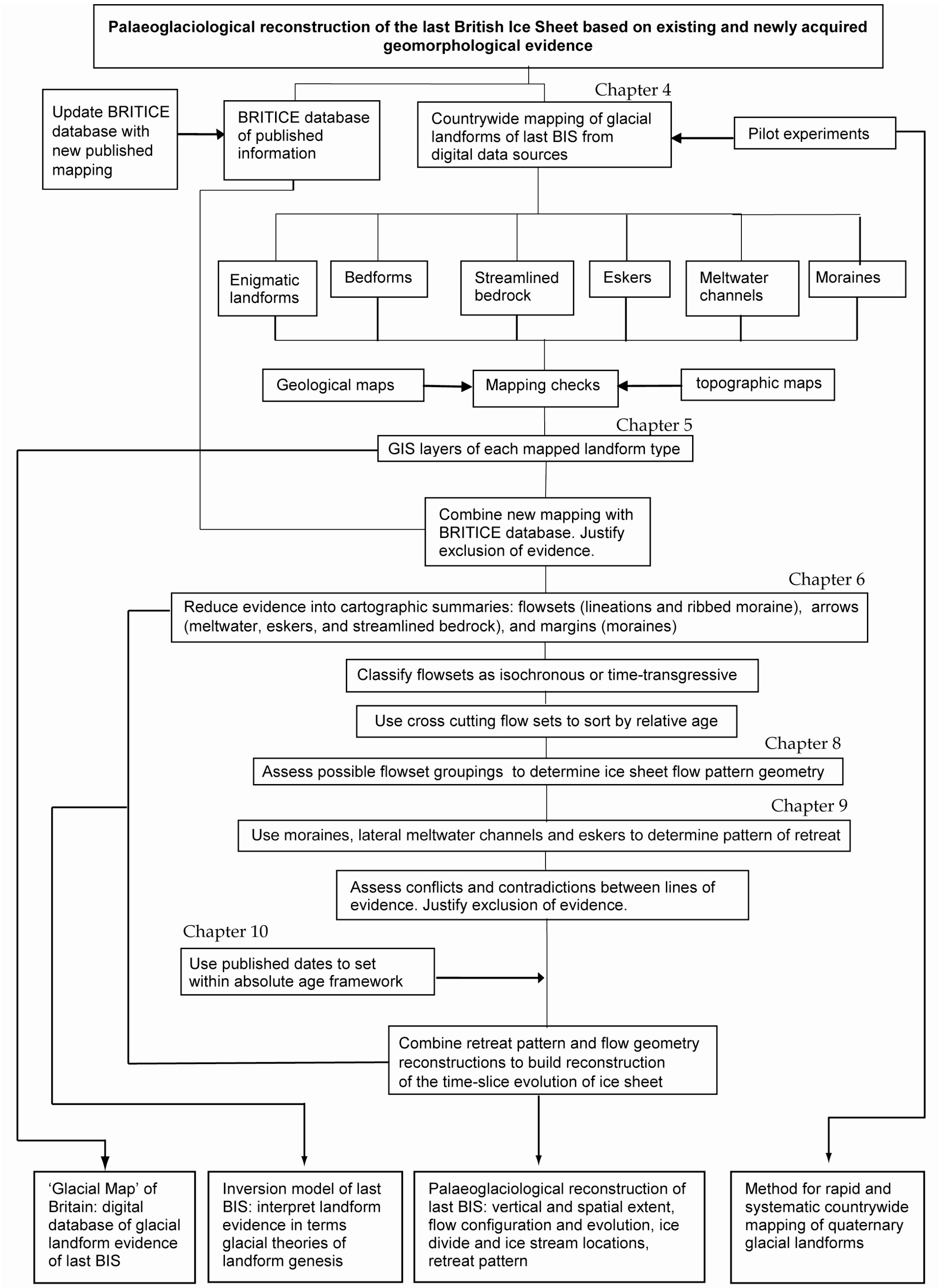


Figure 3.18 Flow diagram showing the steps involved in the reconstruction of the last British Ice Sheet detailed in this thesis. Steps are labelled with chapter numbers in which results are discussed and presented.

Chapter 4

Countrywide mapping of glacial geomorphology

4.1 Introduction

The principal component necessary for any inversion of the glacial landscape is a glacial map covering the whole of the former bed of the ice sheet. To reconstruct ice sheet scale dynamics, comprehensive and consistent maps of geomorphology for the former ice sheet bed are required. Field mapping over the last one hundred and fifty years has identified the main distribution and pattern of glacial landforms produced and preserved by the last British Ice Sheet, and is summarised together in the first Glacial Map of Britain and accompanying BRITICE Geographic Information System (GIS) database (Clark et al., 2004b; Evans et al., 2005) (figure 1.5). However, it is apparent from this synthesis that despite considerable detail of mapping in some areas, the existing information suffers from inconsistencies in terms of mapping styles and scales. Furthermore, whilst some sites have been revisited and remapped many times, other significant areas remain unmapped. This precludes the use of the current glacial map in an inversion of the glacial landscape as the evidence on which to base and constrain interpretations is spatially fragmented and inconsistent (figure 4.1). The purpose of this chapter is to document the approach and methods used to produce a consistent countrywide glacial map that will form a more reliable basis for an inversion model for the last British Ice Sheet. This chapter is closely coupled with chapter 5 which presents the resulting glacial maps.

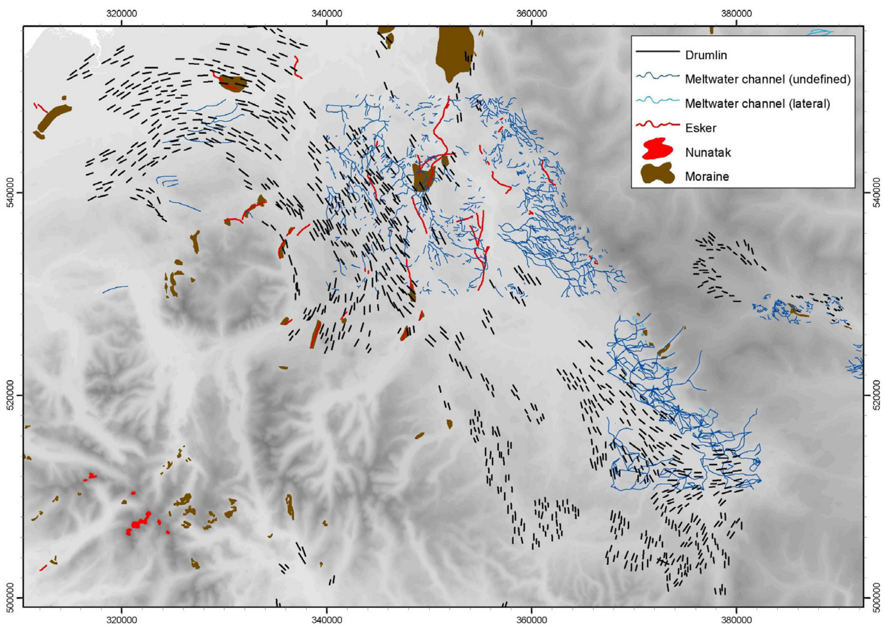


Figure 4.1 Detail from part of the Glacial Map of Britain (Clark et al. 2004b) centred on the Vale of Eden and Solway lowlands. Meltwater channel distribution demonstrates the 'edges' problem of the BRITICE data. Channels are mapped in detail for some BGS map sheets but absent from adjacent sheets. Drumlin mapping is patchy in the Vale of Eden. It is difficult to believe that the mapped drumlin distribution is a representative sample of the total population for this area. Flow patterns reconstructed from this distribution would therefore be incomplete. Grid spacing is 20 km, Ordnance Survey co-ordinates.

4.2 Mapping approach

A systematic synthesis of the glacial geomorphological information from the whole area covered by a former ice sheet is most easily and rapidly achieved by the use of digital landscape data such as satellite imagery and digital elevation models (DEMs) (Clark, 1997). Remote sensing data is now an established tool for glacial geomorphological mapping (Boulton and Clark, 1990a,b; Clark, 1990, 1993; Punkari, 1993; Clark, 1997; Jordan, 1997, Baily et al., 2003; Boulton et al., 2001; Clark and Meehan, 2001; Clark and Stokes, 2001; Jansson et al., 2002; Jansson et al., 2003, Smith and Clark, 2005; Stokes and Clark, 2003, Clark et al., 2000; Jansson and Glasser, 2004; Jansson, 2005; Jansson and Glasser, 2005; Dunlop and Clark, 2006; Hättestrand and Clark, 2006b; De Angelis, 2007b). Using this type of data a single observer can apply a well defined set of identification criteria to map large areas many times more quickly than would be achieved in the field, and the resulting maps can be directly incorporated into a GIS for further analysis (Clark, 1997). The use of GIS facilitates both the synthesis of local scale field and stratigraphic observations with ice sheet scale mapping, and the examination of the spatial arrangement of landforms and flow patterns for ice sheet reconstruction (Clark, 1997) (chapter 6).

Satellite images record variations in the spectral reflectance of a surface. The most widely used satellite imagery for geomorphological mapping has been the Landsat series of which ETM+ images provide the highest resolution facilitating mapping to a scale of 1: 45 000 (Clark, 1997). The wide area view facilitated by remote sensing imagery provides the capability to identify large scale features of the landscape that would be hidden at the field scale. For example, Clark (1993) first identified evidence for mega scale glacial lineations by using Landsat images to map the geomorphic evidence for the LIS. These huge (1000s km long) features could not have been identified in the field and are now recognised as reliable indicators of ice streaming (Stokes and Clark, 2001). For geomorphological mapping it is preferable to use images collected in the northern hemisphere winter as low elevations of sunlight show a greater level of detail, however obtaining clear images at high latitudes during the winter can be difficult (Clark, 1997).

A Digital Elevation Model (DEM) is a computerised three-dimensional model of a land surface. Each grid cell or pixel has a height value averaged over the area that the grid cell represents on the ground (Clark, 1997). The accuracy of a DEM is dependent on the resolution of the base grid and the complexity of terrain and the source data. DEMs have the advantage over satellite imagery that they record surface elevation directly rather than surface reflectance. Therefore DEMs can be artificially illuminated from numerous directions allowing the landscape to be viewed from multiple angles (Smith, 2003). This also circumvents the difficultly of obtaining low solar elevation (winter) satellite imagery that is also cloud free (Ford, 1984). Because

DEMs document the full three-dimensions of the land surface they are increasingly used in addition to, or instead of, satellite imagery for geomorphological mapping (Clark and Meehan, 2001; Dunlop and Clark, 2006). In addition, with a DEM it is possible to exaggerate the vertical scale so that landforms of shallow height can be seen more clearly in flat areas.

Shaded relief images are the most common way of visualising DEM data (Smith and Clark, 2005). Artificial illumination of the DEM surface produces a shaded relief image of the landscape that replicates the shadows seen in nature, given the same combination of solar elevation and sun position. The clarity of features will vary depending on the relationship between solar azimuth and the orientation of the feature; landforms perpendicular to the illumination direction will be highlighted by the resultant shadows whereas landforms that are parallel to the illumination will be obscured (Clark and Meehan, 2001) (figure 4.2). Lidmar-Bergström et al. (1991) assessed the use of relief maps to recognise and map glacial landforms and recommended illumination from two directions to reduce the inherent bias of solar illumination from one direction. A detailed discussion of the problems of azimuth biasing and solutions for mapping are discussed in Smith and Clark (2005). It is essential to use multiple images with different solar positions to obtain an accurate map of the landscape. Mapping from an overhead illuminated DEM is recommended for bias free mapping of landform shape (Smith, 2003). In an ‘overhead’ illuminated image the solar elevation is placed at 90º to the horizontal. However, this ‘overhead’ image is less familiar to an untrained eye and the absence of shadows can make it difficult to identify features. Therefore in this thesis the method of Clark and Meehan (2001) was employed, i.e. a minimum of two orthogonal visualisations and one ‘overhead’ image were generated for mapping.

The main limitation of DEMs and satellite imagery for geomorphological mapping is that they do not provide information on the internal composition of landforms. The critical assumption is that landforms can be identified and classified on the basis of their morphology alone. It was not feasible within the scope of this PhD to conduct sedimentological investigations of each mapped landform to confirm their genesis. In the majority of cases landforms do display a characteristic shape and in the majority of cases morphology has not been significantly altered by post-glacial processes.

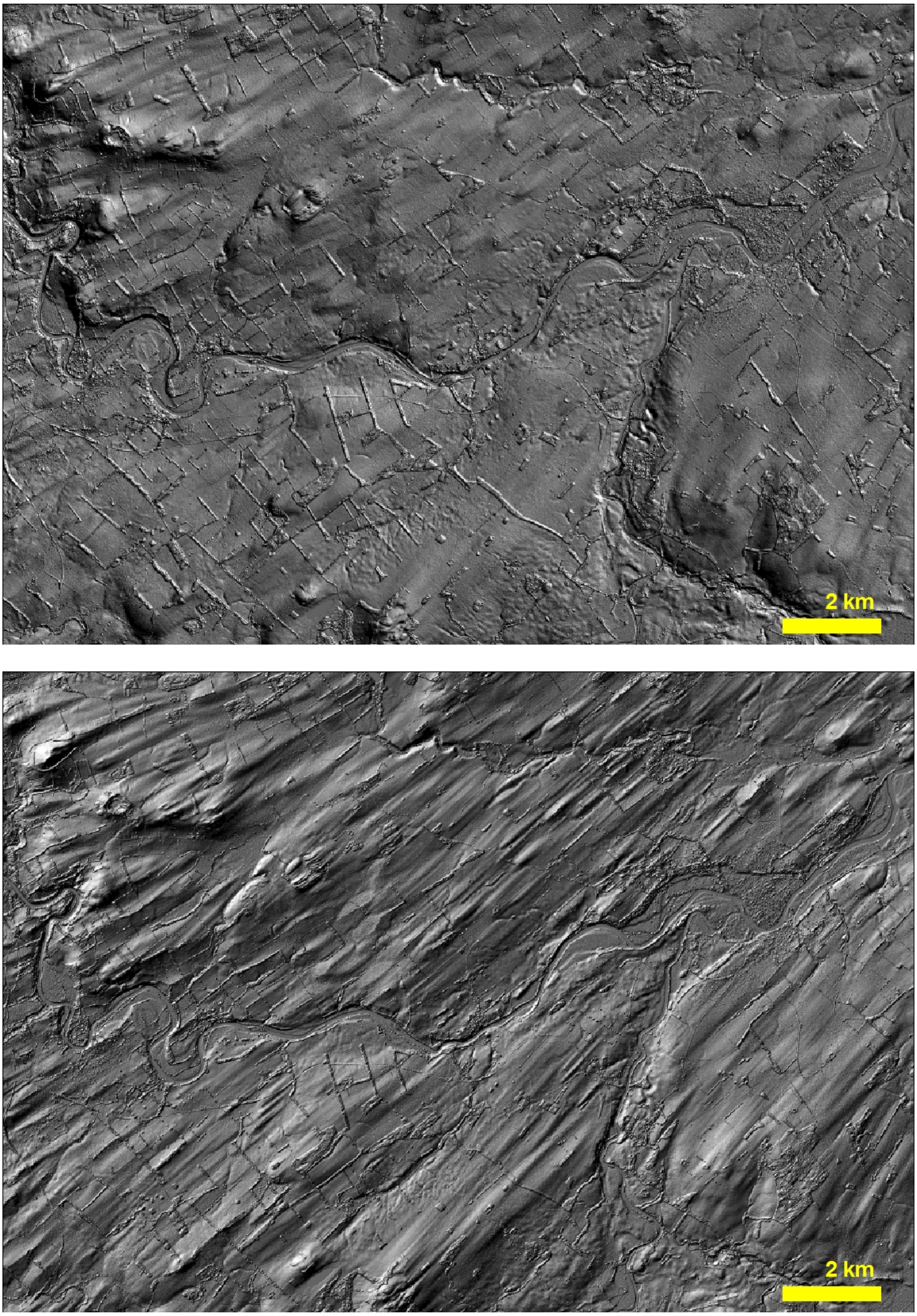


Figure 4.2 Demonstration of the azimuth bias problem. Relief-shaded visualisations of part of the Tweed basin close to Kelso and the junction between the River Tweed and River Teviot with orthogonal solar azimuth directions. In the upper image the area is illuminated from the NE in the lower image from the NW. The SW-NE trending lineations are clearly visible in the NW image but virtually absent in the NE image. Mapping conducted using only one of the two images would result in wildly different drumlin patterns. Both images have a vertical exaggeration of 4X. NEXTMap Britain data from Intermap Technologies, obtained under licence from British Geological Survey ©NERC.

4.3 Mapping methods

A systematic procedure for mapping the whole country was developed by conducting pilot experiments over two areas (figure 4.3). The Wensleydale pilot was used to examine the difference in mapping from DEMs of different horizontal resolution (50 m vs. 5 m). The Solway Firth pilot area was chosen to include as many different landform types as possible. Both pilots were designed to determine the level of detail for mapping that would be practicable in the time available and provide the most palaeoglaciological information. They also provided the opportunity to practice mapping a range of different landform types and determine how each should and can be mapped. To ensure geometric consistency all mapping and datasets were projected as British National Grid. Unless stated otherwise all maps and figures in this thesis are presented on British National Grid.

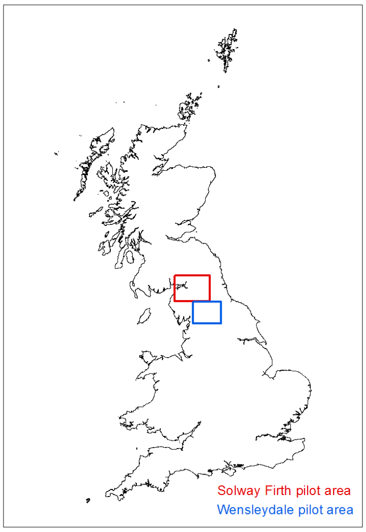


Figure 4.3 Pilot locations.

4.3.1 Data sources for mapping

The primary data source for mapping glacial landforms was the NEXTMap Britain elevation dataset for England, Wales and Scotland, produced by Intermap Technologies in 2003 (figure 4.4). This dataset was purchased in 2004 by the British Geological Survey (BGS) on behalf of the Natural Environmental Research Council (NERC). The elevation data was derived from airborne Inferometric Synthetic Aperture Radar (IfSAR or InSAR) measurements collected from a Lear jet flying at night in 2002 and 2003. For a description of the principles of InSAR see Mather (2004: 250-259). The NEXTMap data has a ground resolution (grid size) of 5 m and a vertical accuracy of 0.5 m, a major improvement on other national datasets (Smith et al., 2006). The dataset includes a Digital Surface Model (DSM) and a 'bare earth' Digital Terrain Model (DTM) which has had vegetation and urban features 'removed'. This is achieved by a combined process of an automatic algorithm followed by a manual check. Initially, the DTM was used for mapping, as in the pilot studies, as it was thought that this would be most suitable for mapping geomorphology since urban centres and forested areas would not pose a distraction to the eye. However, on comparison of the two datasets and discussion with colleagues using the NEXTMap data for hydrological modelling, it was observed that there was a significant degree of smoothing of topography in the DTM, masking subtle features (figure 4.5). After this realisation, mapping progressed using the DSM and areas already mapped using the DTM were re-examined with the DSM. Large urban centres continue to be an obstacle, as the overall effect of the rough urban landscape is to mask the underlying geomorphology. This is often very inconvenient, for example the city of Glasgow irritatingly lies directly above a major drumlin field, and so it is difficult to map the geometry of the drumlins precisely (figure 4.5). Overall, the NEXTMap Britain dataset is of very high quality with few of the artefacts and errors seen in other elevation datasets. A discussion of the accuracy of the data is given by Dowman et al. (2003). The scale limit for the NEXTMap data is around 1: 6,000; from here the data starts to become pixelated and unsuitable for mapping (figure 4.6).

Winter cloudless Landsat TM images, available from BGS for the whole of Britain, were used to supplement the DEM (figure 4.7). This data has a spatial resolution of 30 m and was mainly used to confirm areas of surface bedrock. The NEXTMap Britain DEM that was available at the time of mapping did not include the Isle of Man. Mapping on the Isle of Man therefore was based on the Landsat TM imagery and the lower resolution Ordnance Survey (OS) LANDFORM PANORAMA DEM. This DEM has a grid size of 50 m and was derived from OS contour data.

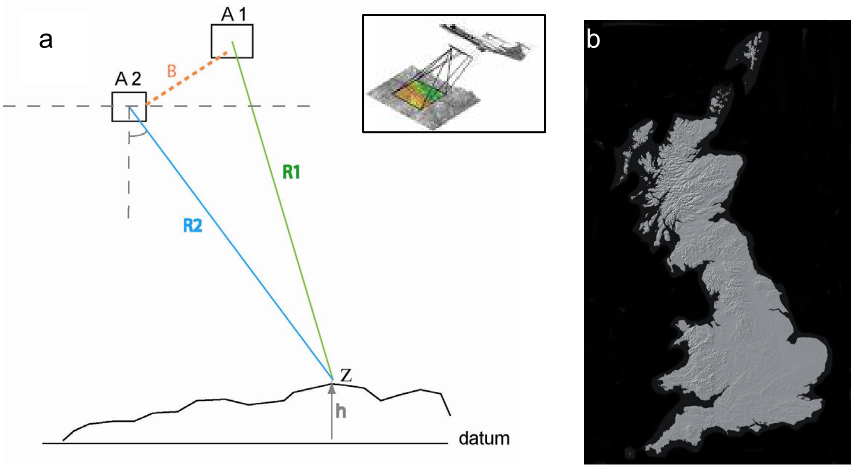


Figure 4.4 NEXTMap DEM generation and coverage. a) Principles of InSAR. In the case of the NEXTMap data, two antennae (A1 and A2) are mounted on the same platform (Lear Jet), the phase difference between the return radar signal received by the two antennae (R1 and R2) from site Z is a function of the elevation (h) above a datum at site Z and the distance between the two antennae (B); b) coverage of NEXTMap Britain dataset, at the time of mapping the Isle of Man was not covered by the data

For the pilot mapping in Wensleydale, comparison was made between the results of mapping from the NEXTMap dataset with that from a lower resolution DEM. This area, approximately 4,000 km^2, contains some classic examples of glacial geomorphology, containing the valleys of Wensleydale, Swaledale. Ribblesdale, Eden, Lune and Wharfedale. Figures 4.8a and 4.8b show drumlin mapping from the 50 m OS DEM and 5 m NEXTMap DEM respectively. As expected, mapping from the lower resolution OS DEM was more difficult and with fewer landforms identified. Often a general lineament grain in the landscape could be seen, but this disappeared when zooming in to map the break of slope. This could lead to direction and shape errors as there is a temptation to impose a traditional ovoid shape on drumlins even when the break-of-slope cannot be clearly seen. The shape, size, and orientation of drumlins were much more readily observed on the NEXTMap data. This information is vital to identifying distinct drumlin populations and coherent flowsets (see chapter 6). A 50% increase in the number of mapped drumlins was achieved using the NEXTMap data (figure 4.8).

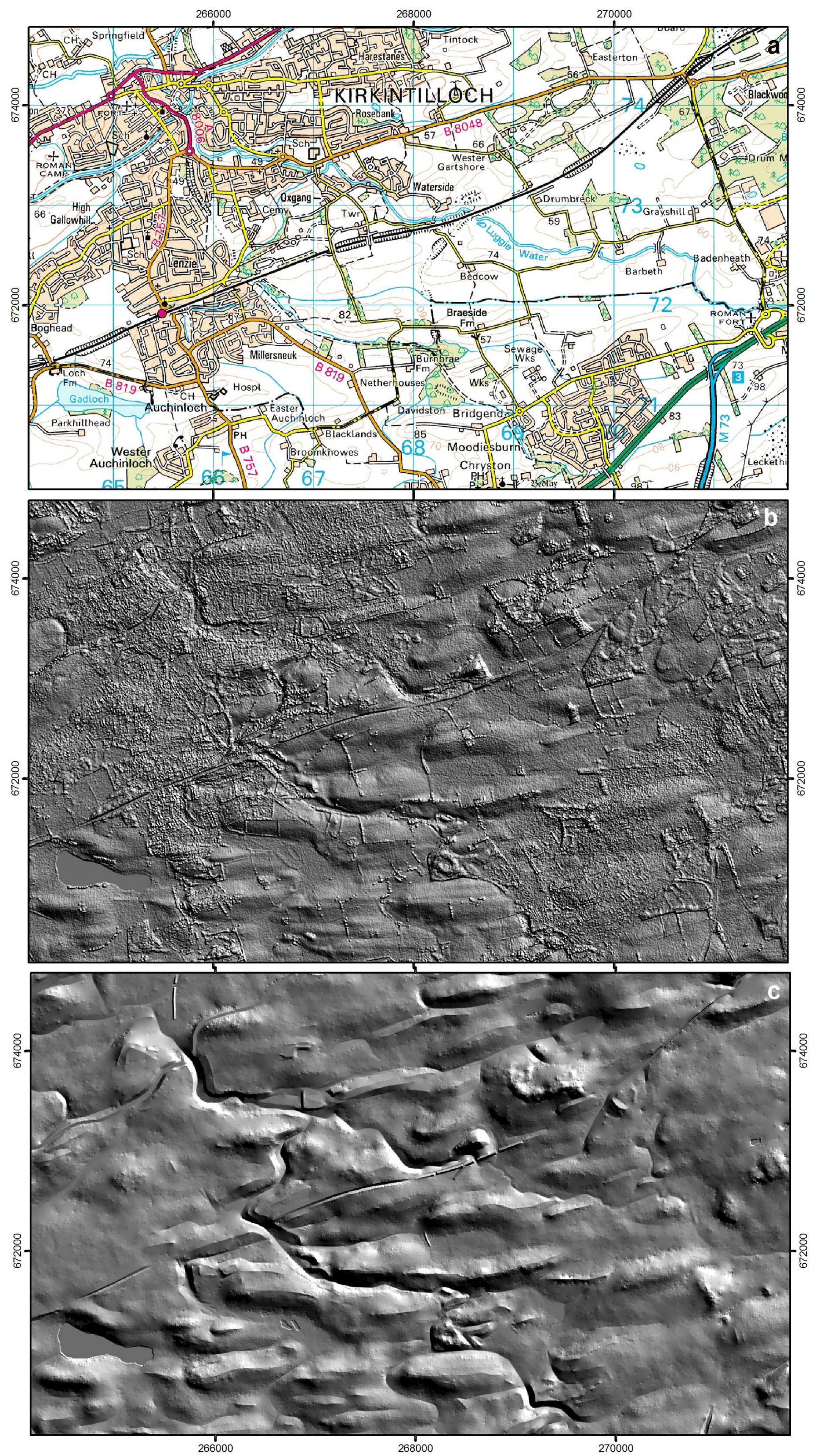


Figure 4.5 Appearance of urban area on digital surface model (DSM) and digital terrain model (DTM) a) 1:50,000 OS map of Kirkintilloch north of Glasgow, b) NW relief-shaded image of DSM, c) NW relief-shaded image of DTM. The algorithm used to remove vegetation and cultural features to produce the DTM appears to have a smoothing effect on the data and a hint of vegetation and cultural features remain. The railway line is clearly seen on the DTM running broadly W-E over the area. Drumlins in the south of the image are clearer on the DSM. Grid spacing is 20 km, Ordnance Survey co-ordinates. NEXTMap Britain data from Intermap Technologies, obtained under licence from British Geological Survey ©NERC. Ordnance Survey data ©OS copyright/database right. An Ordnance Survey/EDINA supplied service.

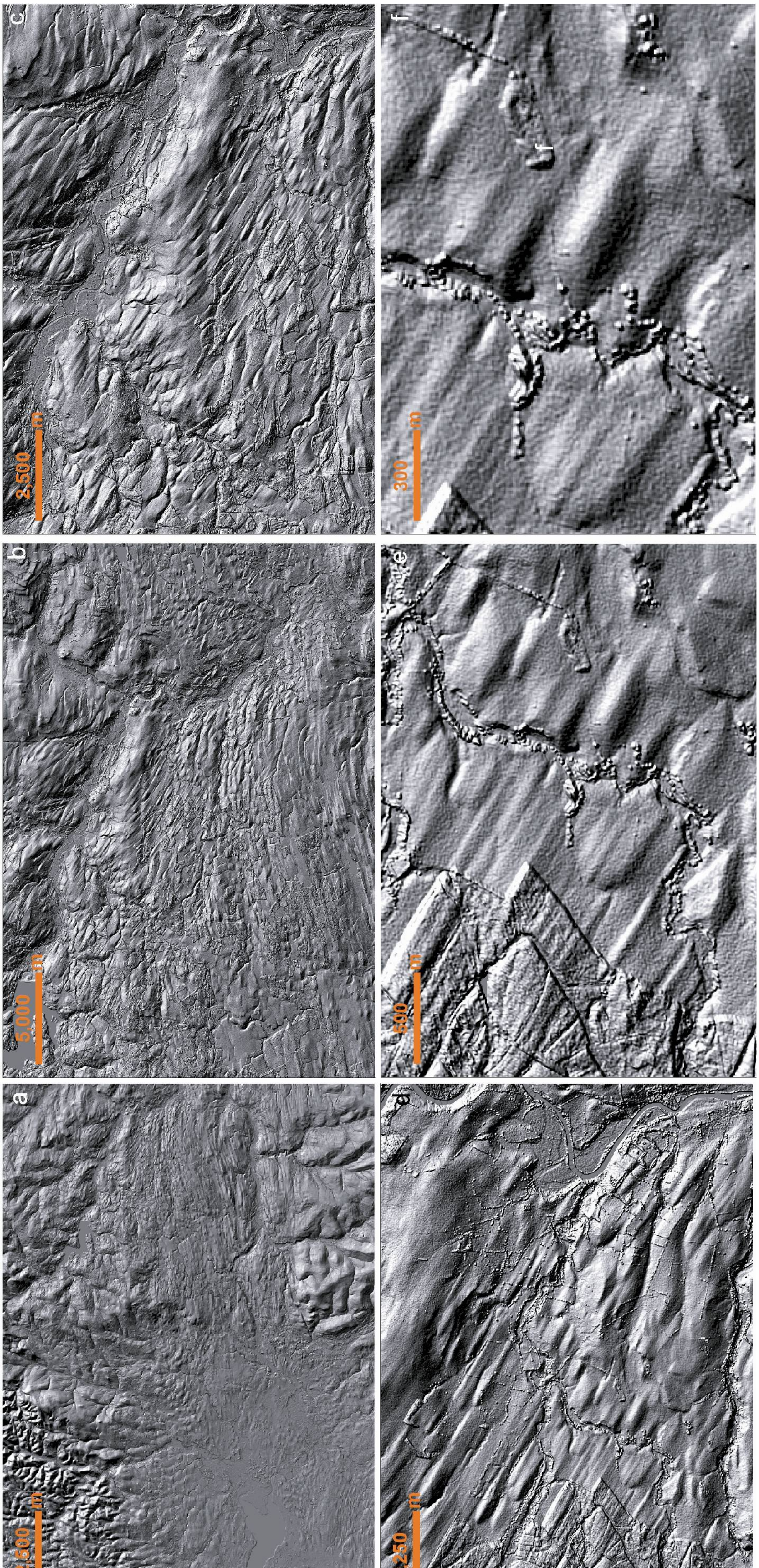


Figure 4.6 Relief-shaded visualisations of the NEXTMap DSM from Solway and the Tyne Gap viewed at different scales (landscape to individual drumlin) a) 1:250,000; b) 1:100,000; c) 1:50,000; d) 1:25,000; e) 1:10,000; and f) 1:6,000 (scales relate to image viewed on a 19" computer screen). After 1:6,000 the data becomes pixelated. Mapping was generally conducted at the 1:10,000 and 1:6,000 scales for precise delineation of landform margins and crest-lines. Scrutiny of the landscape at 1:25,000 scale and smaller facilitated interpretation and identification of landforms by context.

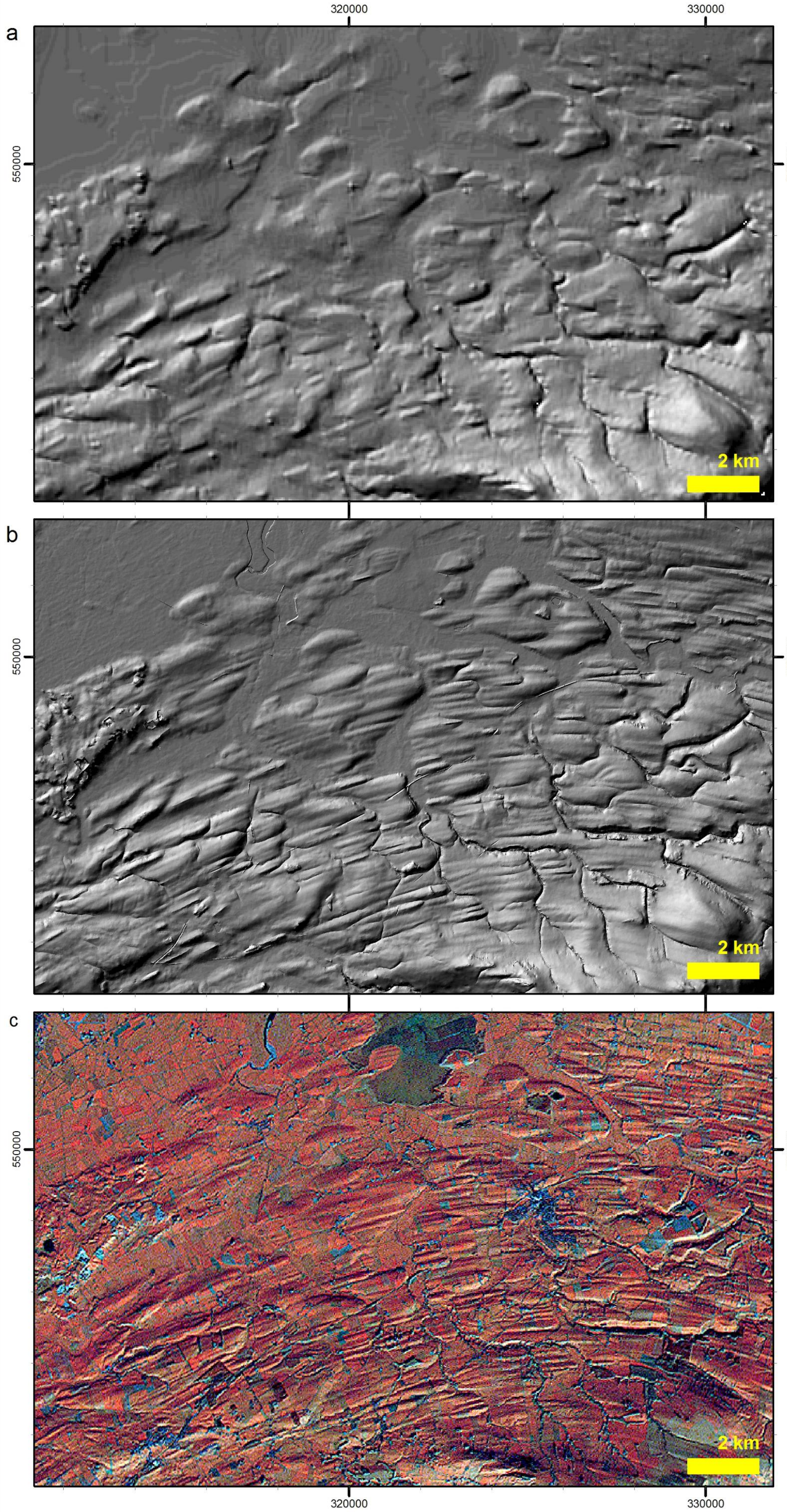


Figure 4.7 Example and comparison of resolution of data sources used for mapping for part of the Solway lowlands drumlin field west of Carlisle a) OS PANORAMA LANDFORM DEM, 50 m resolution derived from 10 m contour data; b) NEXTMap DTM, 5 m resolution derived from InSAR measurements; and c) Cloud free Landsat TM colour composite image, 30 m resolution. Primary data sources used for mapping is NEXTMap DEM, supplemented by Landsat TM. NEXTMap Britain data from Intermap Technologies, obtained under licence from British Geological Survey ©NERC.

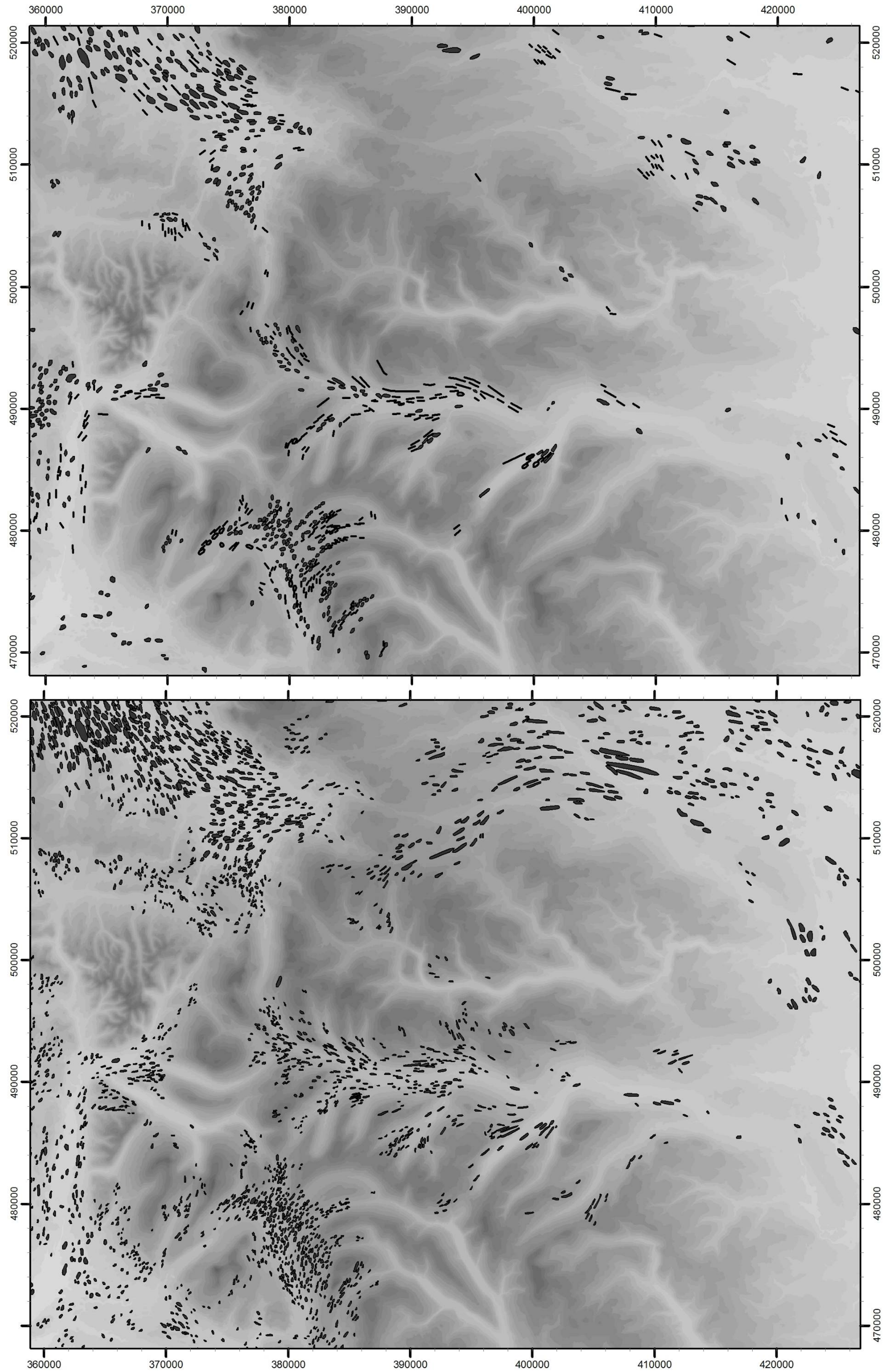


Figure 4.8 Drumlin maps for the Wensleydale pilot derived from (a) 50 m grid resolution OS PANORAMA LANDFORM DEM and (b) 5 m resolution NEXTMap DTM. It was much easier to precisely map drumlin outline by break-of-slope using the higher resolution data. In some cases although lineations could be identified on the OS DEM it was only possible to map crest lines. There was a 50 % increase in the number of mapped drumlins in this area by improving the resolution of the DEM data.

4.3.2 Mapping procedure

Processed visualisations of the NEXTMap data, supplemented by winter Landsat imagery, were used to conduct countrywide mapping of five principal landform types: subglacial bedforms (drumlins and ribbed moraine), moraines, eskers, meltwater channels (lateral and subglacial) and streamlined bedrock. These landform types have a clear morphological expression and have been used successfully in inversion models of other palaeo-ice sheets (Boulton et al., 2001; Clark and Meehan, 2001; Clarhall and Jansson, 2003). Table 4.1 describes the characteristics used to identify landforms on the DEM visualisations. Figures 4.9, 4.10 and 4.11 show how targeted landform types appear on visualisations of the NEXTMap data.

Table 4.1 Mapped landform types and identification characteristics. Landform types were selected by the requirements of the glacial inversion model: ice directed landforms (glacial lineations, ribbed moraine, and subglacial meltwater channels) and ice marginal landforms (eskers, lateral meltwater channels, and moraines). The Glacial Map of Canada (Prest et al., 1968) was used as a template to determine choice of mapped landform types and style of mapping. Definitions after Hättestrand and Clark (2006b) and De Angelis (2007b).

Landform type	Identification characteristics	Mapping style
Drumlins	Streamlined hill with long axis aligned in direction of ice flow. Commonly composed of till with a stoss and lee end. Generally occur in groups or fields. Direction of ice movement determined by the position of stoss end. Asymmetric plan form. Drumlins may be dissected or partially eroded by postglacial fluvial erosion.	Break of slope outline of individual landforms
Crag and tails	Streamlined till tapers away from bedrock bump or crag in direction of ice flow. May be dissected or partially eroded by postglacial fluvial erosion. Layer also contains larger scale drift tails that follow bedrock escarpments as exemplified in figures 4.9 and 4.20.	Crestline of individual features
Mega-scale glacial lineations (MSGL)	Highly attenuated streamlined landforms. Distinct from drumlins as have high elongation ratios and more symmetrical rectilinear plan in opposition to the classic 'basket of eggs' shape of drumlins. Generally long and may be dissected or partially eroded by postglacial fluvial erosion.	Crestline of individual features
Ribbed (rogen) moraine	Groups of regularly spaced ridges composed of glacial sediments. Formed transverse to ice flow. Often superimposed by drumlins. Ridges maybe dissected by post-glacial fluvial channels.	Break of slope outline of individual ridges
Eskers	Ridges composed of glaciofluvial sediments. Generally have very sharp crest and sides. Cross profile has inverted V shape. Commonly mildly sinuous and form anatomising networks with tributaries that join main ridge at acute angles.	Crestline of individual ridges
Meltwater channels	Dry and/or misfit channels. Channels are distinct from fluvial channels as have wide flat bottoms and steep sides. Size of channel incongruent with modern catchment size or catchment may be absent Subglacial type may form networks and have up and down long profiles. Lateral types occur as flights 'hanging' on valley sides running oblique to contours. No distinction made in terms of size of channel. Likely that many small channels exist below the resolution of the DEM.	Central axis of individual channels
Moraines	Individual ridges with a defined crest or spreads of glacial drift or till. May have arcuate plan shape and form at the mouths of valleys. Surface roughness or irregular 'texture' on DEM (figure 4.10c). Oblique area visualisation often useful to aid identification. Steep ice contact slope on at least one side of the feature. No distinction is made between ice contact features composed of glaciofluvial or glacial drift deposits. Spreads can have irregular, flat or multi-crested upper surface. May also include hummocky moraine. Use of distribution of other features and context to pin point likely locations for moraines, e.g. abrupt ends in drumlin patterns, vegetation changes in satellite imagery, and disrupted river patterns. Layer contains all types of constructional ice contact landform.	Large moraines: break of slope outline of individual features. Ridges and small moraines: crestline of individual ridges.
Streamlined bedrock	Exposed bedrock surfaces streamlined by ice flow. Includes 'rock' drumlins and roche moutonées.	Summary line in same orientation of suite of features
Landscape grain	Drift material that appears streamlined but impossible to indentify individual drumlins. Speculate that these are areas of fluted terrain and landforms below the resolution of the DEM.	Summary line with same orientation as grain

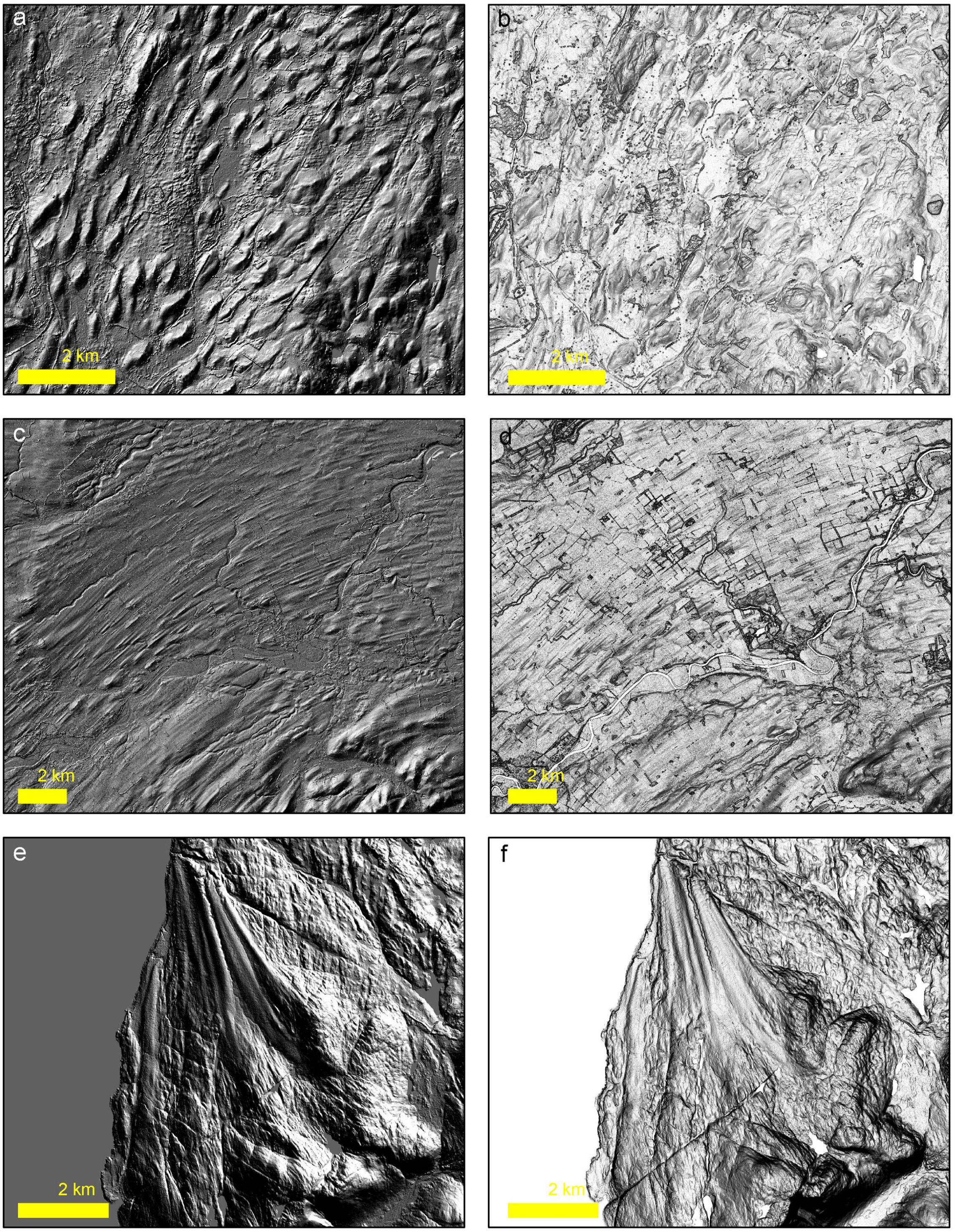


Figure 4.9 Examples of how glacial landforms appear on the NEXTMap DSM data (lineations). a) NE relief-shaded visualisation of a drumlin field close to Barrow in Furness; b) overhead relief-shaded image of the same drumlin field close to Barrow in Furness; c) NE relief-shaded visualisation of mega-scale glacial lineations in the Tweed basin; d) overhead relief-shaded image of the same mega-scale glacial lineations in the Tweed basin; e) NW relief-shaded visualisation of streamlining in lee of bedrock bump (mapped as part of crag and tail layer) near Applecross, Torridon. Ice flow direction is SSE to NNW. Tails are dissected by meltwater channels at northern tip; f) overhead relief-shaded image of the same crag and tails near Applecross, Torridon. NEXTMap Britain data from Intermap Technologies, obtained under licence from British Geological Survey ©NERC.

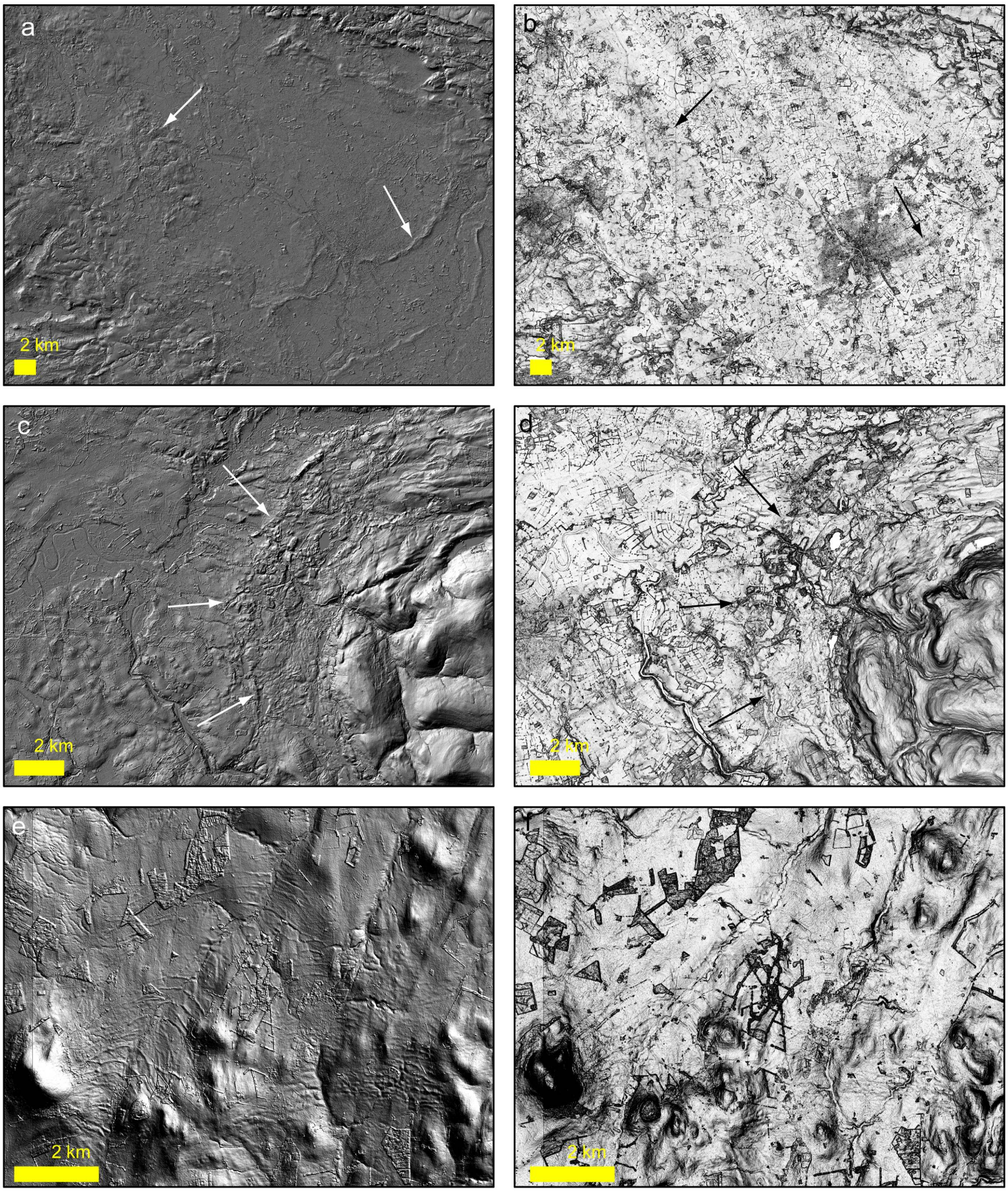


Figure 4.10 Examples of how glacial landforms appear on the NEXTMap DSM data (moraines). a) NE relief-shaded visualisation of moraines in the Vale of York, moraines are pinpointed by arrows; b) overhead relief-shaded image of same moraines. This area is relatively flat and therefore moraines are difficult to see on the overhead image alone, although clearly seen on the NE image; c) NE relief-shaded visualisation of kame-moraine at Brampton; d) overhead relief-shaded image of same area. Similarly to the above image (b) it is difficult to see the moraine on the over head image; e) NW relief-shaded visualisation of moraine ridges close to Aberchirder in NE Scotland; f) overhead relief-shaded image of same moraine ridges. These moraines can be seen on both the NE and overhead image. Moraine spreads (a and c) can be identified by difference in 'texture' of surface in moraine in relation to surrounding area. Moraines are more difficult than other landforms to identify using solely the overhead images (b, d, and f). Break-of-slope identification using the overhead image in flat areas (b) is difficult. NEXTMap Britain data from Intermap Technologies, obtained under licence from British Geological Survey ©NERC.

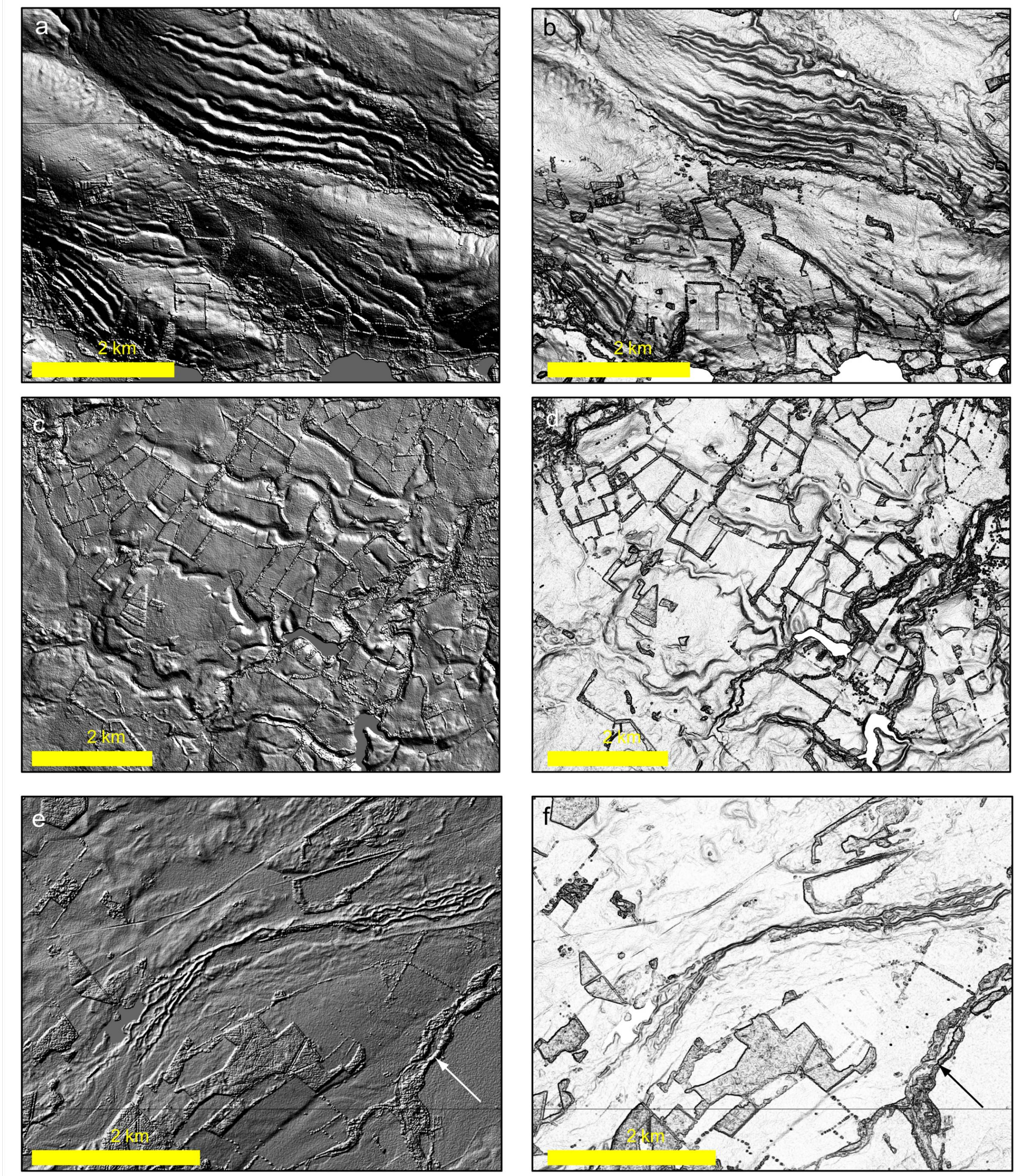


Figure 4.11 Examples of how glacial landforms appear on the NEXTMap DSM data (meltwater channels and eskers). a) NW relief-shaded visualisation of flight of lateral meltwater channels northwest of Blairgowrie; b) overhead relief-shaded image of the same lateral meltwater channels; c) NE relief-shaded visualisation of subglacial meltwater channels close to Edinburgh; d) overhead relief-shaded image of the same subglacial meltwater channels; e) NW relief-shaded visualisation of Flemington esker system, arrow highlights line of trees that could be confused with esker system, and adjacent patch of woodland clearly stands out because of the sharp rectilinear boundaries; f) overhead relief-shaded image of the same esker system. NEXTMap Britain data from Intermap Technologies, obtained under licence from British Geological Survey ©NERC.

Mapping was by manual on-screen digitising directly into GIS vector layers within the computer programs Erdas Imagine and ArcGIS. To reduce azimuth bias, a minimum of two orthogonal visualisations and one 'overhead' image were generated from the NEXTMap data (figure 4.12). Different contrast stretching was applied to improve landform detectability. Pilot mapping was used to experiment with and then determine the mapping style for each landform type. The second pilot area was adjacent to the first (Wensleydale) centred on Carlisle and the Solway Firth lowlands and covering an area of approximately 5,800 km^2. This area was chosen in order to include a range of glacial landforms and settings, including the flat coastal plain and upland areas of Northumberland and the Tyne Gap.

Figures 4.13 and 4.14 show examples of cartographic representation used for mapping each landform type. For all landform types except streamlined bedrock and 'grain', mapped features represent individual landforms. The resolution of the NEXTMap data enabled precise mapping of the break of slope outline of drumlins. Although break of slope mapping of drumlins is more time-consuming than crestline mapping it captures not only the orientation and length of each individual drumlin but also the overall size of the drumlin and a means for estimating the elongation ratio (length/width). Elongation ratio is a common statistic in studies of drumlin morphometry and useful in the organisation of flowset patterns (chapter 6). Direction of ice flow was determined by the orientation of drumlin stoss and lee ends.

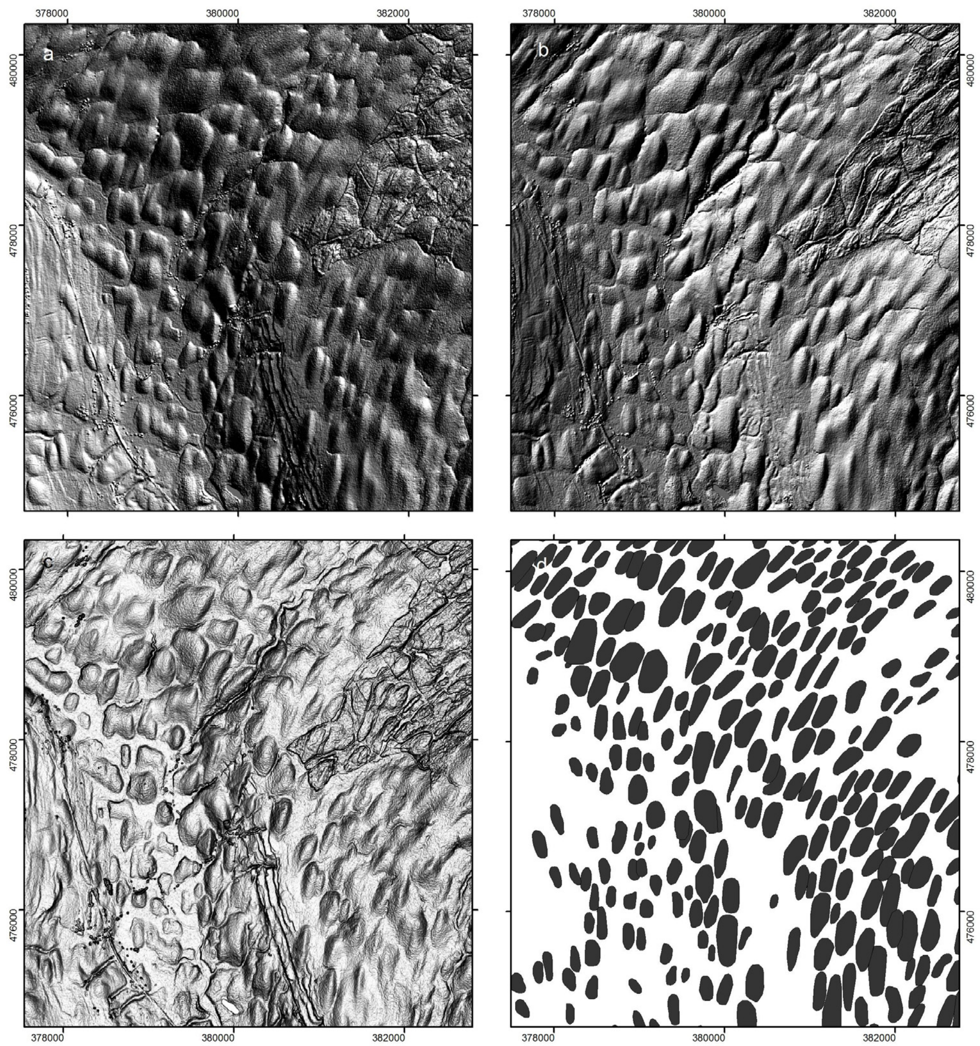


Figure 4.12 A minimum of three relief-shaded visualisations were used for mapping. a) Relief-shaded image of NEXTMap DSM illuminated from the NE, b) Relief-shaded image of NEXTMap DSM, illuminated from the NW, c) 'Overhead' relief-shaded image of the NEXTMap DSM, and d) mapped drumlin polygons. NEXTMap Britain data from Intermap Technologies, obtained under licence from British Geological Survey ©NERC.

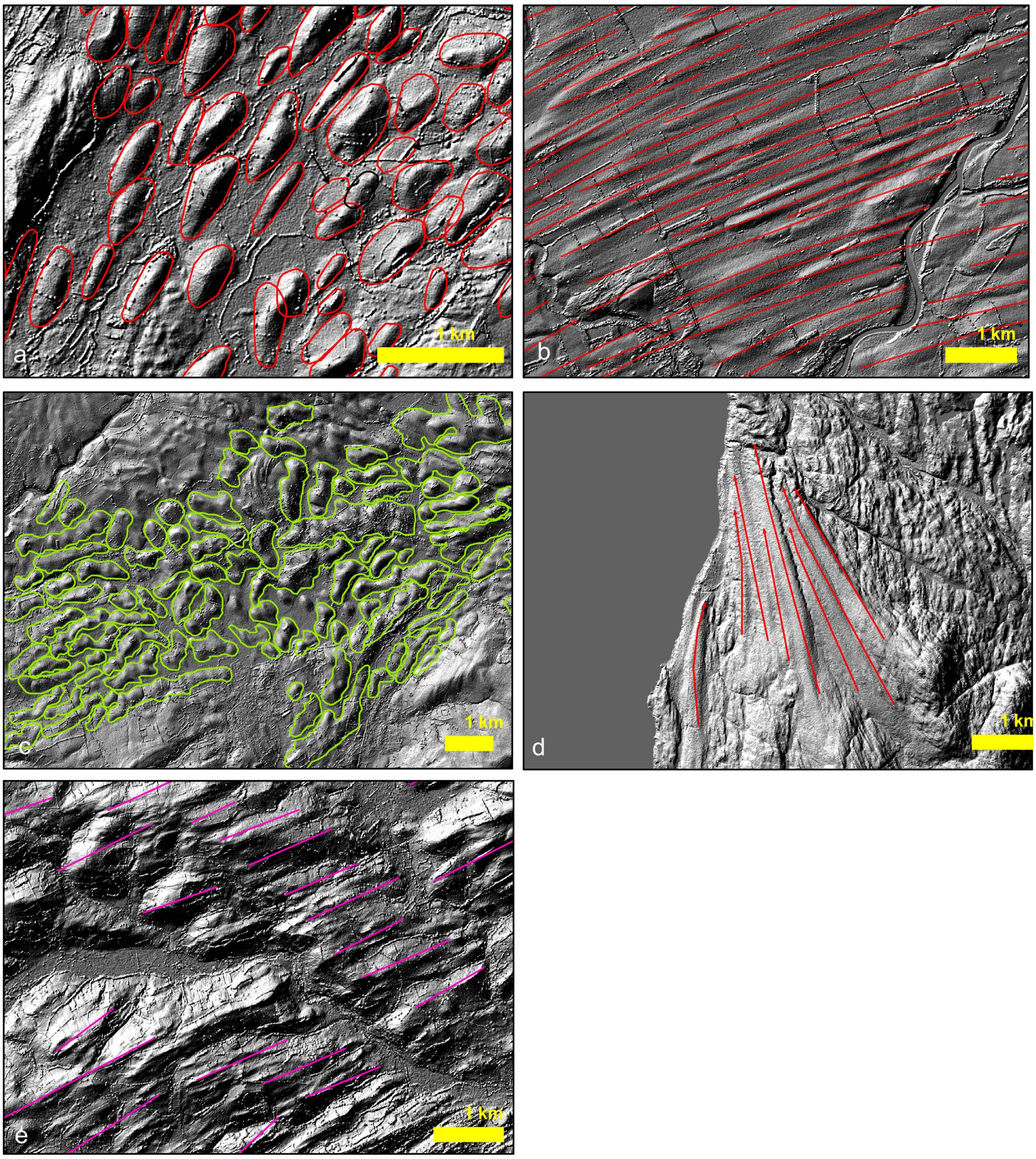


Figure 4.13 Examples of style of mapping used for each landform type (drumlins, MSGL, ribbed moraine, crag and tails, and streamlined bedrock). Map layers are shown superimposed on relief-shaded visualisations of DEM for illustration only. The outline of drumlins and ribbed moraine may not appear to coincide with the break-of-slope seen on the relief image. This is due to the azimuth bias problem of viewing from a single illumination direction discussed in the main text and exemplified in figure 4.2. Break-of-slope mapping was conducted using the overhead image and so is can accurate record of the drumlin shape. Drumlin outline mapped along break-of-slope at the drumlin base. In some areas post-glacial deposition will have raised the level of the ground in the inter-drumlin hollow above the base of the drumlin. In these cases the break of slope will therefore not match exactly the position of the drumlin base. It is assumed that in general postglacial deposition in inter-drumlin hollows will be equally distributed around the drumlin and so will only serve to reduce the overall size of the mapped drumlin and not affect drumlin shape. The only way to confirm the level of the true drumlin base would be to use ground penetrating radar or boreholes to examine the underlying stratigraphy (impractical for this volume of data). The overall advantages of mapping break of slope are thought to outweigh the minor anticipated errors due to post-glacial sedimentation. These drumlins are close to Barrow in Furness (a), arrow points to erroneous drumlins that are really inter-drumlin hollows. The actual drumlin is outlined in black. Positive and negative relief has a similar appearance on the overhead image leading to the mapping of inter-drumlin depressions. The majority of these drumlins were removed during repeat pass mapping. Mega-scale glacial lineations (MSGL) in the Tweed basin are mapped along crest-lines (b). Ribbed moraine ridges are mapped by break-of-slope. These ridges are north of the Forest of Bowland (c). Crag and tails mapped along crestline. These are close to Applecross (d). Streamlined bedrock mapping by lines in general direction of streamlining, representative of but not individual landforms (e). NEXTMap Britain data from Intermap Technologies, obtained under licence from British Geological Survey ©NERC.

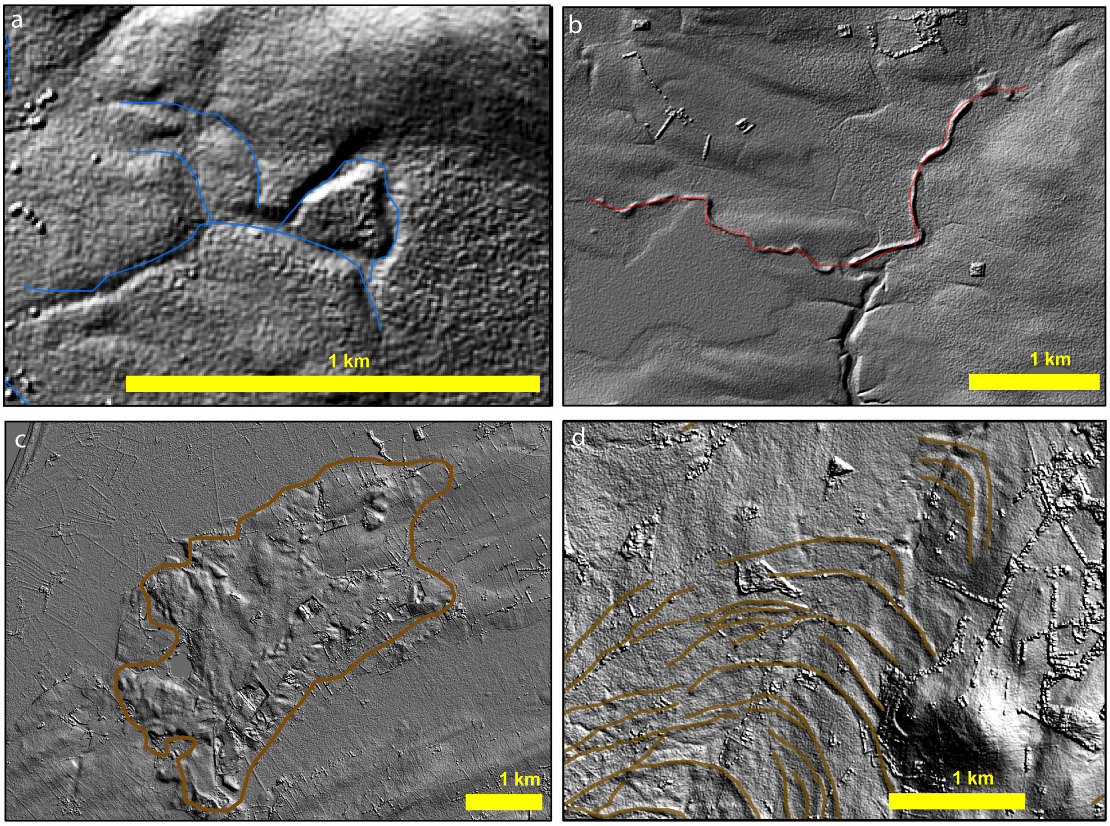


Figure 4.14 Examples of mapping style for different landform types. Meltwater channels in the Vale of Eden (a) mapped along centre-lines, eskers north of the Tweed (also mapped by Evans et al. (2006)) (b) and small moraines such as these ridges close to Aberchirder in NE Scotland (d) along crest-lines. Large 'moraines' such as this ice contact delta in the Solway lowlands by break-of-slope mapping (c). The 'moraine' layer contains all types of ice contact landform with no distinction between types, for example in this example the feature is an ice contact delta rather than a 'classic' moraine. Arguably the layer could be more precisely referred to as a layer of ice contact landforms. NEXTMap Britain data from Intermap Technologies, obtained under licence from British Geological Survey ©NERC.

Mapping progressed across the country by 100 x 100 km OS tile (figure 4.15), landform type by landform type. Thus repeated passes of the entire glaciated area were made, and mapping was reviewed at each stage. As mapping was conducted by a single observer the resulting maps are internally consistent in terms of bias due to skill and experience in landform identification. It was inevitable that mapping skill would improve during the period of mapping, therefore by mapping landform type by landform type, rather than area by area, differences in quality at the start and end of mapping were minimised. Bedforms were mapped first as these were deemed to be the most significant in terms of the reconstruction and with the clearest morphological expression. The scale of mapping varied with the size of landforms. The same area was mapped repeatedly at a range of scales so that all sizes of landforms were captured. Smaller scale viewing of the landscape was used for examining landscape contexts as an aide to landform identification and to identify large features. Precise mapping of break of slope was conducted at a scale of 1:20,000 to 1:10,000. This is comparable with field mapping which is generally conducted at a scale of 1:10,000 (Mitchell and Riley, 2006). The regional overview was often invaluable to identify landforms, followed by scrutiny at a larger scale for precise mapping of the landform outline. Care was taken to ensure consistency of cartographic representation over different spatial scales. Pilot mapping highlighted the need for an 'enigmatic' mapping layer for landforms that could not be identified. This layer served to speed up mapping by enabling delayed decisions about landform interpretation. Each landform layer was accompanied by a corresponding speculative layer for equivocal landforms, e.g. 'drumlin' and 'drumlin spec'. Features within these layers were often later incorporated into main layer after consultation with reference datasets (section 4.3.3).

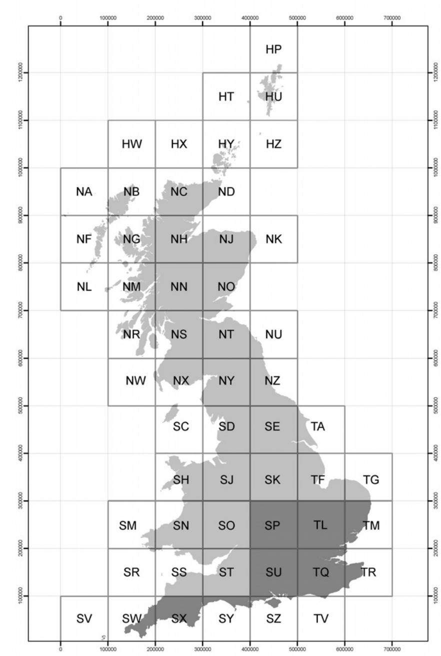


Figure 4.15 Ordnance Survey 100 km x 100 km tile codes. Mapping was conducted by systematic scrutiny of all tiles that lie within the Devensian drift limit (shaded in light grey). Mapping progressed tile by tile.

4.3.3 Ancillary datasets and mapping checks

Periodically mapping was reviewed in consultation with more experienced geomorphologists at the University of Sheffield and British Geological Survey. In the initial stages, when mapping skill was developing, mapped features were thoroughly inspected by supervisors and colleagues as each 100 x 100 km square was completed, and more frequently during the pilot mapping. During the final stages, mapping was shown to colleagues and visiting academics in a series of review workshops focussing on difficult areas and enigmatic landforms. In addition to these checks reference was made to a number of datasets.

4.3.3.1 BRITICE+ database and glacial map

The new mapping presented in this thesis is complementary to, and builds upon, previously published and predominantly field based mapping contained within the BRITICE database. As already stated, the BRITICE database was compiled from a number of sources spanning several decades and therefore contains inconsistencies in terms of mapping styles, scales and landform nomenclature. The BRITICE database has a census date of 2002. Mapping published subsequent to this date was scanned, geo-corrected, and digitised, in the same manner as used to compile the original glacial map (Clark et al., 2004b) and added to the original database to form BRITICE+. A list of added mapping sources is given in table 4.2 and the increase in coverage to the original glacial map shown in figure 4.16.

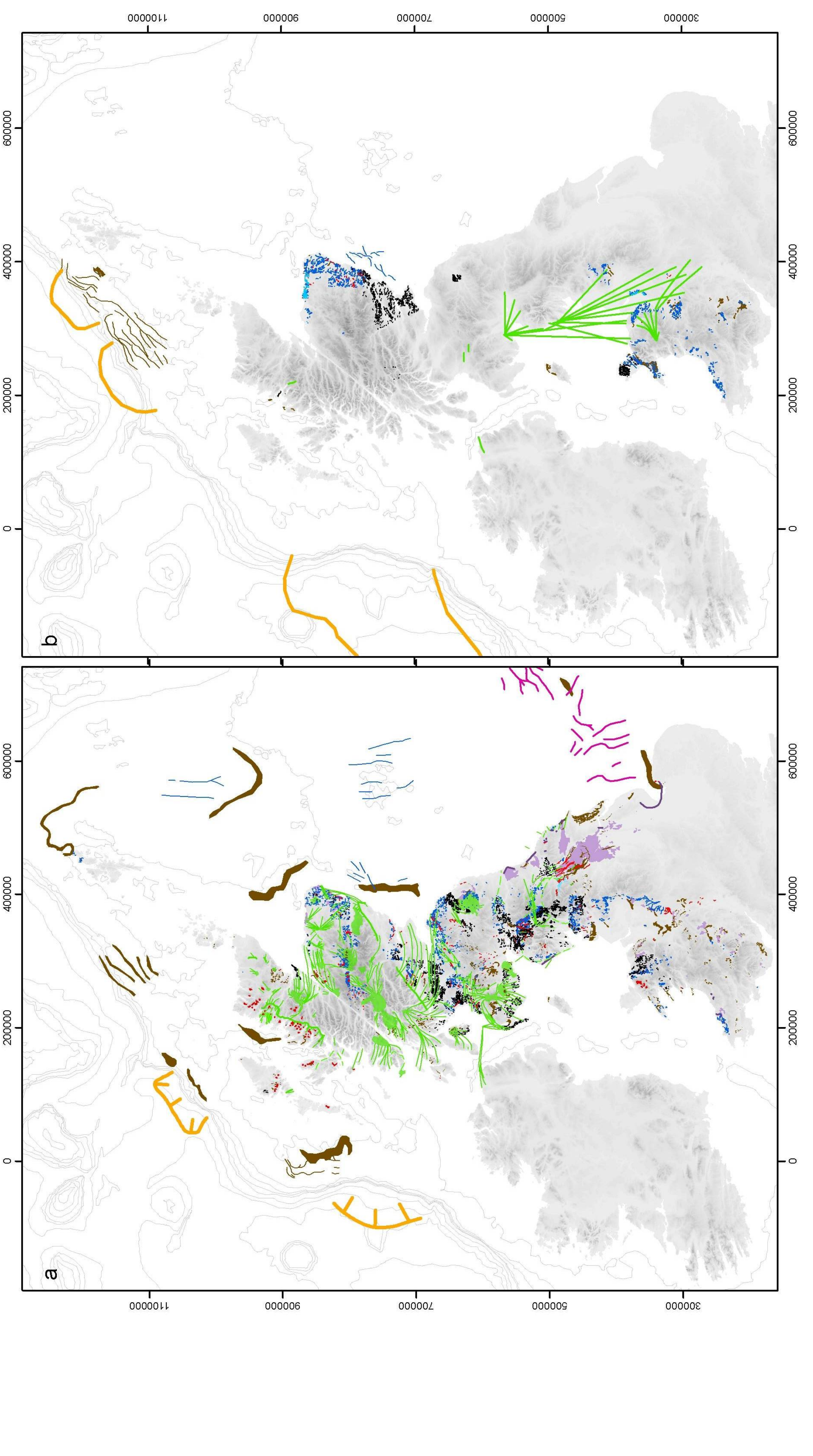


Figure 4.16 a) Original Glacial Map of Britain from BRITICE database of published information; b) Recently published results (2002- December 2007) added to original BRITICE database.

Table 4.2 Additions made to the BRITICE GIS database 2002-2008. The list is not exhaustive, especially since mapping published since January 2008 has not been included. Notable exclusions include lineament mapping in South Wales by Jansson and Glasser (2008) and new offshore moraine and meltwater channel mapping by Bradwell et al. (2008b).

Feature description	Location	Reference
Meltwater channels, moraines, moraine ridges, and eskers	NE Scotland coastal region	Merritt et al. (2003)
Meltwater channels	Afon Teifi	Etienne et al. (2006) and Glasser et al. (2004)
Moraines	Hebridean shelf	Stoker et al (2006)
Moraines	NW Shetland shelf	Davison (2004)
Meltwater channels	Mid Cheshire Ridge	Glasser and Sambrook-Smith (1999)
Moraines and drumlins	Summer Isles	Stoker et al. 2006
Drumlins and offshore meltwater channels	Strathmore	Golledge and Stoker (2006)
Drumlins	Tweed	Everest et al. (2005)
Moraine ridges, meltwater channels, and drumlins	Wye and Usk Valleys	Lewis and Thomas, (2005)
Lineations (mainly 'rock drumlins')	Wales	Janssen and Glasser (2004)
Moraine ridges, moraines, drumlins, and meltwater channels	Anglesey and Lleyn Peninsula	Thomas and Chiverell (2007)
Glaciolacustrine sediments, meltwater channels and moraines	Rossendale Forest	Crofts (2005)
Mega-scale glacial lineations	Minch	Stoker and Bradwell (2005)
Bedrock 'mega-grooves'	Assynt	Bradwell (2005)
Moraines and moraine ridges	NW continental shelf	Stoker et al. (2006)
Moraine ridges	Wester Ross	Everest and Kubik (2006)
Moraine ridge	Northern Scilly Isles	Hiemstra et al. (2006)
Moraine ridge, meltwater channels	NE Wales	Thomas (2005)
Meltwater channels and eskers	Cheshire-Shropshire Plain	Worsley (2005)
Erratic transport paths	Scottish, Lake District and Welsh erratics in Cheshire Plain	Mackintosh (1879)
Offshore mega-scale glacial lineations	Witch Ground	Graham et al. (2007)
Moraines	Herefordshire	Richards (2005)
Moraines	Isle of Man	Thomas et al. (2004)

During mapping the information in the BRITICE database was compared with the DEM visualisations. In the majority of cases the relevant features were identified on the DEM and in the correct geographic positions. However, some of the features in BRITICE have been incorrectly located due to poor geo-referencing in the original source (Clark et al., 2004b). All landforms contained within the BRITICE database were remapped using the DEM to ensure consistency of mapping style. BRITICE GIS layers were also used as a guide to aid identification of landforms. The BRITICE database was especially useful for providing examples of the appearance of moraines on the DEM when learning how to recognise moraines. The similarity of new mapping with detailed field mapping included in the BRITICE database formed a further check on the quality of mapping, demonstrating that mapping conducted remotely reproduced mapping conducted in the field (figure 4.17). Where features within the BRITICE database appeared absent from the DEM they were considered to relate to features below the resolution of the DEM. For example the moraines of Peacock (1984) on Lewis are difficult to pick out on the DEM. In a few cases BRITICE information was reinterpreted, for example drumlins were reinterpreted as ribbed moraine ridges in OS tile SE (figure 4.18).

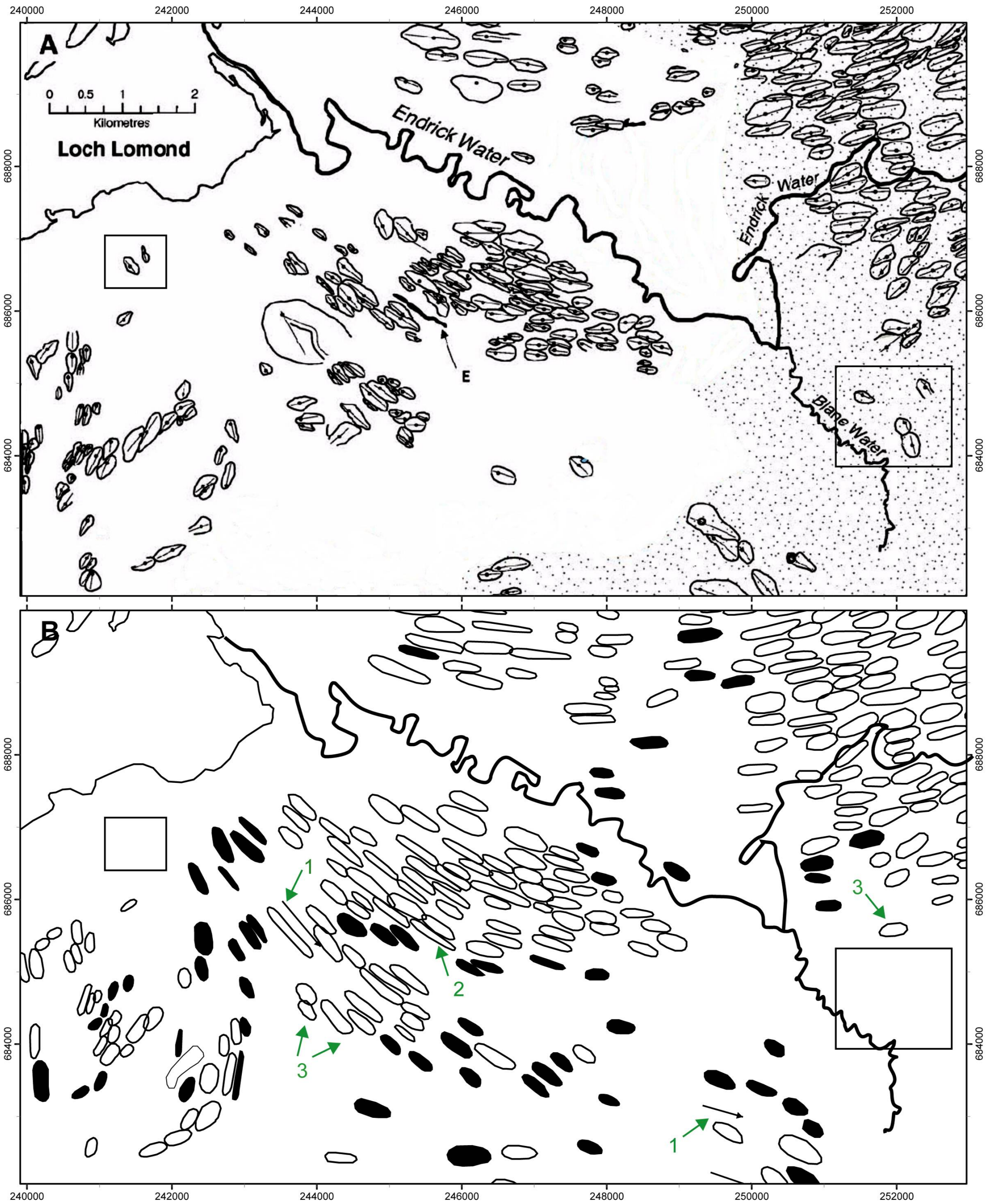


Figure 4.17 Comparison of new mapping from remote sensing imagery with mapping conducted in the field. New mapping shows good agreement with detailed field mapping in terms of overall distribution and pattern. A) Map figure reproduced from Smith et al. (2006). Field mapping originally conducted by J. Rose 1965-1970. Drumlin outlines, crest-lines and stoss ends are marked. Red boxes enclose drumlins that are missing from the new mapping, B) New mapping, shown in same colours as field map (A). Drumlins that concur with field mapping are shown in outline. Solid black polygons represent drumlins that are missing from the field map. Crag and tails are shown as black arrows in the direction of ice flow. Green arrows pinpoint locations where there is a difference in interpretation between field mapping and new mapping; 1 = drumlins reinterpreted as crag and tail features, 2 = In the field, mapped as esker, but as thin linear drumlin during mapping from DEM, 3 = groups of drumlins that have opposite orientation in field mapping.

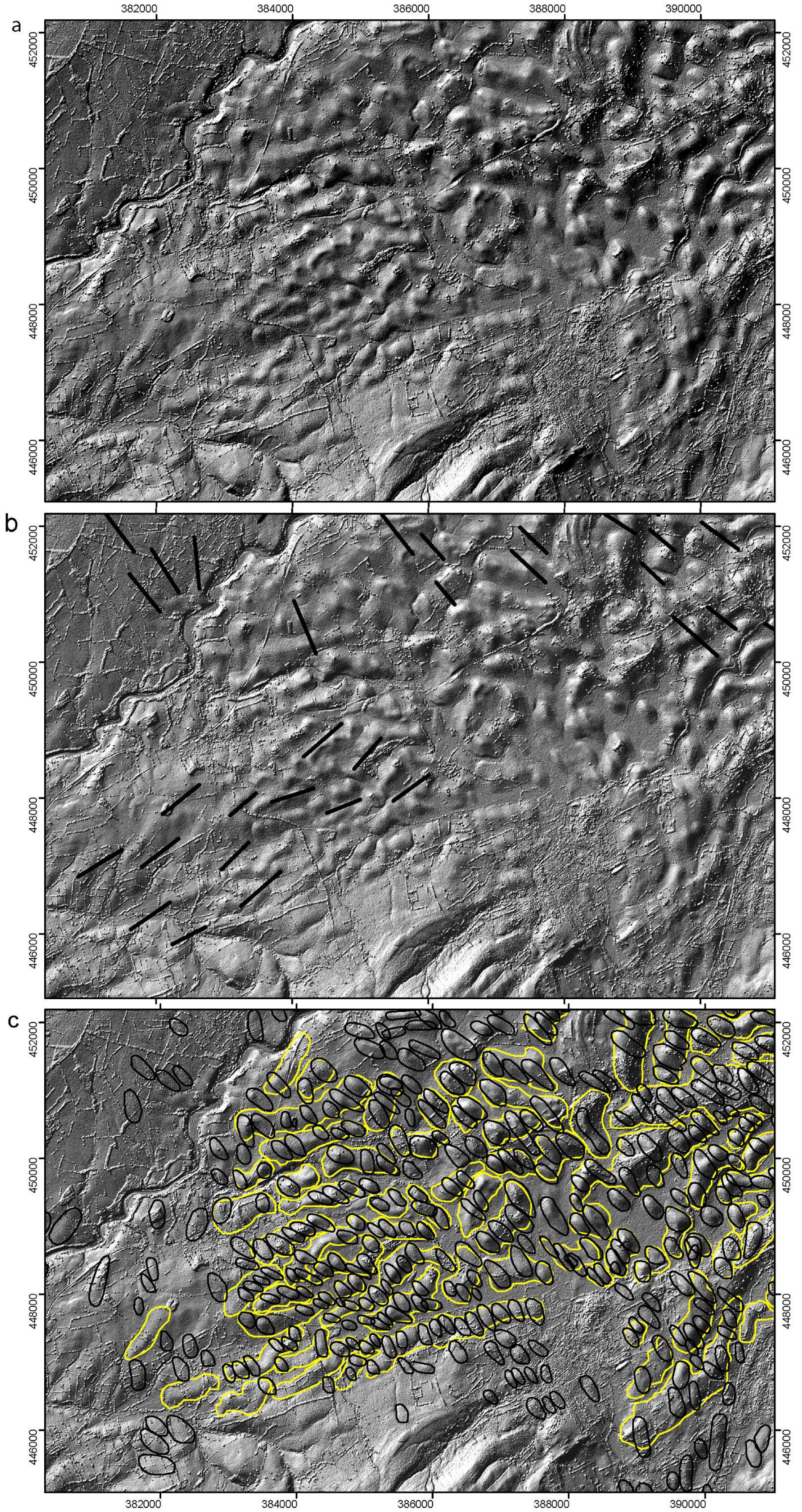


Figure 4.18 A rare example of conflict between new mapping and that contained within the BRITICE dataset for an area west of Skipton; a) NW relief-shaded image of the NEXTMap DSM, b) overlain by BRITICE drumlin layer (in this image drumlins are from Raistrick (1933)), c) overlain by new mapping. Drumlins in black, ribbed moraine ridges in yellow. The most striking difference between the two datasets is the dramatic increase in mapped bedforms for this area. Ribbed moraine ridges are superimposed by drumlins both indicating ice flow towards the SE strengthening evidence for NW-SE ice flow. South-westerly trending drumlins from the BRITICE database are reinterpreted as ribbed moraine ridges. NEXTMap Britain data from Intermap Technologies, obtained under licence from British Geological Survey ©NERC.

4.3.3.2 Reference datasets

British Geological Survey (BGS) bedrock, structural, and superficial (drift) maps, Ordnance Survey topographic maps, and aerial photography were employed to check mapping quality. There was no time available for fieldwork and therefore checks did not involve detailed surveying of the landscape or sedimentological analysis. Limited field visits to part of the Solway pilot mapping area at an early stage of mapping were conducted and served to confirm mapped landforms and gain an appreciation of the limitations of the remote sensing approach to mapping. Bedrock, structural and superficial geology maps were available in digital format under licence from BGS at a scale of 1:50,000 and were used for comparison with mapping layers within the GIS. Superficial geological maps provide information on the distribution of till, glaciofluvial sands and gravels, and bare rock and therefore improved confidence in landform classification, especially with respect to eskers and moraines. Bedrock and structural geology maps facilitated rejection of bedrock streamlining that is primarily a function of underlying geological structure and therefore an unreliable indicator of ice flow directions. BGS have developed a drift thickness model for Britain derived from the BGS borehole archive and DEM data (figure 4.19). This was a useful additional source of information, particularly to differentiate streamlined drift features, such as drumlins, from bedrock streamlining (figure 4.20). Differentiation of erosional and depostional landforms is important as they have different palaeoglaciological implications (table 3.1). Streamlined bedrock is likely to reflect the cumulative effect of erosion throughout the last glacial and previous glacial cycles. A key assumption in the interpretative framework employed in this thesis (Chapter 3) is that the pattern and distribution of drumlins is an accurate record of the ice flow direction at the time of drumlin formation, and therefore can be used to determine ice flow directions at a point in time. Streamlined bedrock may only record average flow pattern directions and is therefore treated as a second order record of ice flow patterns in the inversion scheme. As a further check and to supply extra detail in confusing areas, the British Geological Survey aerial photo archive was examined where necessary.

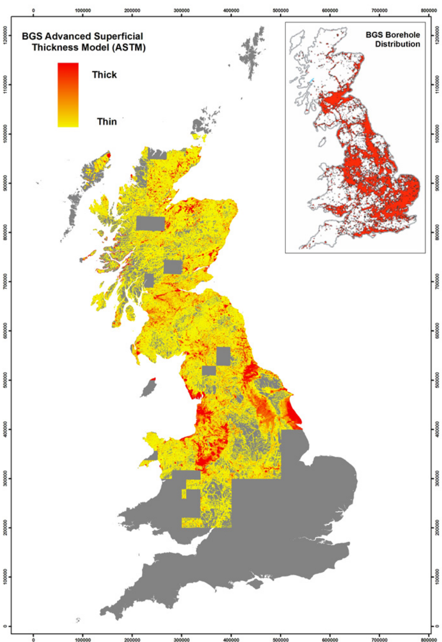


Figure 4.19 Coverage of British Geological Survey Advanced Superficial Thickness Model (ASTM). Inset map shows distribution of borehole archive from which the model is derived. Gaps in the ASTM coverage are due to gaps in the superficial geology mapping as not all BGS sheets have been mapped for superficial deposits at a scale of 1:50,000. Reproduced with the permission of the British Geological Survey ©NERC. All rights reserved.

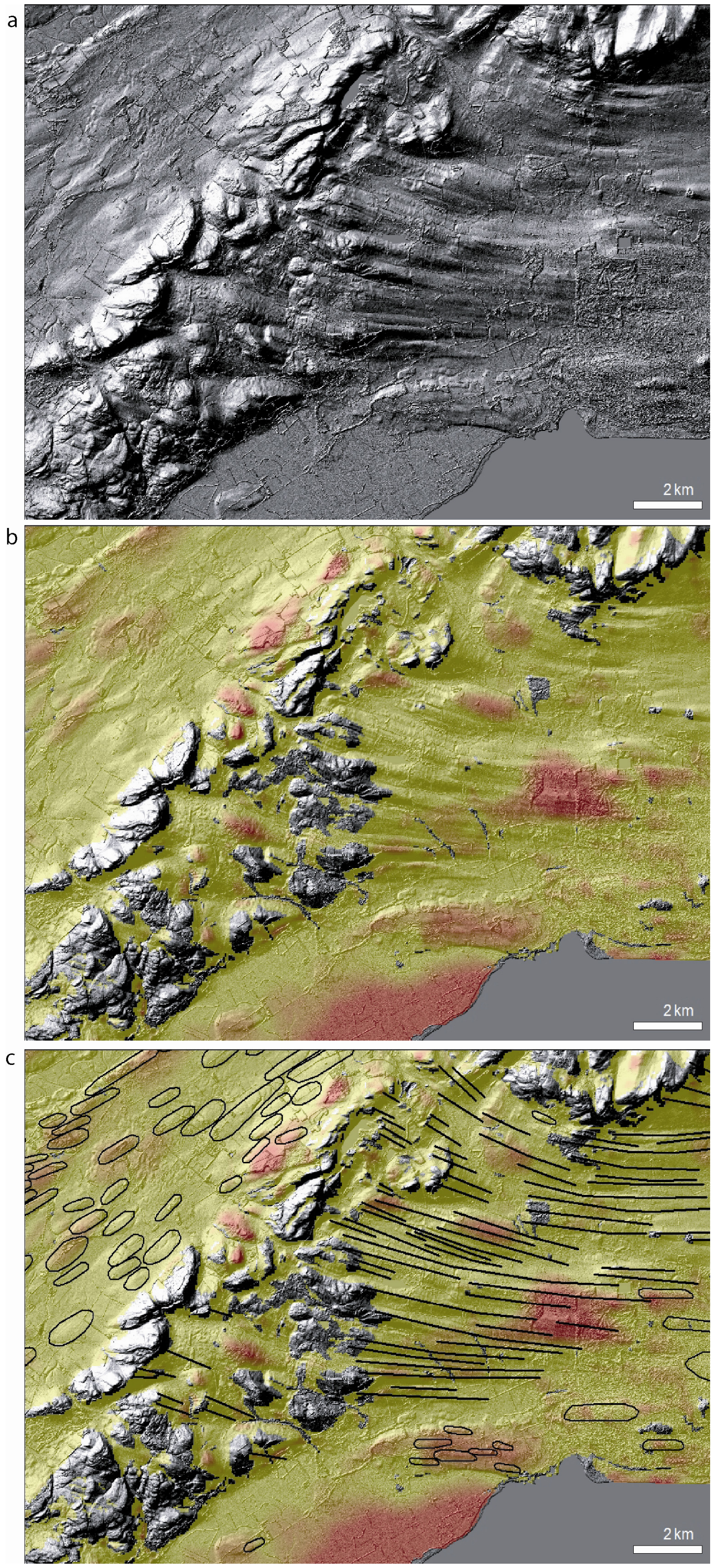


Figure 4.20 The British Geological Survey Advanced Superficial Thickness Model (ASTM) was employed to ensure that identified drumlins are composed of drift (area north of the Firth of Forth): a) Relief-shaded image of NEXTMap DSM. Visualised from the NW with 4X vertical exaggeration; b) relief-shaded image overlain by semitransparent ASTM surface viewed as a red-yellow choropleth map where red is greatest distance to rock-head or thickest layer of superficial sediments. 'Holes' in the ASTM surface show area where bedrock is exposed or covered by superficial material less than 1 m thick; c) Mapped drumlins (polygons) and large scale streamlining associated with bedrock bump (groove ploughs) mapped within the crag and tails layer (lines) are shown in black. ASTM data is reproduced with the permission of the British Geological Survey ©NERC. NEXTMap Britain data from Intermap Technologies, obtained under licence from British Geological Survey ©NERC.

Topographic Ordnance Survey (OS) maps which are available in digital format at a scale of 1:50,000, from OS Digimap via EDINA, were used to identify areas of forest and confirm locations of urban areas which often have a remaining expression in the DTM, and are present in the DSM (figure 4.5, 4.21 and 4.22). In some cases the names of places also confirmed landform identification. The blue line network of fluvial drainage marked on OS maps was used to check meltwater channel mapping (figure 4.21).

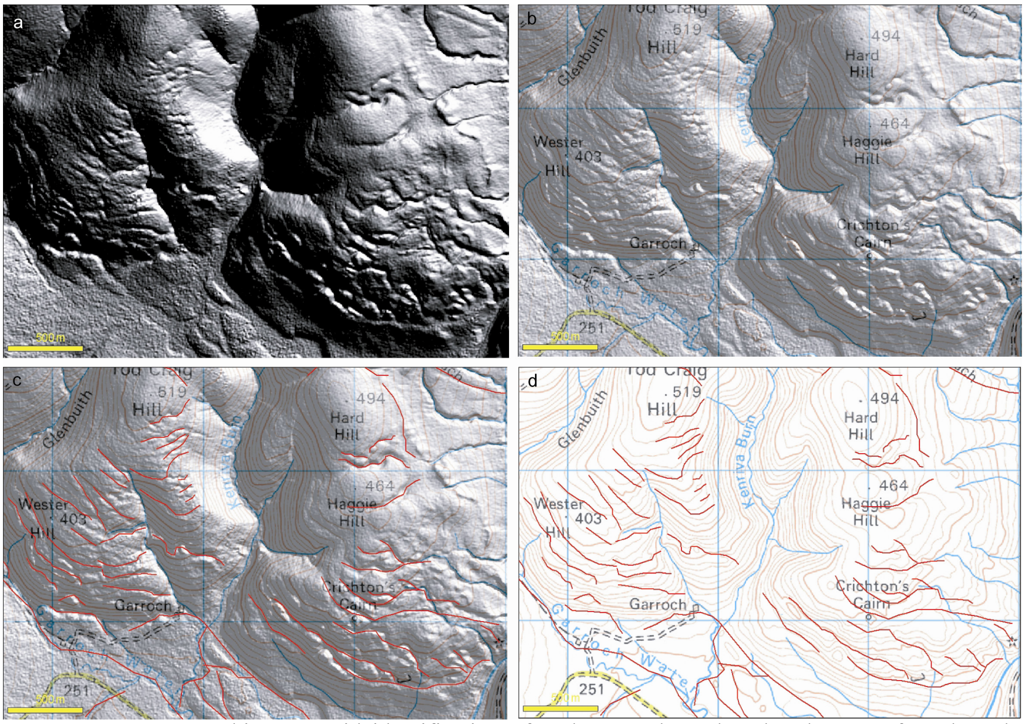


Figure 4.21 Topographic maps aid identification of meltwater channels. The absence of modern drainage (demarcated by the blue line network) confirms channel status as meltwater channels relating to drainage of the last ice sheet. Contour lines on Ordnance Survey maps also aid classification of channels as marginal or subglacial (section 6.7.1). a) relief-shaded visualisation of DEM illuminated from the NE with 4X exaggeration of area east of Thornhill in Nithsdale b) overlain with semi-transparent OS map, c) mapped meltwater channels in red, and d) meltwater channels on OS map. OS Digimap data © Crown Copyright/database right 2004. An Ordnance Survey/EDINA supplied service. NEXTMap Britain data from Intermap Technologies, obtained under licence from British Geological Survey ©NERC.

4.4 Summary

A systematic approach to mapping five principal landform types using a high resolution DEM was undertaken to produce a series of consistent glacial maps for the whole of the former bed of the last British Ice Sheet that presently lies above sea level. This is the first time that such an approach has been employed for the whole of Britain. Five principal landform types were mapped in accordance with what is required for a glacial geomorphological inversion model of the last BIS. The DEM was visualised from a minimum of three solar azimuth directions to ensure accuracy of mapping of landform shape. The resulting maps are described in chapter 5 and enclosed with this thesis as a series of A0 sheets. Confidence in mapping quality is achieved by examination of mapping with geological and topographic maps and, where available, high quality field mapping. New mapping replicates the existing distribution of features in areas that have been subject to detailed field examination.

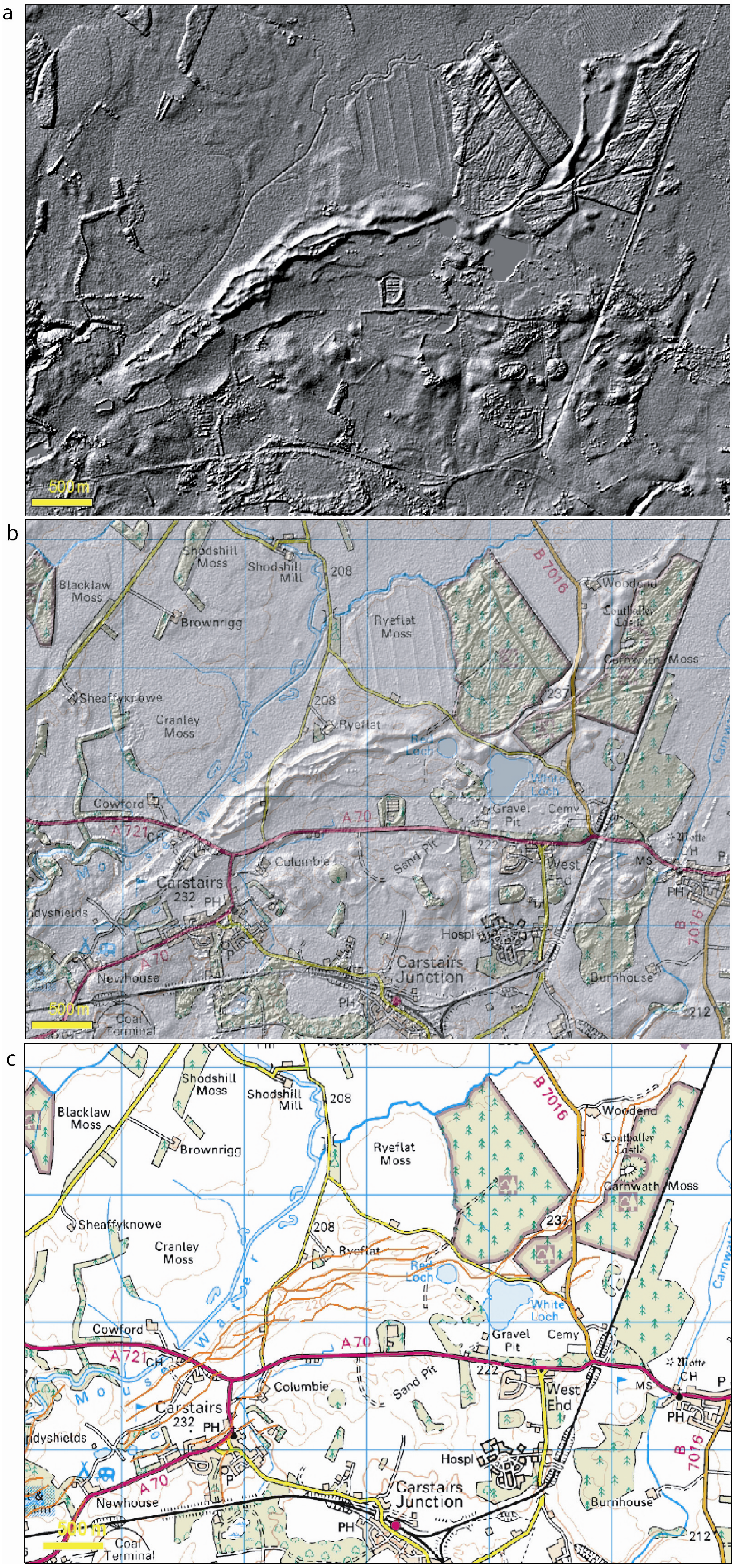


Figure 4.22 Topographic Ordnance Survey maps were employed to aid interpretation of landforms. By overlaying the map over the DEM it is possible to discriminate between true eskers and roads: a) Relief-shaded visualisation of DSM illuminated from the NW, 4X exaggeration close to Carstairs; b) OS map overlain on the relief-shaded image.; and c) mapped eskers overlain on OS map shown in orange. The topographic map clearly shows that the sharp crested feature south of the main esker system is a road. OS Digimap data © Crown Copyright/database right 2004. An Ordnance Survey/EDINA supplied service. NEXTMap Britain data from Intermap Technologies, obtained under licence from British Geological Survey ©NERC.

Chapter 5

Mapping results

5.1 Introduction

Chapter four described the methods used to conduct systematic mapping of glacial geomorphology. This chapter presents the results and describes the mapped distribution of landforms. The results are presented in four A0 size map sheets contained within the folio which accompanies this thesis (and figure 5.1 and 5.2). The landforms have been divided into two maps for clarity. Map 2 records the pattern and distribution of subglacial bedforms (drumlins, crag and tails, mega-scale glacial lineations, and ribbed moraine) (figure 5.1). Map 3 records the distribution of meltwater channels, eskers and moraines (figure 5.2). Each map comprises a north and south sheet to allow mapping to be presented at a reasonable scale to allow scrutiny of individual landforms at A0 size (1: 525,000). The mapped outlines and crestlines of individual landforms have not been modified to improve cartographic quality, and so the maps are, in effect, hard copies of GIS vector layers. It is envisaged that cartographic modifications will be made to improve the appearance of the maps before publication. For example, it may be necessary to stylise the meltwater channel mapping to avoid flights of closely spaced channels appearing as a solid block of colour. The Glacial Map of Canada and the Glacial Map of Britain have been used as templates for the map colours and design. The OS PANORAMA DEM provides the topographic background on the map shaded dark-light grey with darker shades representing higher ground.

It is notable on both maps that the area covered by the Loch Lomond Stadial ice cap in Scotland is virtually devoid of landforms. As described in chapter four, this area was examined as part of the systematic mapping across the country and therefore the absence of landforms is a reliable reflection of the paucity of identifiable landforms in the area. It is probable that the region contains landforms that are below the resolution of the DEM. The entire area is characterised by hummocky glacial deposits or moraines. This operates like a screen or mask over the landscape obscuring and perhaps erasing landforms created by the larger Late Devensian ice sheet, although Golledge (2007) has suggested that older landforms are visible beneath the Loch Lomond landforms. Furthermore, it was important not to misappropriate Loch Lomond Stadial age features as being part of the assemblage attributable to last major ice sheet. In this regard, the lack of a similar database to that of BRITICE for the existing published mapping of landforms of Loch Lomond Stadial age was problematic.

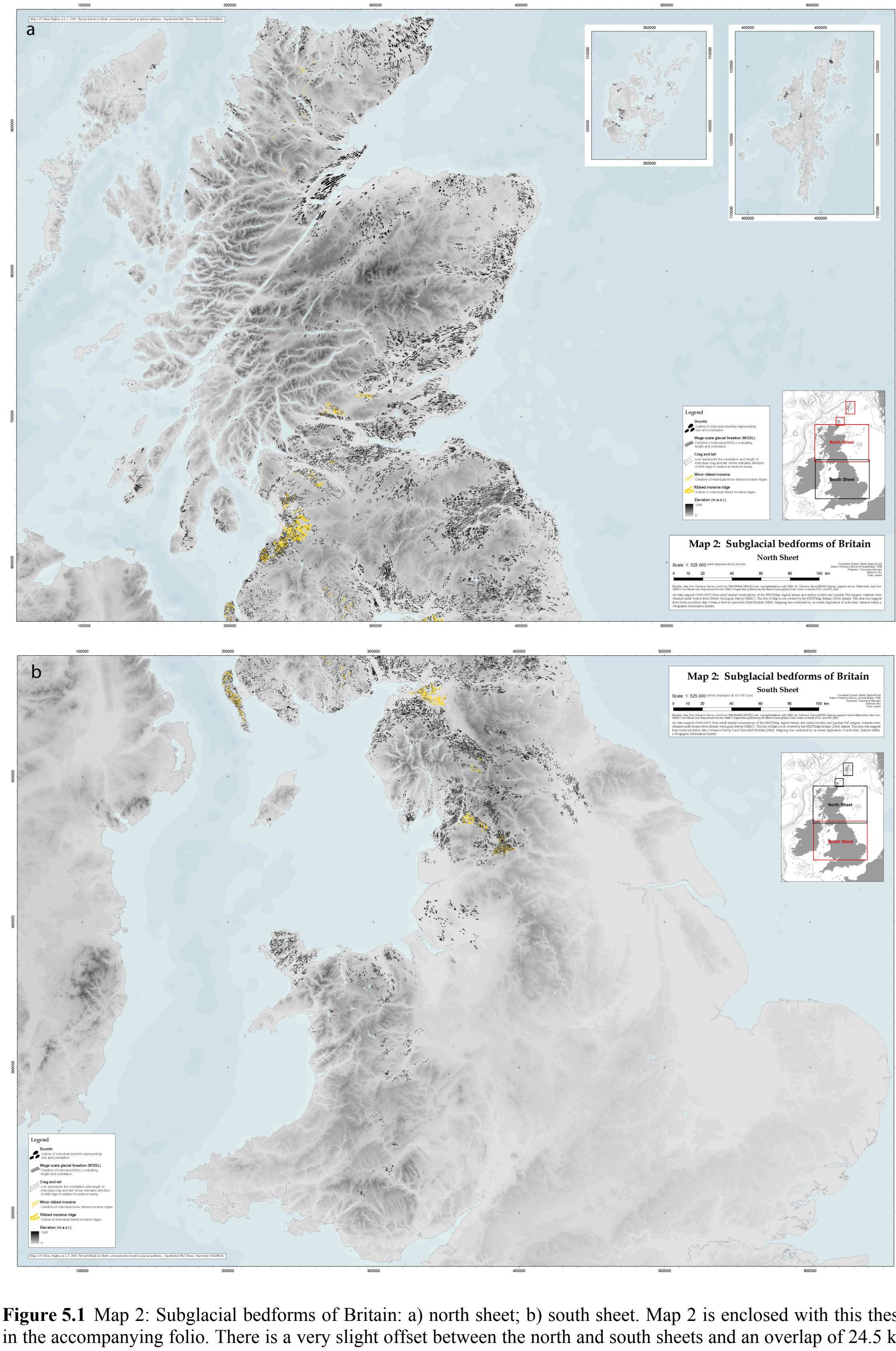
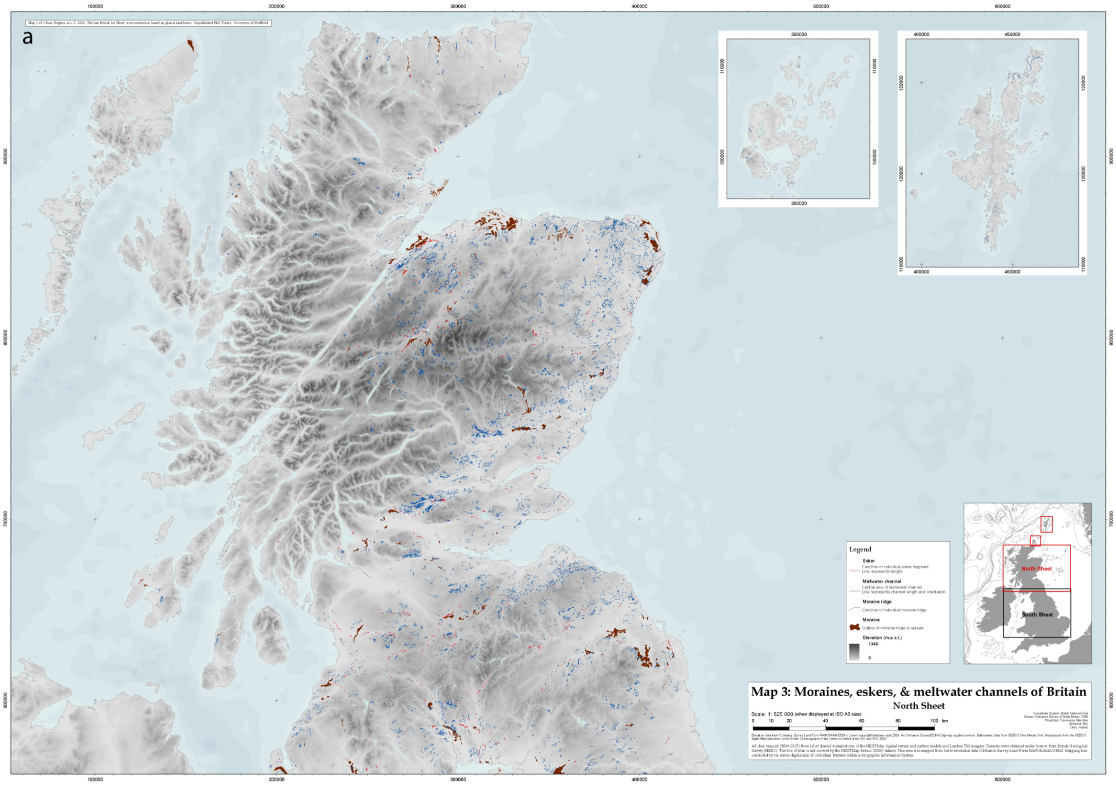


Figure 5.1 Map 2: Subglacial bedforms of Britain: a) north sheet; b) south sheet. Map 2 is enclosed with this thesis in the accompanying folio. There is a very slight offset between the north and south sheets and an overlap of 24.5 km between the North and South sheets.



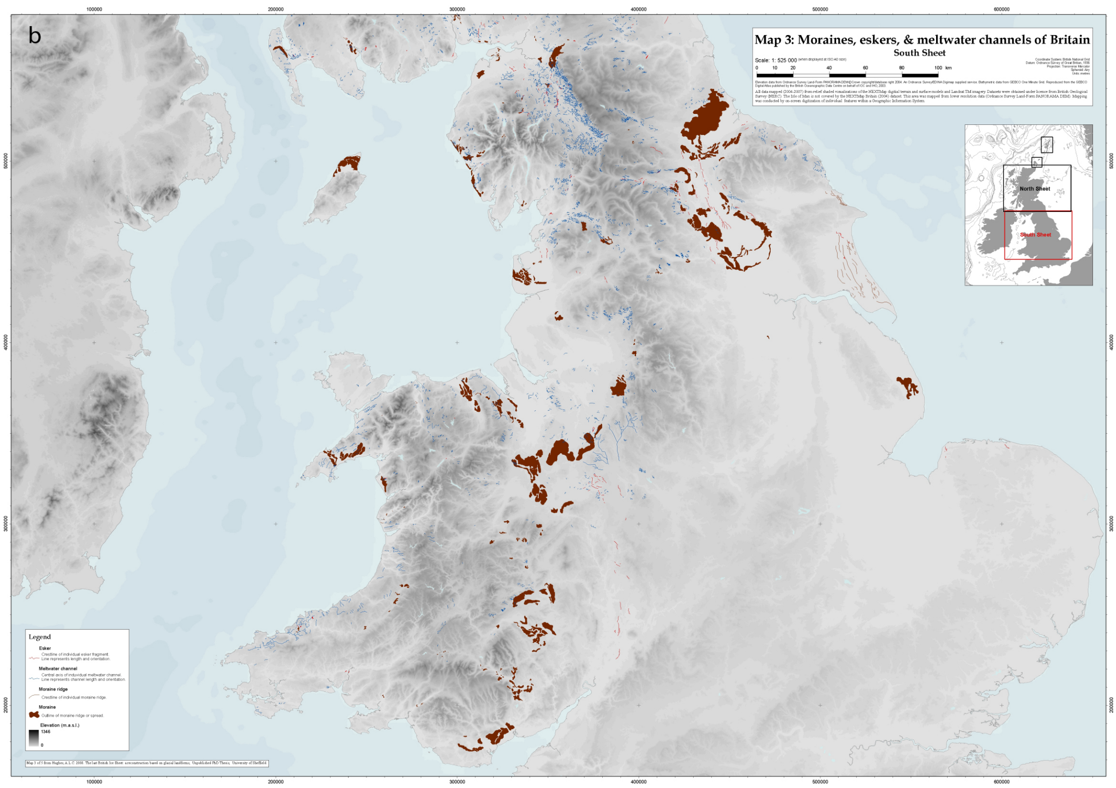


Figure 5.2 Map 3: Moraines, eskers and meltwater channels of Britain: a) north sheet; b) south sheet. Map 3 is enclosed with this thesis in the accompanying folio. There is a very slight offset between the north and south sheets and an overlap of 24.5 km between the North and South sheets.

5.2 Subglacial bedforms (Map 2)

Map 2 includes the family of glacial landforms that are commonly termed subglacial bedforms: lineations (drumlins, crag and tails, and mega-scale glacial lineations) and ribbed moraine (figure 5.1). For the reasons discussed in the preceding chapter (including rigorous quality control checks against geological maps and comparison with detailed field mapping (where available), it is estimated that mapping of subglacial bedforms is 90 % complete. The map is therefore close to a true representation of the distribution and population of subglacial bedforms for Britain. The break-of-slope outline of drumlins are shown as filled black, crag and tails are shown as grey arrows pointing from crag to tail, mega-scale glacial lineations (MSGL) are black crestlines, and ribbed moraine is yellow (filled outlines or ridge crestlines). As stated in the introduction the maps have not been altered to improve cartographic quality and therefore outlines and crestlines represent the actual area or length dimensions of individual features. As drumlins are shown filled, it is not possible to show on the map where drumlin cross cutting occurs.

5.2.1 Drumlins, crag and tails, mega-scale glacial lineations

The new map replicates and extends the locations of known drumlin fields in Britain (figure 5.3) and also provides more detail on drumlin numbers, morphometries and spacing than documented by existing maps in most areas.

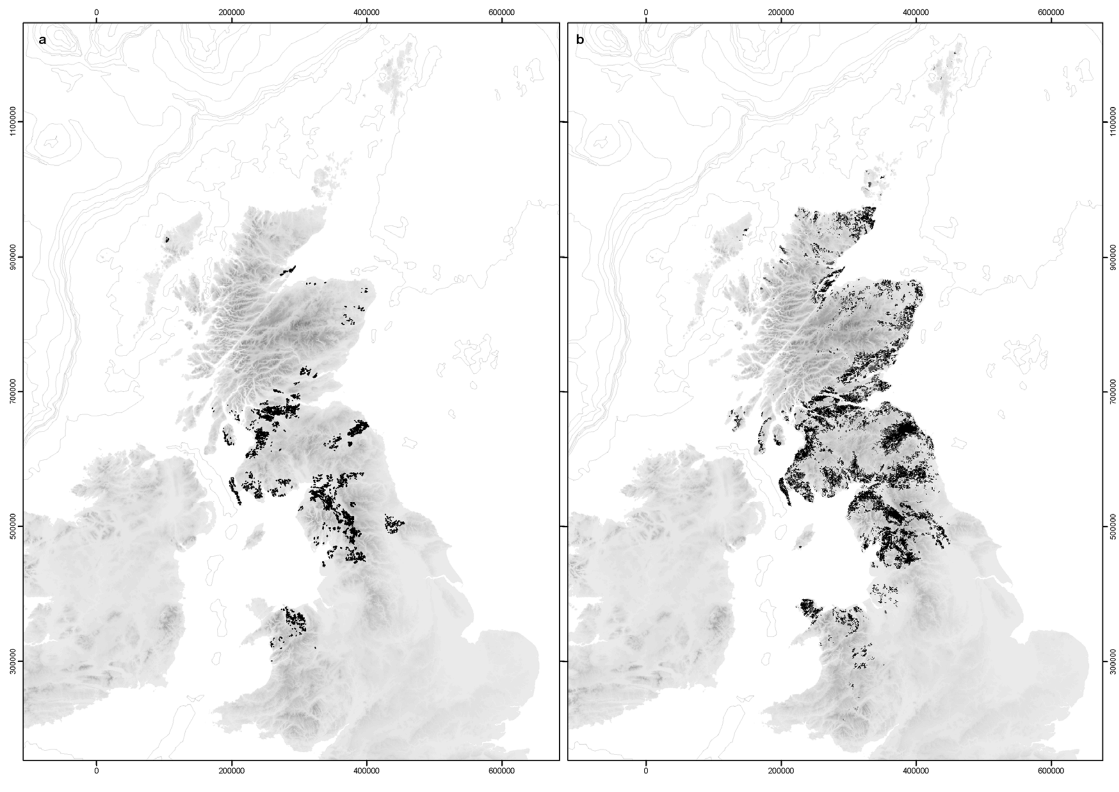


Figure 5.3 Comparison of drumlins contained within BRITICE database (a) and drumlins, crag and tails, and mega-scale glacial lineations from new countrywide mapping (b). New countrywide mapping has increased the number of known drumlin fields. British National Grid coordinates, interval between tick marks 100 km.

It was noted in chapter four that where drumlin mapping has been conducted in detail for a local area, the new mapping is successful in reproducing the same level of detail. Both the number (i.e. detail) and the overall distribution of drumlin mapping is greatly increased from that summarised in the Glacial Map of Britain (figure 5.3), especially in Scotland. In some cases (e.g. Anglesey) drumlins are mapped where previously they had only been described in the literature. The map contains 5,901 crag and tails, 248 MSGL crestlines, and 36,222 drumlins, as opposed to the 5,956 drumlins in BRITICE and 8,552 in BRITICE+. The newly mapped distribution and pattern of drumlins generally concurs with previous mapping, if available, and adds extra detail. Notable differences occur in Easter Ross where drumlins of Peacock (1984) are reinterpreted as crevasse-squeeze ridges, Ayrshire where drumlins are reinterpreted as possible moraine ridges (Holden, 1977), the Tweed where drumlin orientation is about 30 degrees different to that of the drumlins mapped by Clapperton (1970) and in the Yorkshire Dales where drumlins are reinterpreted as ribbed moraine (Raistrick, 1933) (figure 4.18).

A striking observation from the map is that the distribution of drumlins clearly outlines the distribution of topography (Map 2). Drumlin fields predominantly occur in lowland areas with the majority of upland areas free of subglacial landforms, e.g. Southern Uplands, Scottish Highlands, Wales, Lake District and northern Pennines. Nevertheless, drumlins do occur at high elevations, up to 677 m in the Lune Forest in the Pennines, east of the Vale of Eden (OS ref. NY 79731 23849). Field mapping by Mitchell (2007) has also uncovered drumlins above 650 m in the north Pennines. There are very few drumlins in regions where there is a high variability in topography, e.g. Wales, Scotland, Orkney and Shetland. It is likely that this is, in part, a function of the distribution of glacial sediment. Other gaps or ‘holes’ in the distribution of drumlins are associated with the routes of major rivers (e.g. figure 5.4). It is suggested that drumlins close to the river course have been buried by fluvial sedimentation during the Holocene. An examination of these areas with ground-penetrating-radar would be useful to test this hypothesis. Post glacial modification is also apparent at the scale of individual drumlins; meltwater and fluvial erosion results in the modification and/or bisecting of the classic oval geometry in some cases. Mapping was conducted to reflect existing drumlin form. By qualitative examination, the distribution of drumlins does not appear to be controlled by geology since drumlins occur across the country on a number of different rock types.

A variety of drumlin morphometries were identified (figure 5.5 and Map 2). Detailed analysis of drumlin morphometry statistics has not been conducted in this thesis. As part of a separate project, the length, width, and elongation ratio of British drumlins has been analysed and the results are presented in Clark et al. (in press). In this thesis differences in drumlin morphometry are used in a purely visual way to aid identification of flow patterns, discussed in chapter 6. Drumlins are commonly superimposed on other drumlins and ribbed moraine ridges (figure

5.6). There are 133 instances of drumlin superimposition. Drumlin lengths range from 9 m to 3.5 km, with a mean length of 570 m. The greatest density of drumlins is in the Central Valley of Scotland.

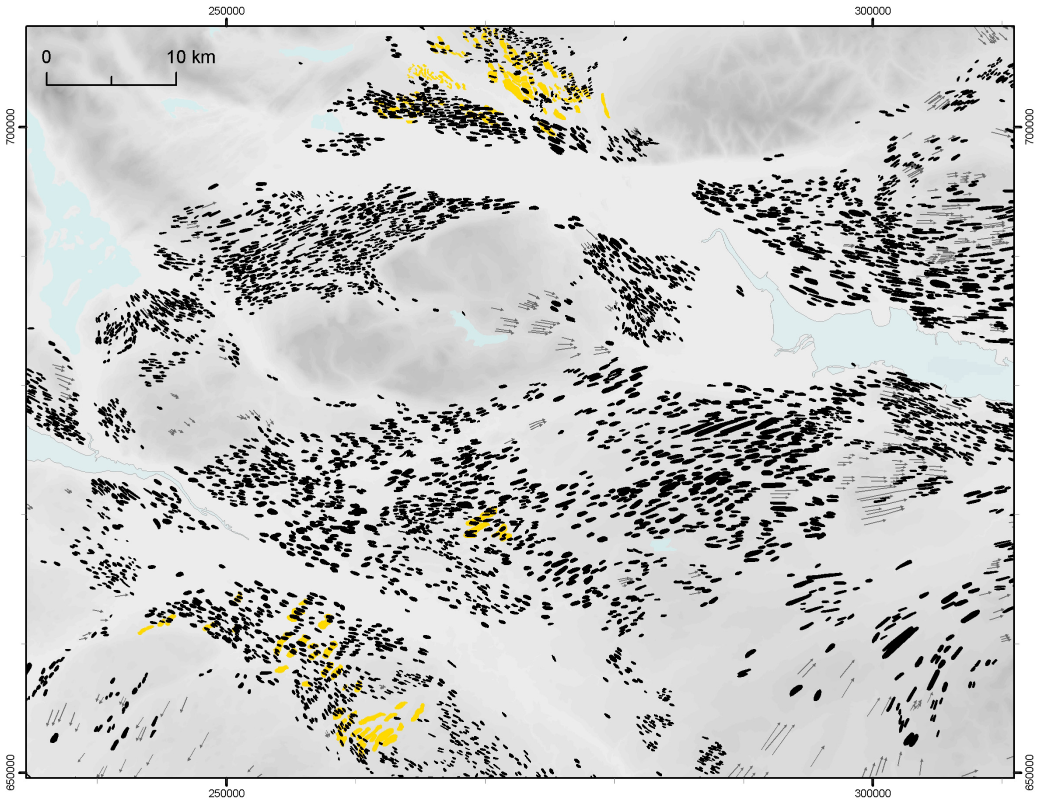


Figure 5.4 Drumlin fields in southern Scotland are segmented by the courses of Rivers Clyde and Forth. It is suggested that drumlins have been buried and thus obscured by Holocene fluvial sedimentation. Part of subglacial bedform map (Map 2) centred on Glasgow, Scotland. Colours are the same as in Map 2. British National Grid coordinates, interval between tick marks 50 km.

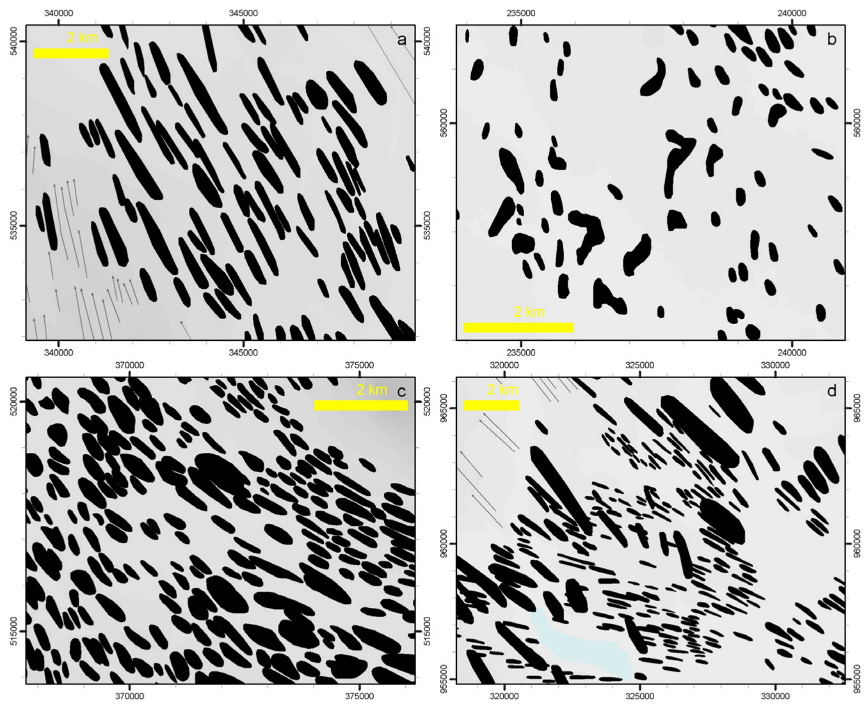


Figure 5.5 A range of morphometries are exhibited by the drumlins of Britain. For example; thin, elongate, 'spindle' shaped drumlins close to Penrith (a), irregular, 'tadpole' shaped drumlins in the Marchars of Galloway (b), classic ovoid shaped drumlins in the Vale of Eden (c), and area of Caithness with two distinct populations of drumlins on the basis of length. British National Grid coordinates.

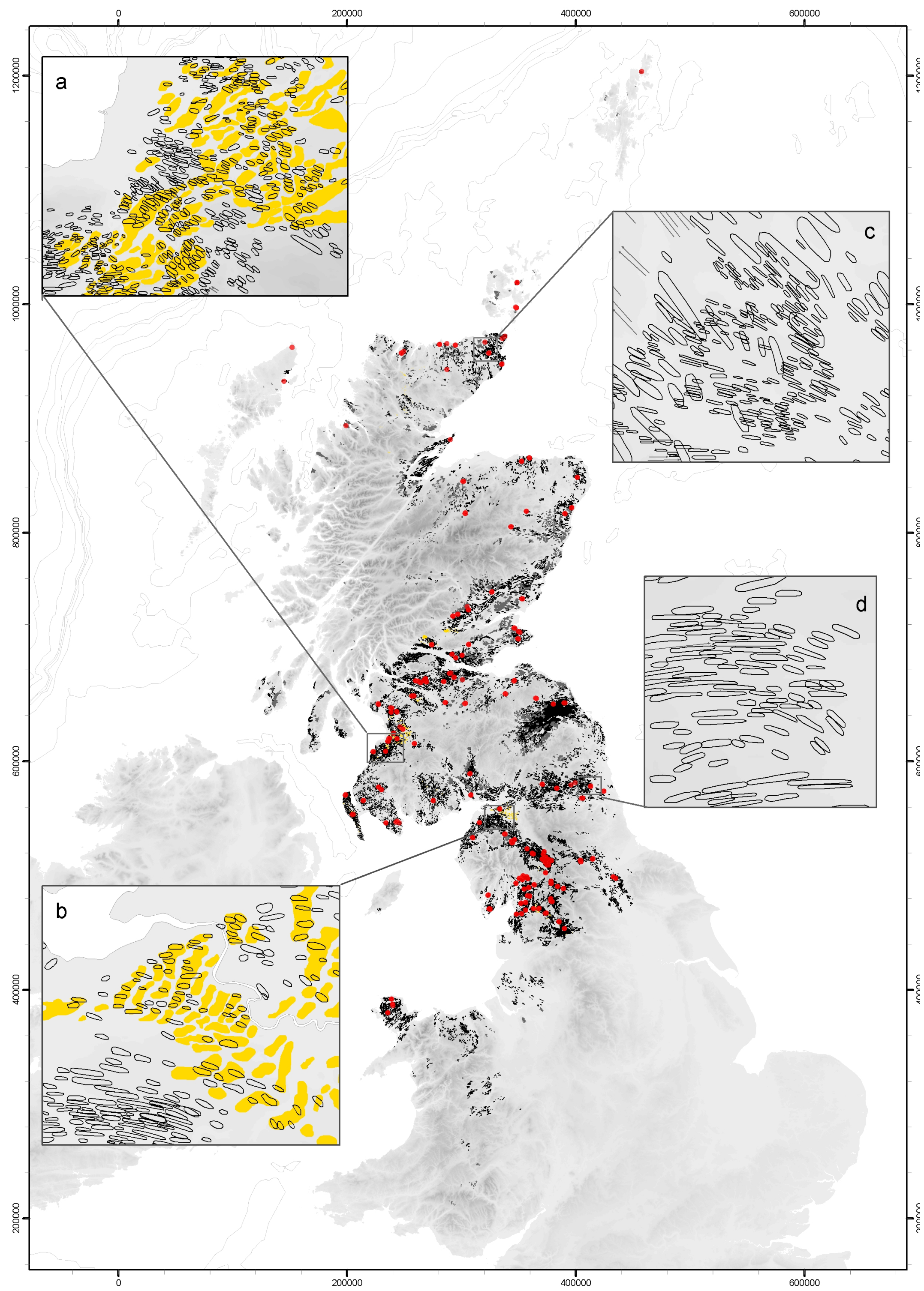


Figure 5.6 Subglacial bedform map with locations of cross-cutting or superimposed landforms marked in red. Examples of types of cross-cutting shown in enlargements a) and b) drumlins superimposed on ribbed moraine in Ayrshire and Solway lowlands, and c) and d) cross-cutting drumlins. Drumlins shown in outline only so that nature of superimposition can be observed. British National Grid coordinates, interval between tick marks 200 km.

MSGL, distinguished from drumlins on the basis of tendency towards a more oblong or rectilinear shape (chapter 4; table 4.1) only occur in the Tweed Basin. Long drumlins do occur in other areas (e.g. on Easter Ross and Strathmore) but never in the same number, frequency, or with the same distinctive rectilinear shape as in the Tweed and are therefore not identified as MSGL and remain in the drumlin layer. The Tweed MSGLs are smaller than examples from other palaeo ice sheets such as the Laurentide, ranging from 2 km to 16.5 km long. Crag and tails are most common in Scotland and are often associated with drumlin fields. Lengths of drift tails ranges from 113 m to 8.2 km. There are a few groups of crag and tail features that stand out on the map because they are orientated in an opposite direction to that expected (e.g. onshore) or in conflict to the direction of orientation of neighbouring landforms. Interpretation of these features is discussed in chapter 6 (table 6.1). During the checking process described in chapter 4, the drumlin, MSGL, and crag and tail speculative layers were reduced significantly by transferring individuals into the main layer, and the speculative layer presently contains only a small number of drumlins (n = 2,881) (figure 5.7).

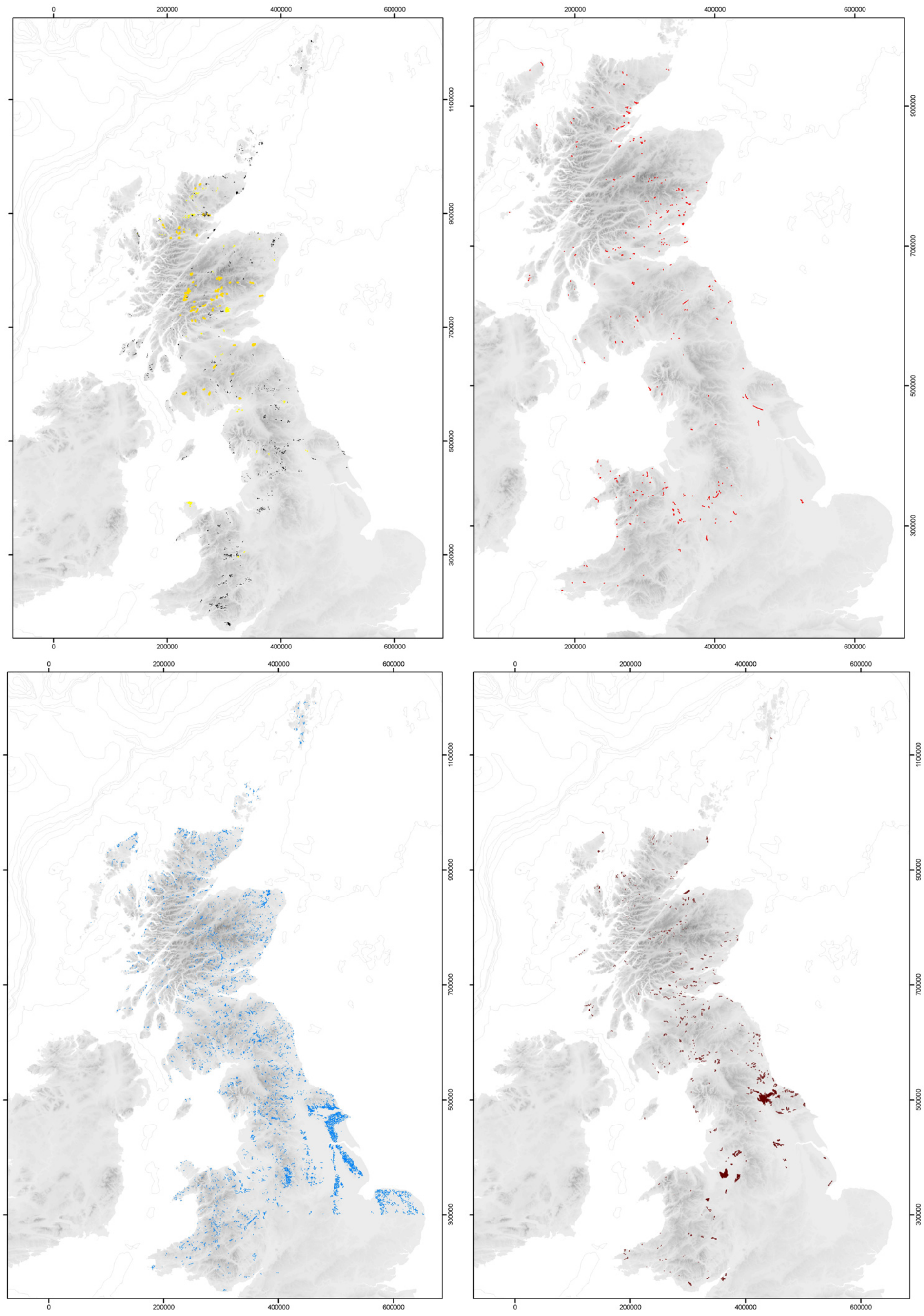


Figure 5.7 Distribution of landforms contained within speculative layers: a) subglacial bedforms, b) eskers, c) meltwater channels, and d) moraines. Although identified and digitised during the mapping process these features were not incorporated on the main maps because they were not considered reliable enough. British National Grid coordinates, interval between tick marks 200 km.

5.2.2 Ribbed moraine

Ribbed moraine occurs in only a few locations (Map 2; figure 5.1) and until recently ribbed moraine has rarely been observed in Britain in contrast to discoveries in Ireland and beneath other palaeo-ice sheets (Dunlop and Clark, 2006; Finlayson and Bradwell, in press). The only considerable area of ribbed moraine in Britain is in Ayrshire, where ribbed moraine covers an area of 750 km^2. Elsewhere, ribbed moraine exists in discrete patches (e.g. northern Scotland). Two main morphometries of ribbed moraine are identified: thin widely spaced ridges that are not over printed and occur in valley bottoms (figure 5.8a), and broad flat ridges that are typically superimposed by drumlins (figure 5.8b) and generally occur in low lying expansive settings. The first type of ribbed moraine appears to be exclusively restricted to Scottish locations. The second type occurs mainly in lowland locations and appears pushed up or stacked against topographic highs in Ayrshire and Lancashire.

In some areas the location of drumlins that superimpose ribbed moraine ridges appear to be in part controlled by the distribution of the underlying ribbed moraine, for example, on the Rhins of Galloway (Map 2). This suggests remoulding of the ribbed moraine ridges to form drumlins. The map contains a total of 1,868 ribbed moraine ridges grouped in 19 separate patches or fields. The ribbed moraine speculative layer contains a potential additional 1950 ribbed moraine ridges. The location of these is shown in figure 5.7a. It would be valuable to field check these sites to corroborate or reject their status as ribbed moraine fields.

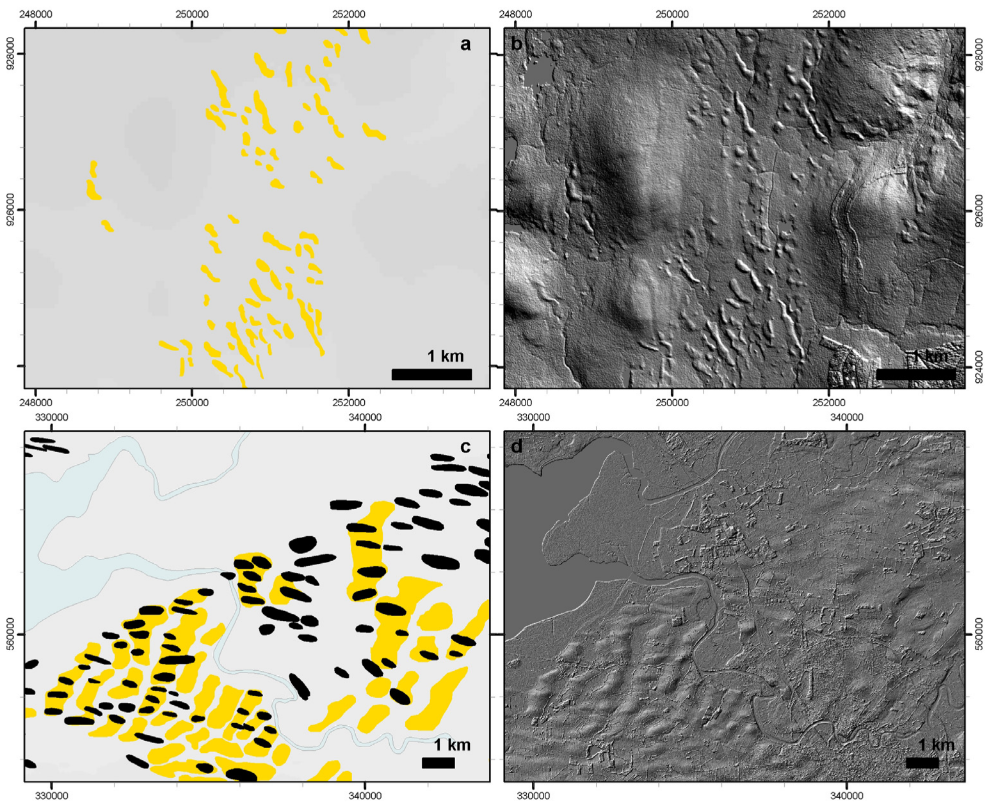


Figure 5.8 Two main types of ribbed moraine observed in Britain: thin widely spaced ridges constrained in bottom of valley in northern Scotland (a and b), broad closely spaced ridges superimposed and partly remoulded by drumlins in Solway lowlands (c and d). Shaded relief images of NEXTMap DEM (b and d). British National Grid coordinates.

5.3 Eskers, meltwater channels and moraines (Map 3)

Map 3 shows the distribution of eskers, meltwater channels, and moraines. Following the glacial map of Canada and the Glacial Map of Britain eskers are red crestlines, meltwater channels are blue centrelines, and moraines and moraine ridges are brown outlines or crestlines. A reduced version of the map is shown in figure 5.2.

5.3.1 Eskers

The greatest density of eskers is within the belt of glaciofluvial material that runs along the Central Valley of Scotland between Glasgow and Edinburgh and in the valley of the River Spey in Scotland (figure 5.9; Map 3). Prominent esker chains also occur in the Vale of York. Mapped eskers in Britain are relatively short in comparison to examples from other ice sheets, including the Irish Ice Sheet. Mean esker length for Britain is 744 m. Lengths range from 36 m to 8,586 m. The map contains a total of 1,792 esker ridges. There are no eskers mapped on Shetland, Orkney or the Outer Hebrides and only a few in Wales. Eskers mainly occur at low elevations; mean elevation of the mid point of each esker fragment is 165 m, the range of elevations at which eskers are found is 2 m to 840 m. Eskers generally occur in valley bottoms although there are examples of eskers on higher slopes, such as in the Southern Uplands. Eskers running broadly N-S along the Severn Valley stand out on the map since they are beyond the accepted drift limit for the Late Devensian ice sheet (chapter 2). These eskers are also contained within the BRITICE database.

Figure 5.9 BRITICE esker layer (a) compared with results of new countrywide esker mapping (b). Circles mark eskers that are contained within BRITICE layer but were not observable on the DEM and so are not included in new mapping. British National Grid coordinates, interval between tick marks 200 km.

In general the new mapping reinforces the existing information on the distribution of eskers in Britain (figure 5.9). There are a number of eskers that are contained within the BRITICE database that were not distinguishable on the DEM or satellite imagery used for mapping in this study (figure 5.9). It may be the case that these eskers are below the resolution of the imagery. It is also possible, due to the value of sand and gravel as a resource, that parts of or whole eskers may have been removed by quarrying and are therefore no longer present. There are 862 eskers contained within the speculative layer (figure 5.7b). Many eskers were rejected in the process of discussions with experienced mappers as being reminiscent in form to dissected sheets of glaciofluvial outwash. Following this, the cross profiles of eskers were checked to ensure a characteristic sharp inverted V shape and eskers orientated with valley long profiles and close to present day river courses were treated with caution and placed in the speculative layer. For these reasons, it is thought that the mapping under-represents the true number of eskers and the map is estimated to be 70% complete. Further mapping using aerial photography and field checking would remedy this.

5.3.2 Meltwater channels

The map contains a total of 14896 channel fragments and extends the coverage of meltwater channels across the country, removing the detailed patch problem inherent in the BRITICE dataset and discussed in chapter 2 and Clark et al. (2004b) (figure 5.10). Very few channels were identified in western and northern Scotland, the Outer and Inner Hebrides, Orkney, Shetland, and the Isle of Man. Meltwater channels therefore appear to be more common on the eastern side of the country, although this may reflect the difficulty in identifying meltwater channels in highly structured bedrock.

The meltwater channel layer is considered to be 60% complete. Focus was on obtaining a representative map of the overall distribution of channels. Mapping was conducted at the reconnaissance level rather than attempt to map every individual channel. Small channels in particular are likely to have been missed. No differentiation is made between small and large channels on the map. A major problem for identification of meltwater channels was the re-use of meltwater channels by the present day fluvial drainage network. To avoid the misappropriation of fluvial channels that are not reusing meltwater channel courses into the map, where the morphometry of a channel led to an equivocal interpretation and the OS topographic map indicated the presence of a stream or river, channels were treated with caution and excluded. Caution was also observed where dry channels were observed on calcareous bedrock, in case the surface terrain reflects not meltwater erosion but underground channel systems. In both cases the channels remain in the speculative layer (figure 5.7c) for later field and aerial photo checking. There are a total of 10,819 meltwater channel fragments within the speculative layer.

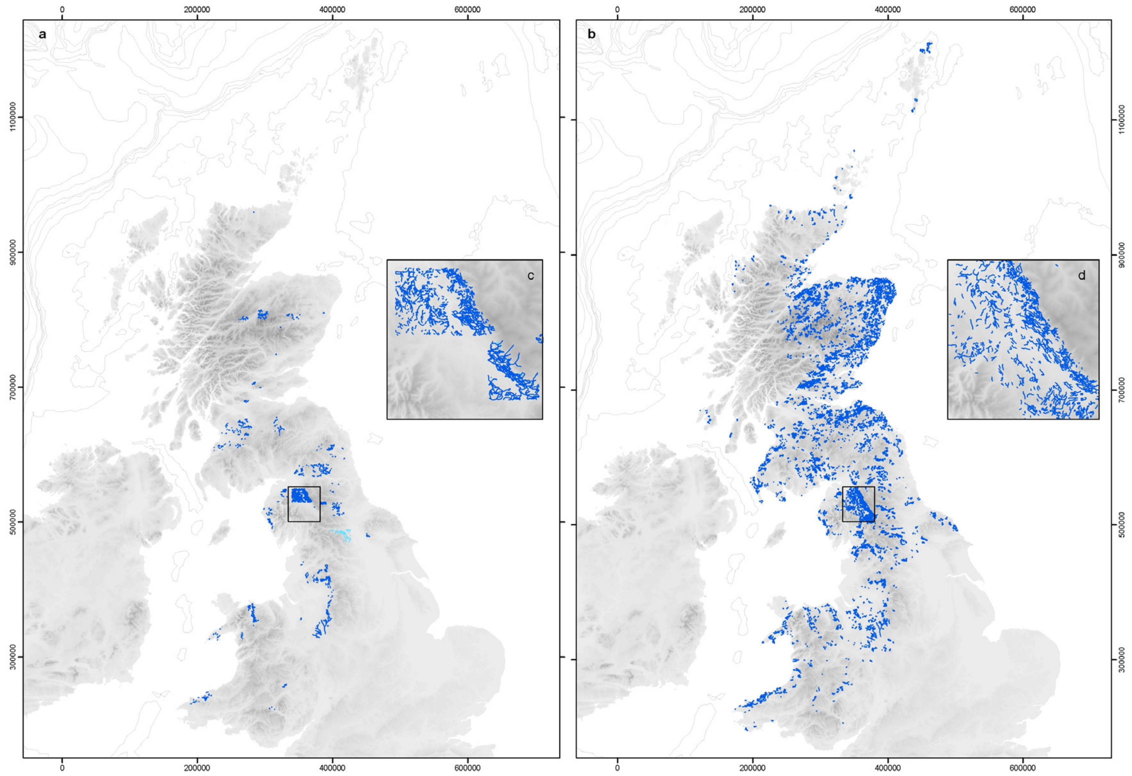


Figure 5.10 BRITICE meltwater channel layers (undefined = blue and lateral = light blue) (a) and results of new countrywide mapping of meltwater channels (b). Coverage of meltwater channel map now extends across the country. New mapping has also resolved the patchy nature of the BRITICE compilation, e.g. Vale of Eden (c and d). British National Grid coordinates, interval between tick marks 200 km.

Channels were subsequently classified into subglacial, marginal, proglacial, and submarginal categories before use in the glacial inversion model. Classification is not shown on Map 3. This process is described and the results presented in chapter 6.

5.3.3 Moraines

There are a few large arcuate moraines marking the limit of ice in the Vale of York and Welsh-English borders. However, the majority of mapped moraines are restricted to valley settings or occur as large 'spreads' of hummocky glacial material, e.g. in the Tees lowlands. The ratio of features in the moraine speculative layer to that in the moraine layer is smaller than any other landform type (823:1,417) (figure 5.7d). Some of the moraines contained within BRITICE are not recognisable on the NEXTMap data (figure 5.11). There are thus more moraines contained in the BRITICE and BRITICE+ databases than in the new mapping. Missing from the new map in particular are small valley moraines within upland regions, e.g. Dales and Lake District and Southern Uplands. Moraine mapping is therefore thought to be only 60% complete. A total of 1,417 moraines and moraine ridges are contained on the map. No distinction is made here on the type of the moraine. The moraine layer requires field checking to determine the type of moraine that has been mapped and to reduce the size of the speculative layer.

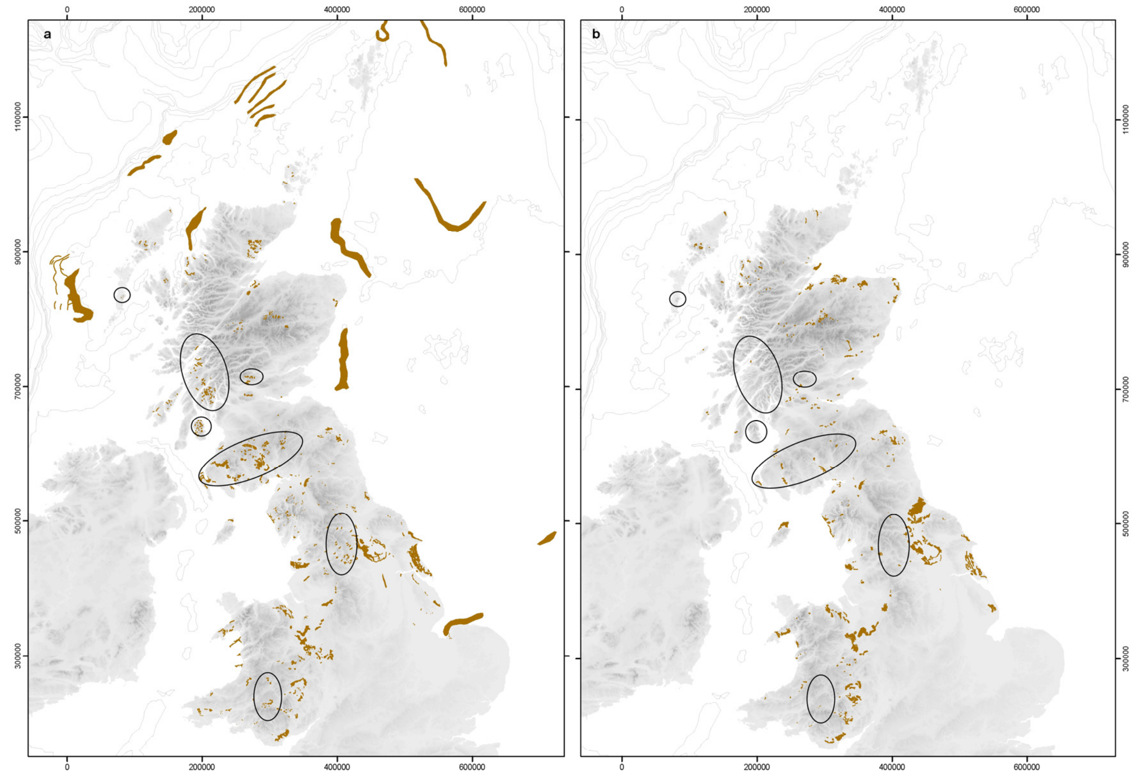


Figure 5.11 BRITICE moraine layer (a) and results of new countrywide mapping of moraines (b). Moraines in southern Scotland and smaller moraines not observable on the DEM are marked. British National Grid coordinates, interval between tick marks 200 km.

5.4 Streamlined bedrock and landscape grain

Streamlined bedrock and landscape grain layers are not shown on the accompanying maps. Instead, the distribution of this mapping is shown in figure 5.12. Glacially streamlined bedrock is highly related to any underlying geological structure and is likely to have been formed over several glacial cycles and therefore may not be exclusively a function of the flow configuration of the last ice sheet, but rather a cumulative record of flow patterns. Streamlined bedrock is therefore regarded as a 'second order' indicator of ice flow patterns, but remains useful as it can extend flow information into areas where glacial deposits are thin, sparse, or non existent. Individual landforms were not mapped; instead a representative line was drawn in the direction of streamlining. Caution was exercised in highly structured bedrock terrains to avoid simply mapping geological structure, by consultation with BGS tectonic maps. The mapping is therefore below the reconnaissance level and is likely to under-represent the true occurrence of bedrock streamlining. The distribution of streamlined bedrock is opposite to the drumlin pattern as it reflects the location of exposed bedrock, generally in upland locations, thus filling 'holes' in the drumlin map.

The landscape grain layer was used to record areas of streamlined sediment that could not be resolved to the level of individual landforms, i.e. those instances where a streamlined element to the landscape could be recognised but the size of the component landforms (presumably drumlins or flutes) are below the resolution of the data. It would be interesting to obtain higher resolution data for these areas or make field visits to investigate the reality of the landforms. In a similar manner to streamlined bedrock this layer was treated as a second order indicator of flow pattern information in subsequent analysis.

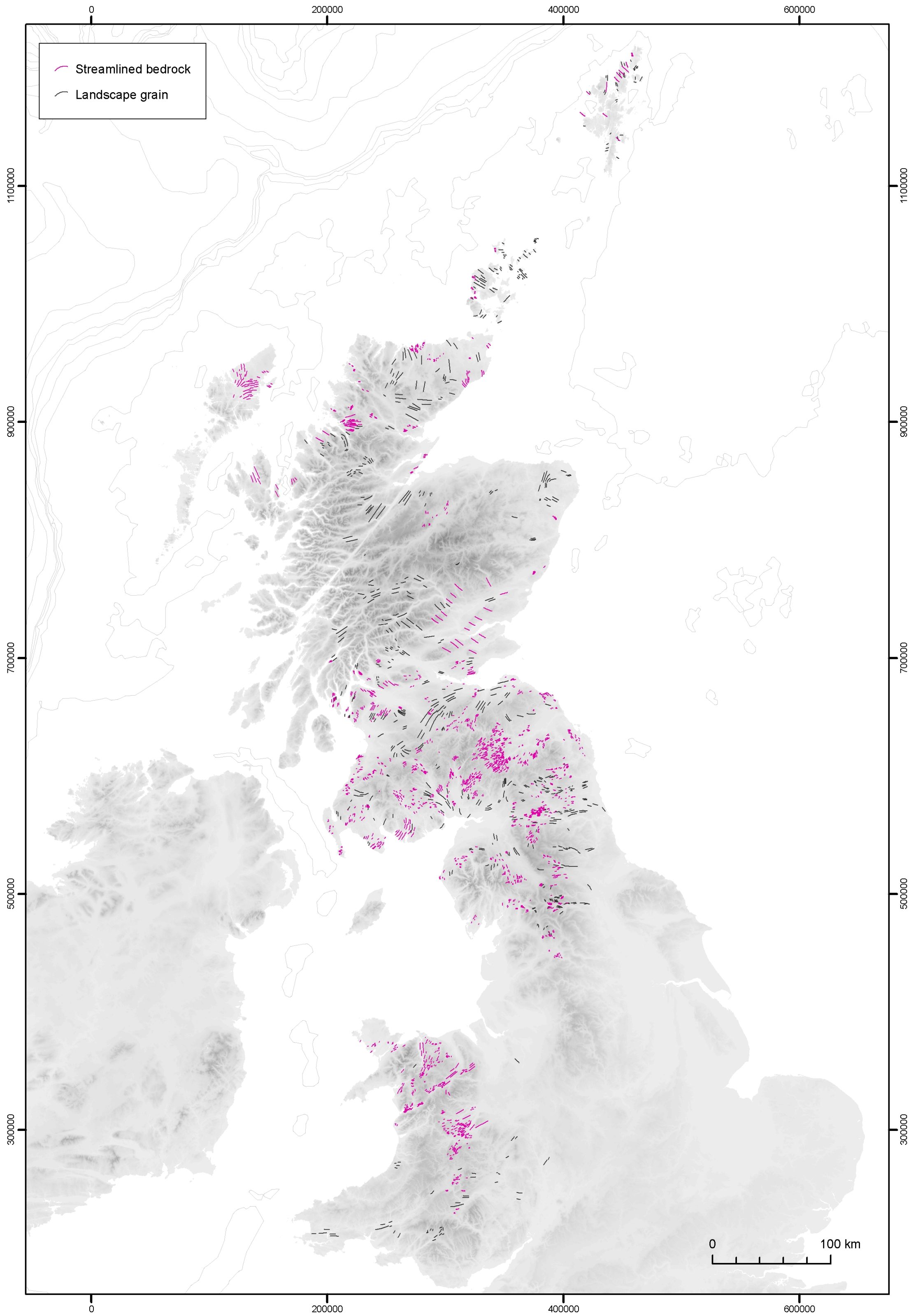


Figure 5.12 Map of streamlined bedrock (pink) and landscape grain (grey) distribution in Britain. Landscape grain follows direction of streamlining given by landforms below the resolution of the data. British National Grid coordinates, interval between tick marks 200 km.

5.5 Summary

The enclosed maps (maps 2 and 3) record the results of the first consistent countrywide mapping of glacial geomorphology of Britain. The maps are considered to reflect the true distribution and pattern of glacial landforms. Over 60,000 features are contained within the maps. The subglacial bedform map is estimated to be 90 % complete and therefore close to an accurate representation of the population of subglacial bedforms for Britain. Field work and aerial photo mapping is likely to extend the number and distribution of meltwater channels, eskers and moraines, as well as being necessary to refine the mapping of these landforms. In particular, moraines need to be field checked in order to define the context of deposition. The maps provide the first consistent basis for an inversion of the glacial landscape that will be discussed in the following chapters. It is anticipated that these maps will be useful beyond the glacial inversion model described in this thesis by providing a framework for more detailed local scale field mapping and sedimentological observations and to identify fruitful locations for future offshore investigations. The maps build upon previous work conducted primarily by field investigations over the century of interest in the last British Ice Sheet and contained within the Glacial Map of Britain. The maps provide a coherent basis for interpreting spatial patterns in the landform record, and enable point information, such as sedimentological observations to be set in a broader context.

Chapter 6

Flowset analysis (flowset-ology)

6.1 Introduction

Now we have a consistent map of glacial geomorphology (chapter 5; Maps 2 and 3) we can attempt an ice sheet scale reconstruction. The geomorphological record is both complex and fragmentary. Thus, the first stage of the inversion approach to ice sheet reconstruction seeks to reduce this multifarious record into a manageable volume of information by grouping landforms into summary assemblages. This is a process of rationalisation that presumes that landforms with similar characteristics were created under similar conditions. The theoretical basis for this process was outlined in chapter 3. This chapter will detail the methodological procedure and present the resulting landform summaries. These are the building blocks for the ice sheet reconstruction presented in chapters 7-10. The process of deriving cartographic summaries from the glacial maps will be described for each landform type in turn. For clarity in this chapter, I have imposed a logical stepwise process; in reality it is iterative with changes at one stage necessitating return to earlier stages to reject or accept alternative scenarios of flow pattern groupings or to revisit flowset delimitation.

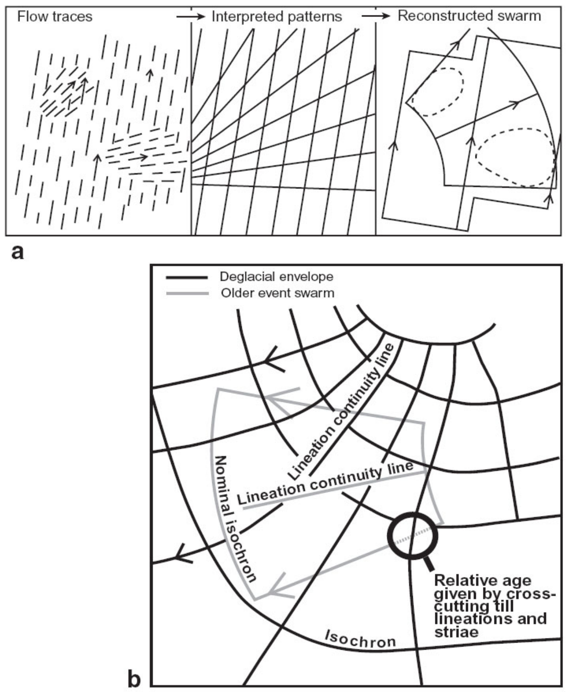


Figure 6.1 A flowset is a cartographic summary of a distinct phase of ice flow: a) Flow patterns are identified from the glacial map (drumlins, MSGL, crag and tails, etc) and grouped into landscape level flowsets (swarms/fans); b) Flowsets are represented cartographically by summary lines in the direction of ice flow (lineation continuity line) are bounded by a box which delimits the spatial extent of the flow traces comprising the flowset. Where flowsets intersect the relative age of flowsets can be determined on the basis of cross-cutting flow traces. Reproduced from Kleman et al. (2006).

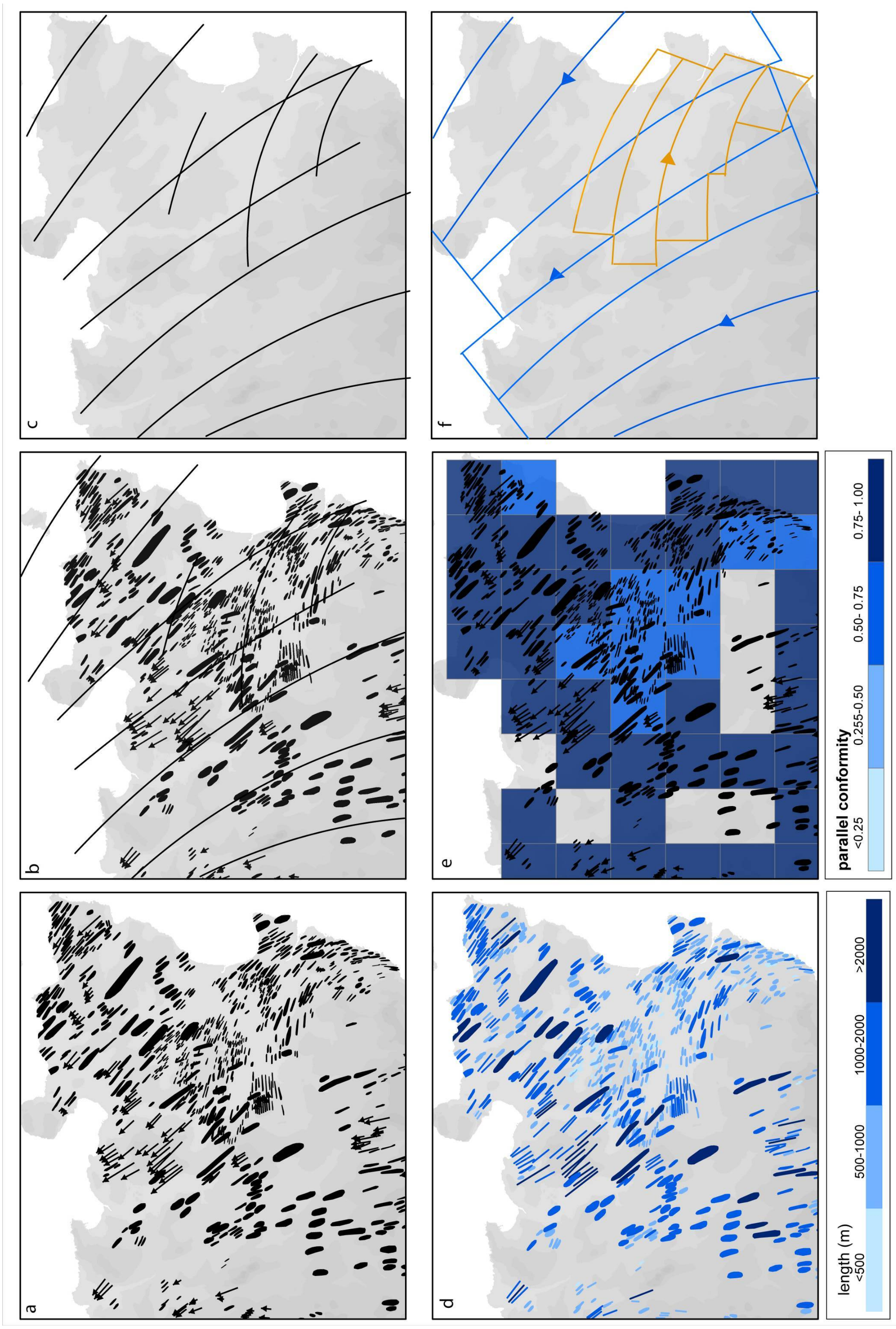
6.2 Lineation flowsets

A flowset defines a coherent group of lineations representing a discrete phase of ice flow (figure 6.1). Drumlins, crag and tails, and mega-scale glacial lineations are considered together as all provide information on flow pattern directions and orientations. Flowsets are identified by inspection of the spatial arrangement of these landforms shown on the glacial map (Map 2) with consideration of morphometry, i.e. length, elongation ratio (length/width), parallel conformity, landform spacing, and orientation. Flowset delineation is a problem of pattern recognition. Identification proceeds in a series of steps (figure 6.2):

1. Reduce lineation mapping to lines summarising ice flow directions (flow lines). Flow lines connect lineations of the same orientation and instances of cross cutting are investigated.
2. Group flow lines into plausible flow patterns. Conceptual models of potential flow pattern topologies are used as an aid (figure 3.7). Considerations include the plausible spatial extent of flow patterns, the amount of discordance that can be accommodated within the same flow pattern, the justification of interpolation over gaps in the landform record to connect flow patterns, and the degree of curvature that is deemed glaciologically plausible. Various grouping arrangements are explored and recorded as different possible scenarios.
3. Conduct a morphometry check on flow pattern groups. Groups should contain drumlins of a similar length, elongation ratio, etc.
4. Conduct a direction check on flow pattern groups. Examine whether the composite lineations are orientated in the same direction.
5. Produce map of flowsets from preferred arrangement of flow pattern groups. Steps 3 and 4 used to make decisions between alternative scenarios.

Steps 1 and 2 were initially conducted on paper. To facilitate visual inspection of the lineation record the drumlin, crag and tail and mega-scale glacial lineation mapping was printed out at two scales of 1:77,389 and 1:600,000 onto ISO size A0 sheets (figure 6.3). This facilitated a wide area view in order to examine spatial patterns. Each area was printed two or three times at each scale depending on complexity. This enabled several iterations of the same area to try out different organisations of flow lines. At the initial stages, no reference was made to topography to aid flow pattern groupings. Later topography was used to direct choice of alternative scenarios. Flow patterns were then digitised as GIS layers within the computer programme ArcGIS for steps 3 and 4 and to combine flow patterns across areas.

Figure 6.2 Over page. Flowsets are identified from the glacial lineation record through examination of spatial distribution and patterns which can be summarised in a series of stages: a) Glacial Map of drumlins (outlines) and crag and tails (arrows); b) Drumlins are reduced to flow patterns; c) Flow patterns considered without glacial map underneath. In this case there are two main discordant ice flow directions recorded – due NNW and due E; d) Morphometry characteristics (such as length) are used to aid grouping of flow patterns; e) parallel conformity of drumlins (the degree to which neighbouring drumlins are of a similar orientation) highlights areas of discordance between flow patterns; and f) flow patterns are organised into two discrete flow patterns. In this example stages d and e are not necessary as the drumlins can be clearly differentiated into two populations at stage a. The stages are therefore shown for illustration purposes only.


a
b
c
d
e
f
length (m)
<500
500-1000
1000-2000
>2000
parallel conformity
<0.25
0.255-0.50
0.50- 0.75
0.75- 1.00

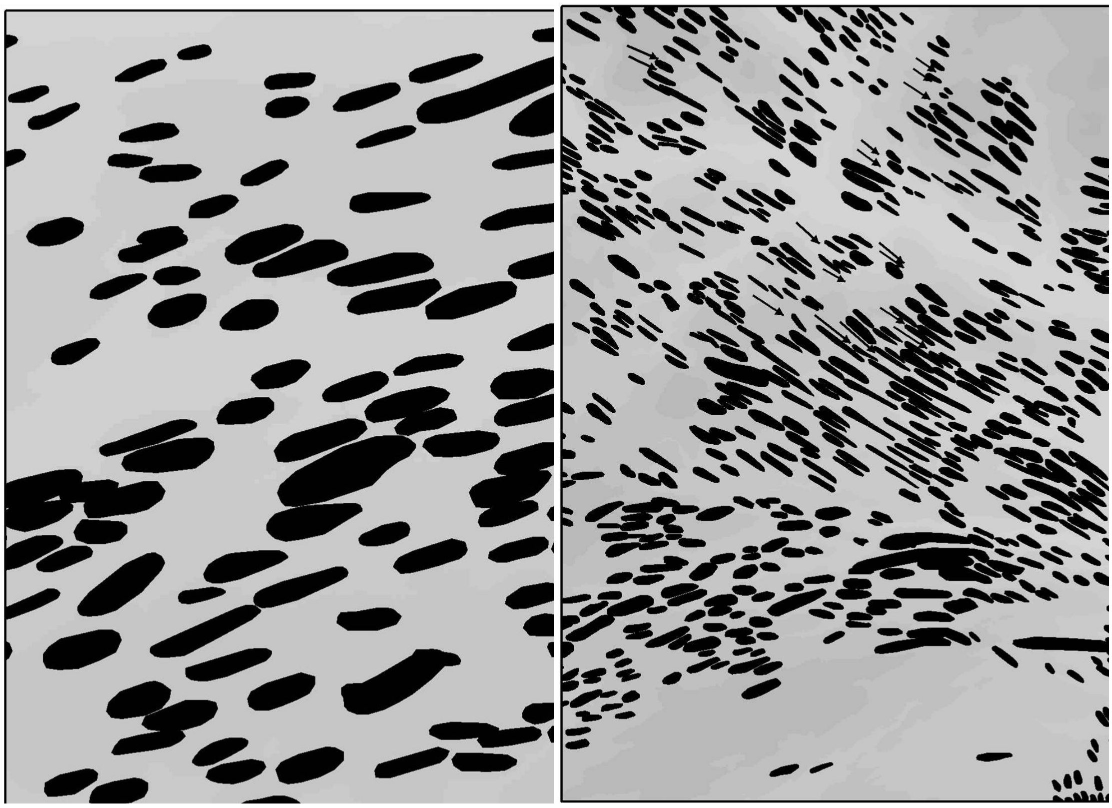


Figure 6.3 To investigate flow patterns recorded in the glacial map, subglacial bedform mapping was printed onto ISO size A0 sheets. Initially patterns were examined at a scale of c. 1:80,000 (left) and then at a scale of 1:160,000 (right). It was necessary to print out at this scale to consider individual drumlins and appreciate the wide area view beyond the constraints of a typical 19" computer screen.

Flow patterns were examined using the maps alone. Reference to the relief-shaded images of the glaciated landscape was only made in the final stages of flowset identification in order to revisit problematic areas. Examination of drumlin morphometry was done on a purely visual basis. Lengths and widths of drumlins were calculated using the area and perimeter statistics generated automatically in the GIS in order to derive an estimate of the elongation ratio of each drumlin. The methodology used is presented in Clark et al. (in press). In order to quantify parallel conformity it was necessary to convert drumlin polygons into lines, so as to derive a value for the orientation of each drumlin. A GIS extension was used to identify the longest straight line distance across each drumlin polygon (Jenness, 2007). The tool also produces a shapefile of the lines and a value for the azimuth of the line. The longest line is an approximation of the crestline of each drumlin. The crestline orientation of 50 randomly selected drumlins was measured by hand and compared to the calculated azimuth values. This produced an r^2 value of 0.996 and so the 'longest-line' approximation is accepted as appropriate. The orientation values were treated as axial data (0-180º) because they had been calculated automatically so there is no guarantee that the direction of orientation is correct. Parallel conformity was examined by calculating standard deviation of orientations of all drumlins within a 5 km grid square, using a standard formula for calculating the standard deviation of vector data (Mardia and Jupp, 2000). This gives a value between 0 and 1, with higher values representing similarity between drumlin orientations and hence high levels of parallel conformity. If grid squares contained fewer than three drumlins the standard deviation was not measured.

The locations of superimposed drumlins and other subglacial bedforms were recorded in a shapefile as two lines representing flow pattern directions. Figure 5.6 in the preceding chapter shows the location of cross cutting lineations. This was used to aid flowset differentiation and later in flowset classification (section 6.2.2).

Figure 6.4 shows the composite landforms and cartographic summary of fs6 in the Moray Firth. This flowset was relatively straightforward to identify because it is not overprinted and exhibits a 'classic' flow pattern topology of converging ice flow. Lineations are parallel and smoothly change in size along the length of the interpreted flow line. In contrast, recurrent or multigenerational ice flow with only minor differences in flow direction poses a particular identification problem. It is very difficult to tease out distinct events. In the Vale of Eden there are several generations of very similar flow directions, but different drumlin populations are indicated by mixture of morphometries and superimposed landforms (figure 6.5). Topography appears to have a strong effect on ice flow patterns of the last British Ice Sheet (figures 6.6 and 6.7).

The interpreted flowsets are presented in table 6.1 and Map 4 (figure 6.8). The flowsets are numbered and coloured arbitrarily. A reduced version of the map is shown in figure 6.8. One hundred flowsets were identified. It is not possible to describe in detail the delineation of each flowset in turn. Instead, the characteristics of each flowset and the security of identification and classification (section 6.2.2) are listed in table 6.1. Most problematic areas for flowset identification are where there appear to be several recurrent generations of ice flow in broadly similar directions e.g. central valley of Scotland. In the early stages of flowset identification the tendency was to separate subtle changes in flow patterns. Later as the flow patterns were considered at smaller scales flow patterns were combined and amalgamated. Flowset identification was reassessed and revised many times with the initial 145 flowsets rationalised to the final total of 100. It is important to state that the final total of an even century is purely happenstance; this was not a target number.

Flowset delineation is a subjective process. Attempts have been made to automate the organisation of lineation patterns into flowsets (e.g. Smith, 2003). However, to date none of these has proved an adequate replacement for the human eye. The morphometry and direction checks serve to bolster flow pattern groupings although it is acknowledged that different observers may produce some differences in flowsets from the same data. Discussion with colleagues and other glacial geomorphologists experienced in the delineation of flowsets from former ice sheet beds ('flowset-ologists') about flow pattern groupings was conducted in an attempt to minimise this. It is reassuring in this regard that the flowset map (Map 4) reproduces some of the same major ice flow patterns that have previously been suggested for the last British Ice Sheet (figure 2.11) and that in the majority of situations different observers produce similar flowsets.

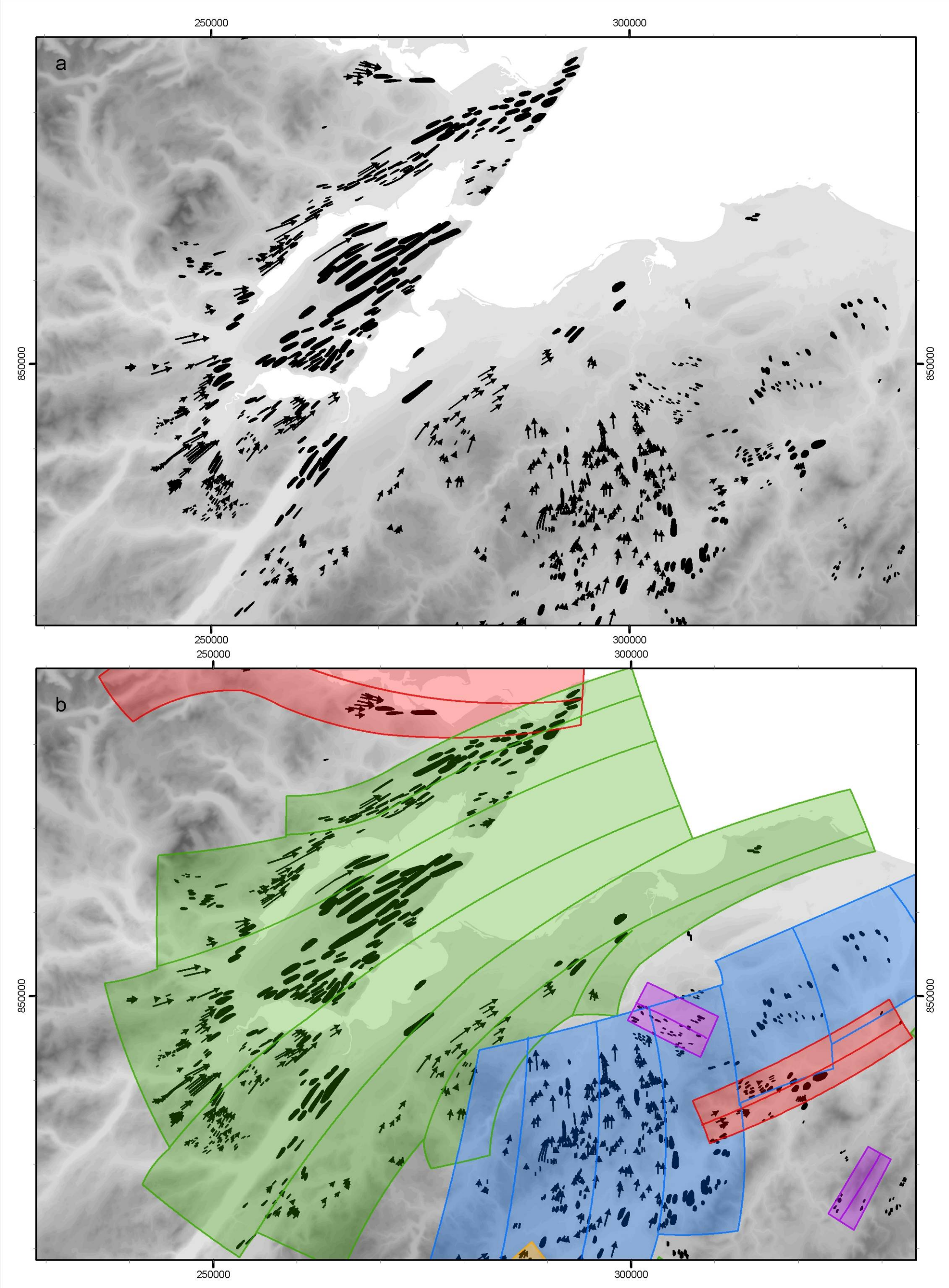


Figure 6.4 Example of interpreted flowset (b) and composite landforms (a). This is fs6 in the Moray Firth (green). The flow pattern converges into the mouth of the Firth. There are some minor orientation differences between drumlins and crag and tails within the flowset but overall the flowset shows high parallel conformity and is classified as an isochronous flowset (see section 6.2.2).

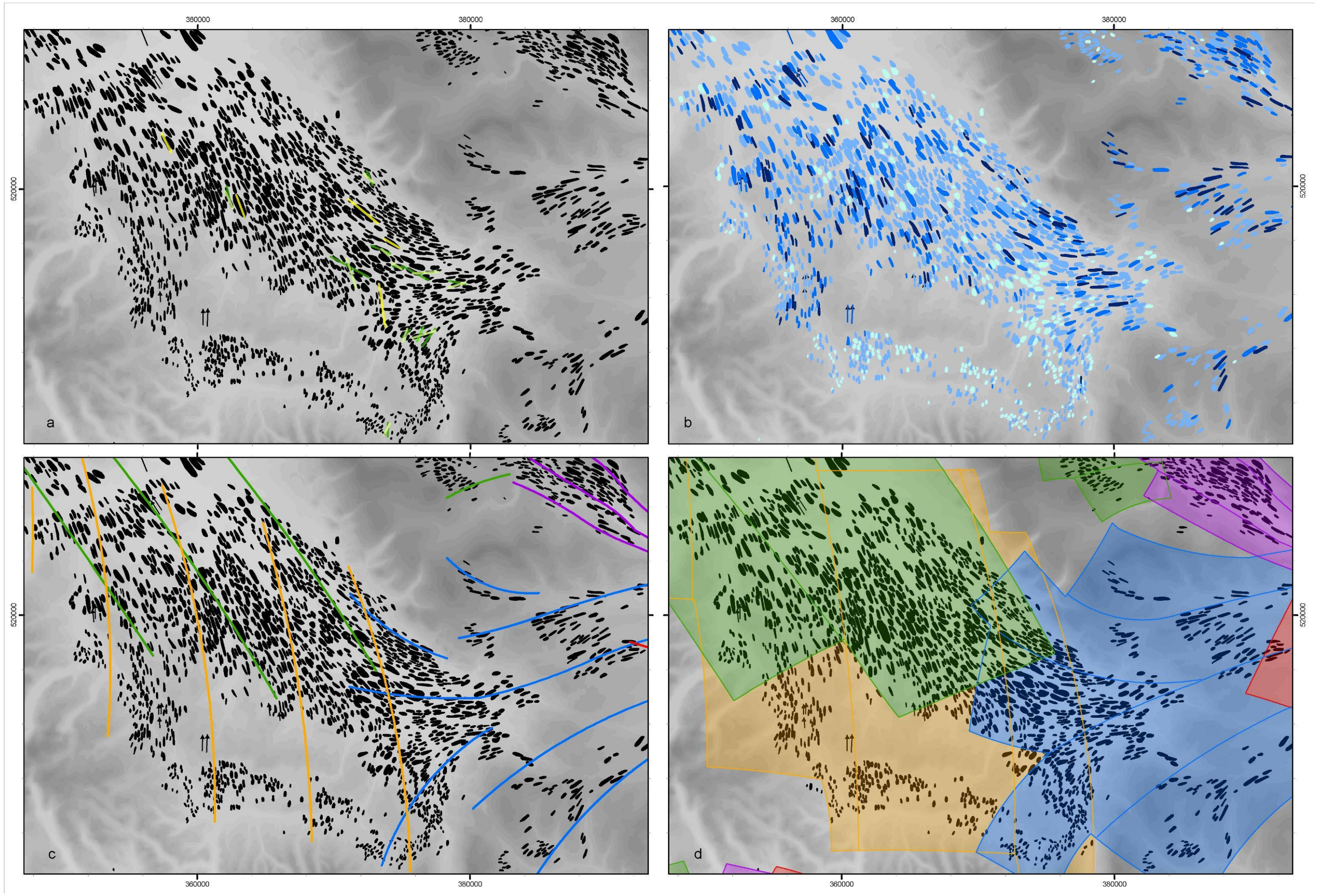


Figure 6.5 In the Vale of Eden flowset delineation was more taxing than in other areas and as illustrated by the example shown in figure 6.2. Superimposed drumlins (a) and a mixture of drumlin morphometries (b) suggest that the drumlin field is made up of more than one population of drumlins. However, there is little orientation difference between drumlins which makes it difficult to tease out discrete flow events. On the basis of differences in drumlin morphometry and careful consideration of flow patterns and drumlin superimposition three flowsets are identified (fs99 = green, fs66 = orange, fs15 = blue) (c and d).

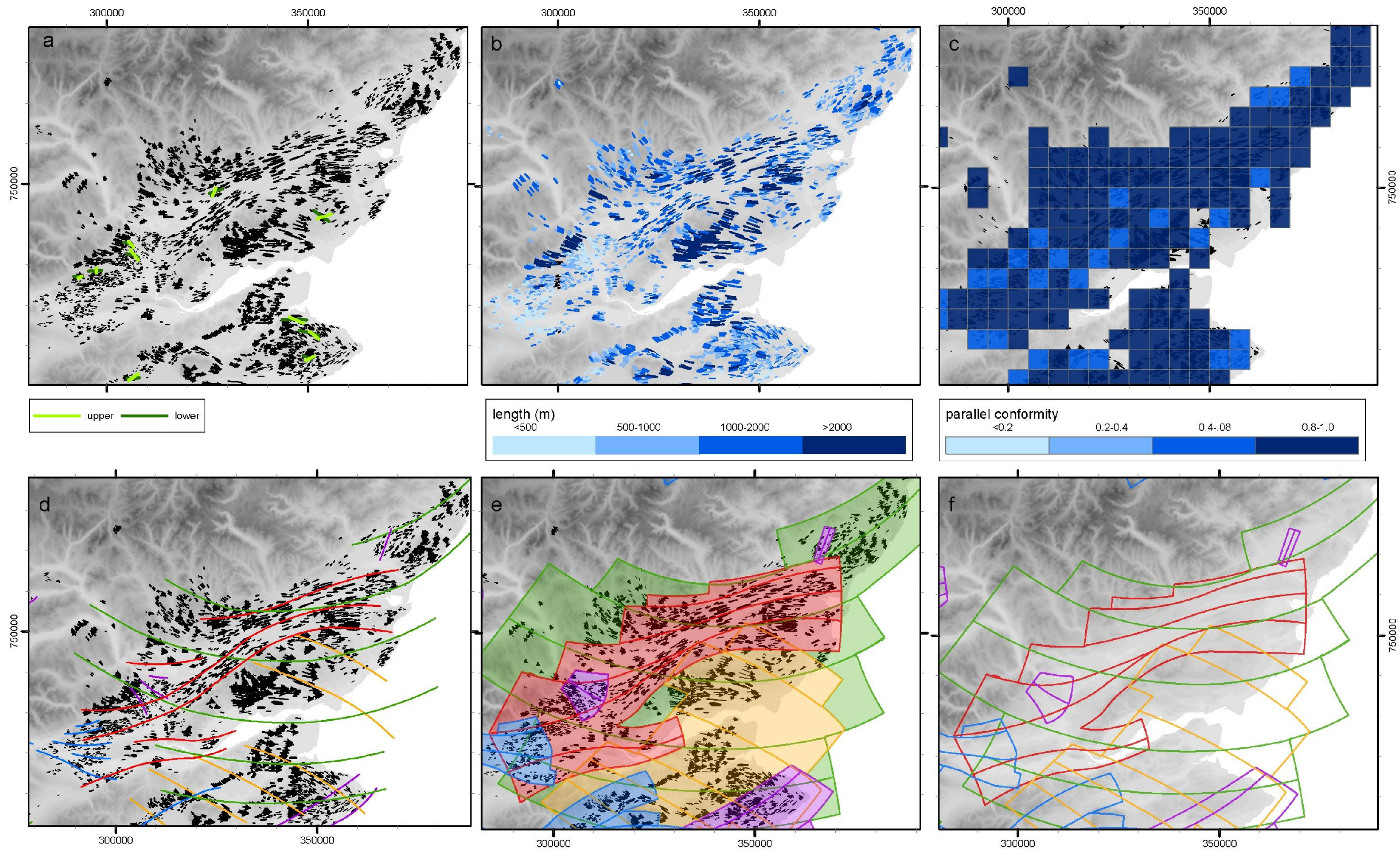


Figure 6.6 Topography appears to have a strong influence on flow patterns. This example is from Strathmore in eastern Scotland. Lineation map and cross-cut locations (a). Drumlins and crag and tails coloured up by length (b). Parallel conformity in Strathmore breaks down in the southwest of the image and along the Sidlaw Hills (c). Five flowsets are identified in this area fs51 = green, fs45 = red, fs7 = orange, fs50 = purple, fs49=blue (d-f). Fs51 and fs7 are independent of topography whereas fs45 is deflected around the Sidlaw Hills. Fs50 and fs49 comprise shorter drumlins (b) and are likely to be related to retreat of ice into the higher ground.

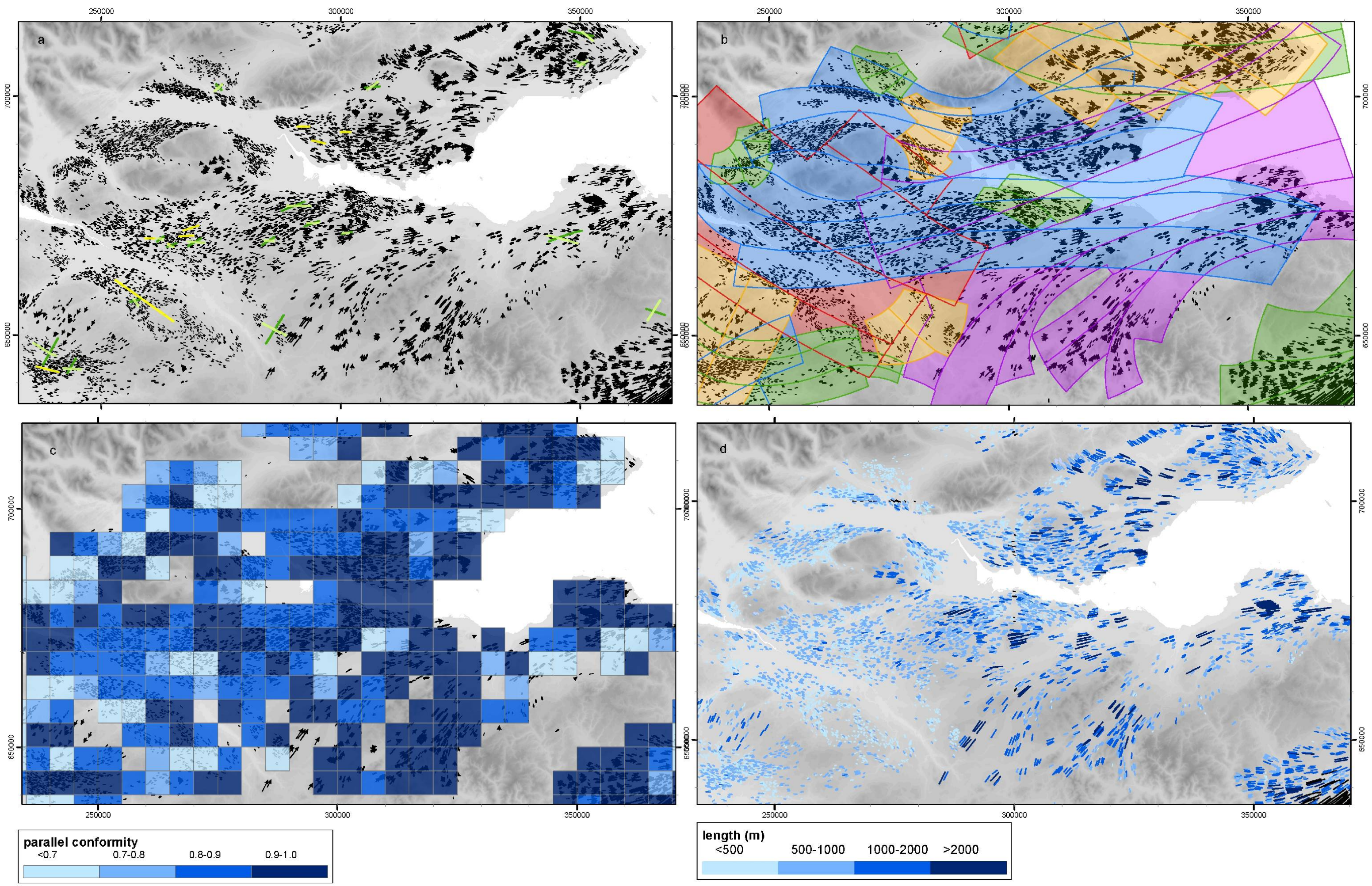


Figure 6.7 The Central Valley of Scotland contains a high density of drumlins. There are numerous sites of crosscutting and a wide range of drumlin morphometries (a and d). The parallel conformity in this area is generally high (>0.7) (c) and >0.9 around the mouth of the Firth of Forth. Drumlin lengths also increase in the eastern half of the image close to the mouth of the Firth (d). Eight flowsets are identified in this area. The largest is fs19 which runs broadly W-E into the Firth of Forth (purple). Superimposed on this ice flow is fs45 which weaves around the topographic obstacles of the Ochill Hills and Campsie Fells

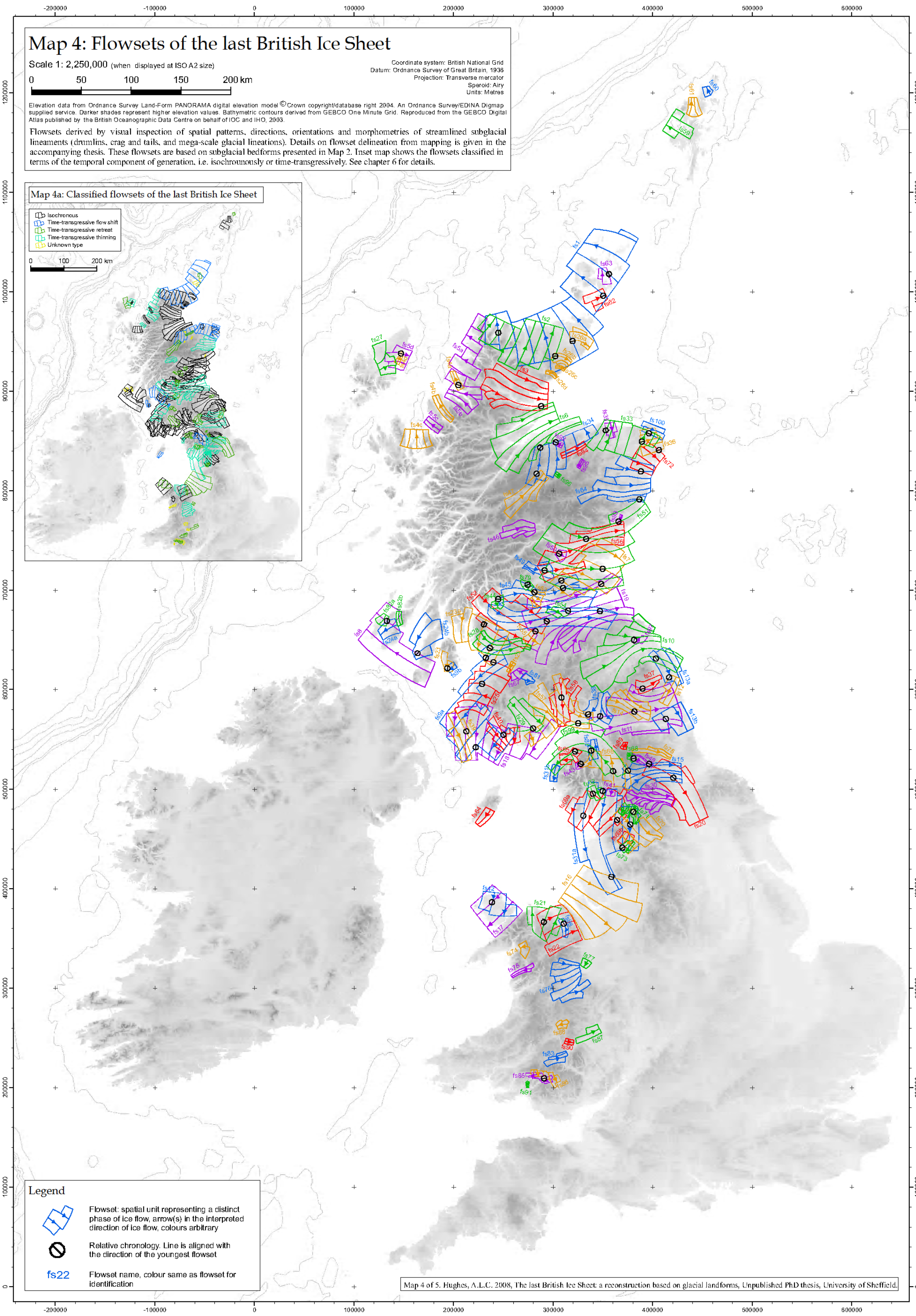


Figure 6.8 Map 4 enclosed with this thesis in the accompanying folio. Flowset colours are arbitrarily chosen to distinguish flowsets where they overlap. The inset map shows the flowsets coloured up by type.

Table 6.1 Interpreted flowsets for the last British Ice Sheet derived from countrywide mapping of subglacial lineations (drumlins, crag and tails and mega-scale glacial lineations). Map 4 shows the location of flowsets identified by flowset number. Procedure for classification of flowsets into different types e.g. time transgressive (TT) or isochronous (ISO) is described in section 6.2.1. Determination of relative age is detailed in section 6.8.Relative age is expressed in the style of a fraction, e.g. 1,3/2 indicates that fs1 and fs3 are younger than fs2.The 6th column describes the relationship of the flowset to other landforms.

Flowset No.	Type	Ice stream	Description	No. of lineations	Aligned meltwater and/or ice contact landforms	Erratics	Relative age
1	TT flow shift		Large flowset over Northern Scotland and Orkney independent of topography. Merged from two previous flow pattern groupings. Long, elongate drumlins with high parallel conformity, less clear lineations in the west. In east matches limit of shelly till on Caithness. Minor fluctuations in orientation within the flowset between NNW-SSE to NE-SE. Streamlined bedrock supports flow direction. Figures 6.2 and 6.12	Many 100+	Subglacial meltwater aligned	Shelly till over Caithness and Orkney picked up by flow over Moray Firth and North Sea. Same orientation as erratic trains of Scarlet conglomerate from Wick	**1**/2
2	ISO		'Feels' topography in northeast. Aligned with erratic transport paths. Ribbed moraine in same direction (rm13). Large flowset independent of topography. Streamlined bedrock supports flow direction	Some 30+	Eskers aligned but confined to valley bottoms, unlikely to be contemporary with flowset.	Flow direction supported by erratic train from granite outcrop; erratics could be used to extend flowset to east.	1,3 / **2**
3	ISO		'Feels' topography. Convergent flowset towards the coast. No cross cuts within flowset. Drumlin size large. Ribbed moraine aligned in same direction underneath. Erratic transport path aligned, and possibly suggests that flowset extends to south but no preserved lineations. Streamlined bedrock supports flow direction. Figure 6.10.	Few 20+	Eskers at coast but not contemporary; submarginal meltwater channels aligned	Erratic train supports flow direction, outcrop at head of flowset; Inchebae augen-gness erratic transport paths could extend flowset to S over Os tile NH and western part of NJ	6/**3**/2
4a, b c, d	ISO	Tributary of Minch Ice Stream	Flowset supported by streamlined bedrock aligned in same direction. Highly elongate drumlins and crag and tails. By location supports Minch Palaeo-Ice Stream (Stoker and Bradwell, 2005). Flowset may represent tributaries of ice stream after Bradwell et al. (2007). Flow patterns orientated approximately due north into The Minch grouped together over the 'empty' area of evidence offshore. Streamlined bedrock supports flow direction and extends flowset.	Few 10+	-	Shelly till on tip of Lewis indicates flow over Minch before deflection to NW; Erratics support ice flow direction westward.	5/**4**
5	TT thinning		Takes account of topography and contains discordant and cross cutting lineations. High length and elongation ratios. Supported by streamlined bedrock. Some of crag and tails within flowset point in the opposite direction to the rest of the composite lineations.	Few 10+	-	Torridonian sandstone outcrop and erratic trains define eastward limit of flowset	**5**/4
6	ISO	Moray Firth Ice Stream	Convergent flow lines into the Moray Firth supports concept of the Moray Firth Ice Stream. Constrained by topography. High elongation ratios. Contains very large drumlins. Can be extended to southwest by streamlined bedrock. Figure 6.5.	Many 100+	Eskers aligned, but presume not contemporary due to 'rubber stamped' nature of lineations; subglacial meltwater aligned; marginal channels along southern edge not contemporary	Granite outcrop and associated erratic transport supports flow direction.	**6**/3

Flowset No.	Type	Ice stream	Description	No. of lineations	Aligned meltwater and/or ice contact landforms	Erratics	Relative age
7	ISO		High parallel conformity. Mainly crag and tails. Large flowset independent of topography. Streamlined bedrock supports flow direction. Figure 6.7.	Some 50+	Subglacial meltwater aligned	-	**7**/19 unclear relationship with fs51
8	ISO	North Channel Ice Stream	High parallel conformity. Mainly crag and tails. Location suggests could be part of hypothesized North Channel Ice Stream. Documents major WNW ice flow. Streamlined bedrock supports flow directions.	Some 50+	-	Granite erratics in same direction as flowset (Glen Fyne and others), Ailsa Craig microgranite could extend flowset to southwest.	82/24/**8**
9	ISO		Variety of lineation sizes. Large ice flow pattern independent of topography. Could be contemporary with fs24. Streamlined bedrock supports flow direction.	Many 200+	Subglacial meltwater aligned	Sedimentary outcrop erratics support flowset direction; Loch Doon granite and Cairnsmore of Fleet granite supports flow direction.	25,23,39,18/ **9** Unclear relationship with 40
10	ISO	Tweed Ice Stream	Tweed Ice Stream, Only location of MSGL in Britain. Path offshore unclear as overprinted close to the coast. Topographically constrained. Convergent flow lines typical of ice stream track and systematic change in lineation length along flow line. Streamlined bedrock supports flow direction and extends to southwest. Could be connected to fs13. Figure 6.17.	Lots 1000+	Eskers superimposed during retreat, not contemporary. Subglacial meltwater aligned	Cheviot granite and unspecified outcrop erratics support flowset	97/**10** Unclear relationship with 13
11	TT thinning		Large east-west flowset over top of Pennines. Cross cuts suggest changes in local flow directions as ice sheet thins and takes more account of topography. High length values. Streamlined bedrock supports flow direction but caution as accentuated by geological structure. Location of hypothesised Tyne Gap Ice Stream. Figure 6.12.	Lots 1000+	Subglacial meltwater aligned	-	13,14/**11**
12	TT retreat		Direction of ice flow onshore. Only based on a few drumlins.	Few <10	Aligned with esker.	-	**12**/13
13a, b	ISO		High parallel conformity. Only based on a few drumlins, odd flow direction down east coast, possibly related to fs10 as bends around Cheviots. Streamlined bedrock supports flow direction	Some <50	Subglacial meltwater aligned	-	**13**/11, Unclear relationship with 10
14	ISO		Venturi style flow pattern. High parallel conformity, close spacing and spindle shaped drumlins. Surge type fan of Kleman and Borgström (1996). Streamlined bedrock supports flow direction. Figure 6.10.	Many 100+	Subglacial meltwater aligned	-	**14**/11
15	TT thinning		Ice flow through Stainmore Gap, some smudging and cross cuts at entrance to Stainmore Gap. Streamlined bedrock supports flow direction. Figure 6.6	Many 100+	Subglacial meltwater aligned	Shap granite extends flowset to W and N; Bluecaster dolerite supports ice flow direction	48,20,99,66/ **15**
16	TT retreat		Lobate pattern, very feint drumlins, aligned with moraines.	Few <25	Lobate pattern concordant with moraines.	-	**16**/21,31

Flowset No.	Type	Ice stream	Description	No. of lineations	Aligned meltwater and/or ice contact landforms	Erratics	Relative age
17	ISO		High parallel conformity. Flowset covers whole of Anglesey. Streamlined bedrock supports flow direction and extends flowset to southeast.	Some 50+	-	Shelly till extends flowset to Llynn Peninsula	42/**17**
18	TT flow shift		Ice flow converges into northern Irish Sea. Some smudging of flow patterns and minor fluctuations in orientation. Streamlined bedrock supports flow direction. Possible link to fs17 and fs99 and fs84.	Lots 1000+	-	Cairnsmore of Fleet granite supports flow direction	39,29,40/**18**/9
19	TT thinning	Forth Ice Stream	Convergent flowset into Firth of Forth. High parallel conformity. Initially thick (thin) ice then takes more account to topography as ice thins (thickens). Tributaries to main flowset are discordant where join main trunk of flowset. Streamlined bedrock supports flow direction. Unclear how far west flowset starts. Postulated as a palaeo-ice stream. Figure 6.8 and 6.14.	Many 100+	Eskers aligned along tributaries.	Loch Doon erratics and other transport paths follow flowset direction	45,55, 52/**19**/7 Unclear relationship with 51.
20	TT retreat		High parallel conformity as flow constrained along Vale of York. Drumlins exhibit variations in orientation suggesting smudging.	Some 50+	Eskers aligned, and concordant with moraines.	Shap granite reaches Vale of York indicating source for flow in Lake District	**20**/15
21	TT thinning		High parallel conformity with some variation as 'feels' topography along Vale of Conwy.	Some <50	Subglacial meltwater aligned	Arenig erratics support flow direction	**21**/22
22	ISO		Independent of topography. Streamlined bedrock supports flow direction and extends flowset to west.	Some 50+	-	-	21/**22**
23a, b, c	TT flow shift		Some cross cuts on Arran. 'Feels' topography as converges as flows offshore. Streamlined bedrock supports flow direction	Many 100+	Eskers aligned along tributaries. Subglacial meltwater aligned	Erratics support flow direction	28,25/**23**/9, 52
24a, b	ISO		Could be westward extension of fs9, except that this flowset converges into lower ground offshore. Streamlined bedrock supports flow direction	Few 25+	Eskers aligned, and concordant with moraines. Lateral meltwater channels along edges	Glen Fyne granite extends flowset to N and indicates source area; Ailsa Craig microgranite extends flowset to south.	82/**24**/8
25	TT thinning		Underlain by ribbed moraine, direction supported by erratics, some cross cuts within flowset. Smudging and diversion around minor topographic bump. Streamlined bedrock supports flow direction	Many 100+	Aligned esker Subglacial meltwater aligned.	Loch Doon granite erratics in same direction as flowset	**25**,18/9
26a, b, c, d	ISO		Group of spatially distant flowsets, topographically controlled. Very high parallel conformity. Drumlins are very 'flat', with many less than 2 m high.	Some < 50	Subglacial meltwater aligned	-	**26**/1
27	TT retreat		Based on streamlined bedrock rather than drumlins, divergent lobate pattern out from high ground on Lewis.	Few <5	Subglacial meltwater aligned	-	-

Flowset No.	Type	Ice stream	Description	No. of lineations	Aligned meltwater and/or ice contact landforms	Erratics	Relative age
28	ISO		Very high parallel conformity, no cross cuts, follows topography. Relatively short closely spaced drumlins.	Many 100+	Esker on top	Shelly till and sedimentary outcrop erratics extend flowset to south	**28**/23,9
29	TT retreat		Lobate pattern, difficult to resolve into individual flowsets. Figure 6.12.	Some 50+	-	Cairnsmore of Carsphairn granite in same flow direction	**29**/57
30	TT thinning		Rubber stamped pattern in main valley, but cross cuts in tributaries and higher reaches. Not concordant with moraines in the valley and therefore presumed not contemporary. Convergent ice flow along Wensleydale. Streamlined bedrock supports flow direction. Figure 6.13.	Some 50+	Esker and moraines superimposed, subglacial meltwater aligned, lateral meltwater channels along margins	-	**30**/20
31 a, b	TT thinning		Very large flowset, 'feels' topographic bump of Forest of Bowland. Supported by ribbed moraine (rm9) to north of Forest of Bowland. Streamlined bedrock supports flow direction. Fs31b tentatively grouped with fs31a.	Some 50+	Esker on top Lateral meltwater channels along edges	Criffel granite erratics reach Cheshire lowlands extending flowsets	69,70,41,16/ **31** Unclear relationship with 69
32	TT retreat		Small flowset, constrained by topography	Few <20	-	-	41/**32**/69
33	TT flow shift		Ignores topography, Some discordance and cross cuts. Streamlined bedrock supports flow direction	Some <50	Subglacial meltwater aligned	Bin Hill gabbro and maud diorite erratics in same direction as flowset; netherly diorite extends flowset to west	64,34,35,36/ **33**
34	TT flow shift		Large flowset independent of topography. Could be separated into two separate flowsets. Streamlined bedrock supports flow direction.	Few <25	-	Extends flowset to south, indicating source in Cairngorms	6,47,92,96/ **34**
35	ISO		Very high parallel conformity, small flowset. Flow direction by crag and tails is onshore from the Moray Firth. This is odd but consistent with erratic transport paths	Few <25	-	Odd flow direction towards southeast supported by and extended by Bin Hill gabbro and Blairshinnoch amphibolite erratics	**35**/33
36	ISO		On balance ISO classification due to lack of cross cuts and high parallel conformity. Streamlined bedrock supports flow direction	Some <50	Subglacial meltwater aligned	Peterhead granite in opposite direction	**36**/72, 33
37	ISO		Constrained by topography, few discordances Streamlined bedrock supports flow direction	Some <50	-	-	**37**/11
38	TT retreat		High parallel conformity could be linked to fs14, possible to separate into 2+ flow patterns. Topographically constrained. Emerges out of valley in elephant foot lobate pattern.	Few <25	-	-	**38**/11,57
39	ISO		Very high parallel conformity, ribbed moraine aligned underneath, constrained by topography.	Some <50	Esker on top Subglacial meltwater aligned	Shelly till indicates source for ice flow over offshore area	**39**/18

Flowset No.	Type	Ice stream	Description	No. of lineations	Aligned meltwater and/or ice contact landforms	Erratics	Relative age
40	ISO		Link to fs39 possible. Constrained by topography. Converges into Irish Sea.	Some <50	Esker on top Subglacial meltwater aligned	-	**40**/18 unclear relationship with9
41	TT retreat		Possibly part of fs69. Very small flowset.	Some 50+	-	-	**41**/32/69
42	TT retreat		Splayed pattern over the northern half of Anglesey.	Many 100+	-	Shelly till on Anglesey suggests ice flow from Irish Sea	**42**/17
43	TT retreat		Retreat back into Lake District. Small flowset within central Lake District, constrained by topography.	Few <10	-	-	**43**/66
44	ISO		Lobate pattern, meets moraines, high parallel conformity, fits exactly within Loch Lomond limit, therefore probably relates to this phase	Some <50	-	-	**44**/45
45	ISO		'Feels' topography, relatively thin ice as ice flows around topographic bumps. erratics support direction. Streamlined bedrock supports flow direction. Figure 6.8 and 6.14.	Lots 1000	Lateral meltwater channels along edges Submarginal channels aligned	Loch Doon erratics and other transport paths follow flowset direction	79,54,44/**45**/ 51,19
46	TT thinning		Only made of crag and tail features. Erratics are in same direction. Follows topography but difficult to classify. Streamlined bedrock supports flow direction	Few <20	-	Rannoch granite erratics in same direction as flowset indicate source area	-
47	TT retreat		Few drumlins, aligned with moraines. Streamlined bedrock supports flow direction. Some of the crag and tails in this flowset are in the opposite direction to interpreted flow direction.	Few <20	Subglacial meltwater aligned	Rannoch granite erratics in same direction as flowset indicate source area	**47**/34
48	ISO		Very small flowset within valley.	Few <20	Aligned with moraines. Subglacial meltwater aligned	-	68/**48**/15
49	TT retreat		Topographically constrained flowset containing cross cuts. Figure 6.7.	Few <20	Aligned with Esker	-	**49**/56
50	TT retreat		Small flowset, small drumlin sizes. Figure 6.7.	Few <25	-	-	**50**/56
51	ISO	Strathmore Ice Stream 1	Ignores topography, could be TT flow shift, as there are some minor fluctuations in orientations within the flowset. Ice stream on basis of high length values but very wide and lacks abrupt margins and convergent ice flow patterns. Streamlined bedrock supports flow direction. Figure 6.7.	Many 100+	Subglacial meltwater aligned	Erratics extend flowset to southwest and south; granite erratics and shelly till on coast to N of Aberdeen suggest deflection of flow N along coast	45/**51**/19,93 unclear relationship with7
52	TT thinning		Constrained by topography goes around bump, possible link to fs51. Streamlined bedrock supports flow direction. Some smudging. Large flowset independent of topography in places. Has some characteristics of TT retreat. Figure 6.8.	Many 100+	-	-	**52**/19

Flowset No.	Type	Ice stream	Description	No. of lineations	Aligned meltwater and/or ice contact landforms	Erratics	Relative age
53	TT retreat		Lobate pattern, small drumlins, some minor orientation changes. Figure 6.8.	Some <50	Aligned esker	-	**53**/45
54	ISO		High parallel conformity and small drumlins at mouth of the River Forth. Figure 6.8.	Some <50	-	-	**54**/45
55	TT retreat		Splays out in lobate pattern. Limited size but not constrained by topography. Figure 6.8.	Few <25	-	-	**55**/19
56	ISO	Strathmore Ice Stream 2	Controlled by topography, possible ice stream – convergent ice flow and high elongation ratios of lineations. Streamlined bedrock supports flow direction. Flow is diverted around topographic bumps. Figure 6.7.	Many 50-100	Lateral meltwater channels along edges	-	50,49/**56**/51
57	ISO		High parallel conformity, variety of drumlin dimensions, possibly two flowsets on basis of drumlin populations. Postulate that is westward extension of fs11. Gap in drumlins in eastern Solway lowlands and difference in relative size between two flowsets suggests against this. Streamlined bedrock supports flow direction.	many 100+	Subglacial meltwater aligned Lateral meltwater channels along edges Submarginal channels aligned	Criffel granite in same direction as flowset; could suggest extension into northern Lake District	58,99/**57**
58	ISO		Topographically constrained in valley, but no cross cuts and highly parallel conformable. Streamlined bedrock supports flow direction. Convergent ice flow out of the Southern Uplands. 'Feels' topography.	Many <100	Esker on top	-	**58**/57
59	ISO		Could be part of fs1, or part of independent ice cap on Shetland. Supported by streamlined bedrock.	Few <25	-	-	**-**
60	TT retreat		Could be extended with use of streamlined bedrock, some smudging, possible outlet glacier as converges into Yell Sound. Streamlined bedrock supports flow direction	Few <20	Subglacial meltwater aligned	-	-
61	ISO		Topographically constrained into Bluemill Sound. Streamlined bedrock supports flow direction	Very few <10	-	-	-
62	unknown		Strange direction, no equivalent on mainland, based on speculative drumlins and crag and tails.	Very few <10	-	-	**62**/1
63	TT retreat		Some smudging. Based on small collection of drumlins.	Very few <10	-	-	**63**/1
64	TT thinning		Cross cuts and smudging. Streamlined bedrock supports flow direction	Many 100+	Aligned esker in parts; subglacial meltwater aligned	Source in Cairngorms; granite erratics extend flow direction to W	**64**/72, 51
65	TT retreat		Some smudging. Could be tributary of fs99.	Few <20	-	-	**65**/99
66	TT flow shift		Aligned esker and smudging could indicate TT retreat. Streamlined bedrock supports flow direction. Variety of drumlin sizes and morphometry in the Vale of Eden suggests that there are more than one flow event preserved. Similarity in overall orientation means that it is difficult to separate out events. Figure 6.6.	Many 100+	Aligned esker	-	43/**66**/99,15

Flowset No.	Type	Ice stream	Description	No. of lineations	Aligned meltwater and/or ice contact landforms	Erratics	Relative age
67	TT retreat		Small flowset, chaotic orientations with many cross cuts	Some <50	-	Spango granite and sedimentary erratics could extend ice flow to N	-
68	TT retreat		Topographically constrained and cross cuts. Very small flowset at head of valley.	Few <25	-	-	**68**/48
69a, b	TT thinning		ISO characteristics in parts, but contains cross cuts. Diverted around topographic bump of the Forest of Bowland. Streamlined bedrock supports flow direction	Many 100+	Esker on top Subglacial meltwater aligned	-	32,41,70,73/ **69**/31
70	ISO		High parallel conformity, ‘feels’ topography. Streamlined bedrock supports flow direction. Overlies ribbed moraine field (rm10).	Many 100+	Esker on top Lateral meltwater channels along edges	-	71,41,32/**70**/ 69
71	TT thinning		‘Feels’ topography and contains cross cuts, high parallel conformity, very dense drumlin population	Many 100+	-	-	**71**/70,31
72	TT flow shift		Minor orientation changes but otherwise high parallel conformity. Streamlined bedrock supports flow direction	Some 50+	-	-	36/**72** unclear relationship with 64
73	TT retreat		Small flowset.	Few <20	-	-	**73**/70/69
74	ISO		Constrained to valley, not cross cuts or variation in orientation.	Few <20	-	-	-
75	unknown		Based on speculative drumlins and valley orientation. Streamlined bedrock supports flow direction	Very few <5	-	-	-
76	TT thinning		Influenced by topography, some discordances, streamlined bedrock helps to extend flowset.	Many <100	Subglacial meltwater aligned	-	-
77	TT retreat		Aligned with moraine margins, although parallel conformity high.	Very few <10	-	-	-
78	ISO		High parallel conformity but constrained by valley. Streamlined bedrock supports flow direction	Few <20	-	-	-
79	ISO		Very high parallel conformity possibly connects with flowsets in Strathmore area (fs49). Overlies ribbed moraine aligned in same direction. Topographically constrained.	Some 50+	Lateral meltwater channels along edges Submarginal channels aligned	-	**79**/45
80	ISO		High parallel conformity and elongate drumlins. Uncertain relationship with fs66.	Few <20	-	-	**80**/99,66
81	TT retreat		Smudged flowset. Streamlined bedrock supports flow direction	Very few <10	Esker aligned	-	-
82 a, b	unknown		Uncertain direction. Topographically constrained and very small flowset based on only a few drumlins.	Very few <10	-	-	**82**/24
83	TT retreat		Based on speculative drumlins Streamlined bedrock supports flow direction	Some 30+	-	-	-

Flowset No.	Type	Ice stream	Description	No. of lineations	Aligned meltwater and/or ice contact landforms	Erratics	Relative age
84	TT flow shift		Low parallel conformity, limited number of drumlins, mapped from lower resolution DEM.	Few <20	-	Shelly till on north coast of Isle of Man extends ice flow to N	-
85	TT retreat		Partly based on speculative drumlins. Streamlined bedrock supports flow direction Topographically constrained.	Few <20	-	-	**85**/86
86	ISO possibly		Based on speculative drumlins. Topographically constrained.	Few <20	-	-	85/**86**
87	TT retreat		Based on speculative drumlins.	Few <20	-	-	**87**/90
88	TT retreat		Partly based on speculative drumlins Streamlined bedrock supports flow direction and extends flowset to southeast.	Few <20	-	-	-
89	TT retreat		Based on speculative drumlins Streamlined bedrock supports flow direction and extends flowset to northeast.	Few <20	-	-	-
90	Possibly ISO		Possibly more extensive Streamlined bedrock supports flow direction and extends flowset to north and northeast.	Few <10	-	-	87/**90**
91	TT retreat		Based on speculative drumlins and very small flowset.	Very few <5	-	-	-
92	unknown		Very small drumlins and small flowset. Direction odd in context of rest of flowsets in the area.	Few <10	-	-	**92**/34
93	unknown		Small flowset	Few <10	-	-	51/**93**
94	TT retreat		Constrained by valley, some questionable drumlins	Few <20	-	-	-
95	unknown		Small flowset, constrained by topography.	Few <10	-	-	-
96	unknown		Very small flowset, constrained by topography	Very few <5	-	-	**96**/34
97	TT retreat		Only a few drumlins of very small size.	Few <10	-	-	**97**/10
98	TT retreat		Constrained by topography. Streamlined bedrock supports flow direction	Few <10	-	-	**98**/22
99	ISO		Possible tributary of Irish Sea ice stream. Ice flow swings anticlockwise around the Cumbrian massif. Possibly TT flow shift as some minor changes in flow orientation. Elongate spindle drumlins. Streamlined bedrock supports flow direction. Figure 6.6.	Lots 1000+	Subglacial meltwater aligned Lateral meltwater channels along edges	-	66,65,80/**99**/ 57,15 unclear relationship with31
100	ISO		High parallel conformity, small flowset close to coast. Streamlined bedrock supports flow direction	Some <20	Esker on top	Shelly till in same direction	100/36

6. 2.1 Flowset classification

A key piece of information necessary to correctly interpret the glaciological implications of flowsets is the temporal component of generation. Flowsets can be formed either instantaneously or time-transgressively. Criteria for the differentiation of isochronous (ISO) and time-transgressive flowsets (TT) were listed in table 3.2. The ISO and TT categories should be considered as end members (Clark et al., 2000). The classification of flowsets as ISO or TT is allied to the identification of flowsets from flow patterns and the process may necessitate revisions in earlier flow pattern groupings and flowsets; for example, the rationalisation of two poorly defined flowsets with similar directions into a single time-transgressive flowset.

6.2.1.1 Isochronous flowsets

The simplest interpretation is that the composite lineations of a flowset were all formed at the same time, i.e. instantaneously, by the same flow event. Isochronous flowsets are typified by a 'rubber stamped' imprint consisting of highly parallel lineations, abundant flow traces, an absence of aligned meltwater landforms and cross cutting lineations, and systematic change in elongation ratio along the length of the flow line (Clark, 1999). Isochronous flowsets are a snapshot of part of the ice flow pattern configuration at a single point in time. Two types of isochronous flowset are recognised in the British context: ice flow independent of topography and ice flow deflected by topography (figure 6.9). Of the 100 flowsets identified, 37 are classified as isochronous.

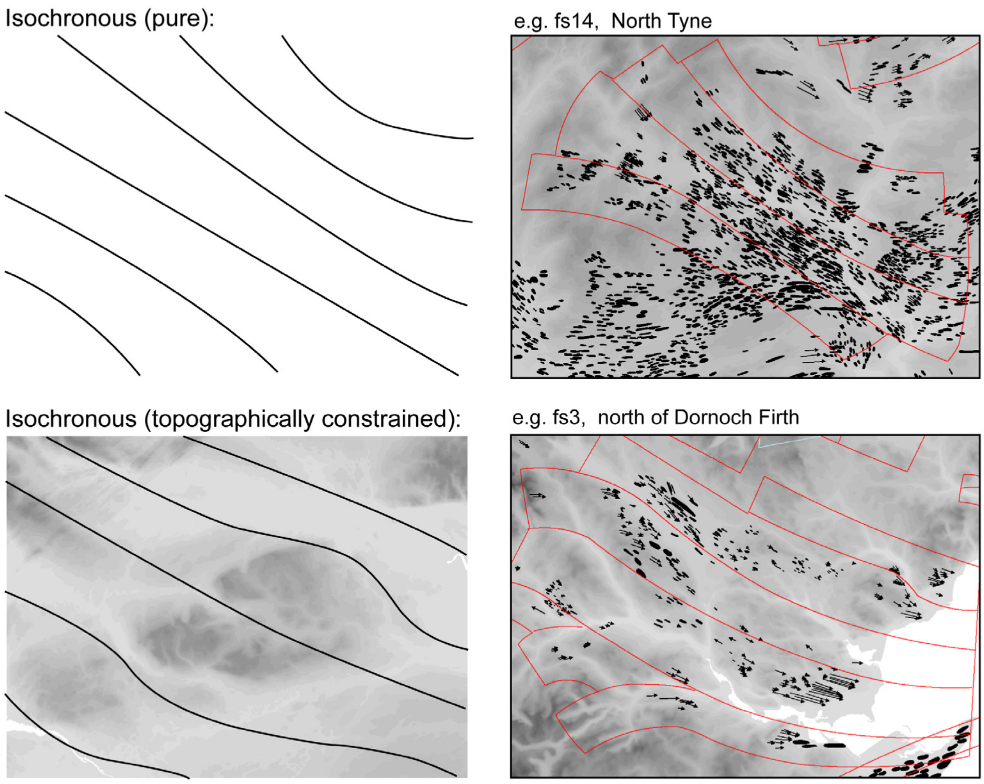


Figure 6.9 Two types of isochronous flowset are identified in Britain. 'Pure' isochronous flowsets are independent of topography; other flowsets contained kinked flow lines which are deflected around topographic highs at a local scale. There are no cross-cuts and the kinks are not discordant with the rest of the flow pattern.

6.2.1.2 Time transgressive flowsets: TT retreat, TT flow shift, TT thinning

Ideally, it would be possible to identify all flowsets as isochronous and therefore separate out all phases of ice flow. However the record is complex and fragmentary and so it is not always possible to do this. Changes in the ice flow configuration lead to remoulding of the subglacial landscape and result in 'smudged' imprints from several phases of ice flow. Where it is not possible to tease out individual ice flow events, the flowsets are described as time-transgressive (TT). Chapter 3 described three possible scenarios for cross-cutting or superimposed flow patterns (in addition to multiple glaciations). Theoretically all of these situations could lead to a smudged lineation imprint. The British context is distinct from Canada and Scandinavia, the former beds of the Laurentide and Fennoscandian Ice Sheets where the flowset approach was developed, because of the high variability in topography over short distances. The subglacial bedform map clearly reflects the distribution of topographic highs (Map 2, chapter 5). In some locations smudged flow patterns were observed that did not fit one of the three explanations above. When examined with topography a pattern started to emerge and that is consistent with what we would expect from ice sheets; topography of the bed will have a greater influence on ice flow when the ice is thin Therefore, we can imagine a fourth possible context for cross-cutting flow patterns and by extension smudged imprints: ice sheet thinning (or thickening) (figure 6.10). This is not a novel concept and was called 'deglacial flow' by Dyke and Morris (1988). In order to explain the flow patterns that have been observed in Britain additional conceptual categories are used to classify flowsets. In Britain TT flowsets exemplify three of the four possible glaciodynamic contexts (figure 6.11).

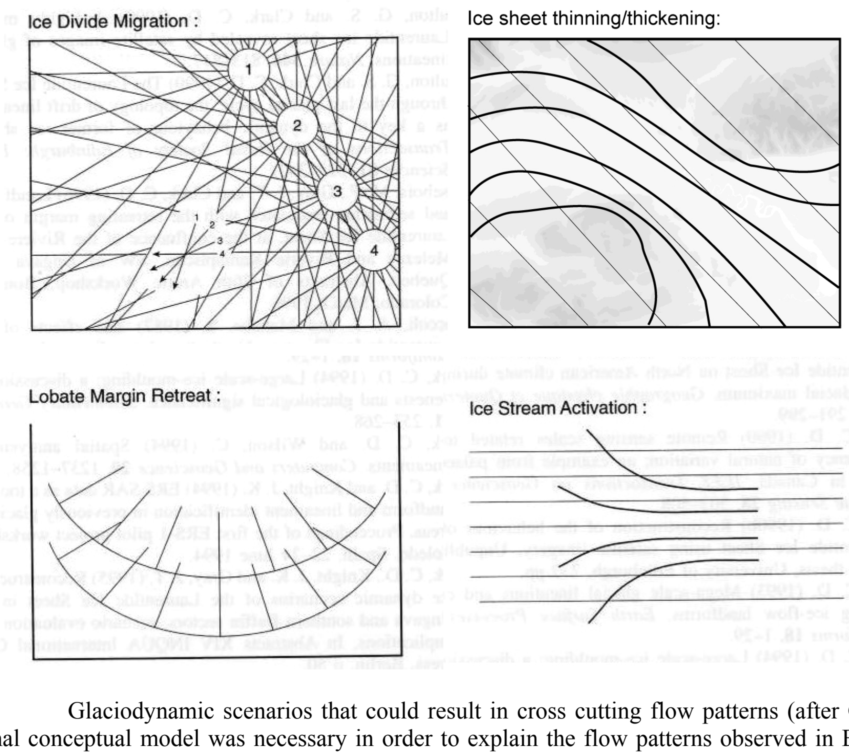


Figure 6.10 Glaciodynamic scenarios that could result in cross cutting flow patterns (after Clark 1997). An additional conceptual model was necessary in order to explain the flow patterns observed in Britain (ice sheet thinning). These conceptual models aid separation of discrete flow events from the glacial map. Where it is not possible to separate out flow events flowsets are recorded as time-transgressive, i.e. the combined result of two or more flow events. All of the above scenarios may be expressed as a smudged imprint.

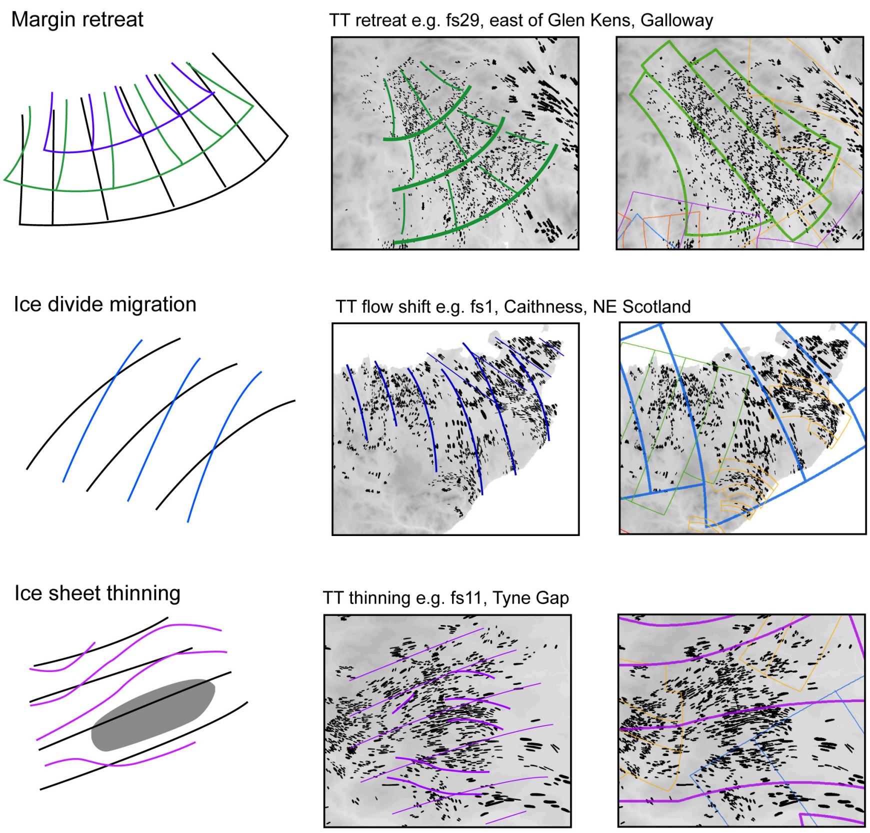


Figure 6.11 Types of time-transgressive (TT) flowset observed in Britain. *TT retreat* flowsets are a result of the bedform generation behind a retreating margin leading to a smudged imprint. This type of TT flowset may also be associated with eskers and moraines. *TT flow shift* are due to smudging of the bedform signature due to continual bedform generation during reorganisation of the ice sheet flow patterns. TT thinning flowsets are due to the increasing influence of topography on flow patterns as the ice sheet surface declines during deglaciation.

- TT RETREAT

Clark (1999) and Clark et al. (2000) suggested that TT flowsets represent lineations formed incrementally behind a retreating ice margin under thin ice and with rapidly varying flow directions. This would produce a smudged signature typified by lobate or splaying flow patterns, close accord with topography, cross cutting lineations, low parallel conformity, and abrupt and unsystematic variations in lineation morphometry. Here this is termed a *TT retreat* flowset. Such flowsets are usually aligned with meltwater and moraine landforms. Flowset number fs29 is an example of a *TT retreat* flowset (figure 6.11). Of the 100 flowsets, 32 are classified as *TT retreat*. We might expect that this flowset type should be the most common as the retreat of the ice sheet will always be the most recent phase of ice flow. The existence of older ice flow patterns must therefore be due to either cold-based retreat or rapid retreat without remoulding of the subglacial landscape.

- TT FLOW SHIFT

Subtle changes in ice sheet geometry during continual bedform generation will lead to a smudged or smeared imprint that reflects two (or more) flow patterns. If the change in ice sheet geometry was separated by a phase of cold based ice or a temporary pause in bedform generation it might be possible to separate out these two flow events but often it is not possible to do this. It is for this reason that the new category of *TT flow shift* is used. Fs1 is an example of this type of TT flowset (figure 6.11). Eight flowsets are classified as *TT flow shift*. This type of smudging was also recognised by DeAngelis and Kleman (2005).

- TT THINNING/THICKENING

This type of smudged imprint occurs when the surface of the ice sheet declines so that the topography of the bed can have a greater influence on local ice flow patterns. Generally the overall flow direction remains the same. Fs11 is an example of a TT thinning flowset (figure 6.11). Of the 100 flowsets 14 are classified as *TT thinning*. Fs19 is classified as a *TT thinning* flowset because of the 'tributaries' that join the southern half of the flowset obliquely (figure 6.12).

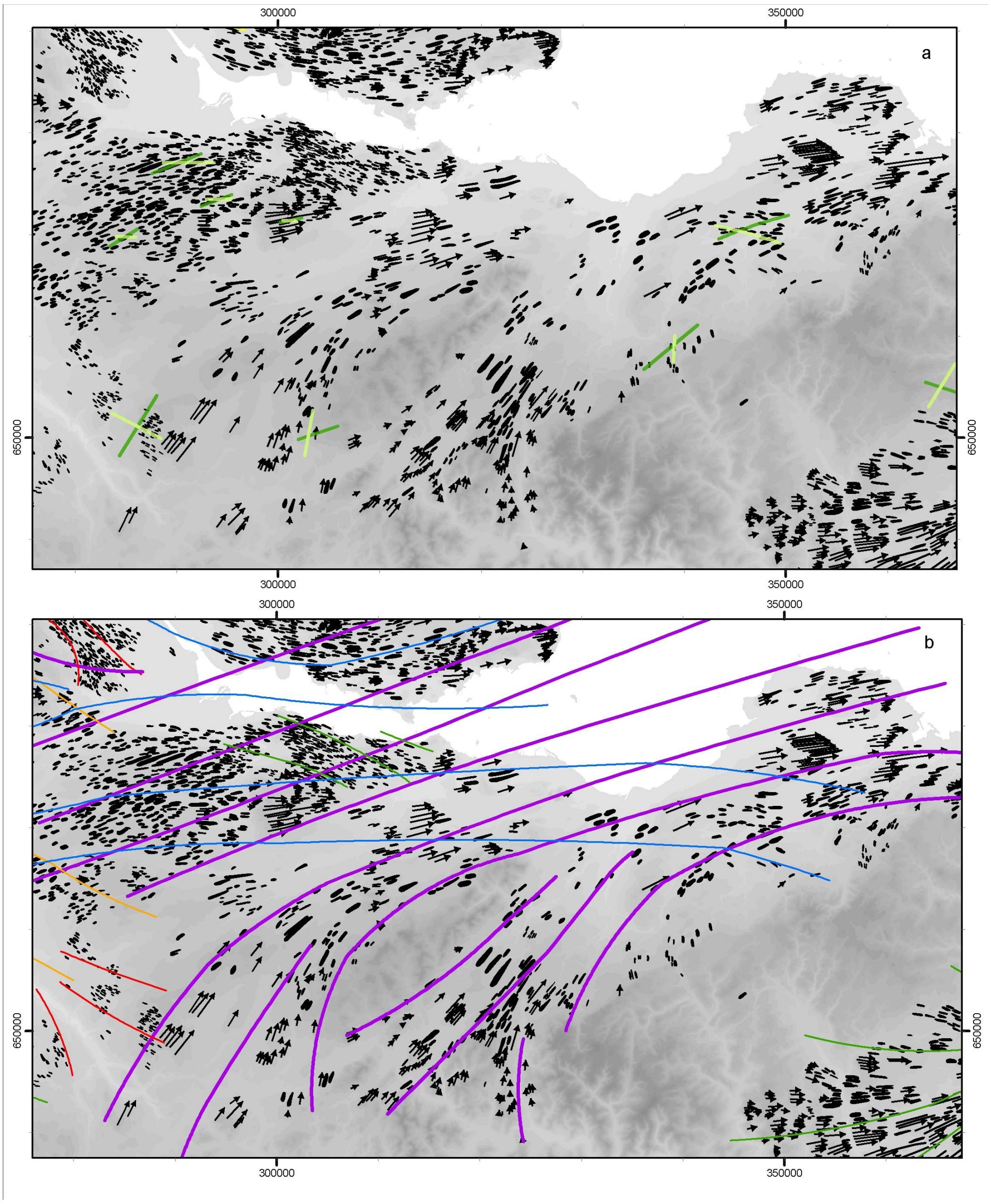


Figure 6.12 Fs19 in the Firth of Forth has tributary flow patterns that join the main trunk of the flowset obliquely and are slightly discordant as they join the main trunk. This flowset is classified as TT thinning because of this slight discordancy but would otherwise be an isochronous flowset.

Figure 6.13 shows the distribution of each type of flowset. This is also shown in the inset map on Map 4. Of the 100 flowsets, 9 could not be classified. This was typically because the low number of drumlins contained within the flowset was not sufficient to examine the differentiation criteria.

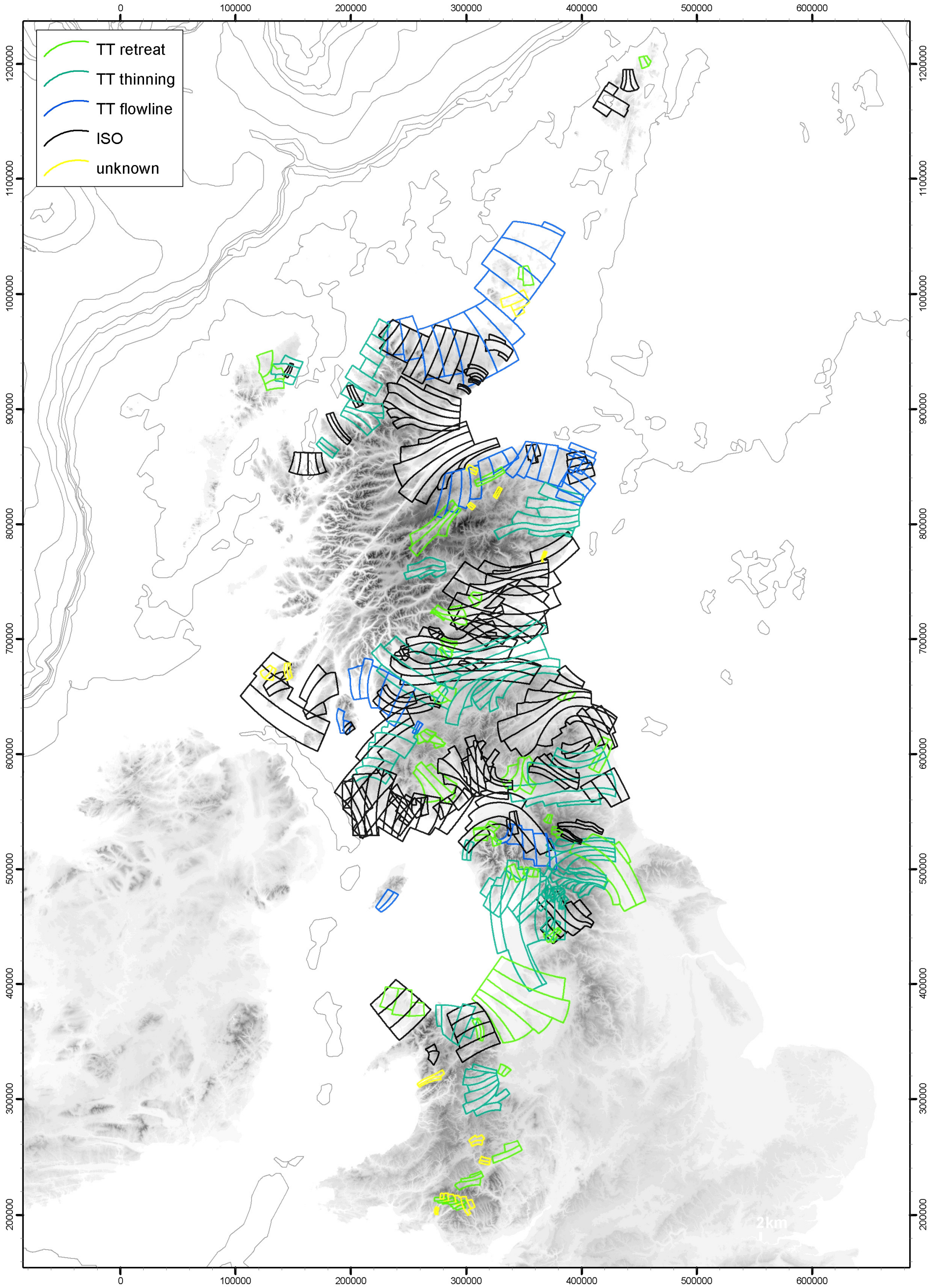


Figure 6.13 Map of flowsets classified by type.

6.2.2 Ice streams

Identification of the former tracks of palaeo-ice streams has been a major focus of research since the recognition of the strong control these anomalously fast flowing 'rivers' of ice have on the ice sheet mass balance/ablation of the Antarctic and Greenland ice sheets (Bennett, 2003). The location of former palaeo-ice streams will determine the major calving locations for icebergs and are therefore important in determining the effect of ice sheets on the ocean circulation system. The palaeo-ice stream landsystem (Stokes and Clark, 1999; Clark and Stokes, 2003) was used to identify the palaeo-ice streams of the last British Ice Sheet (table 3.3). Mega-scale glacial lineations, one of the eight geomorphological criteria, are only present in the Tweed basin. Shorter but morphometrically similar drumlins occur in the Solway. Figure 2.19 shows the locations of the ice streams that have been suggested for the last British Ice Sheet from the literature and table 2.1 lists these. Of the terrestrially based ice streams, only some are substantiated by the new mapping conducted by the author. The majority of ice streams lie offshore and therefore are unlikely to be represented in the terrestrial geomorphological record, unless we can identify possible tributaries or heads of ice streams without the main ice stream track. Figure 6.14 shows an example of palaeo-ice stream track from the Laurentide Ice Sheet.

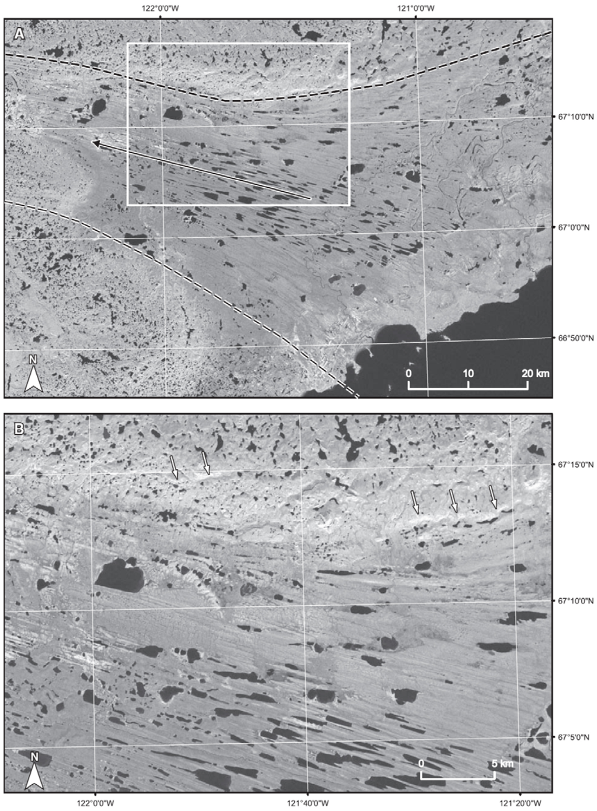


Figure 6.14 Landsat image of the Haldane palaeo-ice stream imprint. Top image shows ice stream extent defined by abrupt lateral margins (dashed black). The palaeo-ice stream track displays a characteristic broad onset zone converging to a narrow trunk. Arrow gives direction of ice flow. Bottom image is an enlargement of the boxed area to demonstrate the characteristic geomorphology used to identify palaeo-ice streams. Arrows indicate ice stream marginal moraine. Reproduced from Winsborrow et al. (2004).

Fs10 in the Tweed valley exhibits similar convergent ice flow patterns, high parallel conformity, abrupt margins, and highly elongate lineations (figure 6.15). This flowset is therefore designated as ice stream status. It is possible that the ice stream extends offshore. The Tweed Ice Stream, which bends south around the Cheviots could be part of the suggested surging lobe of ice in the southern North Sea that impinges on the North coast of Norfolk. This is speculation and would require additional evidence, and the dimensions of the ice stream appear too small to be capable of extending such a distance. The Minch palaeo-ice stream suggested from the identification of elongate lineations in the Minch in seismic data and the presence of the Sula Sgeir fan (Stoker and Bradwell, 2005) is supported by the highly parallel and convergent flow patterns into the Minch exhibited by fs4. Bradwell et al. (2007) also suggest that the lineations and streamlined bedrock comprising this flowset are likely tributaries of the Minch Ice Stream. Golledge and Stoker (2006) suggested a two phase ice stream in Strathmore. I have interpreted a different arrangement of flowsets in this area but also identify two stages of ice flow. Both flowsets (fs51 and fs46) are characterised by highly parallel elongate lineations and converging ice flow. Fs46 is constrained by topography whereas fs51 is not. Fs51 does not have abrupt margins. It is possible that the two flowsets represent two stages of ice stream geometry. Fs51 could also be part of the Witch Ground ice stream identified in the Fladen Ground of the North Sea (Graham et al., 2007). However, in the absence of further evidence to support this, fs51 is not classified as an ice stream flowset.

Fs19 in the Firth of Forth exhibits high parallel conformity and convergent flow pattern topology and abrupt margins. It is postulated that this is a palaeo ice stream track. This is an additional ice stream location to those listed in table 2.1. The Moray Firth has also been suggested as the site of a major ice stream of the last BIS (Merritt et al., 1995); Fs6 exhibits highly elongate and long drumlins and has a convergent pattern into the mouth of the Firth (figure 6.4). The geomorphology therefore supports an ice stream in this location. An ice stream has been postulated in the North Channel to feed the Barra Fan system (table 2.1). Fs8 across the Mull of Kintyre and Islay is composed of highly parallel and long crag and tails and is in the correct location to be part of such an ice stream. Offshore investigation is necessary to confirm this.

In Wales similar flowsets were identified to those reported by Jansson and Glasser (2004). However, it is the opinion of the author that there is not enough evidence to support the contention that these are ice streams. Similarly, fs11 and fs30 constrain highly parallel, elongate lineations in the Tyne Gap and Wensleydale respectively which have also been suggested to be the sites of palaeo ice streams. Yet fs11 in the Tyne Gap is not convergent and does not have abrupt margins. Fs30 in Wensleydale exhibits topographically focused ice flow but the lineations are relatively short (<1000 m). Arguably, using the broadest definition of the term ice stream, any case of topographically focussed ice flow could be described as such, e.g. topographic ice stream (Bennett, 2003). However, in this thesis I take a more conservative view of ice stream terminology, only classifying flowsets as ice streams when they fit the criteria of Stokes and Clark (1999). Ice stream status for these flowsets therefore not suggested.

Figure 6.16 shows the flowsets that are thought to be palaeo-ice streams. A limitation of this project is that new geomorphological mapping is restricted to within the present-day coastline of Britain, whereas the ice sheet most likely extended to the continental shelf edge (Sejrup et al., 2005). It is the opinion of the author that as high resolution seismic datasets become available for the ‘offshore’ portion of the ice sheet bed more palaeo-ice stream tracks will be discovered (Stoker and Bradwell, 2005; Graham et al., 2007) as has occurred for the continental margin of the Scandinavian ice sheet (Ottesen et al., 2005; Ottesen et al., 2008).

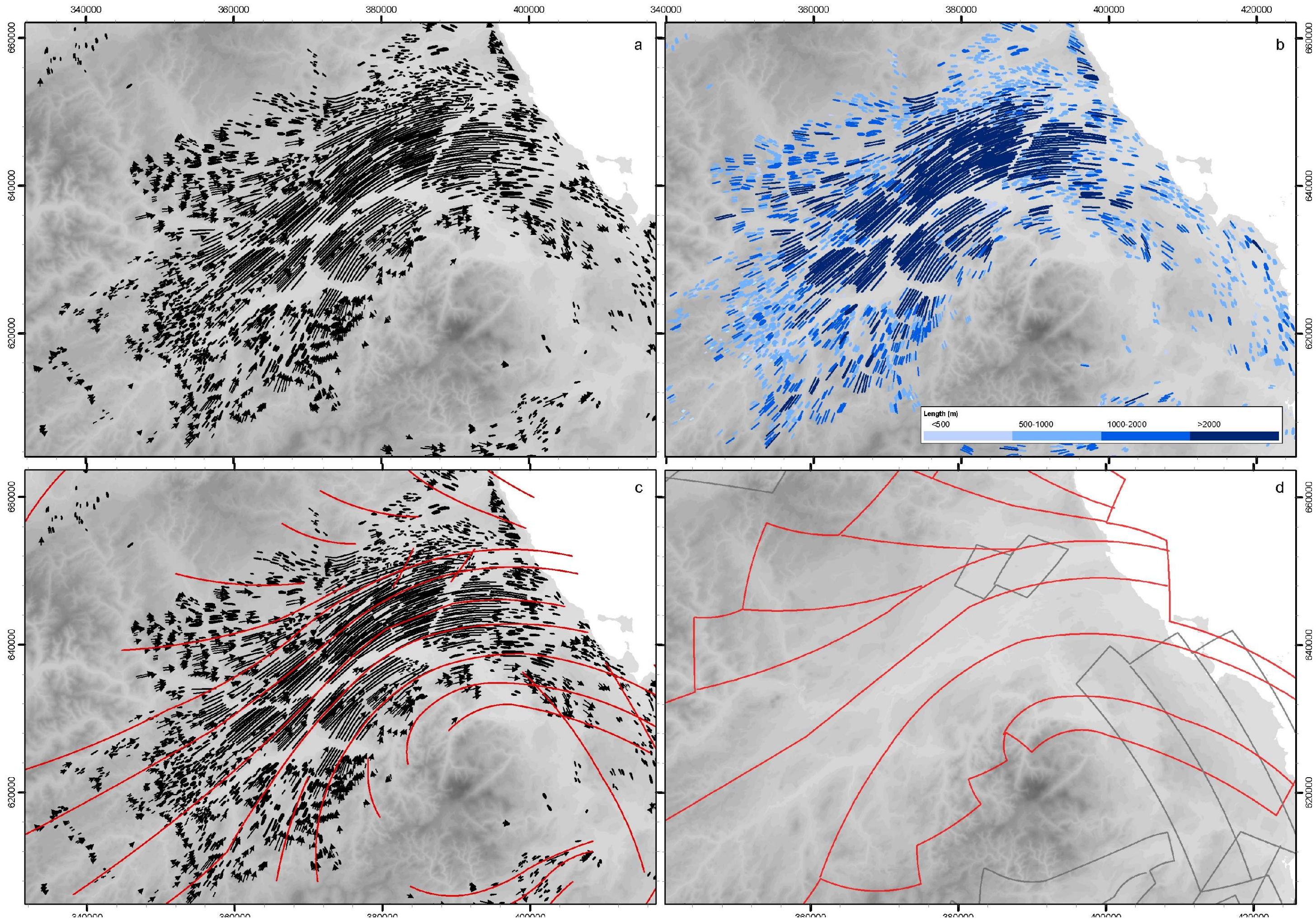


Figure 6.15 Tweed ice stream (fs10). The Tweed is the sole location of mega-scale glacial lineations in Britain (a). Fs10 is an elegant example of an isochronous flowset. Flow traces converge and bedform lengths increase along the interpreted flowline (b). This is a topographically constrained ice stream and is 65 km wide and c.20 km long. It is possible that the ice stream track extends offshore. Interpreted flowset boundary is shown in c and d.

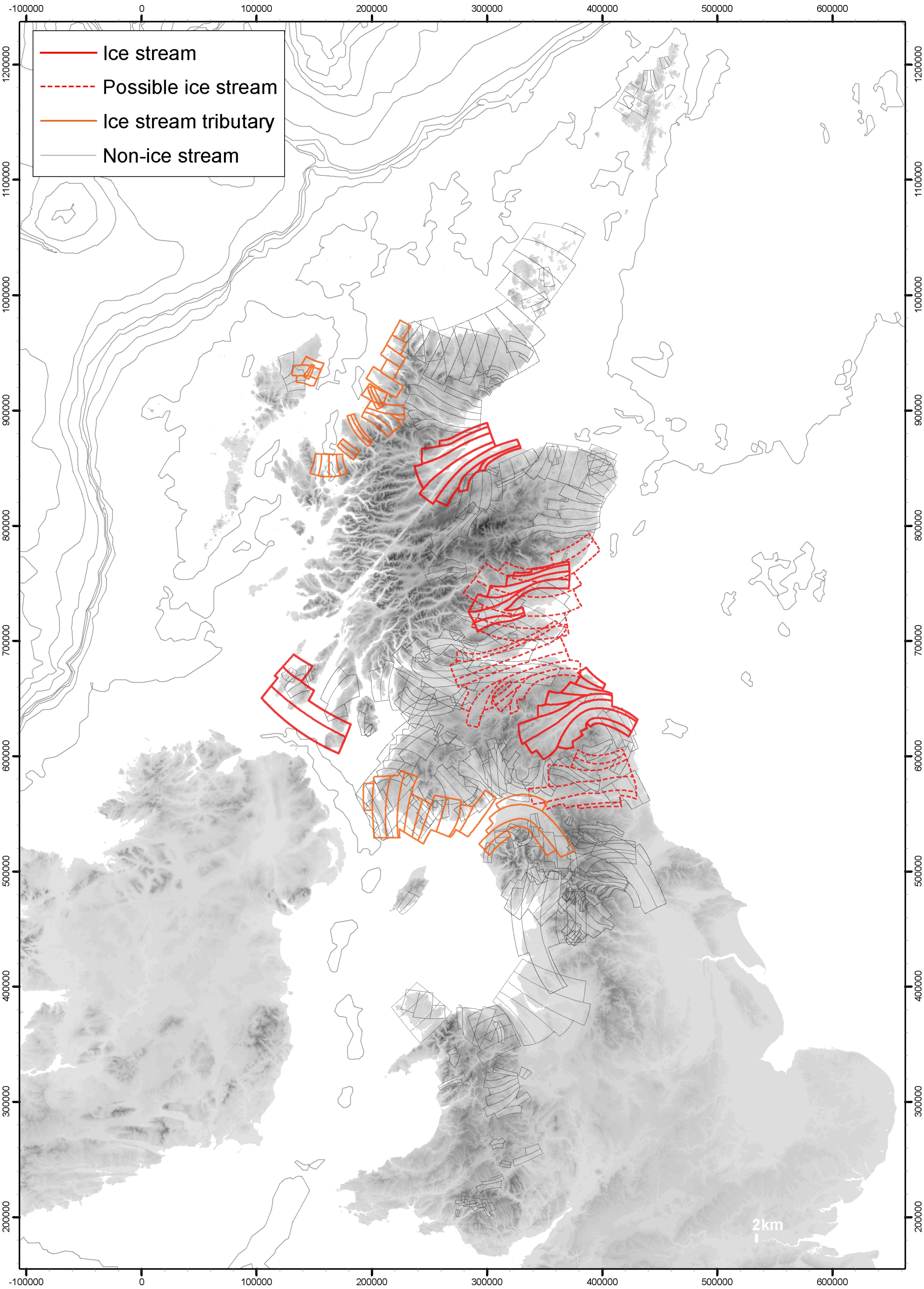


Figure 6.16 Flowsets of the last British Ice Sheet that have been categorised as ice streams.

6.3 Ribbed moraine flowsets

Ribbed moraine flowsets were generated and cartographically produced in a similar manner to lineation flowsets. In Britain no instances of cross cutting ribbed moraine was observed which simplified the process. Ribbed moraine fields were summarised by lines in direction of inferred ice flow and the flowset drawn to encapsulate the spatial extent (figure 6.17). Fields in close proximity and with similar morphometric characteristics were grouped within the same flowset. Figure 6.18 shows the distribution of ribbed moraine flowsets numbering 13 in total. In some cases, although the orientation of ice flow could be determined the direction of ice flow was unclear, and these are marked with an asterisk in figure 6.19. All ribbed moraine flowsets are thought to be isochronous. In all cases of association with drumlins, ribbed moraine is superimposed by the drumlins. Ribbed moraine flowsets therefore always represent older ice flow directions.

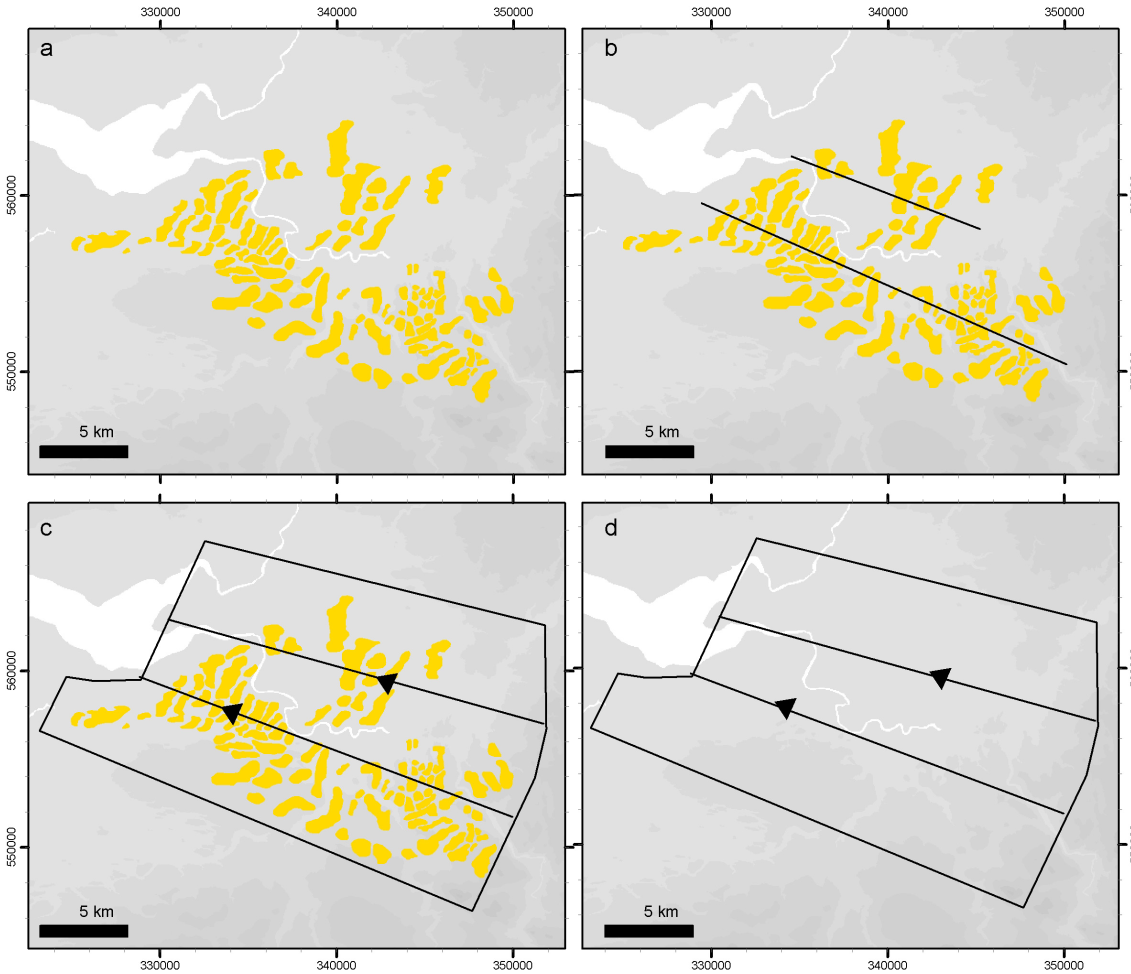


Figure 6.17 Process of generalisation of ribbed moraine flowsets: a) ribbed moraine mapping in yellow, topographic setting in dark-light grey (high to low ground); b) flow pattern inferred from ribbed moraine field, c) cartographic grouping of flow patterns into a single flowset; d) flowset representation of ribbed moraine field. This is flowset number rm7 (located in the Solway lowlands close to Carlisle).

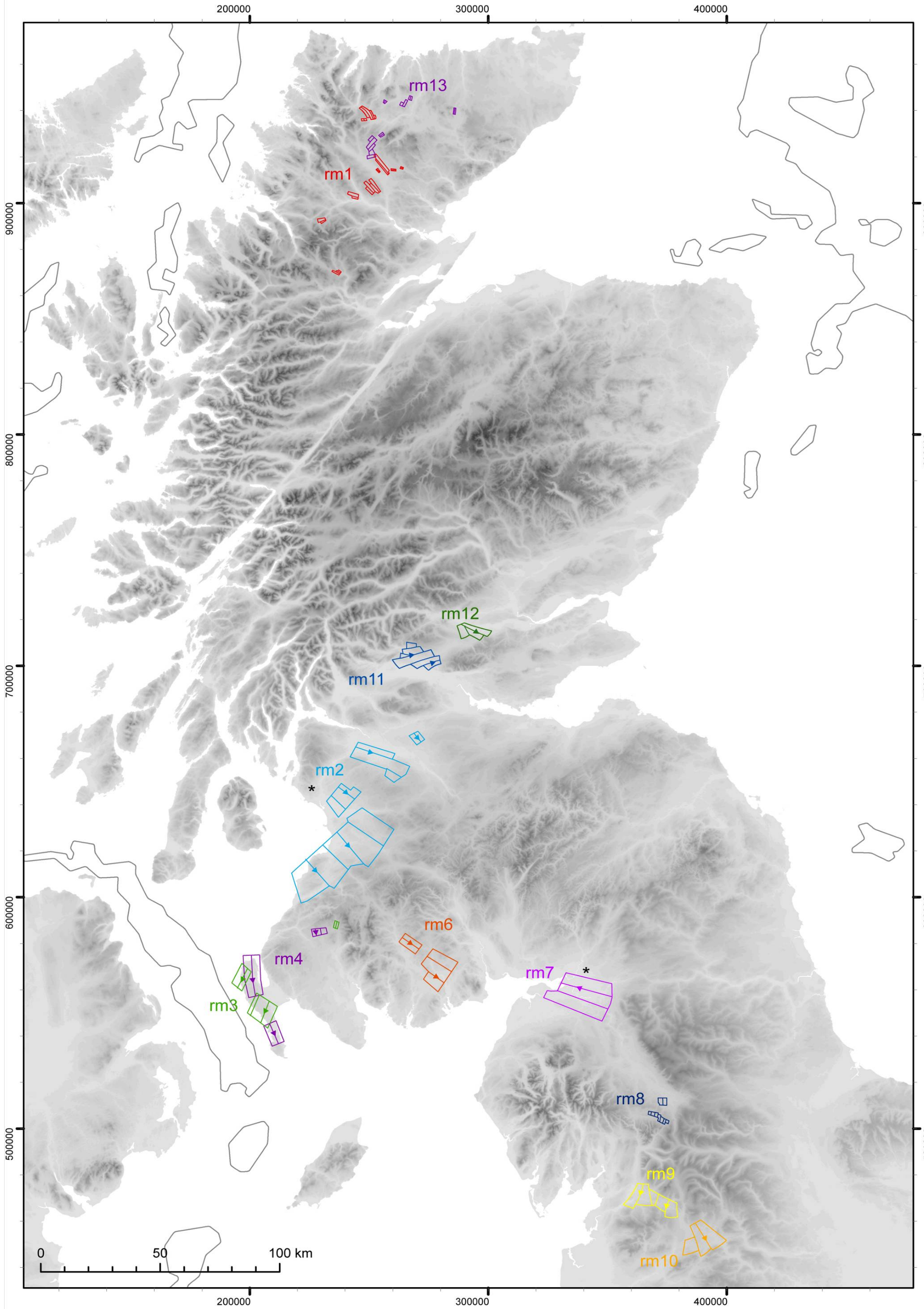


Figure 6.18 Map of ribbed moraine flowsets. Asterisk marks flowsets whose direction is equivocal. However, these ribbed moraine fields are superimposed by drumlins and so the flow pattern direction is taken as the same as the direction of the overlying drumlins.

6.4 Streamlined bedrock summaries

Streamlined bedrock is regarded as a second order level of ice flow information in the inversion model as it is likely to be a cumulative result of the action of the ice sheet over the entire glacial cycle. Streamlined bedrock may reflect consistent ice flow directions throughout the glaciation, but this cannot be confirmed as such features are resistant to remoulding unlike lineations composed of sediment such as drumlins. Streamlined bedrock grain was summarised as arrows in the direction of ice flow (figure 6.19). Figure 6.20 shows a map of the streamlined bedrock 'flowsets'. Table 6.1 records which lineation flowsets are supported and/or extended by streamlined bedrock distribution (figure 6.21).

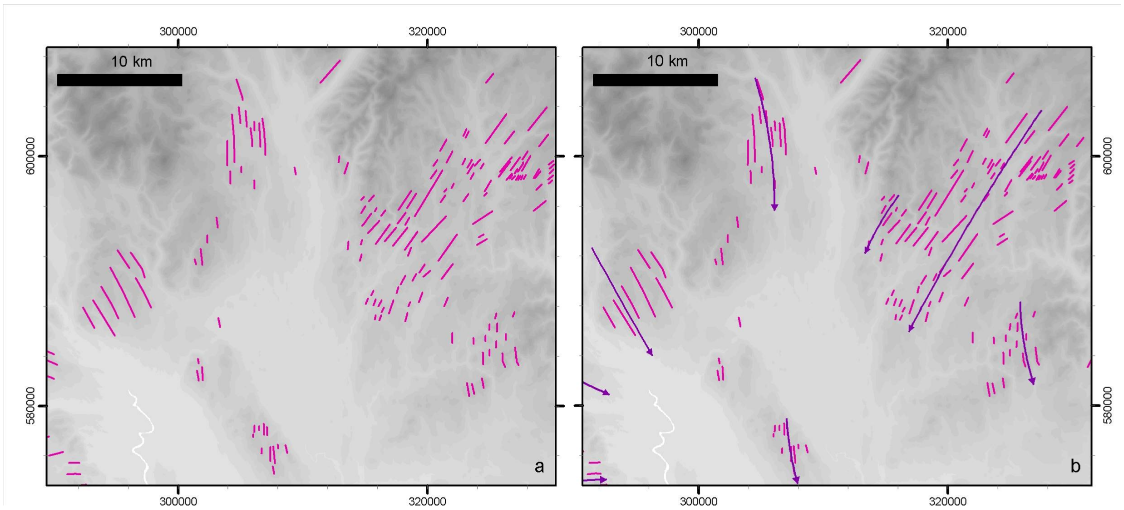


Figure 6.19 Streamlined bedrock grain mapping around Annandale and Nithsdale (a) is summarised as arrows in the inferred direction of ice flow (b).

6.5 Esker generalisation (esker 'flowsets')

Individual and whole systems of eskers are summarised by a single arrow in the inferred direction of ice flow (figure 6.22). As it is assumed that eskers are formed behind a retreating margin, topography is used as a guide to determine ice flow direction when the form of the esker system is ambiguous. At the margins of the ice sheet ice will be thin, therefore subglacial topography will have a strong influence on ice surface slope and hence flow direction. Figure 6.23 shows the summary arrows or esker 'flowsets'. An asterisk marks eskers where it was difficult to infer ice flow direction and reference to other landform elements was necessary. Some eskers are very short fragments of former subglacial conduits; these are left out. The eskers in OS tile SO (which are also included in BRITICE) are some distance beyond the consensus view of the limit of the ice sheet and were excluded from the landform summaries as the original reference indicates that their age is uncertain and they may not relate to the last ice sheet (Whitehead, 1947; Mitchell, 1962). All esker flowsets are regarded as time-transgressive phenomena.

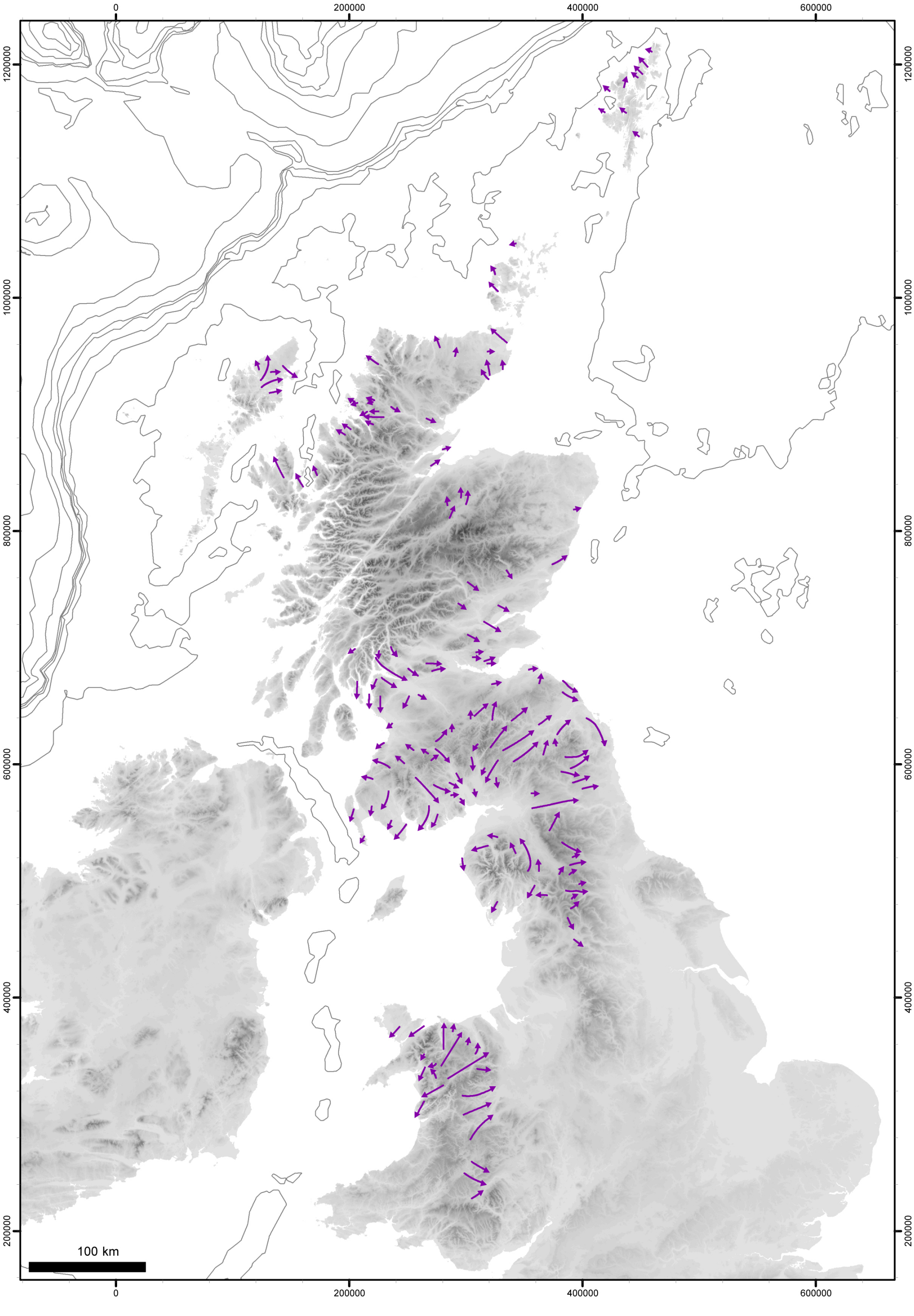


Figure 6.20 Map of streamlined bedrock summary arrows.

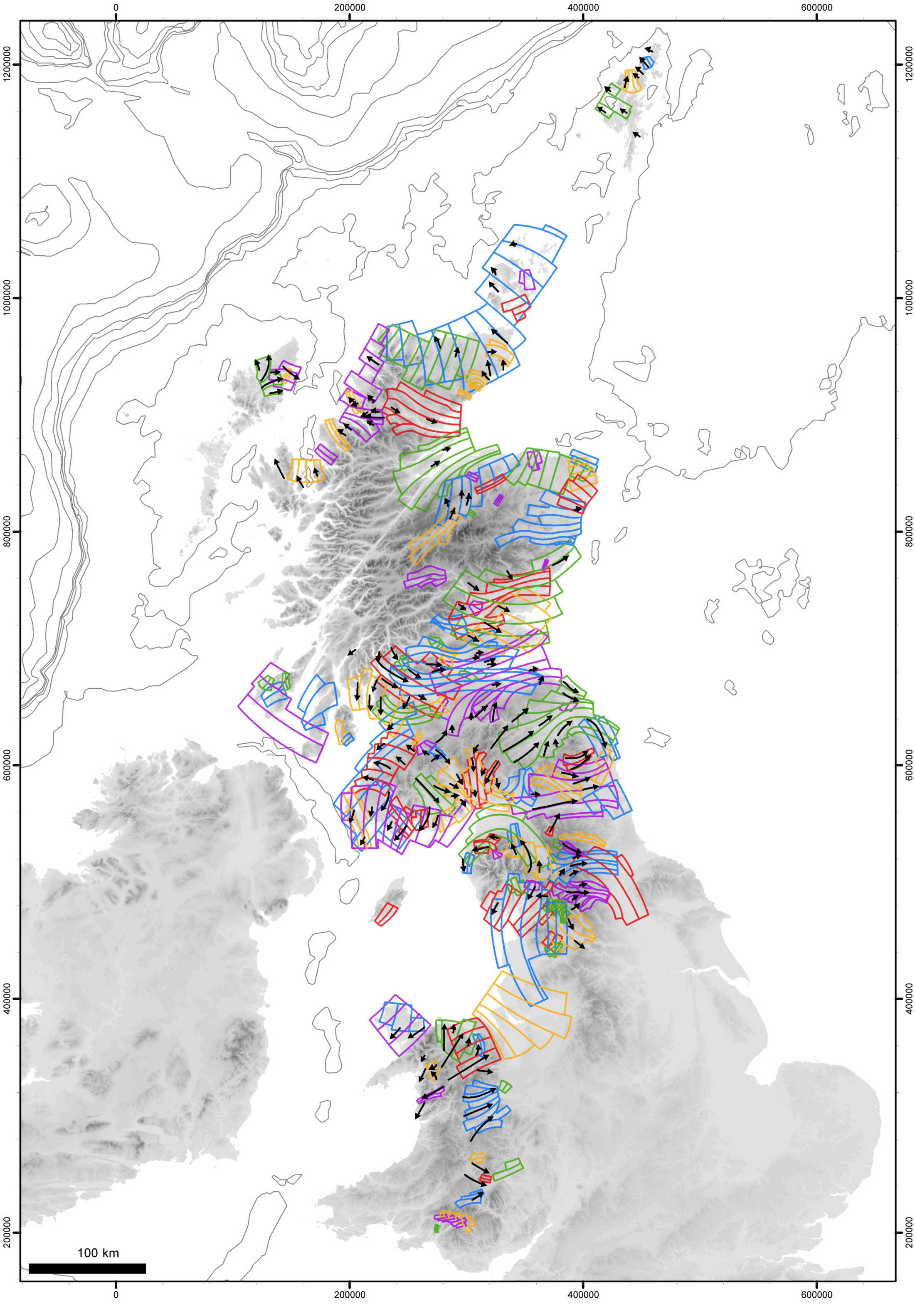


Figure 6.21 Streamlined bedrock flowsets generally support flow patterns derived from lineation flowsets and in some cases extend flowsets spatially. Flowsets in colour. Streamlined bedrock summaries in black.

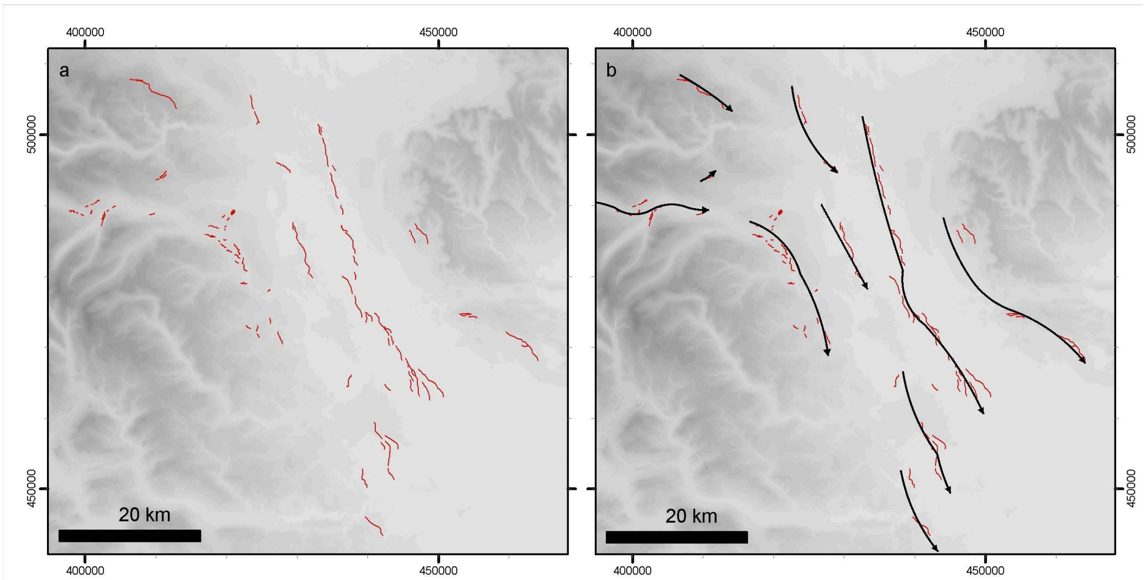


Figure 6.22 Individual and groups of eskers (a) are reduced to summary arrows in the direction of ice flow (b). This example is from the Vale of York.

6.6 Moraine generalisation

Moraines and groups of moraines are summarised as margin positions by a single line (figure 6.24). Topography is used where appropriate to connect moraine fragments, for example to connect valley moraine fragments. No differentiation is made between types of moraines, as this would require additional sedimentological investigation. Therefore, all moraines are assumed to represent former margins or edges of the ice sheet, lateral or terminal. Very small moraines within valleys are excluded as they do not provide much information in terms of the ice sheet scale retreat pattern. It is already assumed that final retreat of ice will be by valley glaciation.

The moraine summaries are presented in figure 6.25. As discussed in chapter five the BRITICE database contains moraines that are missing from the new mapping either because they lie offshore beyond the limit of mapping or are below the resolution of the DEM. Margins derived solely from BRITICE data are differentiated on the map. Some moraines are identifiable but I have interpreted them differently. For example, 'moraines' in the Moray Firth are reinterpreted as drumlins. Therefore, summary margin positions are not derived from these moraines. In general, derivation of margin positions from moraines was straightforward. However, problems were experienced deriving margins from spread-like moraines.

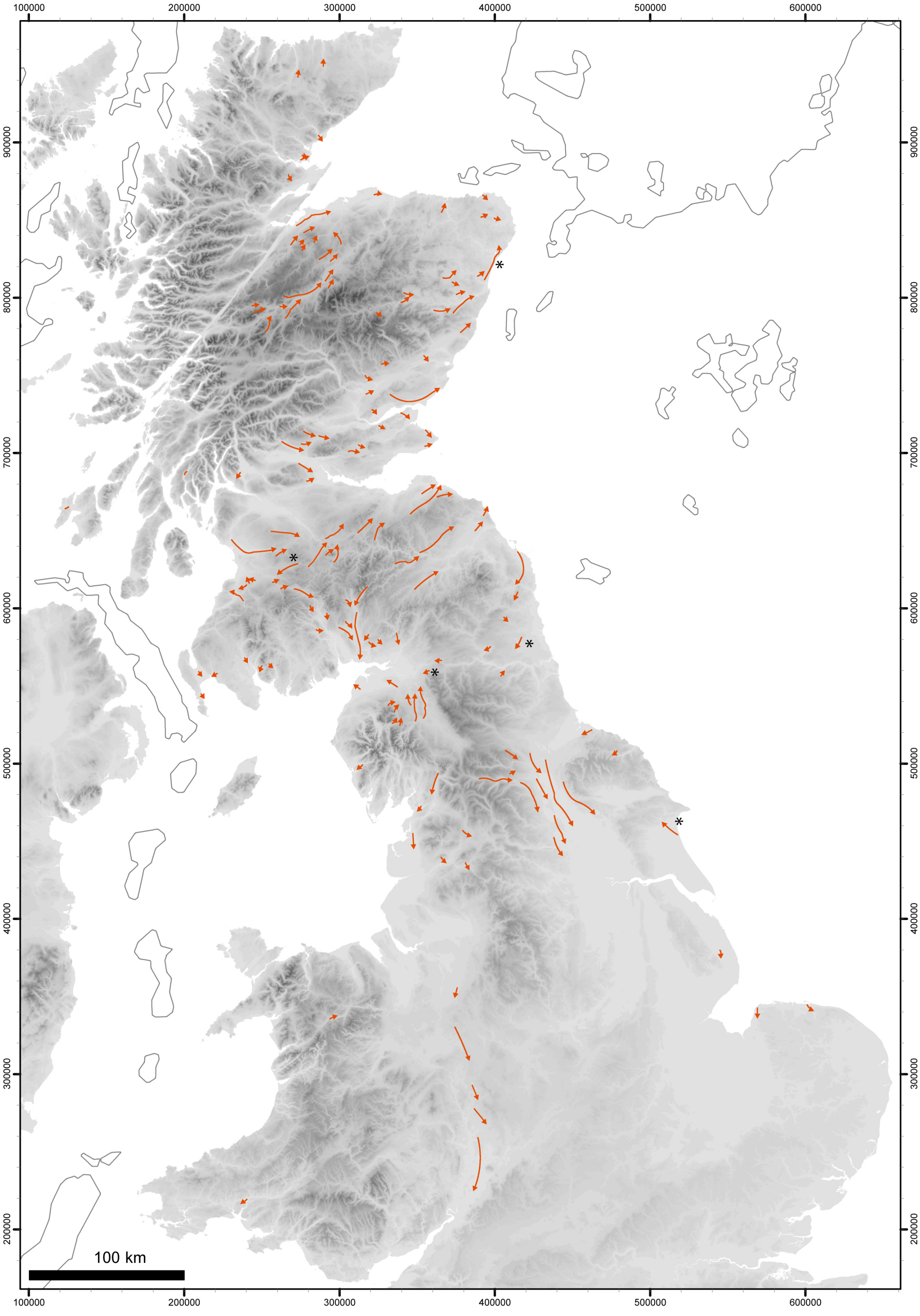


Figure 6.23 Map of esker summary arrows or 'flowsets'. Asterisk marks eskers where identification of flow direction was difficult.

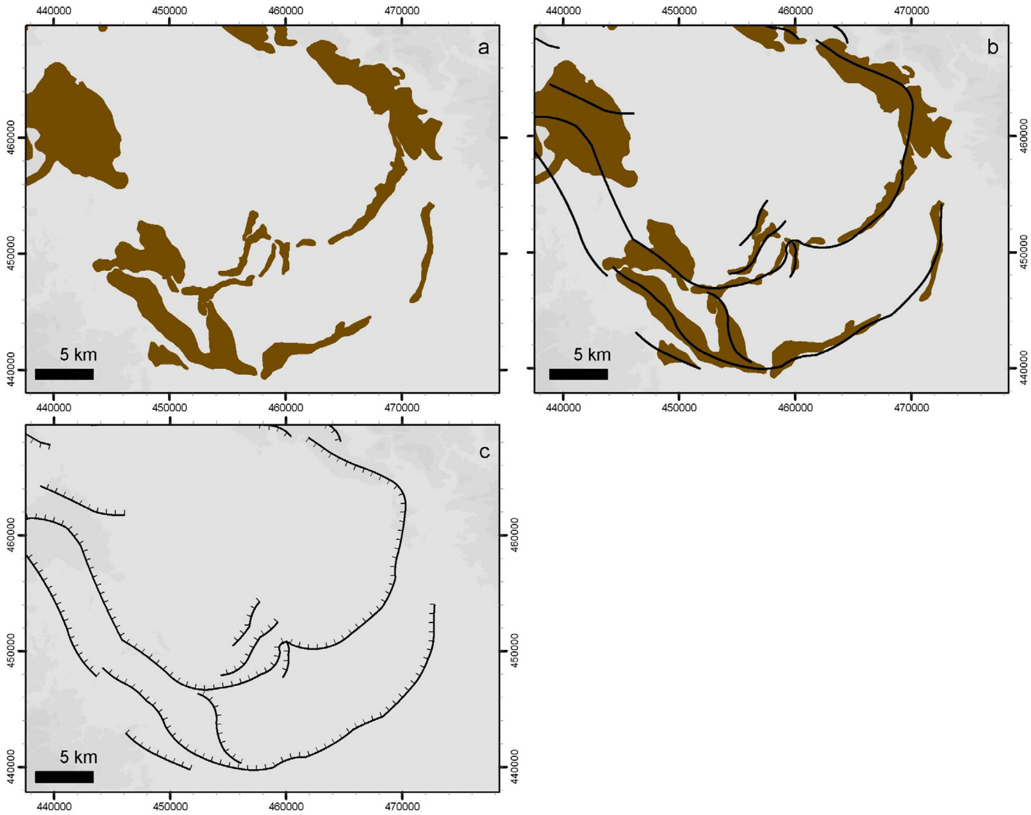


Figure 6.24 Moraine mapping (a) is summarised as lines marking ice margin positions (b and c). Topographic context is used to aid connection of moraine fragments. This example shows the York-Escrick moraine system.

6.7 Meltwater channel generalisation

6.7.1 Meltwater channel classification

Before meltwater channels can be used in the inversion model it is necessary to determine the formative location of each channel; lateral and subglacial channels have specific genetic explanations and are thus considered differently (table 3.1). During mapping, channel types were not distinguished and so now it is necessary to do so. Greenwood et al. (2007) derived a series of diagnostic criteria for the identification of subglacial, lateral, proglacial and supraglacial/englacial channels from a review of the literature on meltwater channel morphometry (table 6.2). They used these criteria to develop a methodology for the visual classification of meltwater channels with reference to a DEM. This was used to classify the channels contained within the BRITICE meltwater layers. The classified channels were used to reconstruct the retreat pattern of the ice sheet. Classification was based on four primary and distinctive observations: setting with respect to topography (valley side or bottom), orientation relative to contours, form, and relationship to other channels. The focus was on distinguishing lateral and subglacial channels as these are the most useful in terms of palaeoglaciological information (figure 6.26) (Greenwood et al., 2007). For a full description of the methodological process of classification, the reader is referred to Greenwood et al. (2007). The same methodology was undertaken to classify the newly mapped channels.

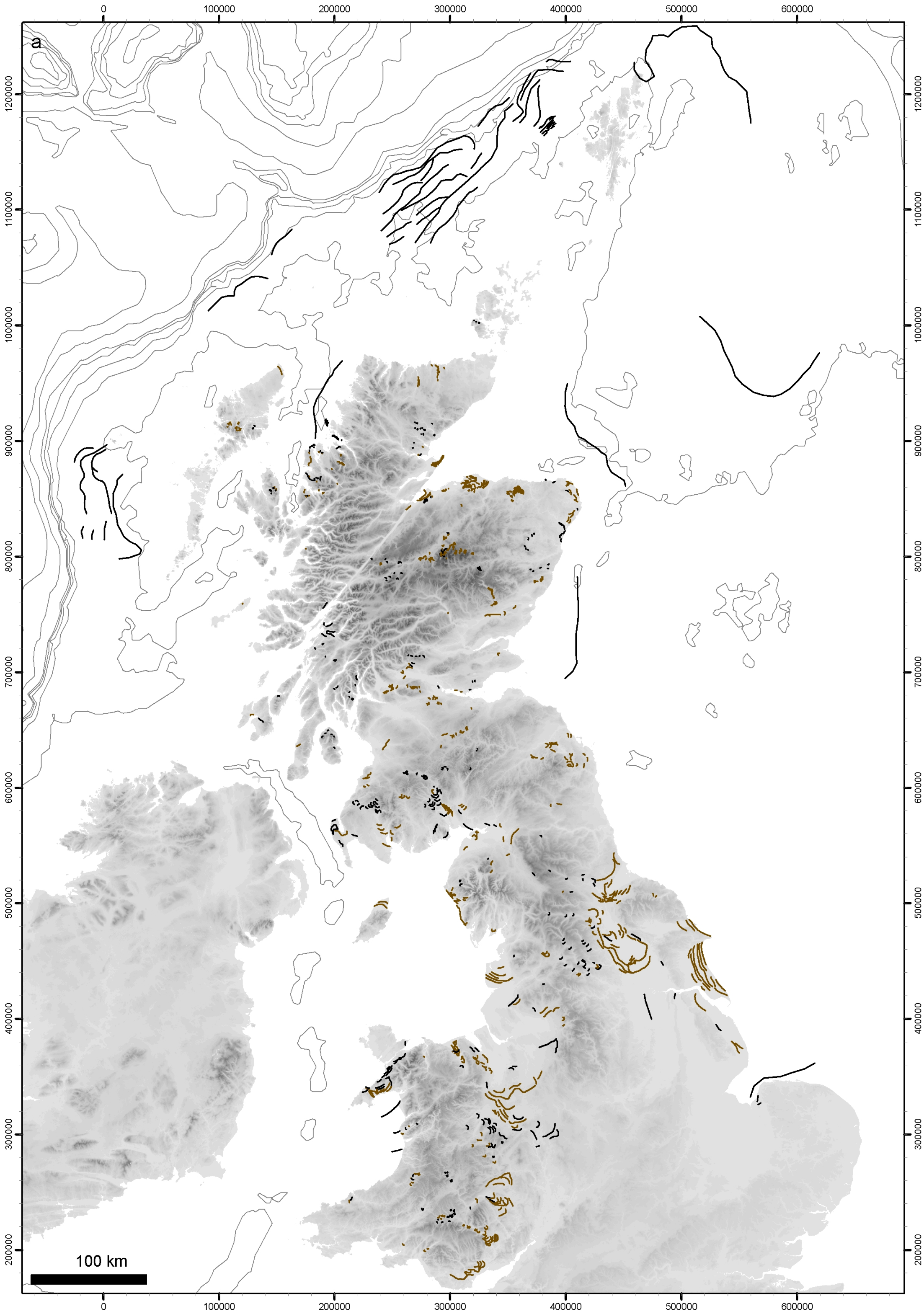


Figure 6.25 Moraine margins summarised from moraine mapping. Margins that are defined solely on the basis of moraines contained within the BRITICE database are shown in black. Margins from new mapping are shown in brown.

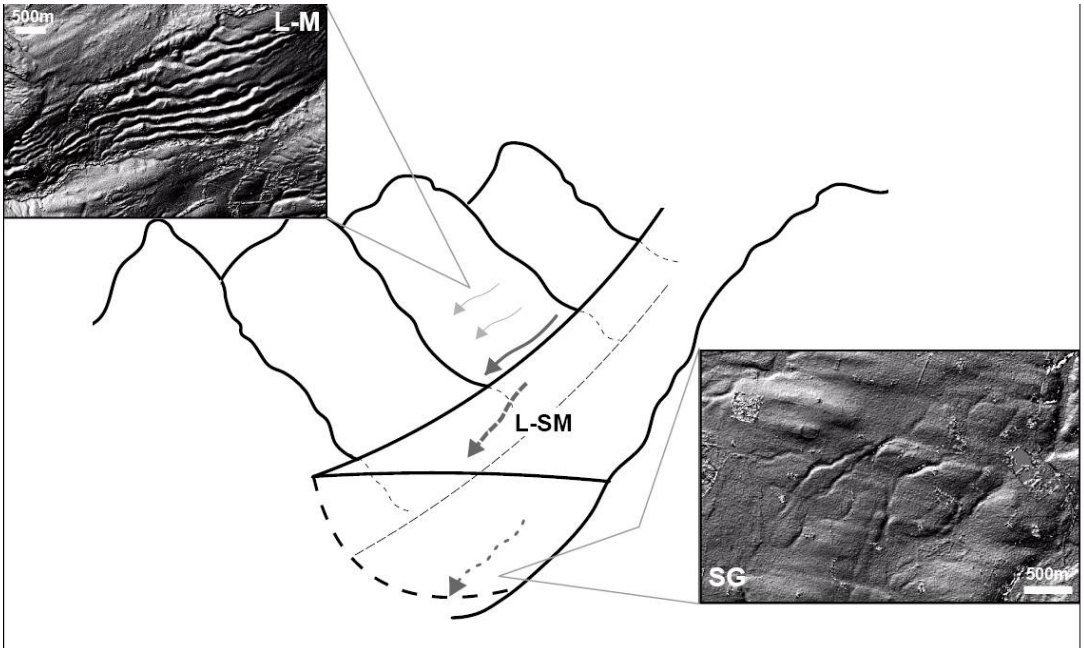


Figure 6.26 Contexts of meltwater channel generation. SG = subglacial, L-M = lateral (marginal) and L-SM = lateral (submarginal). Reproduced from Greenwood et al. (2007).

Channels were visually inspected in combination with both the 'raw' NEXTMap DEM and relief-shaded visualisations. Use of the 'raw' DEM enabled an examination of the long profile to identify the subglacial channels. The DEM and channels were also viewed in 3-D in order to visualise the topographic setting. Two additional fields were added to the attribute table of the meltwater layer: type and confidence to record the channel classification and the security of the classification respectively. Channels were classed as subglacial, marginal, submarginal, proglacial or unknown. The level of confidence (definite, probable or possible) reflects the number of criteria exhibited by the channel and is a subjective measure of security of classification. Figure 6.27 is a map showing the meltwater channels of Map 3 classified by type. Of the 14,914 channel fragments contained in Map 3, 11,997 (80.4%) are subglacial, 1,839 (12.3%) are marginal, 1,059 (7.1%) are submarginal, 19 (0.1%) are proglacial and there are no unknowns. In all cases, it was possible to ascertain a classification. Subglacial meltwater channels are found across the country. The largest networks of channels are constrained to wide valley bottoms and expansive flat areas, e.g. Vale of Eden and NE Buchan. Lateral channels are also spread across the country with the best examples in Scotland. The few proglacial channels identified are close to the drift limit in the Cheshire Plain. There are some differences in the classifications made in this study and the classifications determined by Greenwood et al (2007) (figure 6.28). This can be understood when it is considered that Greenwood et al. (2007) were using a lower resolution 'raw' DEM and did not consider relief shaded images of the landscape. Furthermore there are a number of channels within the BRITICE dataset that were not identified in the new mapping, e.g. in the Yorkshire Dales region.

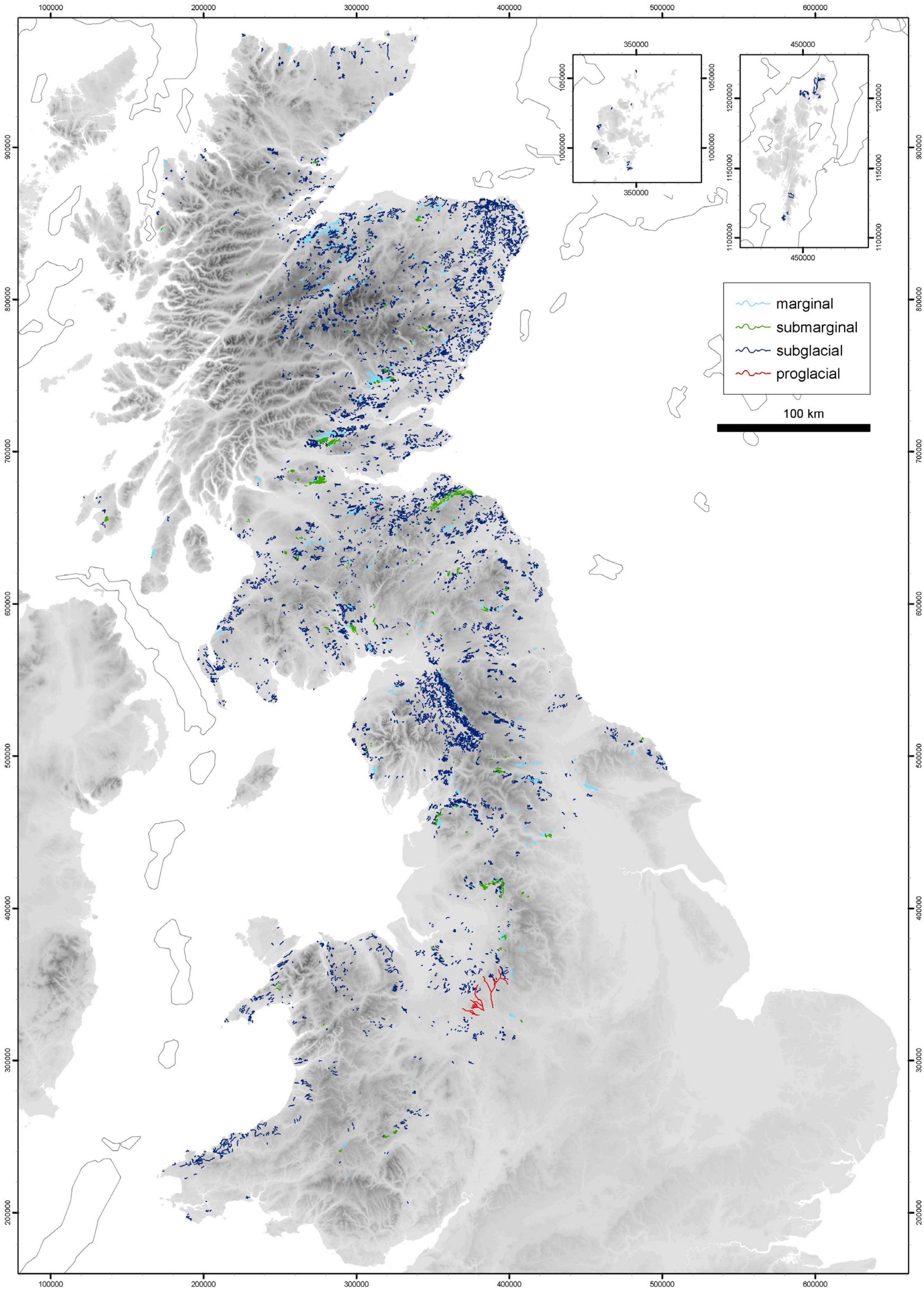


Figure 6.27 Meltwater channel mapping from Map 3 classified by type. This figure is repeated at A3 size on the following pull out page

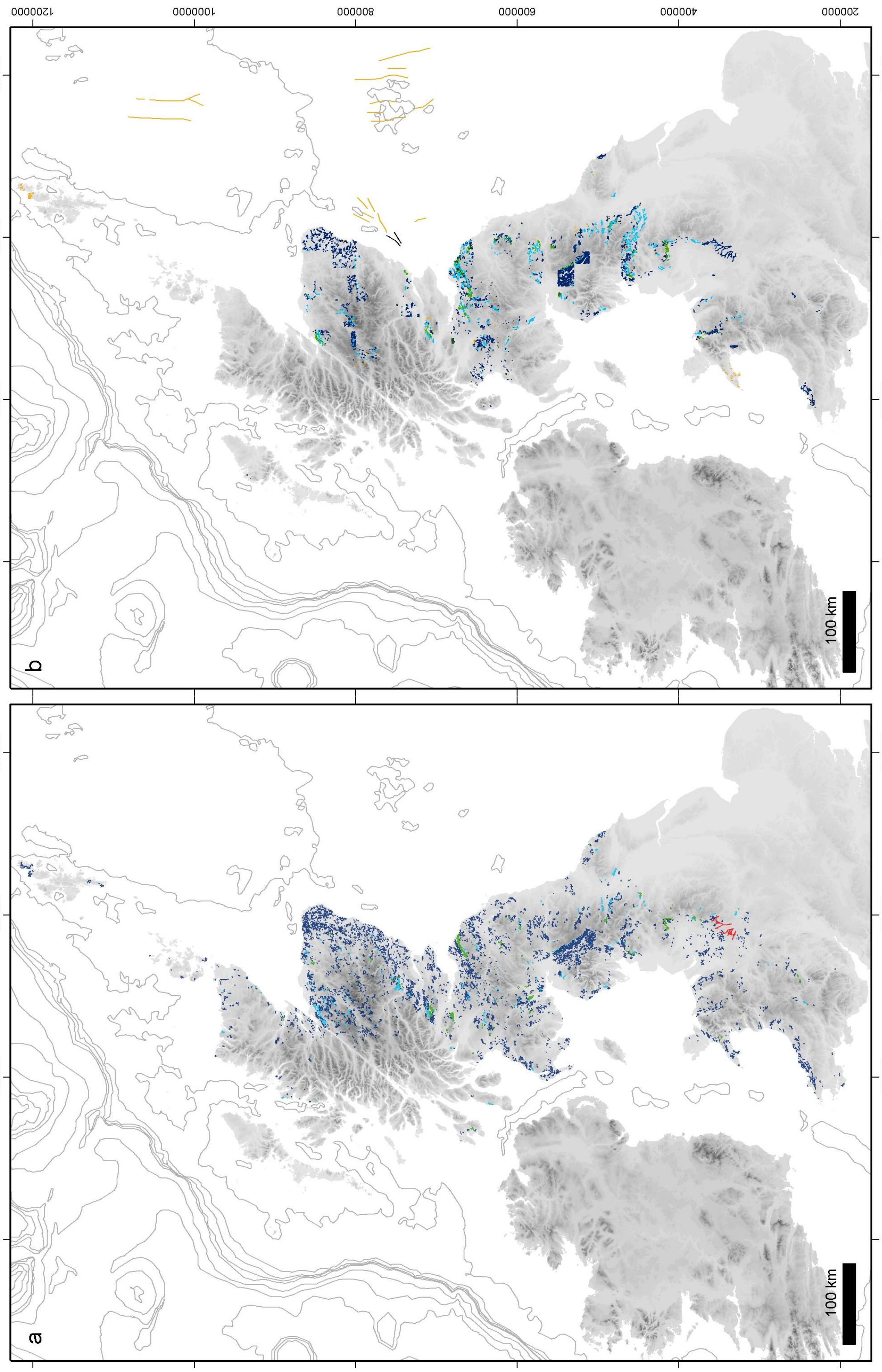


Figure 6.28 Comparison of meltwater classifications made in this thesis from new mapping (a) and those of Greenwood et al (2007) from the BRITICE database meltwater channel layers (b). Channels are coloured in the same way as figure 6.30. The main areas of difference are in the Pennines, Lancashire, the Cheshire Plain, south of Edinburgh and close to Inverness

Table 6.2 Diagnostic criteria for classification of meltwater channels. Lateral channels are divided into two subtypes. Marginal = subaerial water flow along the ice margin. Submarginal = lateral position beneath the ice surface. 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). Reproduced from Greenwood et al. (2007).

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

6.7.2 Meltwater channel summaries (meltwater 'flowsets')

Groups of lateral and subglacial channels were generalised by arrows in the inferred direction of ice flow after Hättestrand and Clark (2006b) (figure 6.29). Topographic setting was used to orientate the arrow. Figure 6.30 shows the distribution of meltwater channel summary arrows or 'flowsets'. Flights of lateral meltwater channels are formed time-transgressively as the ice surface lowers during deglaciation. It is more difficult to ascertain the temporal formation of subglacial meltwater channels, especially when they form networks. It is possible on aerial photographs and by thorough field levelling to identify cross-cutting meltwater channels. However, this was not possible using the DEM alone and so instances of cross-cutting channels have not been examined in this study.

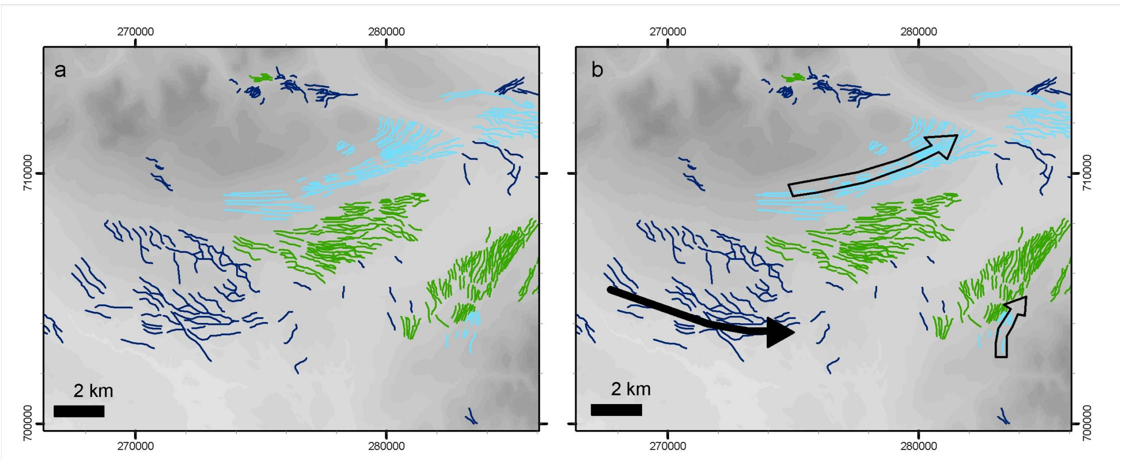


Figure 6.29 Illustration of data reduction to summary arrows. Meltwater channels in Strathallan north of Dunblane classified by type (dark blue = subglacial, light blue = marginal, and green = submarginal) (a). Topographic context is used to summarise flights of lateral meltwater channels and subglacial networks in the direction of ice flow (b). Submarginal channels are not used. Channels classified with only a possible level of certainty are also excluded.

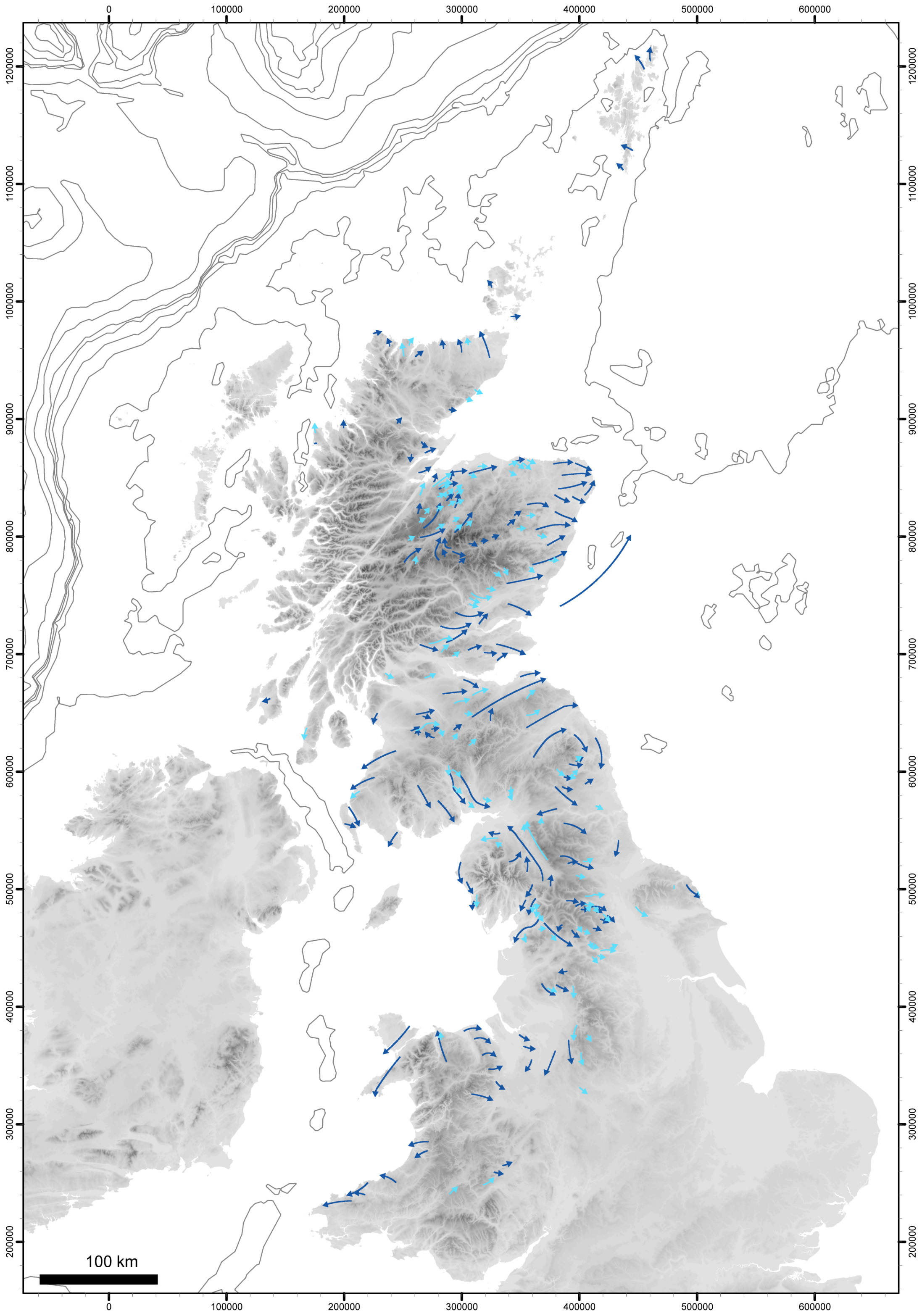


Figure 6.30 Distribution of summary meltwater arrows. Dark blue = subglacial, light blue = marginal.

6.8 Relative chronology

The final stage of the first abstraction of the glacial maps is to examine the relative chronology of events. Where flowsets overlap, the landform record is examined for evidence of cross cutting relationships. The 140 locations of cross cutting drumlins are shown in figure 5.6. At each location the direction of the lower and upper lineation flow pattern orientation was recorded. Locations of 'piggy-backing' drumlins (smaller drumlins superimposed on larger drumlins in the same direction) were also recorded. This information was used to determine the relative age of intersecting flowsets. There is only one case where more than two drumlins cross cut each other. Examination of aerial photographs and the striation record may help to refine the relative age relationships but this was not conducted. The relative chronology of flowsets is shown on Map 4 and in figure 6.31. In 16 cases it was not possible to ascertain relative age and flowsets are therefore regarded as 'floating'. There are an additional five cases of unclear superimposition relationships. These are both listed in table 6.1 and figure 6.32. Drumlins are always superimposed on ribbed moraine and these flowsets are included in the relative age stack of flow pattern information in figure 6.32.

It was less straightforward to identify the locations of cross cutting of other landforms. Subglacial meltwater channel networks in drumlin fields that dissect occasional drumlins could be contemporary or younger than the drumlin field. In the majority of cases eskers are superimposed by moraines and superimpose drumlins. There are two important contradictions to this on the north coast of Buchan, Scotland (OS NJ 954 245) and in the eastern Solway (OS 558 753) where eskers appear to superimpose moraines. Moraines superimpose lateral meltwater channels at OS NJ 542 596 close to the North coast of Buchan.

6.9 Summary

This chapter documented the generalisation of the 'building blocks' that will be subsequently used in chapters 7-10 to reconstruct the last BIS. One hundred and thirteen subglacial bedform flowsets were identified from the bedform map (Map 2) and their relative chronology and temporal classification established. Flowsets were classified in terms of their internal synchronicity (Map 4a) and whether they recorded the tracks of palaeo-ice streams. Eskers, moraines and meltwater channels from Map 3 were also reduced to units of glaciological information represented by summary arrows in the inferred direction of ice flow.

It is envisaged that the flow information summarised in this chapter will be useful for ice sheet modellers wishing to compare model outputs against flow pattern evidence. Numerical models should be able to reproduce the flow patterns delineated by the flowsets.

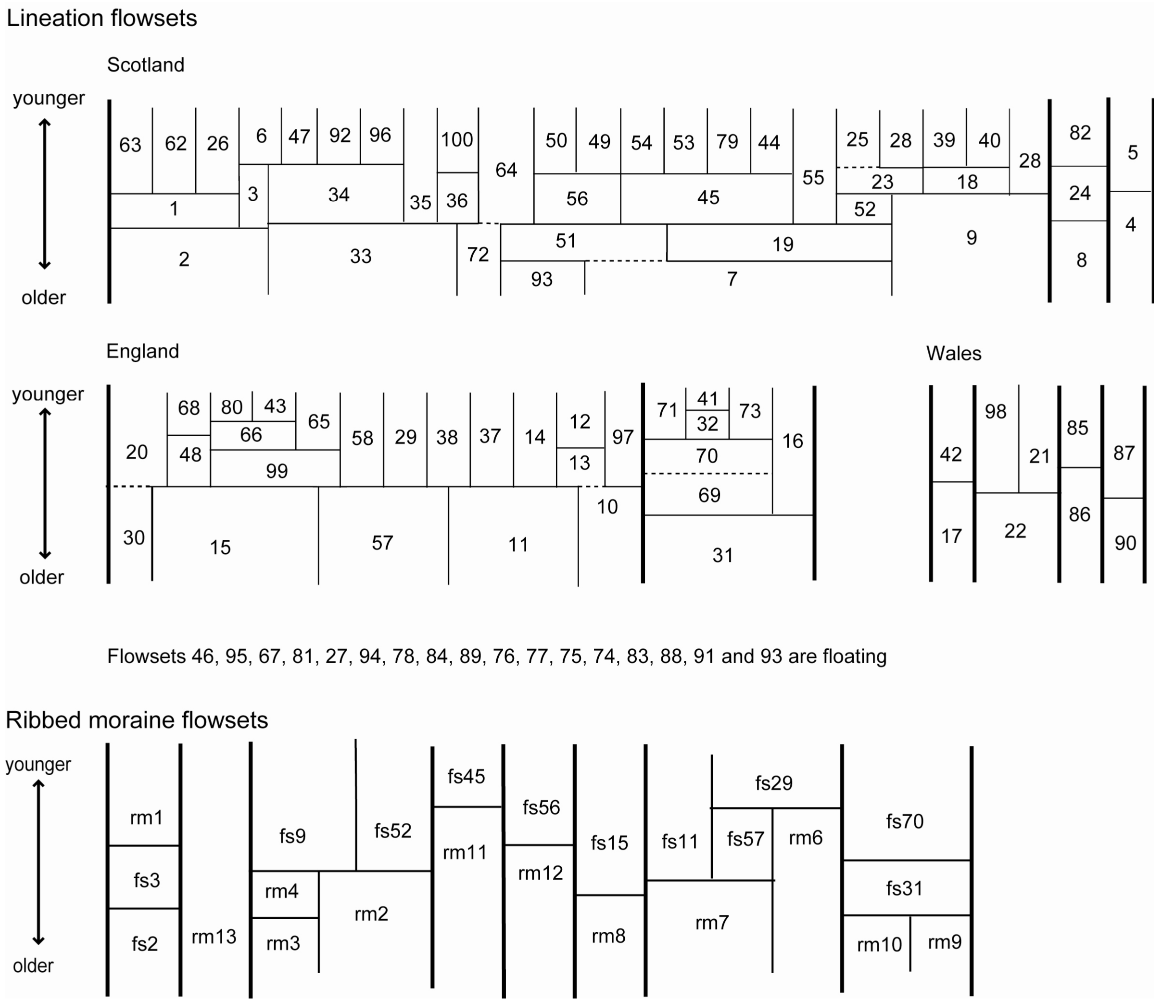


Figure 6.31 Relative chronology table of lineation and ribbed moraine flowsets. Horizontal lines separate flowsets that are known to be older of younger than each other. Vertical lines separate flowsets that could be contemporaneous. Flowsets can thus ‘slide’ up and down relative to laterally adjacent flowsets. Dotted lines indicate insecure flowset relative chronology. This table has been produced by examination of superimposed subglacial bedforms using the NEXTMap DEM.

Chapter 7
Reconstructing the flow geometry and retreat pattern of the last British Ice Sheet

7.1 Introduction

The geomorphological inversion approach adopted by this thesis was outlined in chapter 3. The following chapters (7-10) present the second level of interpretation in the geomorphological inversion, where the discrete units of glaciological information interpreted from the glacial landform record (flowsets and other cartographic summaries) are organised into a reconstruction of the ice sheet. Chapter 6 presented the ingredients or building blocks for the reconstruction on which the interpretations are based. The interpretations presented in this section (chapters 7-11) are therefore highly dependent on the generalisations of the geomorphological record presented in chapter 6. Critical aspects include the internal synchrony of each flowset (time-transgressive or isochronous) and the relative chronology of flowsets. This chapter documents the rules and assumptions used to inform interpretations, and describes the steps undertaken to get from the complex flowset information presented in chapter 6 to a reconstruction of the ice sheet flow dynamics and retreat pattern. Figure 7.1 is a repeat of the flow diagram originally shown in chapter 3 to show how this section fits in the overall scheme.

7.2 The reconstruction process

Two primary outputs of any reconstruction are the evolution of flow geometry over time and the retreat pattern. These are critical parameters which can be used to validate numerical models (e.g. Napieralski et al., 2006; Napieralski et al., 2007). The aim of the reconstruction is to capture the characteristics of the ice sheet as a whole and therefore differs in scope to more traditional reconstructions built up from the gradual accumulation of observations of the geomorphological record. The reconstruction process is more akin to numerical ice sheet modelling. Ice sheet modellers define a set of rules and assumptions (e.g. climate drivers and ice physics) as inputs from which they produce a reconstruction of ice sheet form and behaviour that may, or may not, fit the geological evidence. Here, we rely on mapping (chapter 5) and generalisations (chapter 6), augmented with field data from the published literature, to produce a reconstruction via a logical methodology. The interpretative rules and assumptions grounded in glaciological theory and observations of modern ice sheets are clearly stated (section 7.2.1). We do not set out to incorporate all the mapping, and every published source, but to produce the simplest model that best explains most of the evidence. As with a reconstruction produced by numerical modelling, the approach adopted here may conflict with some of the field evidence and therefore serves to highlight locations and topics for further research.

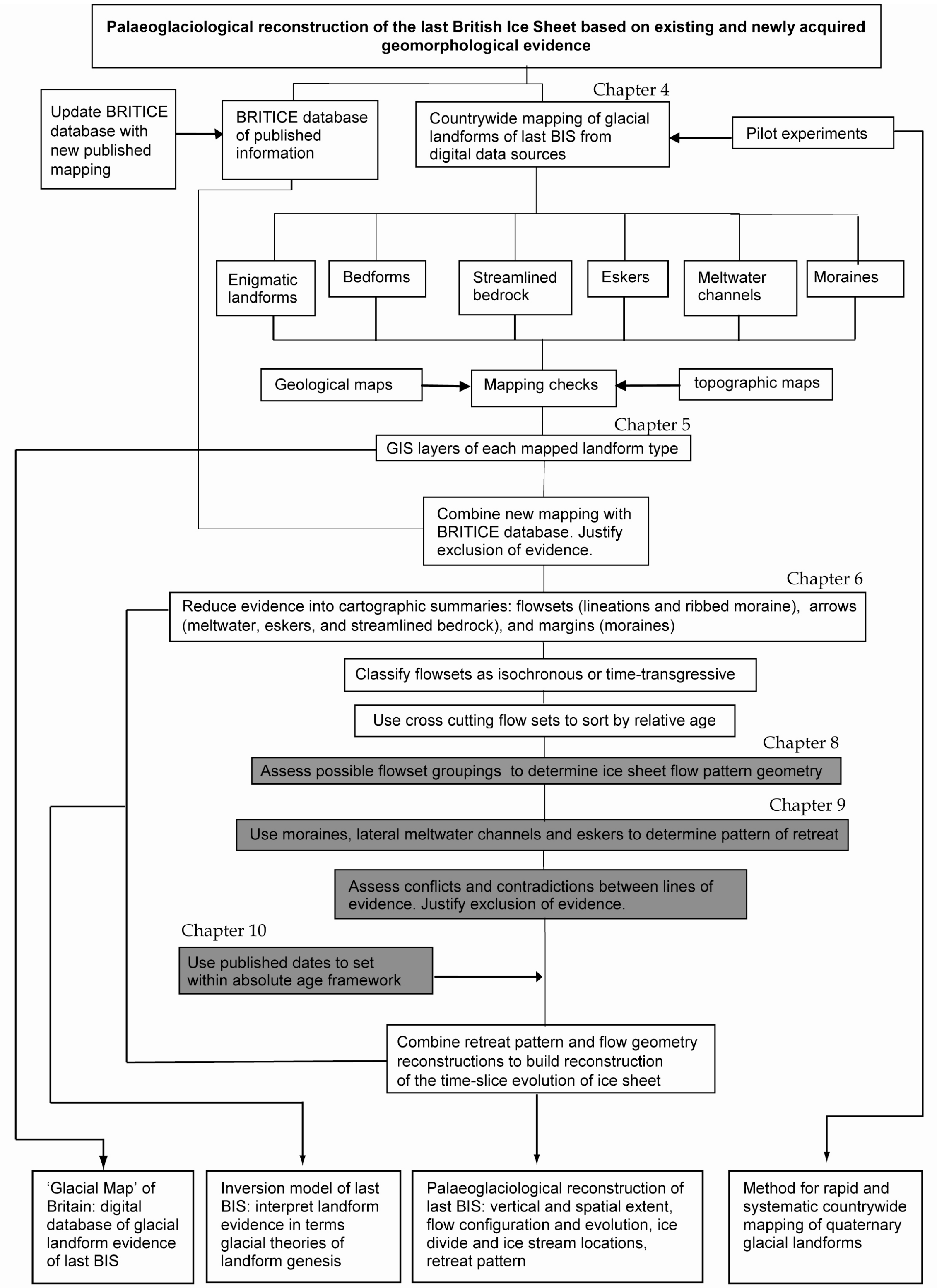


Figure 7.1 Flow diagram showing structure of PhD project repeated from chapter 3. Aim is at the top and objectives at the bottom. The following section comprises the shaded elements.

7.2.1 Interpretative rules and assumptions

The genetic assumptions for the interpretation of the landform record are described in chapter 3. The following additional rules or assumptions inform the organisation of flowsets into scenarios of ice sheet geometry, margin summaries into a retreat pattern, and direct the choice of alternative scenarios where they arise.

1. Ice sheet geometry will be similar to modern ice sheets, i.e. tend towards a broadly symmetrical plan form, with ice flow radiating out from divides.
2. Ice sheet geometry will comprise at least one principle ice divide with the possibility of secondary and tertiary divides branching off from the main divide. Saddles will occur between connected divides.
3. When ice thickness is great, the location of divides alone will control the flow pattern configuration; as the ice thins the topography of the bed will have an increasing influence on flow pattern geometry eventually dominating over orientation changes resulting from divide migration (cf. Kleman et al., 1999).
4. Ice streams are likely to have existed, and been integral to the ice sheet geometry (Bennett, 2003). They are presumed capable of driving rapid configuration changes. They may also briefly cause asymmetric ice sheet form.
5. Moraines represent still stands of the ice margin during retreat. The common (fashionable) interpretation of a moraine as representing a readvance of the ice margin is not adopted. This requires further information from the sedimentological and stratigraphical record. Large sharp crested arcuate moraines, which could be interpreted as readvance features on the basis of morphology alone, are virtually absent from the British terrestrial record, therefore this principle, although conservative, is valid for most of the archive in the absence of sedimentological information.
6. Ice is not constrained to the present day terrestrial landmass. Ice may extend out to the continental shelf in the North and West, to the Scilly Isles in the southwest, and the southern drift limit in England.
7. The Loch Lomond Stadial ice limit is analogous to the margins of the final stages of retreat of the ice mass.
8. Where complexity arises, the simplest solution is chosen.

7.2.2 Interpretative steps

Reconstruction is necessarily an iterative process with many overlaps and revisions between stages. For example, reconstruction of the sequence of events in one region will have implications for the choice of scenario in adjacent regions, and vice versa; changes made in one region may mean that earlier decisions have to be reconsidered. The retreat pattern is dependent, in part, on the organisation of the ice sheet geometry immediately prior to the start of deglaciation and changes in ice sheet configuration during the deglacial will control how retreat occurs. Thus reconstruction of retreat cannot be entirely severed from the reconstruction of earlier flow evolution. For clarity, in this thesis the reconstruction task is divided into a series of steps presented in the following chapters.

One hundred flowsets have been identified for the last British Ice Sheet (chapter 6). The organisation of flowsets into contemporaneous groupings that reflect plausible ice sheet geometries is analogous to attempting to complete a jigsaw puzzle where half the pieces are missing. The preserved record is fragmentary and incomplete by nature and so a degree of interpolation is necessary to group flowsets into plausible overall geometries. Potential flowset groupings are assessed and rejected or accepted on the basis of spatial conformability and the relative chronological rules (figure 7.2). Where it is not possible to determine the relative age relationships between flowsets a greater number of possible permutations can occur. The complexity of the data in chapter 6 demands a regional approach to reduce the number of permutations. The teasing out of the flowsets that are part of the deglacial signature of the ice sheet can also aid the assessment of possible flowset groupings. Chapter 8 presents reconstructed regional flow configurations and examines the phasing of ice streams.

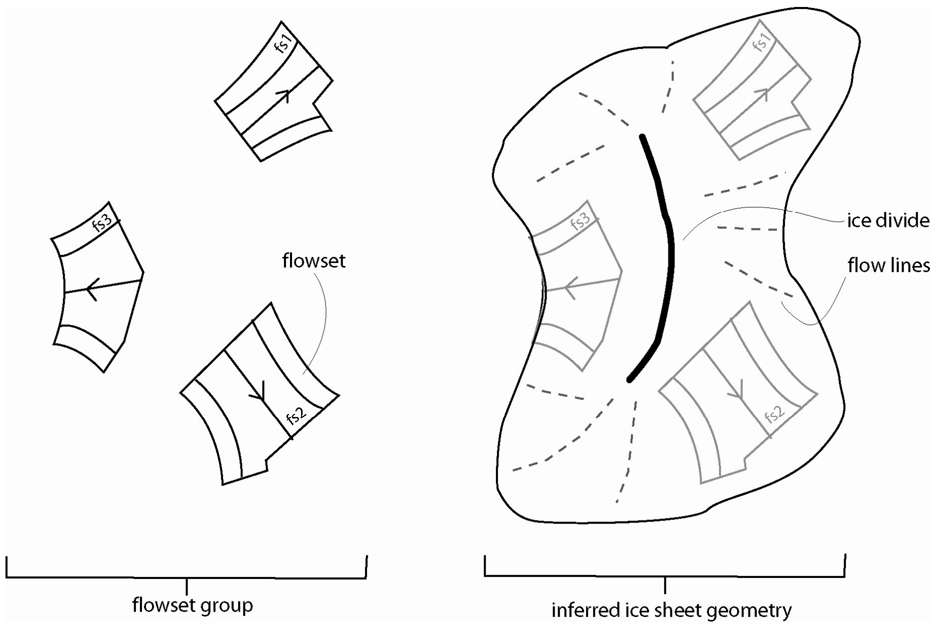


Figure 7.2 Schematic diagram of flowset groups. In the absence of evidence to the contrary, spatially separate flowsets 1-3 can be organised into a plausible ice sheet configuration.

In trying to understanding the complex flowset patterns a focus on the most recent dynamics, i.e. the deglacial signature, appears sensible. Moraines, lateral meltwater channels, eskers, *TT retreat flowsets,* and glacial lake locations are used to reconstruct the retreat pattern of the ice sheet. The retreat pattern reconstructed from these lines of evidence is presented in chapter 9.

Constraining the timing of the retreat pattern in absolute time is essential to understand the relationship between the last British Ice Sheet and climate of the last glacial cycle. This required compilation of all of the absolute dates that relate to the ice sheet. As no database of dates and dated sites existed at the time of starting this project it was necessary to compile a database and GIS layer of dates in order to assess the timing of the retreat pattern. The details of the compilation and the incorporation of the dates with the reconstructed retreat pattern of chapter 9 are described in chapter 10.

7.3 Summary

The following chapters describe and present the results of the second level of interpretation of the glacial inversion scheme. The reconstruction process is analogous to that employed by numerical models, whereby a series of rules and assumptions are used to interpret the input data (flowsets and mapping generalisations) in terms of glaciological theory to produce an ice sheet reconstruction. The reconstruction produced does not therefore attempt to explain all of the evidence but be the simplest glaciologically plausible explanation of most of it. The reconstruction is divided into a series of steps:

1. Identification of possible regional flow evolution geometries from the isochronous, *TT flow shift* and *TT thinning* flowsets and their relative chronology (chapter 8).
2. Reconstruction of the pattern of retreat from moraines, eskers, meltwater channels, *TT retreat flowsets,* and glacial lake locations (chapter 9).
3. Determine the timing of the pattern of retreat using published absolute dates in order to connect up contemporaneous ice sheet margins (chapter 10).

Chapter 8

Regional flow dynamics

8.1 Introduction

The challenge is to assemble flowsets into coherent flow geometry histories of the ice sheet (e.g. figure 7.1). Given the number and complexity of the flowsets discovered for the last British Ice Sheet (chapter 6; Map 4) this is best achieved by examining each region in turn. Regional case studies that reveal key aspects of the ice sheet geometry are presented. Ice streams are a fundamental part of ice sheet geometry and so the implications of the palaeo-ice stream flowsets indentified in chapter 6 are also considered.

8.2 Flow pattern evolution

For the regional subsets the implications of each flowset are considered and flowsets are grouped into plausible ice sheet geometries (e.g. figure 7.1). Primary information on the former flow geometry of the ice sheet is provided by subglacial lineation flowsets and ribbed moraine flowsets. The relative chronology and the temporal component of flowset generation (isochronous or time-transgressive) are further rules which must be satisfied in any reconstruction of ice sheet flow geometry. Streamlined bedrock and erratic distribution are regarded as second order indicators of ice flow patterns as they are likely to be the result of multiple ice flow events, and possibly the cumulative effect of several cycles of ice sheet growth and retreat. Erratic transport paths contained within the BRITICE database are used as further support for reconstructed ice sheet geometries. At the end of each regional assessment the interpretations are pulled together into regional models of flow pattern evolution. The implications for ice sheet dynamics are considered at this stage. Interpretations are described in this order to illustrate the procedure that took us from flowset map to ice sheet geometry evolution. Reference will be made extensively to Map 4 (enclosed as a pull out map for this purpose) and the maps of ribbed moraine flowsets (figure 6.18), streamlined bedrock (figure 6.20) and erratic transport paths (figure 2.16). Reference will also be made to the relative chronology stack. This is reproduced with the flowsets coloured up in terms of classification in figure 8.1.

The flowsets can be neatly divided into three regions (figure 8.2). The central region comprising southern Scotland and England contains over 50% of the flowsets. Due to the nature of overlapping of flowsets it is difficult to crisply subdivide this region. However, subdivision was necessary in order to reduce complexity and this region is considered in four sub-regions with overlapping boundaries (figure 8.2).

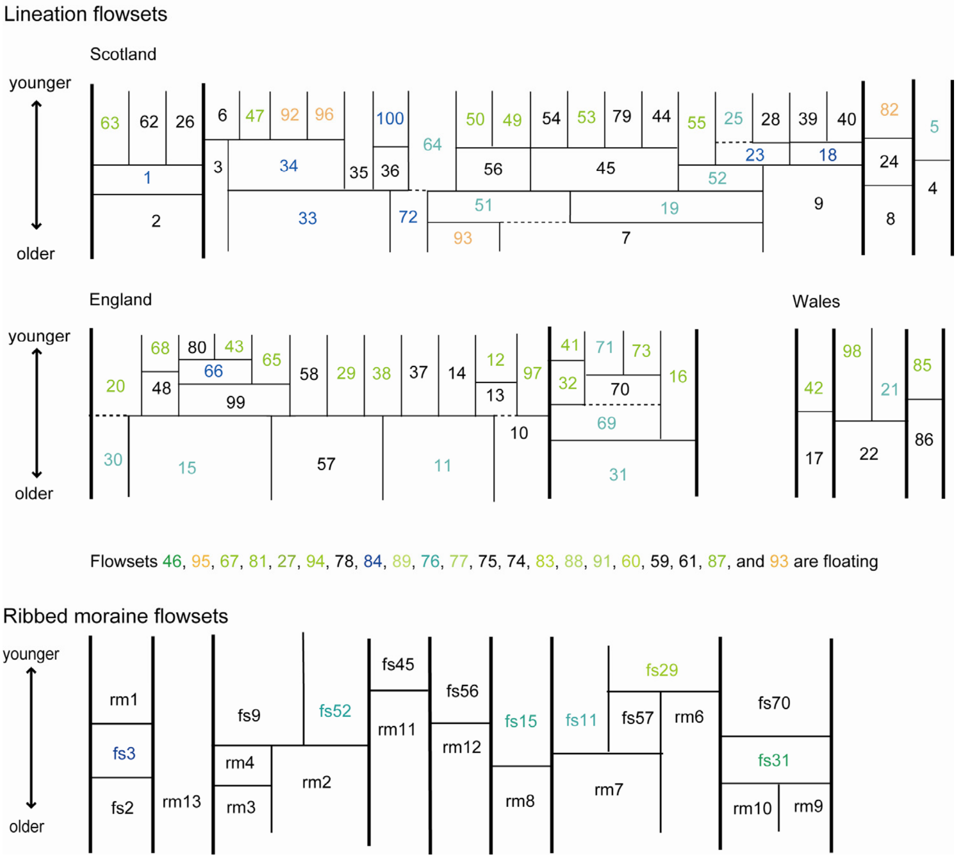


Figure 8.1 Relative chronology table with flowset numbers coloured in terms of classification: Isochronous = black; TT thinning = dark green; TT flow shift = blue; TT retreat = light green; and unknown = orange. As expected, TT retreat flowsets are the stratigraphically youngest flowsets.

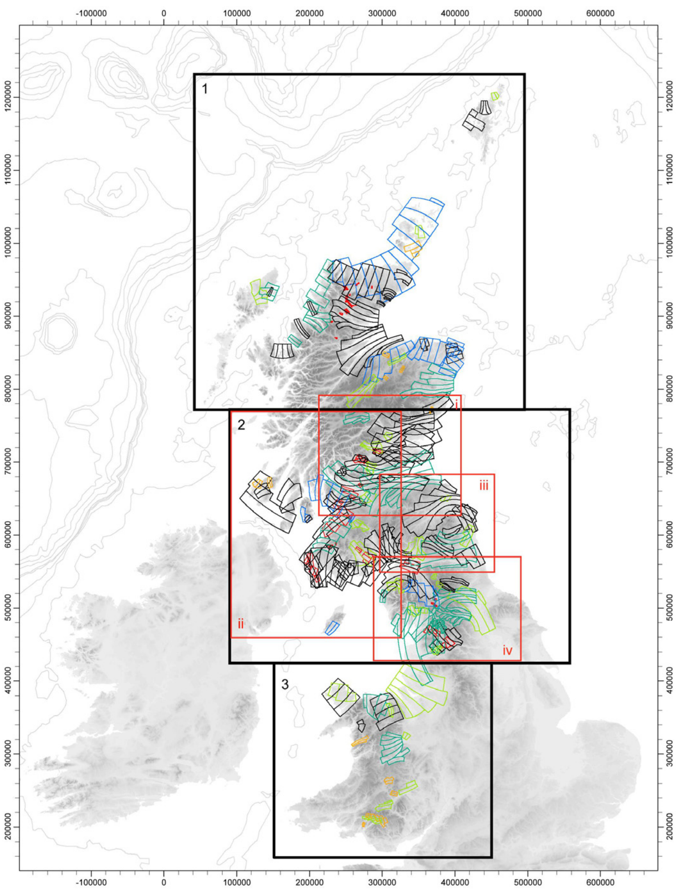


Figure 8.2 Boundaries of regions used to investigate flowset groupings. The spatial distribution of flowsets can be divided neatly into three large regions. Regions 1 and 3 are considered as a whole. Region 2 contains a high density of flowsets (over 50% of all identified) and is therefore more difficult to consider as a whole. Therefore region 2 is divided into 4 overlapping sub-regions (i-iv).

8.2.1 Region 1: Northern Scotland, Shetland and Orkney

This region incorporates mainland Scotland north of the Grampian Highlands, the Outer Hebrides, Orkney and Shetland (figure 8.3).

There are three distinct flowsets on Shetland; fs59, 60 and 61. Streamlined bedrock can be invoked to extend fs59 to cover the length of the islands. It is suggested that fs59 is coeval with fs1 over northern Scotland on the basis of geometric relationship and similar flow direction. Streamlined bedrock orientated SE-NW on Fair Isle support this (Peach and Horne, 1880). As the flowsets do not overlap there is no relative age information for the Shetland flowsets. Fs 60 and 61 indicate flow patterns that were deflected and focused by topography. Therefore, it is argued that these flowsets represent a time after the main ice flow pattern (fs1 and fs59).

There is strong evidence for broadly SE-NW orientated ice flow on Orkney and Caithness (fs1). Fs1 is a regionally significant ice flow event indicating that the ice was thick and independent of topography. Striae on Orkney are consistent with fs1 (Mykura, 1976). The flow pattern necessitates an ice divide running broadly WSW-ENE at least as far south as the Moray Firth. The presence of shelly till on Orkney and Caithness (figure 8.3) indicates that ice passed over marine sediments before reaching the region supporting a starting point of the ice flow south of the Moray Firth. The distribution of Scarlet conglomerate from an exposure close to Wick over Caithness is also consistent with fs1. In northern Scotland there is a degree of smudging within fs1 indicating a shift in ice flow from broadly S-N to SE-NW.

Fs2 is superimposed by fs1, and therefore represents an earlier phase of ice flow towards the NE. Rm13 can be grouped with fs2. Granite and unspecified erratics corroborate this north-easterly ice flow and can be used to extend the flowset over Caithness (figure 8.3). The remaining two flowsets on Orkney are more difficult to interpret and both are based on only a handful of drumlins. Cross-cutting relationships suggest the flowsets are younger than fs1. It is suggested that fs63 was generated during retreat in a southerly direction over Shapinsay. Fs62 indicates an ice centre to the west of Orkney which is difficult to resolve with any of the other flowsets in this region. The relative chronology of this flowset is not secure from the DEM data. Aerial photos would be useful to clarify this. In Caithness, fs26 is topographically constrained and the youngest flow pattern. It is therefore plausible to consider this flow pattern as part of a retreat stage of the ice sheet, when ice had started to retreat from the Moray Firth.

Fs4, adjacent to the Minch, and likely part of the Minch palaeo-ice stream (figure 6.19) (Stoker and Bradwell, 2005) is placed in the same geometry stage as fs1. Deflection of the proposed ice stream around the tip of Lewis is consistent with the dominant ice flow pattern exhibited by fs1.

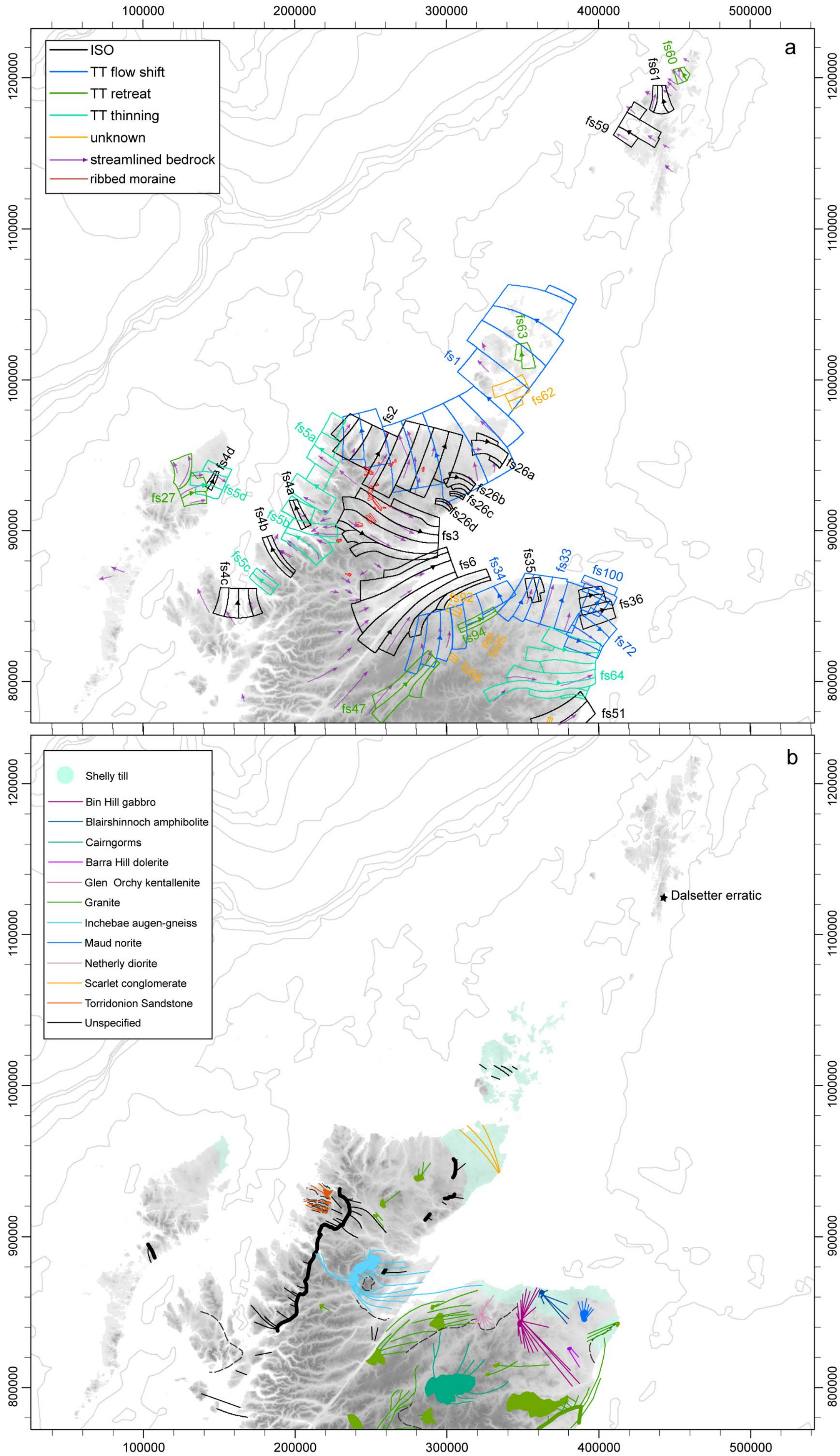


Figure 8.3 Flow pattern ingredients in northern Scotland: a) Lineation flowsets and streamlined bedrock summary arrows. Lineation flowsets are coloured in terms of temporal component of generation (isochronous or time-transgressive); b) Erratic transport paths and source areas from BRITICE database. Locations of shelly till deposits from Charlesworth (1957) and Sissons (1976).

An ice dome must have been present on the Outer Hebrides at this time in order to prevent incursion of ‘mainland’ Scottish ice over the islands. This is consistent with the lack of ‘mainland’ Scottish erratics on the islands which has been previously used to argue that the islands supported an independent ice dome throughout the last glacial (Ballantyne, 1998). There is no new evidence in this thesis to argue that the islands were overwhelmed by Scottish ice. Fs5 and fs3 both suggest that there was an ice divide running N-S along the length of the Northern Highlands. However there is not much space for an ice divide between the heads of each flowset. Therefore it is likely that the flowsets were inscribed at different times and record a slight divide shift. The erratic transport paths can be used to suggest that this ice divide shifted approximately 30 km between two extreme positions (figure 8.4). The shaded region encapsulates the area that has experienced both easterly and westerly ice flow (figure 8.4a). Fs3 relates to the first position of the divide (marked in red), fs5 to the second (marked in blue) (figure 8.4b). It is postulated that rm1 is coeval with or immediately precedes fs3.

In the Moray Firth region fs34 indicates N-S ice flow and is tentatively coupled with fs1 (figure 8.3). This is followed by fs3 documenting ice flow to the east from a N-S orientated ice divide. Erratic transport of Inchbae augen–gneiss can be used to extend fs3 to the south over Easter Ross and the Black Isle (figure 8.5a). Final ice flow, for which there is lineation evidence, is recorded by fs6 which details topographically focused ice flow into the mouth of the Firth. Streamlined bedrock extends the head of this flowset inland (figure 8.3). East of the Moray Firth, flowsets are more complex (figure 8.3). Fs33 is the oldest flowset in this area and is correlated with fs2 in northern Scotland on the basis of flow orientation. This is consistent in terms of the relative chronology with connecting fs34 and fs1. On the basis of geometric arrangement fs72 is connected with fs3 (figure 8.5a). It is suggested that these flowsets represent a phase of ice flow from the Highlands that skirts the north Buchan coast. Similarly, it is tentatively suggested that fs100 is coeval with fs6 (figure 8.5b). These connections are supported by the southerly transport of Netherly diorite, Bin Hill gabbro, Blairspinnoch amphibolite and Barra Hill diorite over Buchan (figure 8.5). The SSE ice flow exhibited by fs35 remains as an unexplained residual flowset that cannot be incorporated into any geometry. Similarly, the SW transport of Peterhead granite inland from the eastern coast of Buchan is unexplained (figure 8.5b).

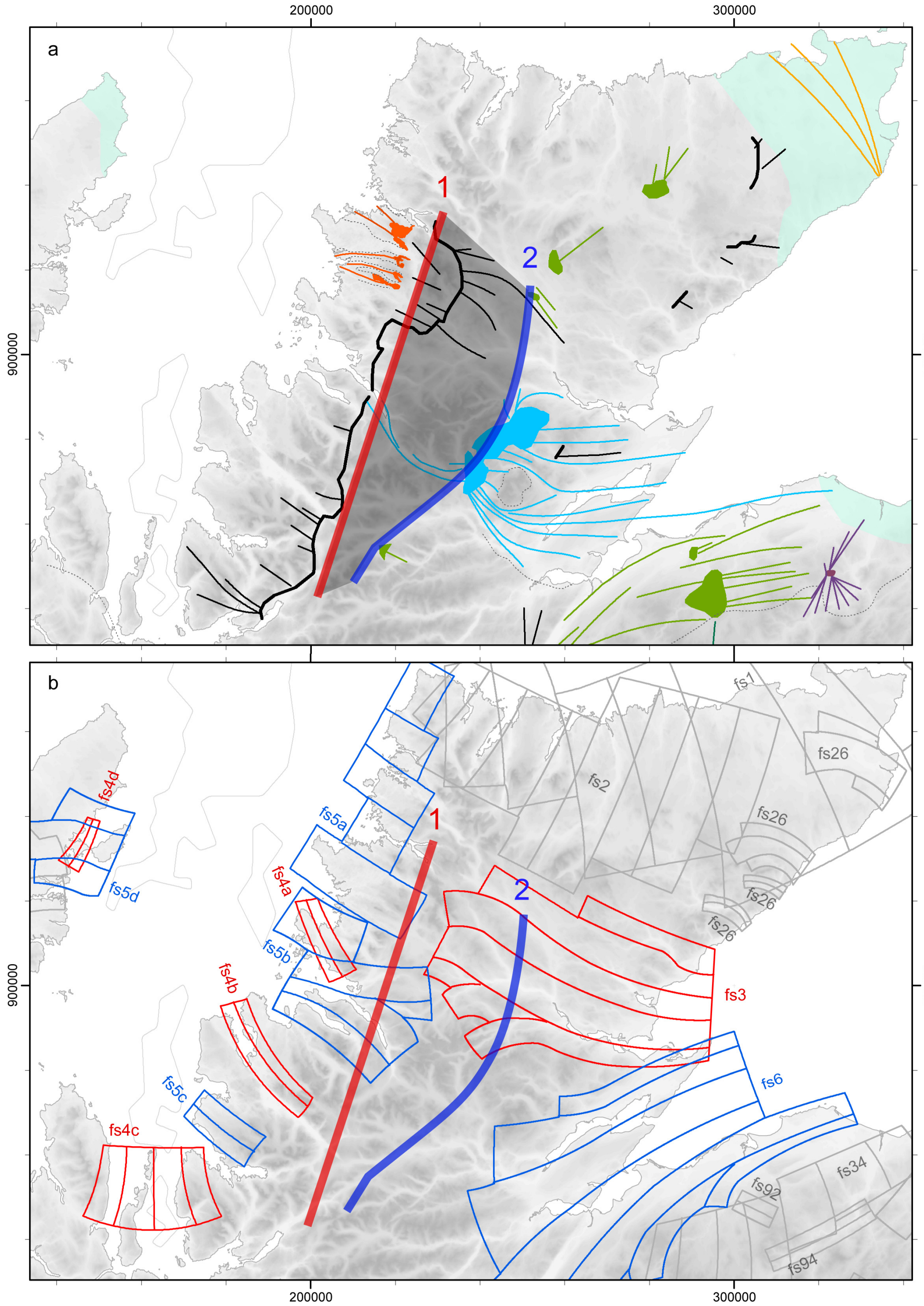


Figure 8.4 Erratics can be used to suggest relative timing of flowsets and therefore movement of an ice divide running broadly N-S over Northern Scotland. Fs3 and 5 both suggest an ice divide running broadly north-south along the ridge of the Northwest Highlands (figure 8.2a). However, the heads of these flowsets are too close to have been the result of the same ice divide position. There is no relative chronologic information between the flowsets but it is possible to use to erratic evidence to separate and group the flowsets. (a) Inchbae Augen Gneiss (light blue) has been transported both east and west. Likewise, an unspecified erratic (black) from an outcrop (thick black) running the length of the Moine Schist Fault has been transported both east and west at the northernmost tip. Other erratics in this area appear to have been transported either to the west (Torridonian Sandstone – orange) or the east (granite – light green). The spatial arrangement of erratic source areas enables two lines to be drawn which demarcate the areas that have experienced ice flow only towards the east (blue), only towards the west (red), and both west and east (shaded area). It is suggested that the shaded area represents the maximum horizontal distance (30 km) between two positions of the ice divide (line 1 and line 2). (b) Fs3 and fs4 are compatible with the first position of the divide (red). Fs5 and 6 are compatible with the second (blue). This relative timing is also consistent with the relative chronology between fs6 and 3 and fs4 and 5. The remaining flowsets in the area are in grey. Erratic colour scheme is the same as in figure 8.3.

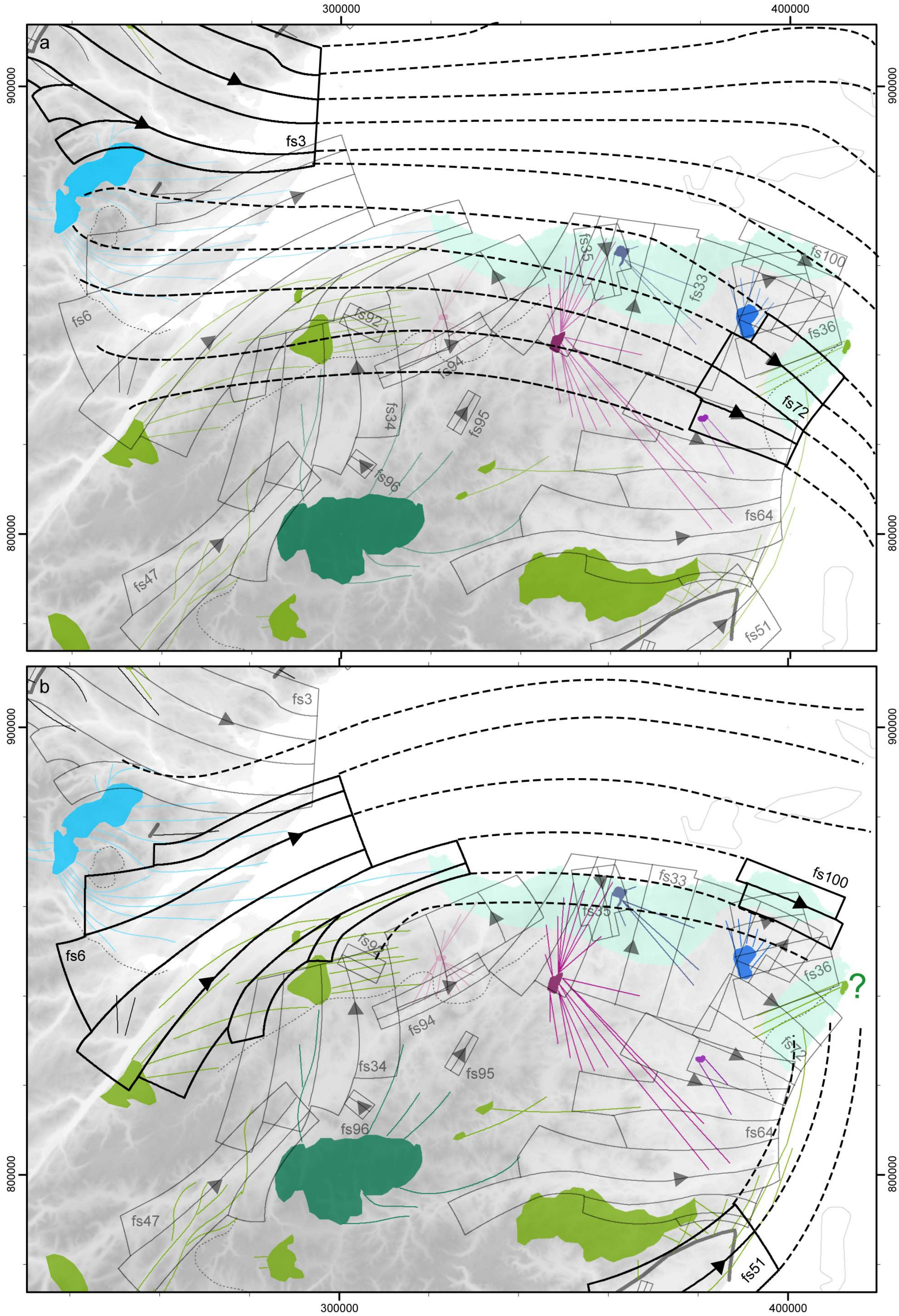


Figure 8.5 Erratics can be used to extend and support geometric grouping of flowsets in Buchan, NE Scotland. Fs33 and 34 recording ice flow towards the north and north-northeast respectively are supported by the distribution of erratics from the Cairngorms (turquoise), Bin Hill gabbro (purple), Netherly diorite (pink) and Blaispinnoch amphibolite (blue). If the eastward transport of Inchbae augen gneiss (light blue) is taken to extend fs3 to the south (dotted lines), geometrically fs3 can be connected to fs72 to form one east-west flow line that runs along the north coast. This is supported by eastward transport of granite and south easterly transport of Bin Hill gabbro and Netherly diorite erratics and dolerite (a). Fs6 and fs100 can be connected and together can explain the distribution of shelly till on the northern coast (b). The south-westward transport of Peterhead granite cannot be explained by the lineation flowsets (marked by question mark).

The above geometric correlations along with relative chronological evidence are weaved into a time slice reconstruction of ice sheet evolution in northernmost Scotland (figure 8.6). From this model it is possible to make inferences about the confluence of Scottish and Scandinavian ice. Initially Scottish sourced ice extended offshore (fs2 and rm13) (figure 8.6a). The Scottish ice then met Scandinavian sourced ice in the North Sea, and was deflected over Orkney and Shetland (fs1 and fs59), forcing an ice divide shift from a NW-SE to a SW-NE orientation. At this time Shetland and Orkney were overwhelmed by WNW ice flow from the North Sea (figure 8.6b) documented by the large and significant ice flow pattern recorded by fs1 and fs59. The single example of a Scandinavian erratic at Dalsetter (figure 8.3) supports this. If this is accepted, flowset relative chronology indicates that the rest of the evidence in the region relates to ice sheet flow patterns following break up of ice in the North Sea (figure 8.6c-f). The Minch palaeo ice stream represented by bold flow lines in the figure may have been within this stage (figure 8.6b) or slightly later (figure 8.6c). After break up (figure 8.6c), broadly E-W ice flowed out of the Highlands (fs3 and rm1) and skirted the north Buchan coastal zone (fs72). Fs62 can be incorporated within this stage. This is a 90º change in flow direction and suggests that collapse of ice in the North Sea forced a reorganisation of the ice sheet flow patterns with the development of a N-S orientated ice divide over the northern highlands. Development of the Minch ice stream in conjunction with collapse of ice in the North Sea may have facilitated development of the N-S ice divide. In the absence of evidence to the contrary it is assumed that the Minch palaeo-ice stream persisted in this configuration with little change to the western side of the ice sheet. The reconstructed flowsets do not indicate that Orkney supported an autonomous ice dome when connected to the Scottish ice mass. This is followed by a slight eastward shift in the N-S ice divide (figure 8.6d). This may have been driven by increased vigour of the Minch ice stream. Fs60 on Shetland is orientated such to suggest an ice divide NE-SW over the islands which fits with fs5 and continued connection to the mainland Scottish ice. Ice then retreated towards the Highlands and Grampians and progressed by ice sheet thinning exemplified by the topographic focussing of fs5 and fs64 (figure 8.6e-f). At some stage ice on Shetland separated from the main Scottish ice sheet (figure 8.6e). The youngest flowsets on Shetland suggest that the islands supported an ice cap independent from the rest of the British Ice Sheet, with fs61 produced by an outlet glacier into Yell Sound (figure 8.6e). This two stage glaciation of Shetland is consistent with models of flow geometry derived from striations (Peach and Horne, 1879; Golledge et al., 2008). Ice retreated to final ice centres in upland areas (Lewis, NW Highlands and the Grampians) (figure 8.6f). The largest uncertainties in the model are the flow patterns in the Little Minch and west of the Outer Hebrides.

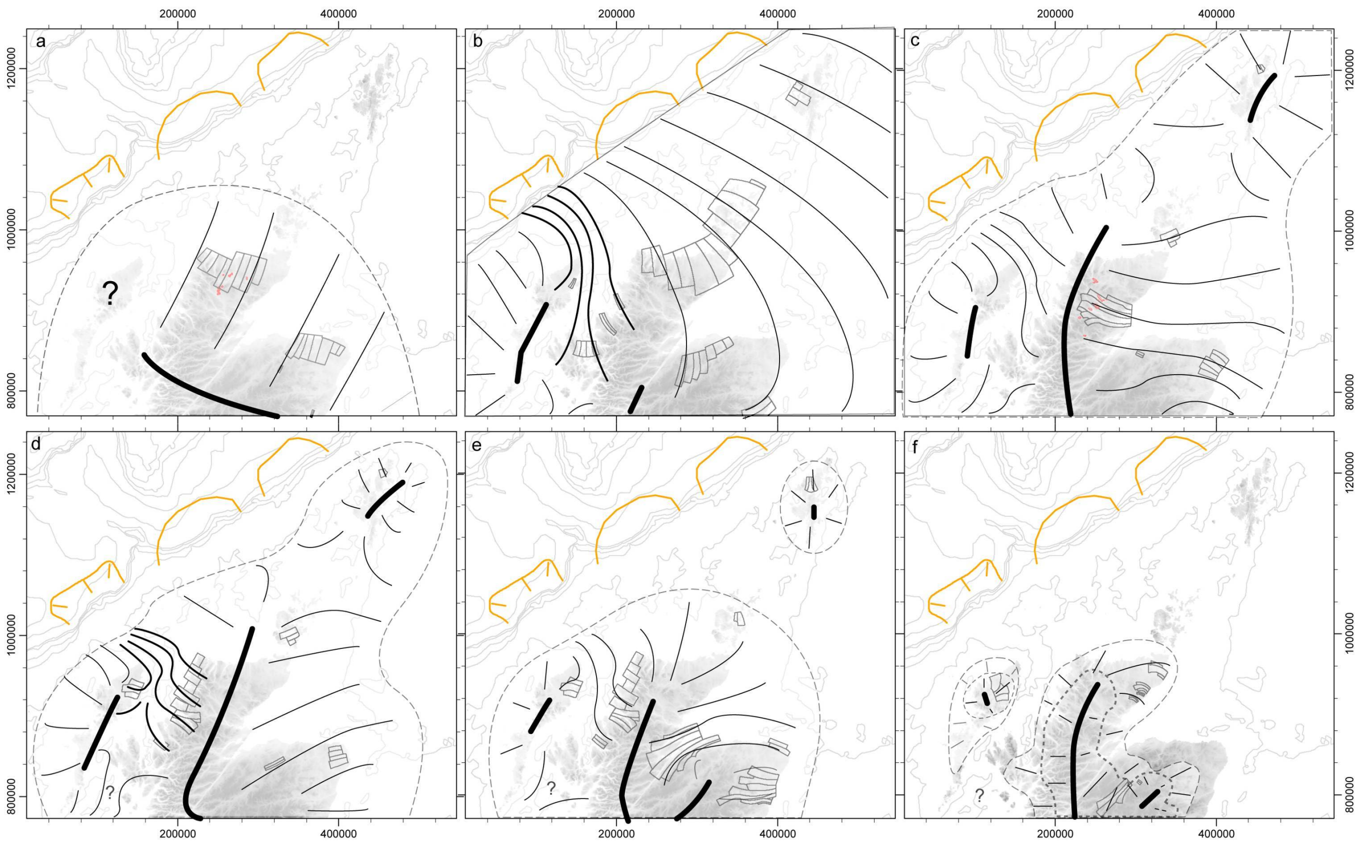


Figure 8.6 Reconstruction of ice flow configuration evolution for Northern Scotland. Flowsets can be organised into a minimum of 6 stages to satisfy geometric relationships and relative chronology. Ice divides are marked by a thick black line. Ice flow patterns by thin black lines. The location of trough mouth fans are shown in orange. Flowsets comprising the ice sheet geometry are in grey. (a) Fs2 and fs33 are grouped into the same time slice documenting ice flow towards the NNE from an ice divide running WNW-ESE. The position of the ice sheet margin is unknown. (b) Fs1 is grouped with fs59 and fs34 in a major ice flow pattern over the whole of the region. The deflection of ice flow towards the NW suggests that the British and Scandinavian ice sheets were confluent in the North Sea at this time. Fs4 can be accommodated within this stage. The deflection of fs4 around the Outer Hebrides suggests an autonomous ice dome centred on Lewis. It is likely that fs4 is part of the Minch palaeo-ice stream (Stoker and Bradwell, 2005). The NNW trending MSGL of the Witch Ground Ice Stream (Graham et al. 2006) could be part of this stage. (c) Collapse of ice in the North Sea results in a reorganisation of the ice sheet. NNE-SSW orientated divide develops over northern Scotland possibly extending over Orkney and connected by a saddle with an ice dome on the Shetland archipelago. It is presumed that the Minch palaeo-ice stream persists during this stage. (d) N-S ice divide shifts eastward but the connection with the Shetland ice cap remains (e) Fs5 and fs6 demonstrate that topography has an increasing role in ice flow patterns and the Shetland ice cap splits from the mainland ice sheet. (f) Deglaciation of the ice sheet is towards the high ground in the NW Highlands, Lewis and Cairngorms.

8.2.2 Region 2: Southern Scotland and England

Due to the number and complexity of the flowsets region 2 is subdivided into four overlapping areas where flow configuration evolution can be resolved. Splitting the area up in this way is not ideal but was a necessary initial step to reduce complexity.

8.2.2.1 Central Scotland

This region extends from mainland Scotland south of the Grampian Highlands to the northern slopes of the Southern Uplands and from the vicinity of Ben Nevis in the west to the Fife coastline in the east (figure 8.2 and 8.7). The Midland Valley of Scotland contains the highest density of mapped drumlins in the country (chapter 5). The reconstructed flowsets show that the main pattern of ice flow was from west to east, with repeated ice flow over the area many times with only slight modifications (figure 8.7a). This area presented a challenge to flowset identification for this reason (chapter 6). The consistent west – east ice flow suggests persistence of an ice divide running broadly NNE-SSW in the vicinity of the Rannoch Plateau.

Fs7 is the stratigraphically oldest flowset indicating initial ice flow towards the SE. Fs19 documents converging W to E ice flow through the Firth of Forth and extends as far west as Coatbridge on the outskirts of Glasgow. Placing the ice divide during this phase of ice flow to the west perhaps over Ayrshire, or Arran. Fs19 is classed as a *TT thinning* flowset on the basis of tributaries that join the main trunk of the ice flow path from the Southern Uplands (figure 6.14). Alternatively the flowset describes *TT thickening* of the ice sheet or the tributaries relate to a later stage of ice flow and should therefore be considered as separate flowsets. The flowset also suggests connection of ice from sources in the Highlands and Southern Uplands of Scotland. Fs19 could be coincident with fs8 or fs9 on the basis of geometry (region 2ii). The relative chronology of fs19 superimposing fs7 is also supported by the erratic transport paths (figure 8.7b). Granite and an unspecified erratic are transported SE (fs7) and then end up on the eastern Scottish coast, after being transported east by fs19. Fs51 is superimposed on fs19 and therefore represents a later stage of ice sheet geometry. On the basis of orientation fs52 is the southerly extension of this flowset. If connected the two flowsets suggest an ice divide orientated NNE-SSW over the Scottish Highlands.

The youngest flowsets in this area are closely related to topographic obstacles (fs56, 45, and 28). For example fs45 weaves around the Ochill Hills and Campsie Fells. This is interpreted as increasing topographic influence as the ice sheet thins, leading to cold based patches coincident with topographic highs. These flowsets are considered to be part of an early phase of the deglacial pattern with final deglaciation towards the Loch Lomond Stadial limit detailed by fs49, 79, 53, 55, and 54. The relative chronology of the flowsets supports this interpretation. Ribbed moraine flowsets rm12 and rm11 are overlain by fs56 and 45 respectively and describe the same ice flow direction as the overlying drumlins. Fs 23 and 28, and fs10 are considered in sub region 2ii and 2iii respectively.

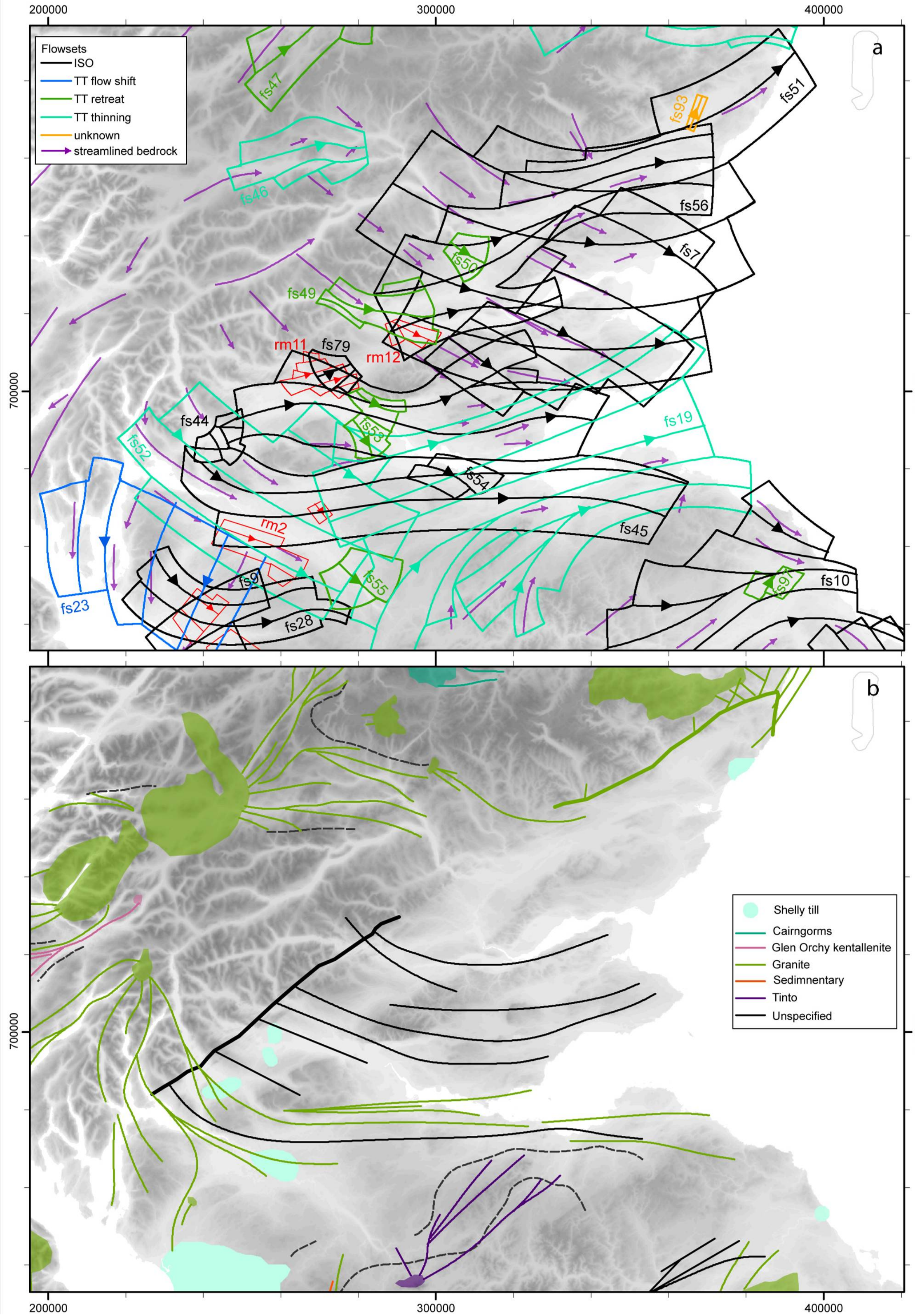


Figure 8.7 Flow pattern ingredients in central Scotland. (a) Lineation flowsets and streamlined bedrock summary arrows. Lineation flowsets coloured by type. (b) Erratic transport paths and source areas from BRITICE database. Erratics and streamlined bedrock patterns support flowsets recording persistent W-E ice flow. Locations of shelly till deposits from Charlesworth (1957) and Sissons (1976).

Figure 8.8 shows the reconstructed flow pattern model for this part of central Scotland. The relentless eastward ice flow reflects a relatively stable ice divide running broadly N-S in the vicinity of the Rannoch Plateau with ice deflected eastwards by the obstacle of topography or a coeval ice mass on the Southern Uplands. Changes in flow pattern in this region are testament to the relative dominance of Southern Upland and Highland ice. Initially fs7 documents expansion of Highland sourced ice into the Firth of Forth (figure 8.8a). Fs19 represents a stage where ice from Southern Uplands and Highlands coalesced resulting in a major ice flow path into the Firth of Forth (figure 8.8b). The divergence of fs19 at the mouth of the Firth suggests that the ice margin was relatively near by and the ice flow path terminated terrestrially, i.e. not at a calving margin. Therefore the North Sea east of the Firth of Forth must have been exposed as dry land due to low sea level. Alternatively the curvature could imply that there was an obstacle (perhaps North Sea ice cover) in the region to cause deflection of Scottish ice. In the latter scenario the British and Scandinavian Ice Sheets must have been confluent. In the following stage (figure 8.8c) Highland sourced ice is dominant over, but continues to be deflected by, ice from the southerly Southern Upland source. This is followed by thinning of the ice sheet exemplified by increased topographic influence on flow patterns (figure 8.8d) and a decline in power of Highland sourced ice. Ice then separates from Southern Upland ice and retreats towards an ice cap centred over the Highlands (figure 8.8e). Deglaciation progresses by ice sheet thinning and topographically controlled retreat.

8.2.2.2 Western Scotland: the North Channel, Kintyre, Ayrshire and Galloway

Figure 8.2 shows the boundaries of this regional subset (2ii). The majority of the flowsets in this area are isochronous in classification, with only three ascribed to time-transgressive retreat (figure 8.9). To the west over the North Channel and Kintyre, fs8 describes a flow pattern over the western isles towards the NW (figure 8.9a). This flowset is independent of topography and supports an ice divide situated over the westernmost Southern Uplands. The deflection of the flowset to the NW suggests the presence of an obstacle to ice flow in the SW over Ireland. Erratic transport paths from the Western Highlands support broadly E-W ice flow (figure 8.9b). Fs9 is the oldest flowset and is topographically unconstrained extending over Ayrshire and Galloway. Fs9 and fs8 do not overlap so fs8 could precede or follow this ice flow. It is possible to use the erratic distribution to aid the relative chronological sorting of the flowsets (figure 8.10). Alisa Crag microgranite is found on the northern coast of Ireland. A scenario can be envisaged where Alisa Crag microgranite is first transported south by Scottish ice (fs9) to a location in the vicinity of the Rhins of Galloway (figure 8.10a) and then transported for a second time to the Irish coast by a southerly extension of fs8 (figure 8.10b). Ribbed moraine flowset rm3 describes a similar ice flow direction to fs9 whereas rm4 is in line with fs18 which describes southerly ice flow into the Irish Sea (figure 8.9). Fs18 is possibly coeval with fs99 out of the Solway Firth (region 2iv) and fs84 on the Isle of Man. Fs18 suggests an ice divide north of Ayrshire.

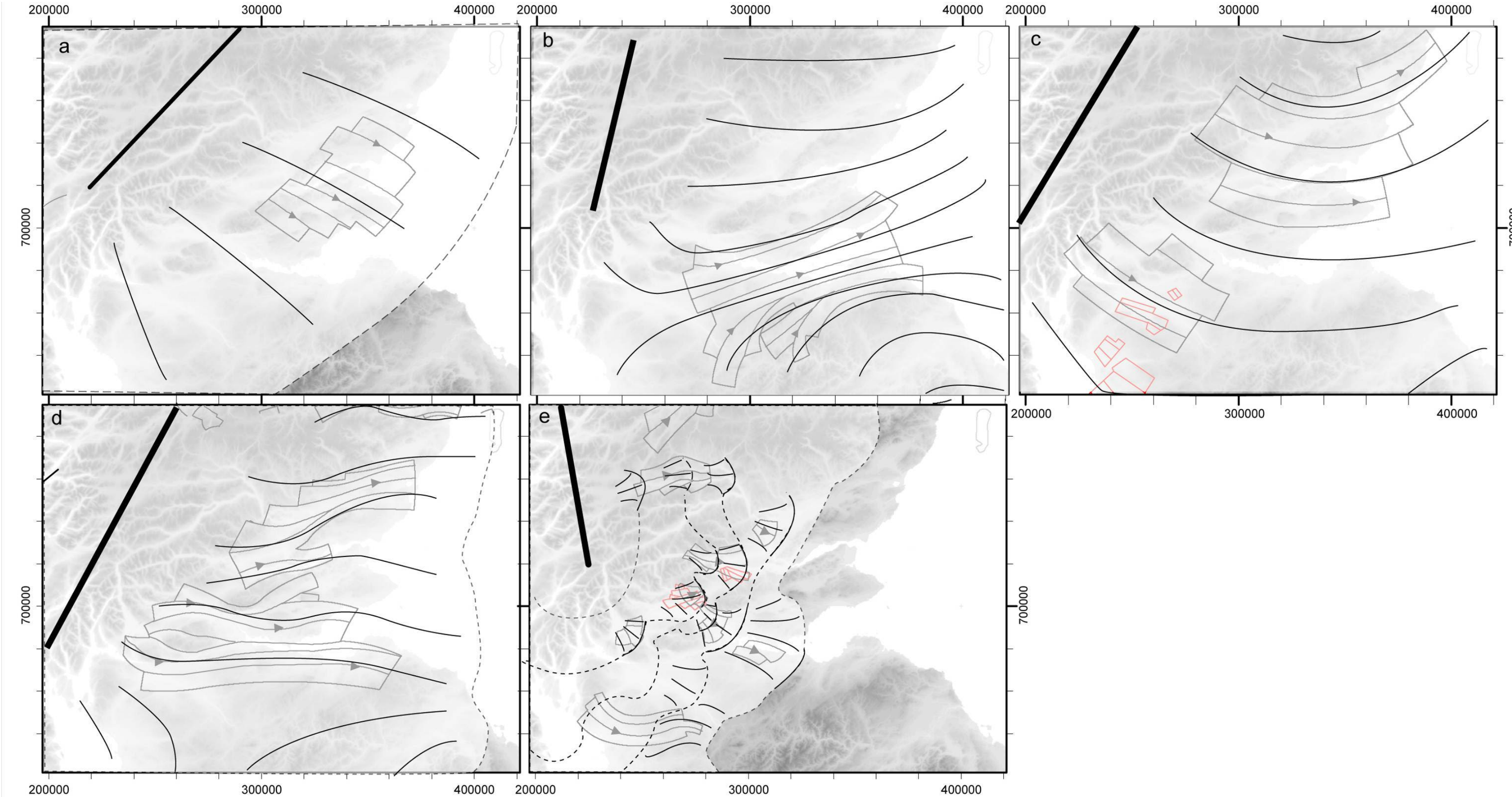


Figure 8.8 Reconstruction of ice flow configuration evolution for Central Scotland. Flowsets are organised into a minimum of five stages. Colour scheme is the same as in figure 8.6 with the addition that ribbed moraine flowsets are shown in red. (a) Fs7 records ice flow out of the Scottish Highlands towards the SE. The location of the ice sheet margin is unknown. (b) Fs19 records convergence of ice flow from a Highland (shown) and Southern Uplands ice (not shown) centres and drawdown into the topographic low presented by the Firth of Forth. Confluence of Highland and Southern Upland sourced ice is inferred. A saddle between the two ice masses is placed at least as far west as Ayrshire. Divergence of flow pattern at the mouth of the Forth suggests that the ice sheet is not confluent with the Scandinavian ice sheet in the North Sea at this time and the North Sea is raised above sea level. It is postulated that fs19 can be grouped in the same geometry as fs8 or 9. (c) On the basis of similar orientation fs52 and fs51 are grouped. Rm2 could also be incorporated within this stage if onshore ice flow direction is accepted. We postulate that Highland ice is dominant over Southern Upland sourced ice at this stage and the British Ice Sheet is confluent with the Scandinavian Ice Sheet in the North Sea to explain the northward deflection of fs51. (d) Collapse of ice in the North Sea and development of a network of topographically constrained ice streams along the eastern margin of the ice sheet (fs45 and 56). It is inferred that the ice sheet is thin as topography has an increasing influence on flow patterns. (e) Deglaciation of the ice sheet towards the NW Highlands and separation of Highland and Southern Upland ice masses.

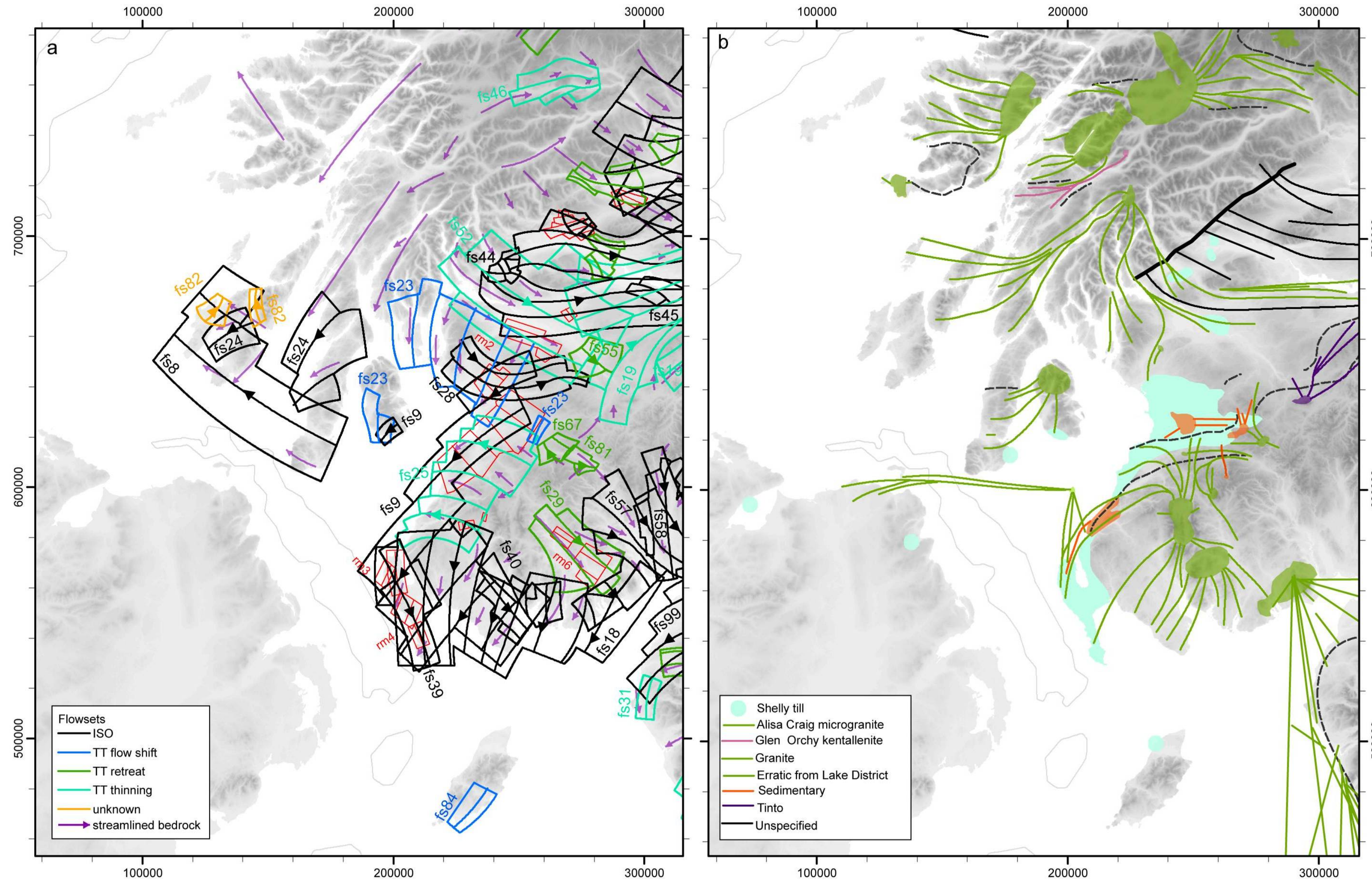


Figure 8.9 Flow pattern ingredients for Western Scotland region. (a) Lineation flowsets and streamlined bedrock summary arrows. Lineation flowsets coloured by type (isochronous or time-transgressive). (b) Erratic transport paths and source areas from BRITICE database. Locations of shelly till deposits from Charlesworth (1957) and Sissons (1976).

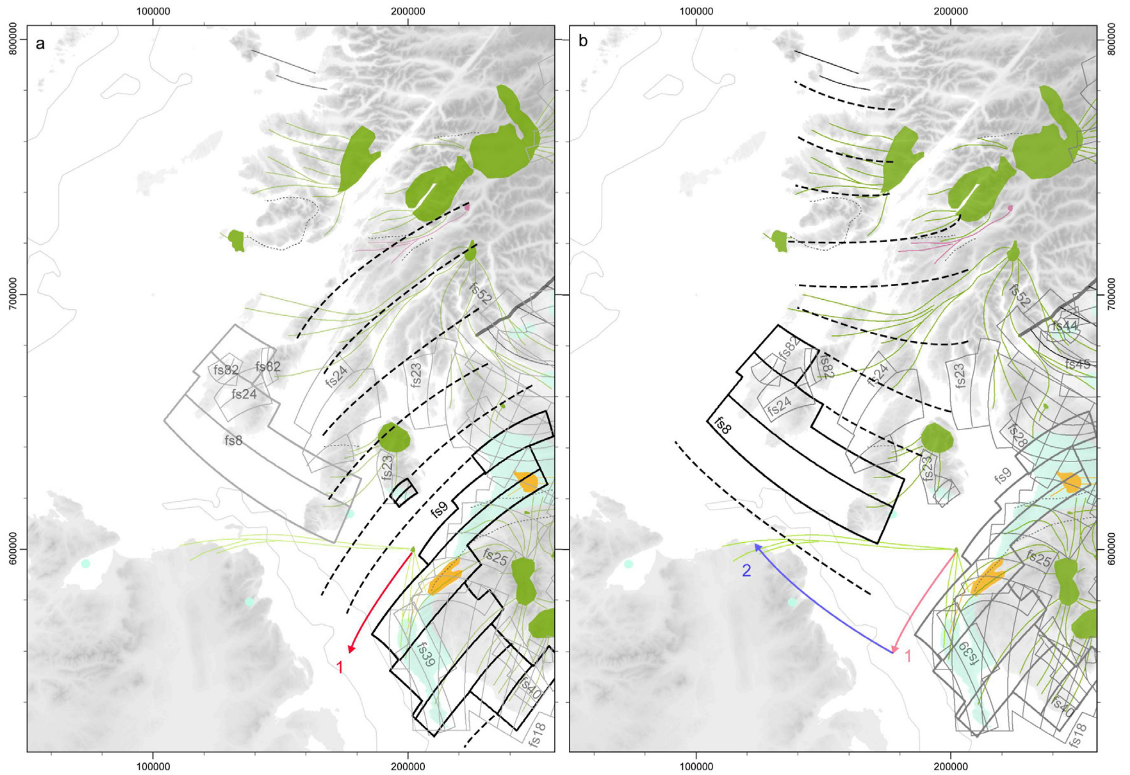


Figure 8.10 There is no relative chronological relationship between fs9 and fs8 but erratic transport paths can be used to understand the relative timing of the two flowsets. Ailsa Craig microgranite is found on the northern coast of Ireland. A situation can be envisaged whereby south-westerly flowing ice (fs9) transports microgranite south-westward (marked by red arrow) (a). North-easterly ice flow (fs8) then transports the erratic to the Irish coast (marked by blue arrow (b). This could also work the opposite way around. Flowsets are shown in grey and erratics with the same colour scheme as figure 8.9.

The remaining flowsets in this region all exhibit some affinity with topography (fs39, 24, 40, 29, 57, 23, 28, 25). It might be expected that these flowsets are therefore all part of the deglacial signature when the ice is thin. Fs24 is superimposed on fs8 and indicates a change in flow geometry, when ice flow is deflected around topography, and an ice source is centred to the northeast of the region. Fs24 is not considered to represent tributaries of fs8 as the curvature of ice flow does not support this interpretation. Fs9 and fs24 exhibit similar orientation but are not grouped into the same ice sheet geometry because of different relationships with topography. Fs24 flows into a basin and follows topography whereas fs9 is not topographically constrained. Fs24 is superimposed on fs8 and indicates a major change in flow geometry, when ice flow is deflected around topography, presumably after the North Channel is deglaciated. Fs82 is based on only a few drumlins and is likely to be part of the deglacial signature or a remnant of earlier ice flow. Fs39, 40 and 57 taken collectively necessitate an ice divide running WSW-ENE over the North Channel. The flow pattern of fs25 suggests an ice divide centred over the western Southern Uplands in accordance with the erratics from Loch Doon. Fs57 could be coeval with this flowset. It is difficult to resolve fs25 with fs39 and 40, all three flowsets are taken as part of the deglacial signature; fs25 suggests retreat to an ice dome on the westernmost Southern Uplands whereas fs39 and 40 suggest an ice centre over Arran. The relative chronology and shape of fs25 is difficult to reconcile with the rest of the flowsets in this area, in particular fs39. For this reason I present four possible scenarios to explain the flow geometry changes inscribed in this area. The ice flow direction represented by ribbed moraine flowset rm2 is uncertain and therefore this flowset is excluded from consideration.

- Scenario 1

In this model (figure 8.11), the relative chronology of fs25 is disregarded.

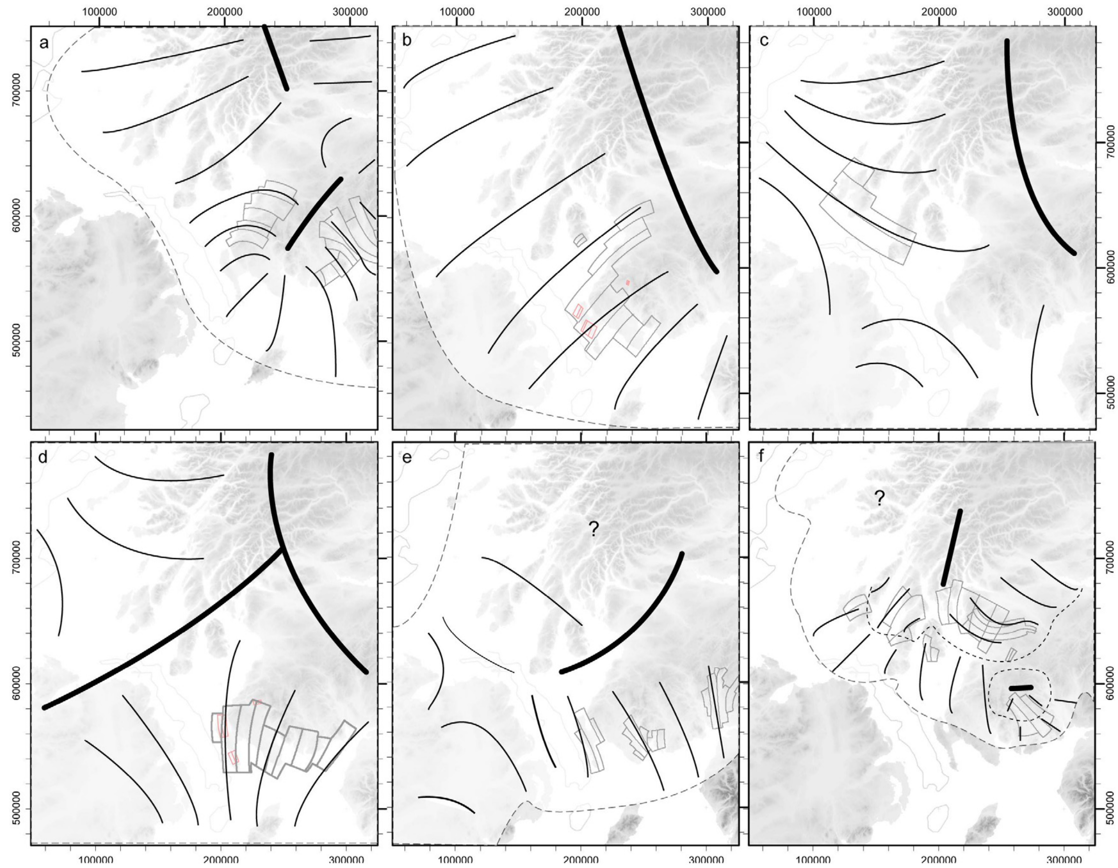


Figure 8.11 Scenario 1: Reconstruction of flow geometry of western Scotland region if relative chronology of fs25 is disregarded and the flowset is taken to represent the oldest ice flow event. (a) Highland and Southern Upland ice is confluent. Unknown position of the ice sheet margin but not coalescent with Irish ice. (b) Highland and southern upland ice connected by N-S ice divide and ice flows SW into Ireland. (c) Scottish ice is confluent with Irish ice to forma saddle over the North Channel. (d) Development of ice stream in the Irish Sea. (e) Irish Sea is deglaciated but ice remains confluent over North Channel. Topographically constrained flowsets suggest thin ice sheet. (f) Deglaciation of the ice sheet towards the Highlands and Southern Uplands.

Fs25 and fs57 are grouped together in an early phase of ice sheet geometry composed of autonomous ice domes on the Southern Uplands and NW Highlands (figure 8.11a). Fs25 is deflected by ice from the Highlands ice centre. The rest of the model adheres to the relative chronology presented in figure 8.1. Fs9 documents ice flow from a NNW-SSE orientated ice divide running across the Midland Valley of Scotland (figure 8.11b). The ‘invasion’ of Scottish ice into Northern Ireland by fs9 is followed by connection between Irish and Scottish ice (figure 8.11c). From the erratic evidence fs9 is placed into a geometry preceding fs8 and by extension confluence with the Irish Ice Sheet. Fs8 is a regionally significant flowset that could have only been inscribed during confluence with the Irish Ice Sheet over the North Channel. It is hypothesised that the flowset is the onshore expression of part of an ice stream draining the central section of the ice sheet towards the Barra Fan. The south-westerly ice flow of fs9 is followed by fs18 (figure 8.11d) which documents ice flow from an ice divide on central Galloway deflected by an ice mass on Ireland into the Irish Sea. It is suggested that fs99 out of the Solway is contemporary with this ice flow. Together the flowsets relate to a time when the British and Irish Ice Sheets were confluent and ice was drawn down into the topographic low provided by the dry Irish Sea. By geometry alone fs23 could be connected with fs18 but it seems more probable that fs23 is related to a later stage of ice flow geometry. Fs39, 40 and 58 are grouped together into a phase of ice sheet geometry after deglaciation of the Irish Sea, but persistence of connection with Ireland and a saddle over the North Channel (figure 8.11e). Fs23, 24, 29 and 28 describe the retreat of the ice sheet following break up of the connection between Irish and Scottish ice.

- Scenario 2

In the second scenario (figure 8.12) the relative chronology between fs25 and fs23 is respected.

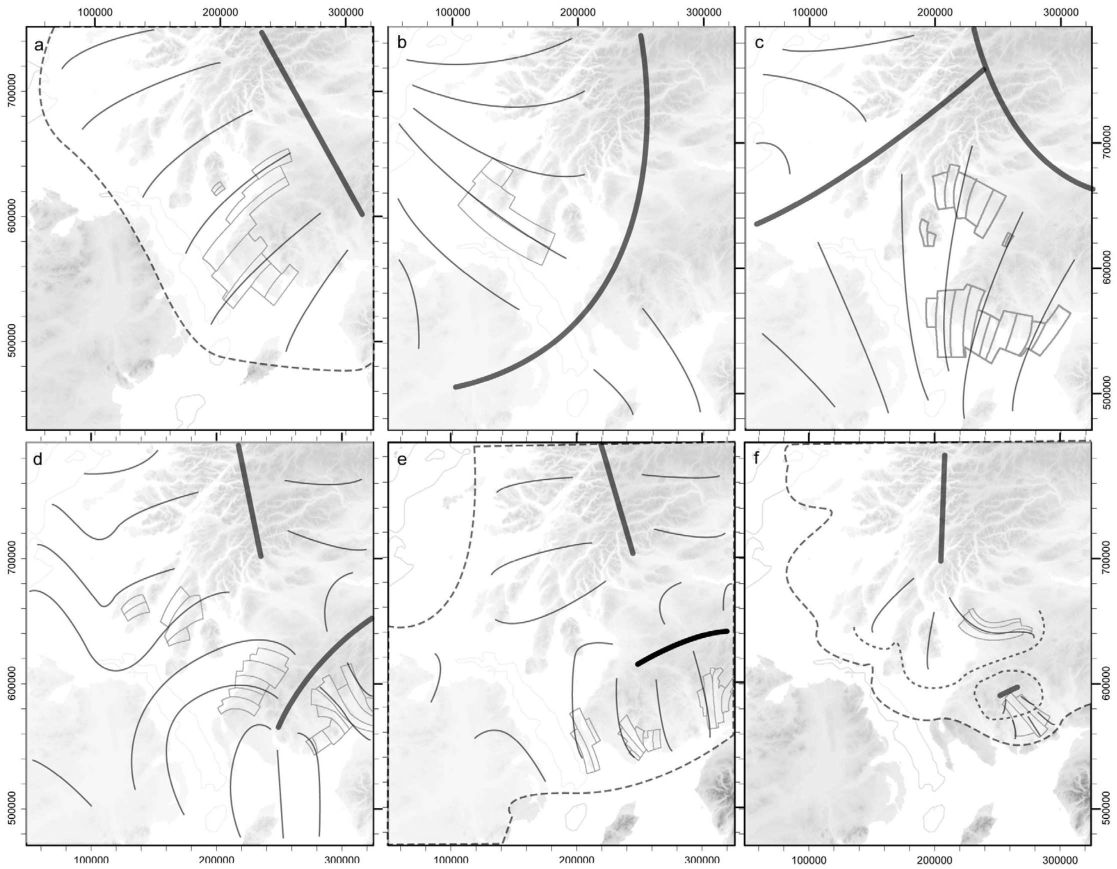


Figure 8.12 Scenario 2: Reconstruction of flow geometry of western Scotland region if relative chronology of fs25 is respected and taken as head of an ice flow event down the Irish Sea. (a) Highland and Southern Upland ice is confluent. Unknown position of the ice sheet margin but not coalescent with Irish ice. Ice flows to SW to 'invade' Ireland. (b) Scottish ice is confluent with Irish ice to form a saddle over the North Channel. (c) Development of ice stream in the Irish Sea. Fs23 taken as the head of fs18. Fs23 exhibits smudging which could be due to changes occurring as the ice sheet changes from (c) to (d). (d) Ice sheet thins and separates to a series of autonomous ice divides but remains confluent. (e) Irish Sea is deglaciated but ice remains confluent over North Channel. Topographically constrained flowsets suggest a thin ice sheet. (f) Deglaciation of the ice sheet towards the Highlands and Southern Uplands.

Fs9 represents initial incursion of a Scottish ice sheet into northern Ireland (figure 8.11a). This is followed by connection over the North Channel and development of an ice stream in the North Channel (fs8) (figure 8.12b). To respect the relative chronology, fs23 is taken as the headward extension of fs18. If fs18 is taken to represent the head of the Irish Sea Ice Stream, this reflects a change in dominance between a North Channel ice stream and an Irish Sea ice stream and a shift in the ice divide northward. Fs23 is a *TT flow shift* flowset and the smudging may reflect minor changes in flow patterns between the stages represented by figure 8.12c and 8.12d. In this scenario, fs57 is placed in a younger geometry than fs18 and therefore fs18 cannot be grouped with fs99. Ice flow continues down the Irish Sea but the ice sheet thins to take more account of topography (figure 8.12d) and Highland and Southern Upland ice separate into two autonomous domes. This is followed by an increase in dominance of the Southern Upland divide (figure 8.12e) and final retreat (figure 8.12f).

- Scenario 3

In the third scenario (figure 8.13) the relative chronology between fs25 and fs23 is reversed and so fs23 becomes part of the deglacial stages of the ice sheet configuration.

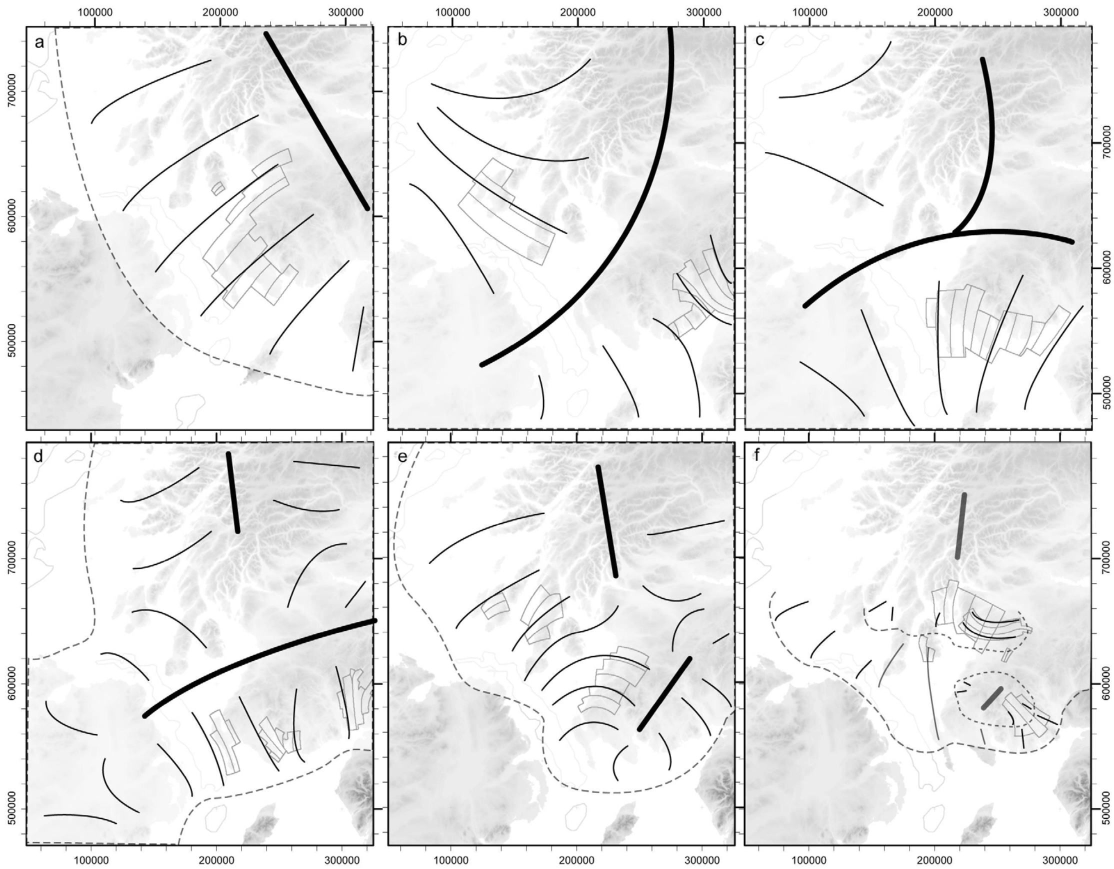


Figure 8.13 Scenario 3: Reconstruction of flow geometry of western Scotland region if relative chronology of fs25 to fs23 is reversed and fs23 taken as the youngest flowset. (a) Highland and Southern Upland ice is confluent. Unknown position of the ice sheet margin but not coalescent with Irish ice. Ice flows to SW to 'invade' Ireland. (b) Scottish ice is confluent with Irish ice to form a saddle over the North Channel. Grouping with fs57 places an ice divide over Galloway. (c) Development of ice stream in the Irish Sea. (d) Irish Sea is deglaciated but ice remains confluent over North Channel. Topographically constrained flowsets suggest thin ice sheet. The ice starts to separate into a series of autonomous ice domes (e) Deglaciation of the North Channel and separation of ice divide into autonomous domes (f) Deglaciation of the ice sheet towards the Highlands and Southern Uplands.

Stage 1 (figure 8.13a) is the same as in scenario 2. This is followed by fs8 which is grouped with fs57 (figure 8.13b). Ice is then topographically focused into the Irish Sea (fs18) (figure 8.13c). Deglaciation of the Irish Sea occurs and the ice sheet thins, but a saddle persists over the

North Channel (fs39, 40 and 58) (figure 8.13d). Ice collapses in the North Channel and fs24 and fs25 are grouped together suggesting division of the ice sheet into two autonomous ice centres (figure 8.13e). Fs23 develops in the transition stage between figure 8.13e and 8.13f. Fs29 documents final retreat to the two ice centres (figure 8.13f).

- Scenario 4

In the forth and final scenario (figure 8.14), the relative chronology is preserved but fs39 is taken as being younger than fs25. Stages 1 and 2 (figures 8.14a and b) are the same as in scenario 3. As in scenario 2, fs23 is grouped with fs18 (figure 8.14c). This is followed by deglaciation of the Irish Sea (figure 8.14d) and an ice divide over the North Channel represented by fs40 and 58. Fs25 can be incorporated into the deglacial signature of the ice sheet with fs24 after collapse of ice in the North Channel (figure 8.14e) and fs39 represents a readvance down the North Channel after Southern Uplands have deglaciated (figure 8.14f).

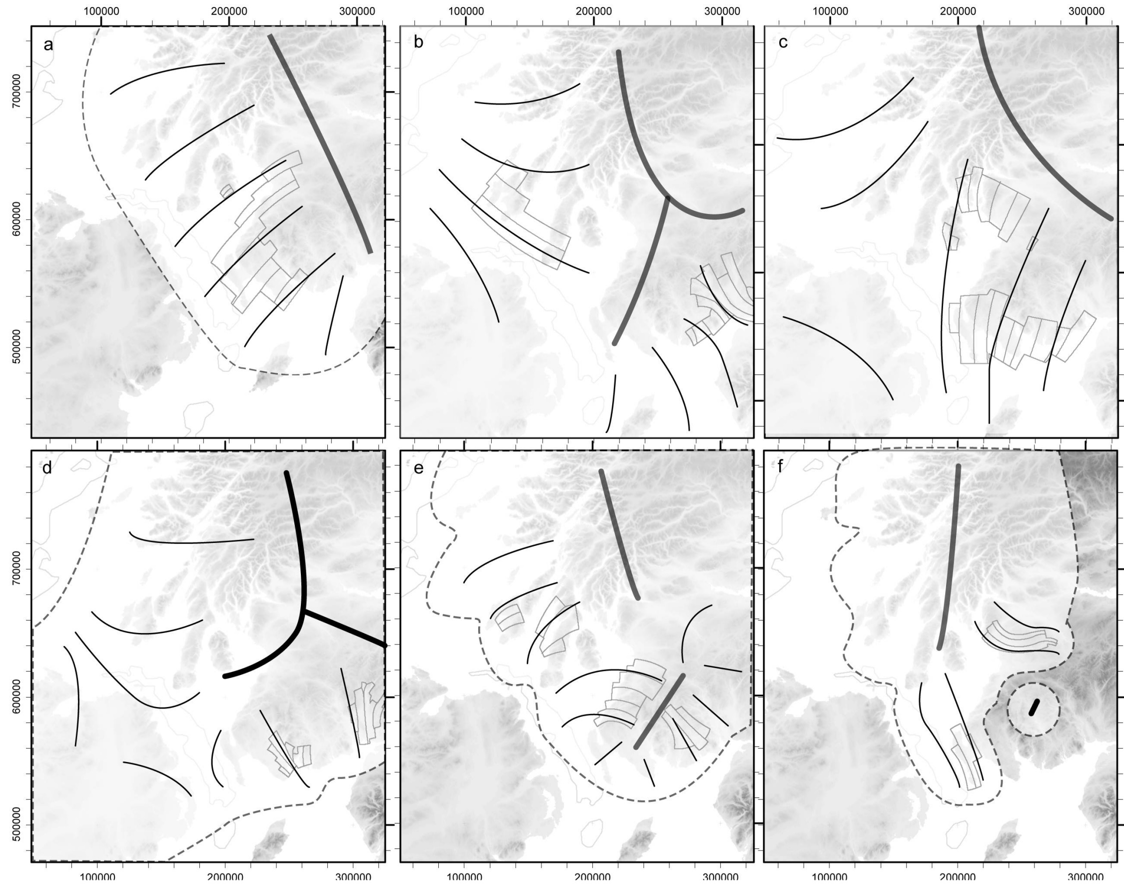


Figure 8.14 Scenario 4: Reconstruction of flow geometry of western Scotland region if relative chronology of fs25 to fs23 is preserved and fs25 taken as deglacial and followed by a readvance of ice from the newly separated Highland ice cap. (a) Highland and Southern Upland ice is confluent. Unknown position of the ice sheet margin but not coalescent with Irish ice. Ice flows to SW to 'invade' Ireland. (b) Scottish ice is confluent with Irish ice to form a saddle over the North Channel. Grouping with fs57 places an ice divide over Galloway. (c) Development of ice stream in the Irish Sea. Fs23 is grouped with fs18. (d) Irish Sea is deglaciated but ice remains confluent over North Channel. Topographically constrained flowsets suggest thin ice sheet. (e) Start of deglaciation of the North Channel and separation of ice divide into autonomous domes (f) Deglaciation of the Southern Upland ice dome is followed by a re-advance of lobes into lowland areas recently deglaciated by retreat of Southern Uplands ice mass.

Scenario 3 is the preferred model of ice flow evolution in this sector of the ice sheet. Scenarios 2 and 4 are less glaciologically plausible and scenario 1 rejects the relative chronology of events completely.

8.2.2.3 The Cheviots and Tyne Gap

The region incorporates northeast England and the Scottish border region south of the Lammermuir Hills (figure 8.15). Fs11 represents a major west to east ice flow over central England through Tyne Gap. This flowset could be the eastward extension of fs57 but the relative size of the two flowsets seems to suggest that this is unlikely. More importantly, fs57 is focused by topography whereas fs11 is not, at least in the initial stages of establishment of the ice flow. Furthermore Criffel granite erratics are only found at the eastern most limit of fs11. Fs57 is therefore thought to relate to a later (or earlier) stage of ice sheet geometry. Fs11 is classed as a *TT thinning* flowset. It is suggested that a broad W-E ice flow persisted in this area until after the initial thinning of the ice sheet during deglaciation. Alternatively fs11 is a *TT thickening* flowset, the early phase of which is coeval with fs57. This is not consistent with the cross cutting drumlins observed within fs11. Fs11 places an ice divide running north-south over the Lake District and Solway lowlands. Fs10 also documents broadly east-west ice flow but is topographically focused into the Tweed basin. This ice flow is possibly contemporary with the later, topographically deflected stage of fs11. It is suggested, in agreement with Everest et al. (2005), that fs10 is the imprint of the Tweed palaeo-ice stream (chapter 6).

Fs11 is superimposed by a series of topographically constrained flowsets (fs38, 14, 37, 12) that all place an ice divide running E-W over the Southern Uplands. There are no flowsets that record ice flow out of an ice divide centred on the Cheviots. In fact, fs10, 13, 37, 12 and 11 all flow around the massif. The restricted extent of Cheviot granite erratics supports this. Fs13 and 12 document ice flow running along the east coast. Fs10 is deflected south at the present day coastline. The explanation for this deflection and the southerly flow of fs13 is equivocal. Ice flow could have been deflected by an offshore ice mass east of the Berwick coast, or more powerful ice flowing out of the Firth of Forth. Fs13 is composed of two spatially separate parts that have been combined into the same flowset on the basis of orientation. It is possible however that these are in fact two distinct flow events. Fs12 and fs38 are classed as *TT retreat* flowsets and therefore document retreat back towards the Tweed and around the Cheviots.

A model of the ice flow pattern evolution of this area is shown in figure 8.16. Ice flow is initially west-east over the area (figure 8.16a). This is followed by ice flow towards the SE, explained by increasing power of an ice divide centred over the Southern Uplands (figure 8.16b). It is postulated that the deflection of ice along the east coast is caused by congestion of ice in the North Sea. This respects the relative chronology of fs11 and fs13, but not fs13 and fs10. The ice sheet then thins and the Tweed Ice Stream (Everest et al., 2005) develops (figure

8.16c). This is tentatively grouped with fs99 (region 2iv). Retreat of the ice sheet progresses by ice sheet thinning around the topographic bump of the Cheviots (figure 8.16d). The ice retreats more rapidly around the Cheviots that out of the Solway lowlands.

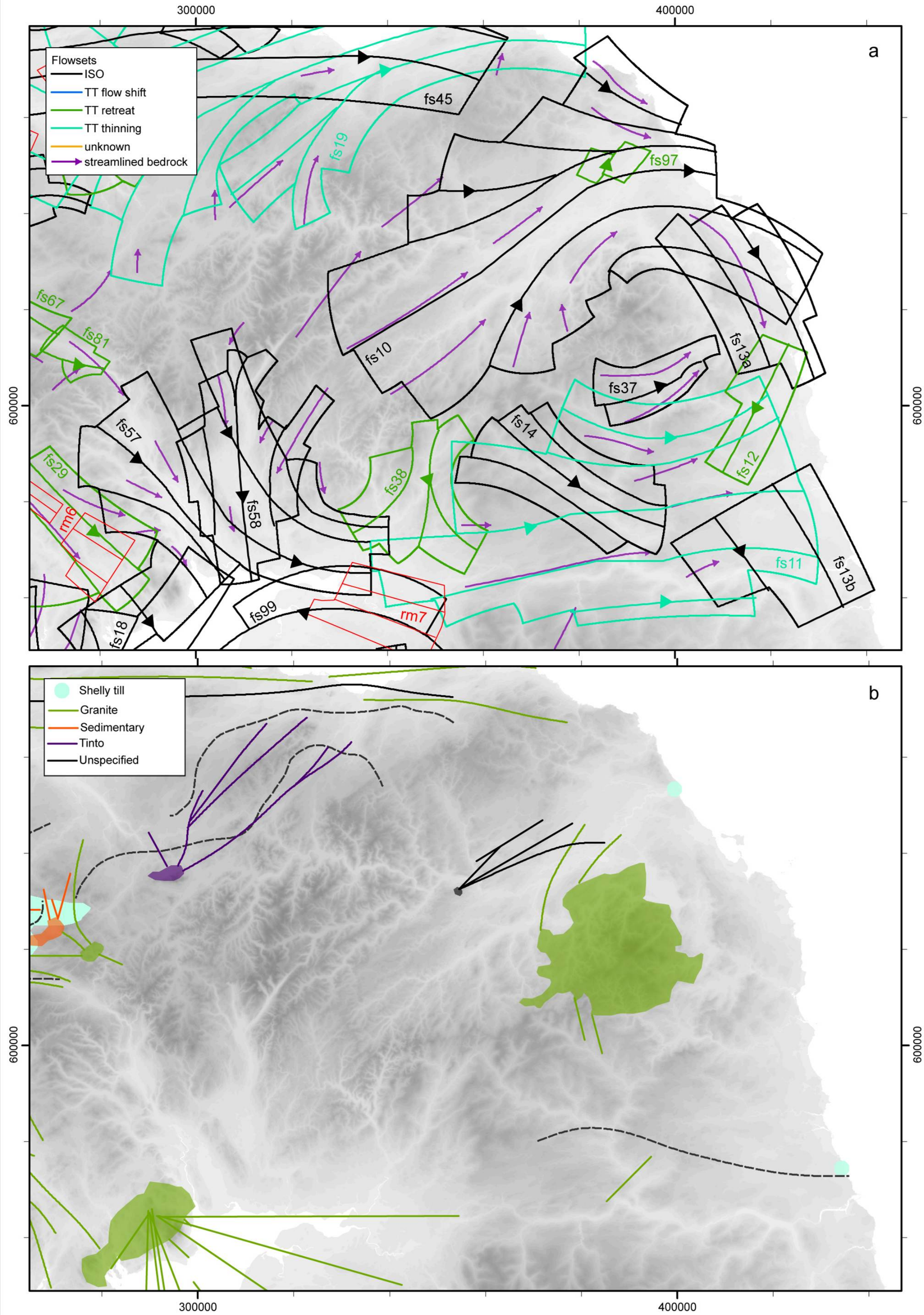


Figure 8.15 Flow pattern ingredients in northeast England and the Scottish borders. (a) Lineation flowsets and streamlined bedrock summary arrows Lineation flowsets coloured by type (isochronous or time-transgressive). (b) Erratic transport paths and source areas from BRITICE database. Locations of shelly till deposits from Charlesworth (1957) and Sissons (1976).

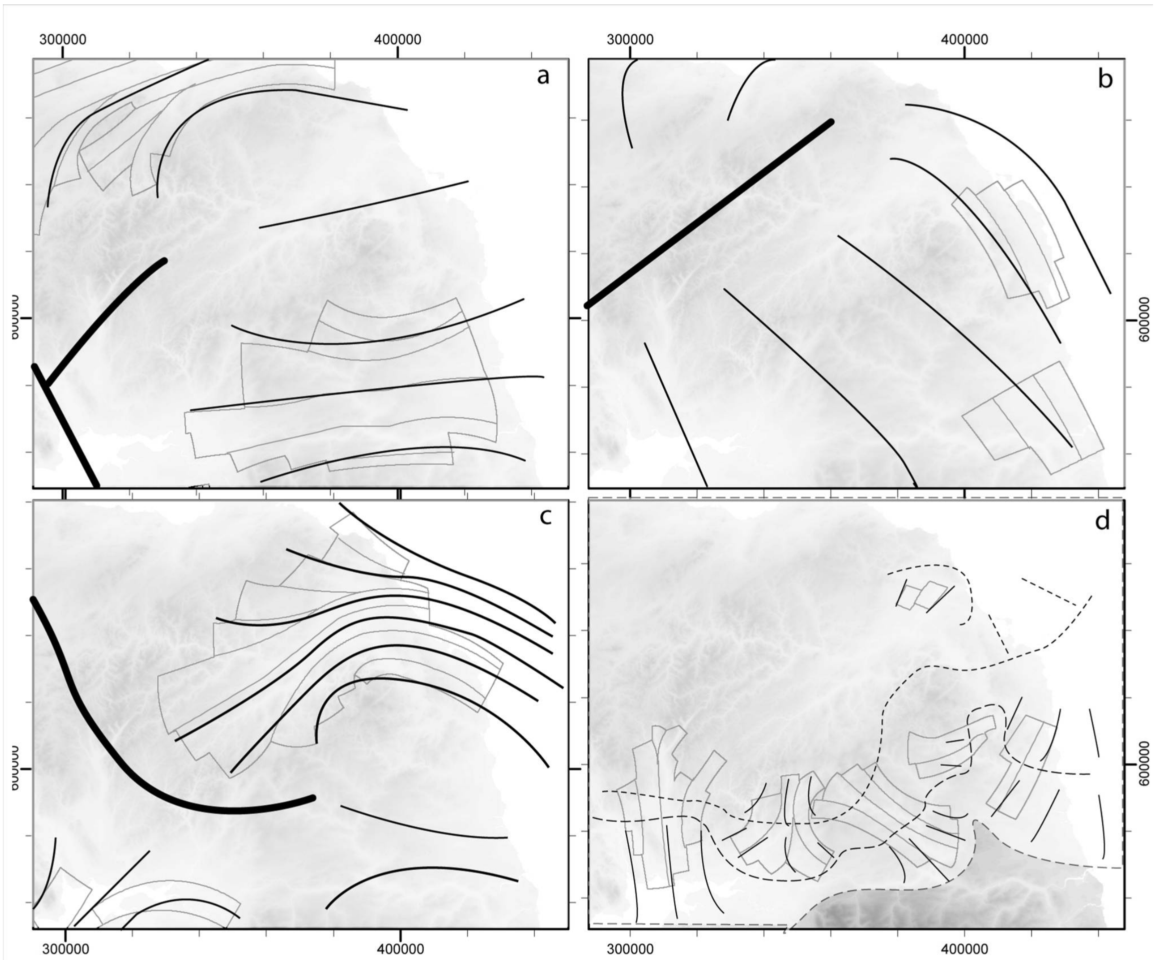


Figure 8.16 Ice flow patterns in NE England can be organised into a minimum of four stages. Ice is increasingly deflected around the Cheviots as the ice sheet thins. (a) Fs11 records a major west-east ice flow that supports a N-S running ice divide at least as far west as the Solway Firth. This is grouped with fs19 and so a secondary ice divide is placed between the two flowsets. (b) Ice flows from a Southern Uplands ice divide southward over the region. (c) The Tweed ice stream (fs10) develops. The ice stream is topographically constrained and it is suggested that the ice stream terminated offshore. The cause of the deflection of fs10 to the SE is unknown.. (d) The remaining flowsets are part of the deglacial signature. And demonstrate increasing influence of topography and retreat around the Cheviots.

8.2.2.4 The Lake District, Lancashire and the Pennines

Figure 8.17 shows the boundaries of this region which incorporates the Lake District, Pennines, Lancashire and the Yorkshire Dales. Flowsets in this region are nearly all diverted by topography (fs30, 15, 99, 66, 65, 43, 78, 89, 73, 69, 32, 41, 71 and 70). It is plausible that the ice sheet was relatively thin in this region throughout the last glaciation, being situated close to periphery of the ice sheet (only c.100 km from the accepted southern drift limit). Flowsets were particularly difficult to define in this area due to the similarities between successive events (see discussion of Vale of Eden flowsets in chapter 6).

No flowset records ice flow *up* the Vale of Eden, but the presence of Scottish erratics indicates that there was incursion of Scottish ice into the Solway lowlands (figure 8.17b). The erratic evidence suggests that the Lake District was not overwhelmed by Scottish ice and supported an ice dome throughout the glacial thus preventing the incursion of ‘foreign’ geologies. It is suggested that incursion of ice into the Solway is represented by fs57 (figure 8.9) and/or rm7.

There is only evidence for ice flow out the Lake District at the end of the glacial (the youngest flowsets fs80 and fs65); otherwise flowsets record ice flow deflected around the Lake District massif (e.g. fs99). The radial pattern of ice flow from a Lake District ice source frequently discussed in the literature is not borne out by the bedform record of ice flow patterns.

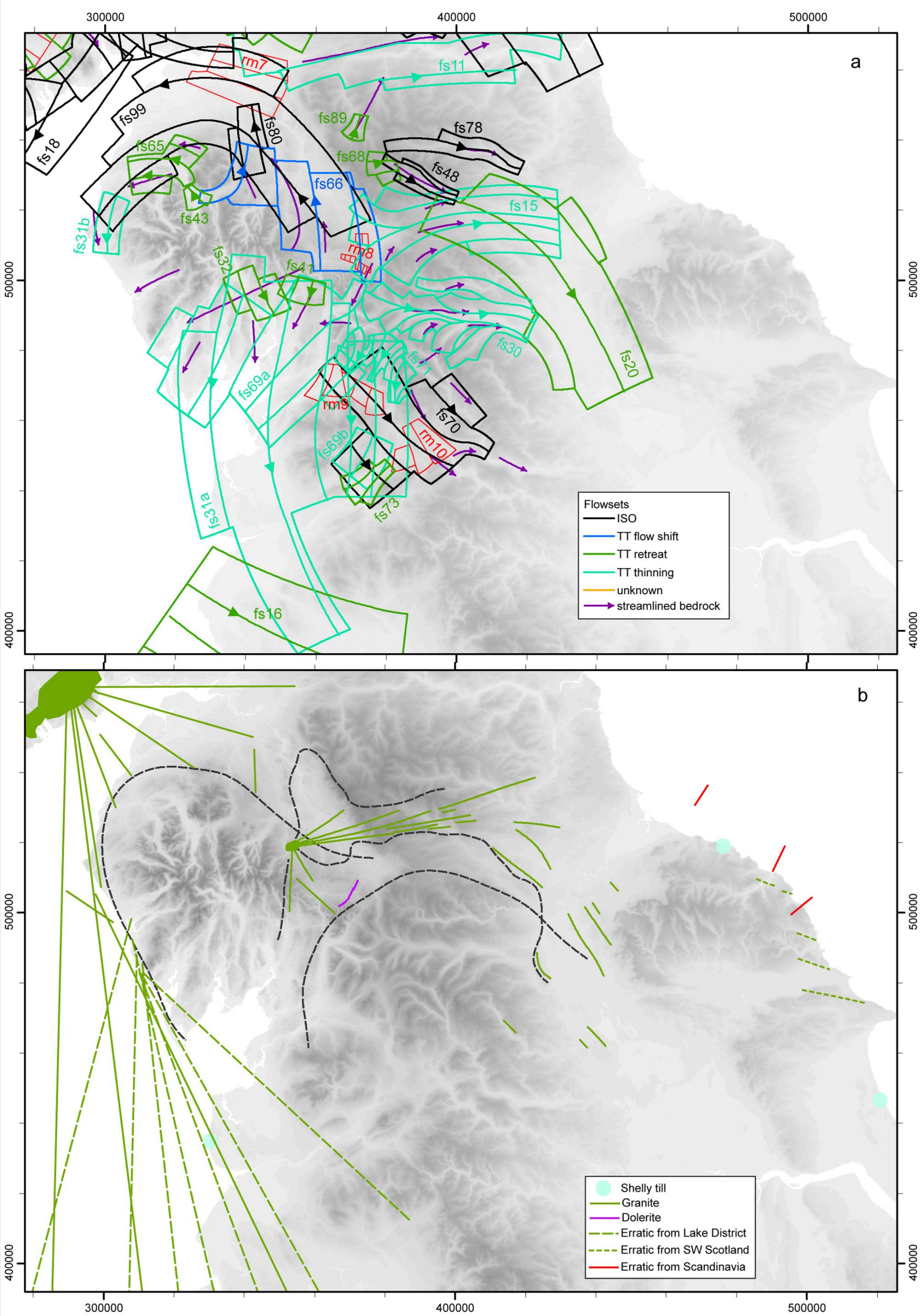


Figure 8.17 Flow pattern ingredients of the Lake District and Pennine region. (a) Lineation flowsets and streamlined bedrock summary arrows. Lineation flowsets coloured by type (isochronous or time-transgressive). (b) Erratic transport paths and source areas from BRITICE database. Locations of shelly till deposits from Charlesworth (1957) and Sissons (1976).

Fs15 and the transport path of Shap granite (figure 8.17b) support a major phase of W-E ice flow from an ice divide at least as far west as the Lake District. This west to east ice flow breaching the Pennines also explains the presence of Lake District and Scottish sourced erratics in eastern England. This stage is tentatively correlated with fs11 to the north. Fs30 in Wensleydale records topographically focused ice flow along the valley. This flow pattern is potentially synchronous with fs15. The proximity to the maximum drift limit and hence a low ice surface can help to explain the greater influence of topography on this flow pattern. Fs30 is a *TT thinning* flowset (figure 8.17a) that becomes increasingly topographically focused and so the early stage of this ice flow that is independent of topography is correlated with fs15. Flowsets 31, 66, 99, 32, 41 and 69 collectively place an ice divide running eastward from the Lake District along the Howgill Fells (figure 8.17a). *TT thinning* flowset fs31 documents N-S ice flow that becomes increasingly deflected by the topographic obstacle represented by the Forest of Bowland. Rm9 is thought to be coeval with fs31. Fs 70 and fs69 record phases when the Forest of Bowland deflected ice to the east and west but are not contemporaneous as they overlap in the eastern side of the Forest of Bowland. The relative chronology between fs69 and fs70 is debateable. Fs69 is tentatively correlated with fs99 and fs18 representing a period of ice drawdown into the Irish Sea. The rest of the flowsets record topographically constrained retreat towards the Howgill Fells and Yorkshire Dales. The movement of ice over the northern Pennines is unclear due to a lack of information. Flowsets 89, 68, 48 and 78 are presumed to relate to the retreat of ice into the Pennines as are all constrained within valleys. Alternatively, they document ice flow within a network of cold based ice divides running along the valley interfluves. Cold based ice covering the summits of the northern Pennines has also been proposed by Mitchell (2007) who conducted field mapping of drumlins in the region around Cow Green reservoir. Fs20 records retreat of ice up the Vale of Eden into the Pennines.

The flowsets are corralled into a five stage reconstruction (figure 8.18). Initially an ice divide ran broadly N-S over the western Lake District (figure 8.18a). Later on the ice divide ran NW-SE from the Lake District over the Howgill Fells (figure 8.18b). It is postulated that this occurred as an ice stream developed in the Irish Sea which eventually evacuated ice from the Solway lowlands (figure 8.18c). The drawdown of ice from the Solway lowlands separated the Lake District-Howgill Fells ice divide from the ice divide over the Southern Uplands. Ice initially retreated towards this divide (figure 8.18d) but deglaciation subsequently progressed by thinning and valley glaciation to numerous sites in the Yorkshire Dales and Lake District (figure 8.18e). There is an absence of information from the Tees lowlands.

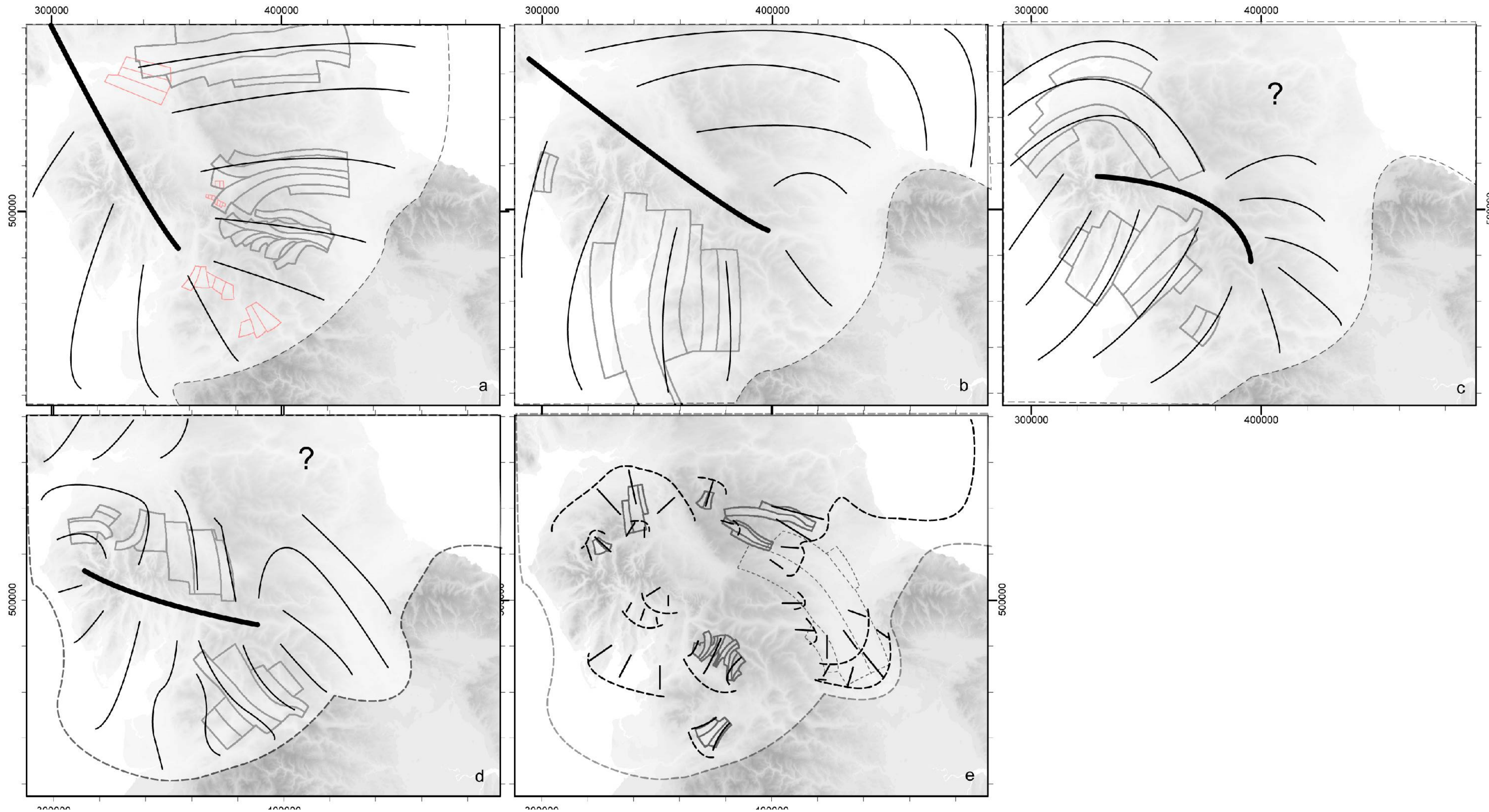


Figure 8.18 Reconstruction of ice flow patterns in the Lake District and Pennine region is explained in a minimum of five stages. (a) Initially a N-S ice divide develops and drives ice eastward. (b) ice divide shifts to accommodate fs31. (c) Ice is drawn down into the Irish Sea and the ice divide runs W-E over the Lake District and Howgill Fells. (d) Irish Sea is deglaciated. (e) Deglaciation of the ice sheet by valley glaciation into the Cumbrian Mountains and the Pennines.

8.2.3 *Region 3: Wales*

Finally, we consider Wales and the English-Welsh borderland (figure 8.19). There are relatively few subglacial bedforms within Wales. Geological structure has a very strong impact on the landscape and so flow patterns derived on the basis of streamlined bedrock features alone are treated with caution as field checking has not been undertaken. There are 17 flowsets from subglacial lineations. Five of these are of uncertain temporal genesis and six are derived on the basis of speculative drumlin mapping (chapter 5). Fs31, 16, and 17 indicate that Irish Sea ice was deflected to the east and west around Wales (figure 8.19a). This pattern is replicated in the distribution of Scottish and Lake District erratics and shelly till on Anglesey and in the Cheshire Plain (figure 8.19b). Irish Sea till is present along the northern coast and in Vales of Conway and Clwyd indicating that ice from the Irish sea was able to penetrate at least this far into Wales (figure 8.19b).

Fs22 is suggested to be confluent with ice in the Cheshire Plain as drumlins on the western Clywddian Range bend sharply towards the SE (Map 2; south sheet). It is postulated that fs31 is part of a flow event that extended into the Cheshire Plain and was contemporary with fs22. The distribution of Arenig erratics supports the presence of ice in Wales before the incursion of Irish Sea ice into the Cheshire Plain (figure 8.19b). On the assumption of ice sheet symmetry fs22 was mirrored by an E-W ice flow that was confluent with fs17. The deflection exhibited by fs17 suggests that Welsh ice occupied part of Cardigan Bay before Irish Sea ice flowed southward. Further south, fs76 and fs90 supports broadly W-E ice flow from a divide running N-S along the length of Wales. Fs76 is a *TT thinning* flowset and therefore this ice flow pattern persists as the ice surface lowers. Fs90 can be extended to the north and south if streamlined bedrock is taken into account (figure 8.19b). Deglaciation of Anglesey and the Cheshire Plain is described by *TT retreat* flowsets 42, 77, and 16. In North Wales fs21 indicates that there was shift in the position of the ice divide from an N-S to a NW-SE orientation. *TT thinning* flowsets fs76 and 21 as well as topographically constrained flowsets 75, 87, and 74 suggest that deglaciation of Wales progressed by a decline in the ice surface height followed by retreat to separate ice centres (fs85, 91, 85, 98).

Flowsets of Wales can be organised into a minimum of three phases of ice sheet geometry (figure 8.20). The zone of confluence between Welsh and Irish Sea ice is placed to the east of the Clywddian range and over the Lleyn Peninsula (figure 8.20a). The Welsh ice sheet then thinned and decoupled from the Irish Sea ice (figure 8.20b). It is possible that the Welsh ice sheet expanded outwards following the removal of the buttressing Irish Sea ice lobes. It is difficult to explain the direction of fs88. This may suggest that the Welsh ice sheet retreated back to a number of ice centres located on the upland areas of the Black Mountains, Brecon Beacons and in North Wales. It is postulated that the Welsh ice sheet was predominantly cold-based as an explanation for the general lack of subglacial bedforms and bedform cross-cutting. Alternatively, the Welsh Ice Sheet was a relatively stable feature in contrast to elsewhere, and all changes due to the coupling and uncoupling with ice from the north or the lack of drift meant that no record was preserved.

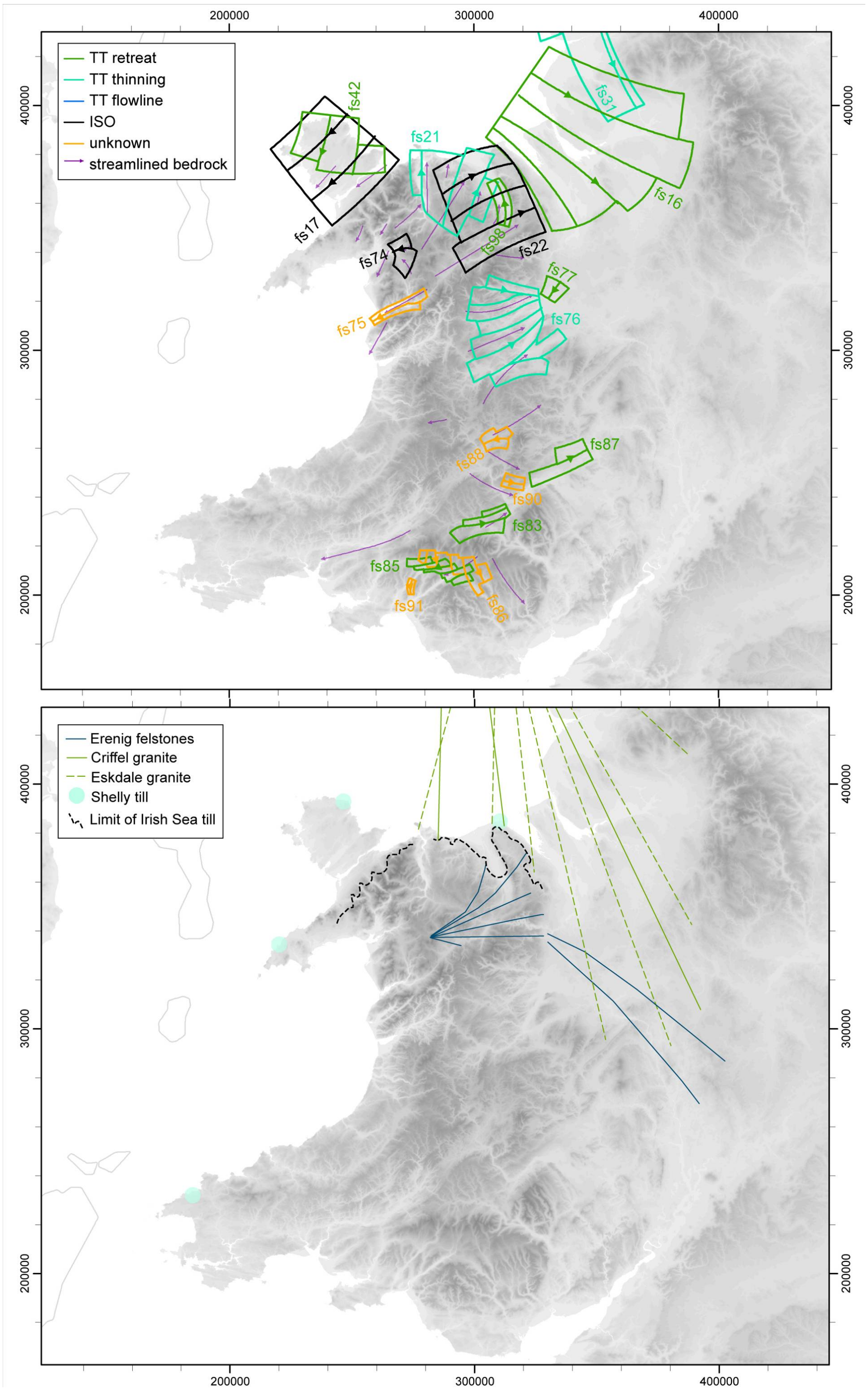


Figure 8.19 Flow pattern ingredients of Wales and Welsh-English borders region. Lineation flowsets and streamlined bedrock summary arrows (upper image). Erratic transport paths, Irish Sea till drift limit and erratic source areas from BRITICE database (lower image). Locations of shelly till deposits from Charlesworth (1957) and Sissons (1976).

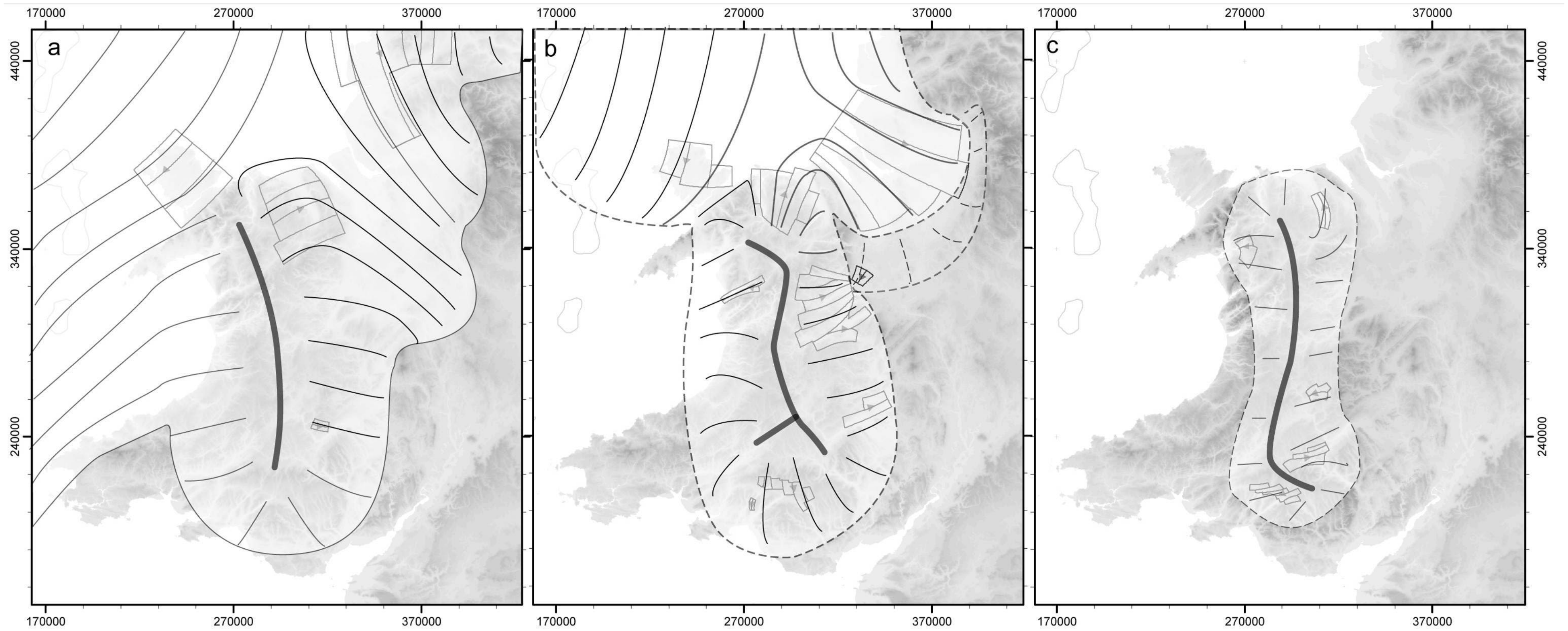


Figure 8.20 Ice flow configuration in Wales can be organised into a minimum of three stages. (a) At the ice sheet maximum the Welsh ice cap is confluent with ice in the Irish Sea. (b) Ice retreats from the Irish Sea and Welsh ice cap geometry changes. Possible expansion of Welsh ice once buttressing effect of Irish Sea ice is removed. Flow patterns more closely reflect topography. (c) Deglaciation of the ice sheet by ice surface lowering and valley retreat. The multiple lobate form of the moraines in the Cheshire Plain (chapter 9) are also indicative of more than one ice flow component, supporting the connection of Welsh and Irish Sea sourced ice in this location.

8.3 Ice streams

Key information from palaeo-ice sheet reconstructions is the location, size and operation of ice streams. Flowsets that define the former tracks of palaeo-ice streams were identified using the criteria of Stokes and Clark (1999) and are listed in Chapter 6 (table 6.1, figure 6.19). This thesis argues that some of the ice streams presented in the literature are not ice streams in the absolute sense (chapter 6). Only those that are corroborated by new mapping and fit the landsystem model of Clark and Stokes (2003) are considered to be true ice streams.

On the basis of size and relative chronology of flowsets it is possible to organise the ice streams alone into groups representing at *least* two possible ice flow configurations (figure 8.21). These groups do not represent snapshots of the ice sheet geometry at any one time but serve as a framework with which to examine ice stream evolution changes over the ice sheet as a whole. One grouping is proposed to occur during maximum extent of the ice sheet when confluent with ice in North Sea and at the continental shelf edge (figure 8.21a). During this phase ice streams occur at the junctions between ice masses, e.g. Scottish and Irish ice in the North Channel and mainland Scottish ice and Outer Hebrides ice in the Minch. Additional ice streams from the literature that are correlative with this stage are shown on the diagram; Clare and Western Bays (Greenwood, 2008), Witch Ground (Graham et al., 2007). Fs51 (Strathmore 1) is tentatively correlated with the Witch Ground ice stream of Graham et al. (2007). A separate phase of ice streaming suggests development of ice streams along the east coast initiated after break up of ice in North Sea e.g. Strathmore 2,. Without reference to chronological information the Minch and Irish Sea ice streams may have operated before and/or after break up of ice in the North Sea. Fs19 is postulated to be an ice stream flowset. This ice stream would have operated when the North Sea was unglaciated but relative chronology of flowsets places it before fs51 and therefore *before* confluence of ice in the North Sea rather than following.

8.4 Summary

The complexity of the flowsets revealed by the mapping (chapters 5 and 6), clearly record critical glimpses of ice sheet behaviour through time. Their complexity however, presents a considerable challenge for any reconstruction of the evolution of the ice sheet as a whole. Given this complexity and that we do not currently have the offshore record or have not yet incorporated Ireland, I have deliberately not proceeded to a full ice sheet scale reconstruction of the flow geometry evolution. The regional analysis presented above provides the essential building blocks for the next phase. When further integrated with data from offshore and Ireland and with more literature it is anticipated that a full British-Irish Ice Sheet reconstruction will be forthcoming. The central part of the ice sheet (region 2) containing 56% of flowsets proved especially difficult to untangle and presented the primary obstacle to this.

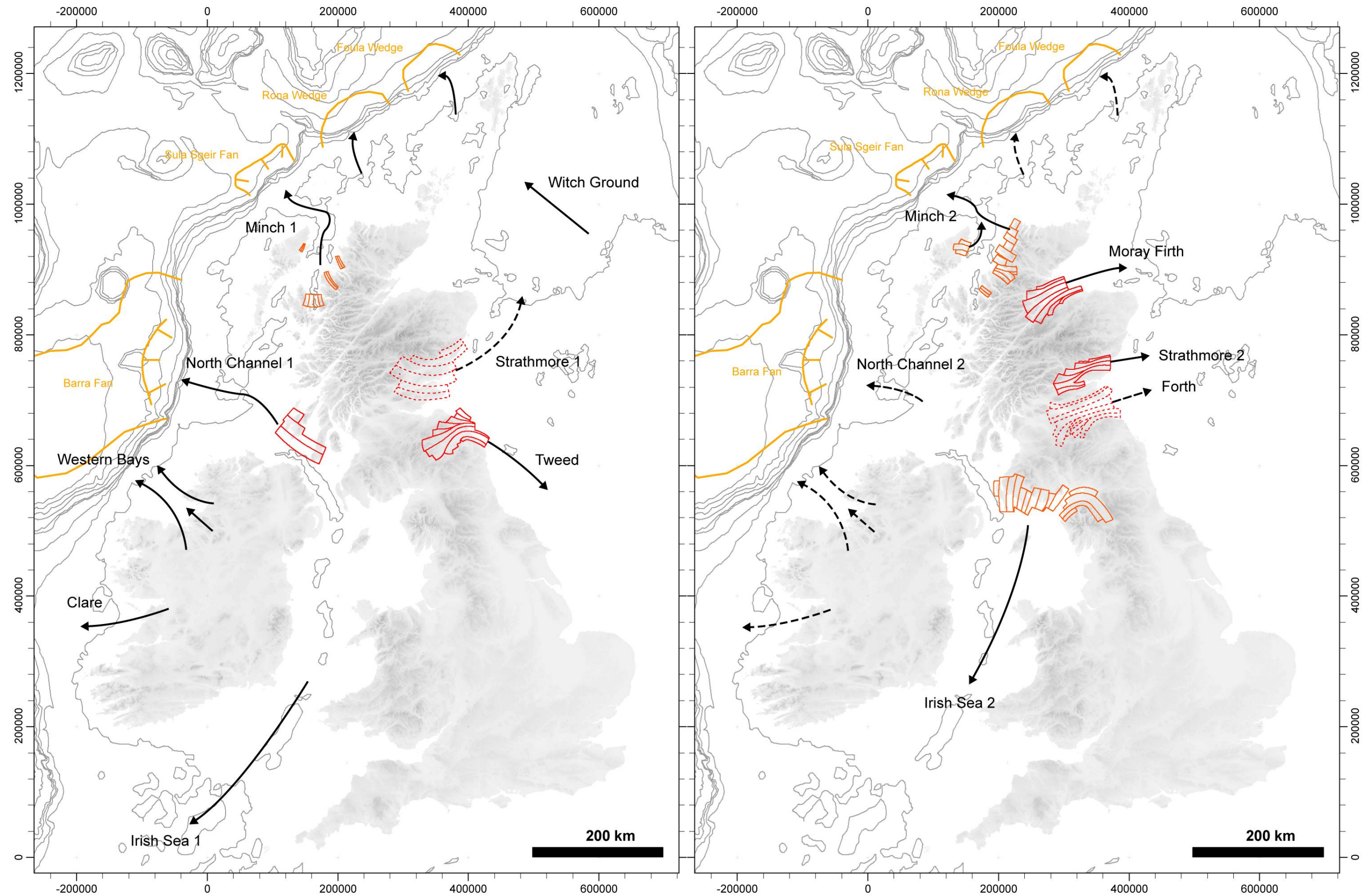


Figure 8.21 Nine ice stream tracks were identified (chapter 6, figure 6.16). These can be organised into two categories based on location and size. It is proposed that the two categories reflect at least two distinct stages of ice sheet geometry: (a) Ice is confluent in the North Sea and the ice streams flow out along the western continental margin. Ice streams on the eastern coast exhibit deflection to the north and south indicative of an ice mass or other unknown obstacle in the central North Sea at this time; (b) No ice in the North Sea and ice streams terminate along the eastern margin. The Minch and Irish Sea ice streams are postulated to have two stages of operation. These geometries are not chronologically constrained and it is likely that they incorporate than one stage of ice sheet configuration. Ice stream flowsets are in red. Possible ice stream flowsets are dashed and ice stream tributaries are in orange. Arrows show possible extension of flowsets and additional flowsets from the literature (Graham et al. 2007; Stoker and Bradwell, 2005). Irish ice streams are taken from Greenwood (2008).

The following chapter will detail the reconstructed retreat pattern. A fruitful next step would be to use this retreat pattern to pull out the flowsets that fit within the ice sheet retreat stages in order to aid grouping of spatially separate flowsets.

In summary, the regional flow pattern scenarios indicate the following:

- Flowsets in north Scotland provide evidence to support confluence of ice in the North Sea. Ice was deflected over Caithness, Orkney and Shetland. The confluence zone between British and Scandinavian ice is not known. The reconstruction presented in this thesis is consistent with the placement of the confluence zone between Shetland and Orkney after Bradwell et al. (2008b).
- Break up of ice in the North Sea was accompanied by reorganisation of the ice sheet geometry and the establishment of a semi-stable N-S ice divide over northern Scotland that persisted until deglaciation.
- The Midland Valley of Scotland experienced persistent west-east ice flow with changes reflecting relative dominance of Highland and Southern Upland sourced ice.
- The ice sheet comprised a number of interconnected ice divides of variable dominance. The Cumbrian Mountains were not a major ice divide location as has previously been assumed.
- Flow patterns document a signature of ice sheet thinning across the country. In several locations, extensive topographically unconstrained ice flow is followed by flowsets that reflect the underlying relief suggesting a lowering of the ice sheet surface during the later stages of the glaciation. Many flowsets are deflected around topographic obstacles. For example the network of ice flow paths that develops in the Midland Valley before deglaciation (figure 8.8e).
- There is no evidence to suggest that ice overwhelmed Lewis or the Lake District. Lobes of ice from primary ice divides were deflected around secondary ice divides e.g. Highland ice around the Grampian ice mass (figure 8.6e), Irish Sea ice around the Welsh Ice Sheet, and domes on topographic highs of the Lake District (figure 8.18c) and the Cheviots (8.16c).
- The Welsh Ice Cap was a stable feature exhibiting little change in configuration.
- Ice streams appear to separate into two groups: large ice streams flowing offshore during maximum extent of ice and topographically constrained ice streams that developed after break up of ice in the North Sea.

This chapter has presented ice sheet configurations based on plausible and judicious grouping of flowsets that reasonably accommodates the flowset geometry, relative chronology and flowset classification evidence. An alternative approach would be to use the flowset map in conjunction with a numerical ice sheet model. The numerical model should be able to generate a series of snapshots of the ice sheet configuration which can be compared with the flowsets and used to organise the flowsets as well as providing evidence to test the numerical model outputs.

Chapter 9

The pattern of ice sheet retreat

9.1 Introduction

This chapter presents a retreat pattern of the last British Ice Sheet reconstructed from the ingredients presented in chapter 6. Moraines and flights of lateral meltwater channels demarcate palaeo-ice margin positions. It is assumed that eskers form behind a warm based retreating ice margin, and so they can be used to infer margin positions and the direction of retreat. *TT retreat* flowsets record bedform generation behind a retreating margin, and so these flowsets document changes in the position of the ice margin with successive parts of the flowset relating to younger dispersal locations (Clark, 1999). Glaciolacustrine sediments indicate the locations of former proglacial lakes. The topographic setting of such sediments can be used to infer the necessary ice margin positions required to dam normal drainage and create the lake. Collectively the cartographic summaries of these landform types are the equivalent of the 'deglacial envelope' assemblage of Kleman et al. (2006) and can be used to define the pattern of retreat of the ice. Initially, each line of evidence was considered individually before combining the lines of evidence together to produce an overall summary retreat pattern map. The logical steps involved in the reconstruction of the retreat pattern of the ice sheet are as follows:

1. Identification of palaeo-margin positions from moraines and ice contact landforms. Inference of palaeo-margin positions from esker, meltwater channel and *TT retreat* flowsets, and ice-dam positions from glaciolacustrine sediment distribution.
2. Use topography, i.e. setting, in combination with palaeo-margin positions to infer successive retreat pattern from each line of evidence.
3. Examine conflicts and agreements between retreat patterns from each line of evidence and combine into overall reconstruction of pattern of retreat.
4. Use published dates and stratigraphy, where available, to fix pattern of retreat to absolute time. This is presented in the next chapter (10).

9.2 Retreat pattern by landform type

9.2.1 Retreat pattern from moraines

Moraines are summarised as ice front positions in figure 6.25. Using topography as a guide the distribution of moraines was used to reconstruct an overall pattern of retreat (figure 9.1). In some areas it was not possible to derive a retreat pattern as moraines were too sparsely distributed for a margin to be drawn. As discussed in chapter 5 and 6 there are relatively few really large arcuate moraines in Britain in contrast to the Laurentide and Fennoscandian ice sheets, but many smaller cross valley moraines and large 'spreads' of morainic topography without a clear crest or ice-contact margin. These latter features probably constitute glaciofluvial outwash.

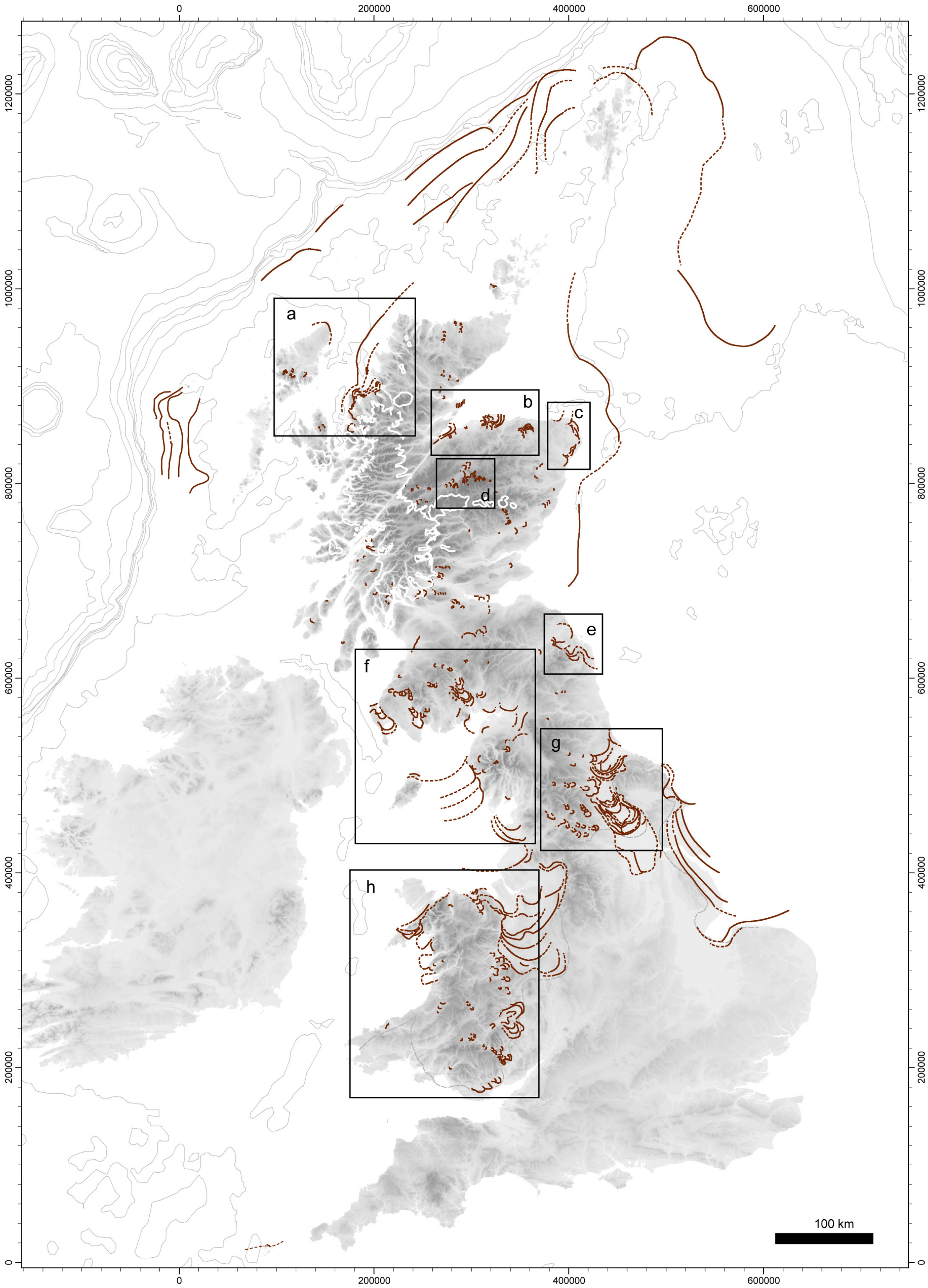


Figure 9.1 Successive retreat pattern derived from mapped and BRITICE+ moraines. Dashed white line marks limit of Loch Lomond Stadial ice sheet. Dashed grey line marks maximum southern limit of last British Ice Sheet. Margins that are directly supported by moraine evidence are in solid brown. Dotted brown lines connect moraines where it was deemed logical to do so, on the basis of topographic context. Boxes show areas shown in more detail in figure 9.1 a-f.

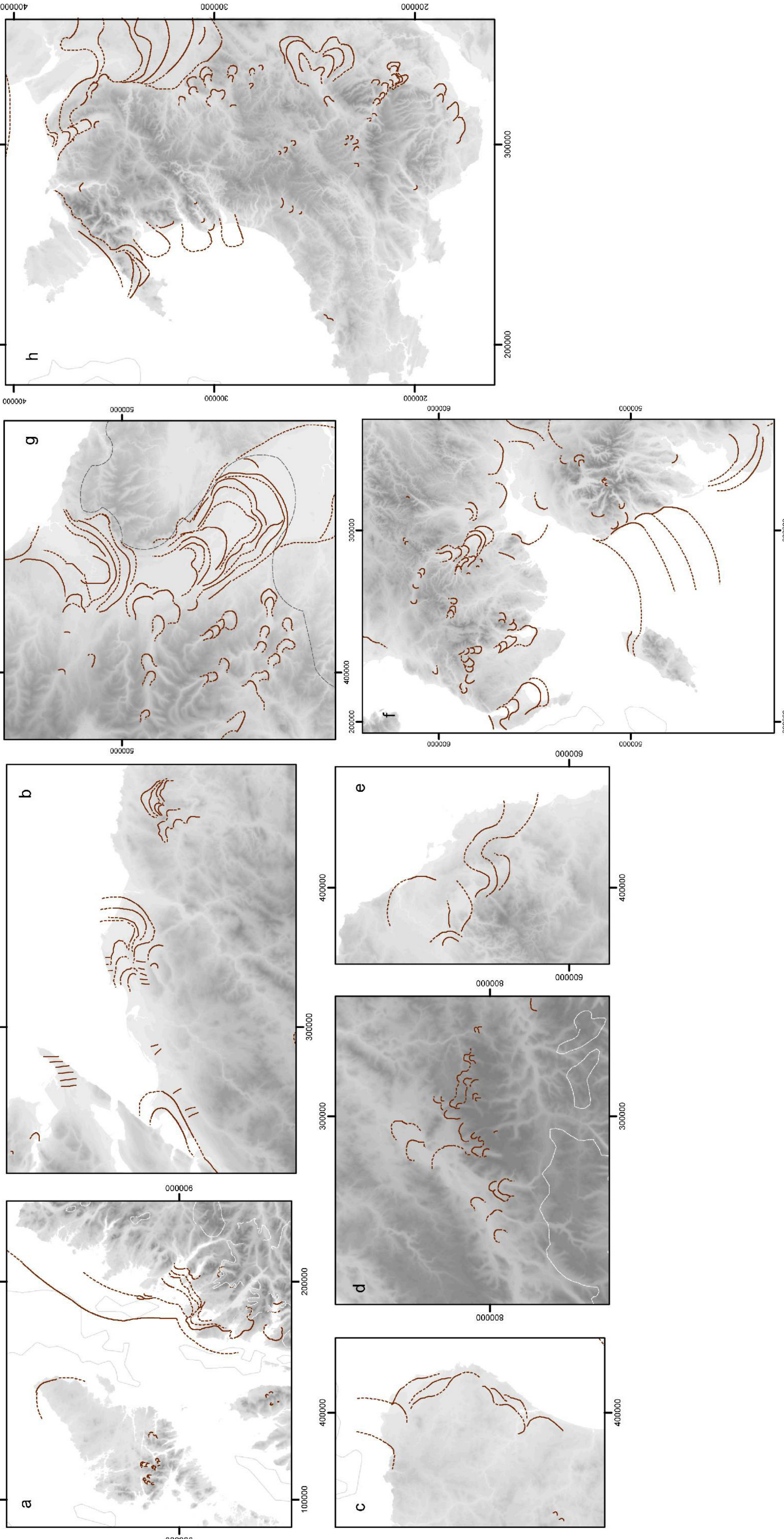


Figure 9.1 a-h Detail of retreat from moraines for selected areas. Location shown in figure 9.1.

The distribution of moraines can be organised into three broad groups on the basis of size and location (figure 9.1): large offshore moraines marking ice front positions on the continental shelf; large terrestrial moraines along the Yorkshire and Lincolnshire coast and in Cheshire Plain, Vale of York (York and Escrick moraines; figure 9.1g), Tees and Fylde; and smaller clusters in association with upland regions (e.g. Cairngorms, figure 9.1d). The following observations emerge from the reconstructed pattern:

- Successive lobate retreat from lowland regions towards northern ice centres. For example retreat from the Cheshire Plain towards the Irish Sea, and up the Vale of York back into the Yorkshire Dales and Tees estuary (figure 9.1g).
- During the early stages of recession and contrary to what might be supposed, ice does not retreat to the nearest high ground. Moraines in the Cheshire Plain document retreat back into the Irish Sea, moraines close to Stranraer indicate retreat towards the North Channel, rather than back into the southern Uplands (figure 9.1.f), and moraines on the Holderness coast indicate ice presence in the southern North Sea.
- The final stage of recession is to local ice caps or ice fields in upland regions, indicated by clusters of small valley moraines, e.g. in the Cairngorms (figure 9.1d), Yorkshire Dales (figure 9.1g), North Uist and Trotternish of Skye (figure 9.1a), and the Black Mountains (figure 9.1h). The detail of retreat in these regions is not reconstructed, although it is of interest at a local scale, it is less informative at the ice sheet scale. The presence of these moraines however does help to determine the overall direction of retreat.
- Lowland retreat pattern is often guided by topography, perhaps in relation to local ice caps and/or emerging nunataks. For example moraines indicate anticlockwise retreat of Tweed ice around the Cheviot massif (figure 9.1e), the Irish Sea ice lobe retreats back towards the Southern Uplands and around the Lake District (figure 9.1f), and Spey ice retreats around Cairngorms (figure 9.1d).

9.2.2 Margin positions from eskers

In chapter 6 groups of mapped eskers were summarised as generalised arrows in the direction of ice flow (figure 6.23). Palaeo-margin positions perpendicular to the summarised ice flow direction were derived from these arrows (figure 9.2). This is based on the assumption that eskers form behind a retreating ice margin during warm based deglaciation (e.g. Kleman and Borgström, 1996) and their orientation reflects the direction of meltwater flow at the ice margin (Benn and Evans, 1998). Along the length of the eastern English coast eskers document retreat towards the north and northeast away from high ground (figure 9.2).

An esker close to Flamborough Head records retreat towards the SE from the Yorkshire Wolds. The direction of retreat of these eskers requires a North Sea ice presence. Dense esker networks provide a detailed pattern of retreat north up the Vale of York and subsequent valley retreat into the Yorkshire Dales along Wensleydale.

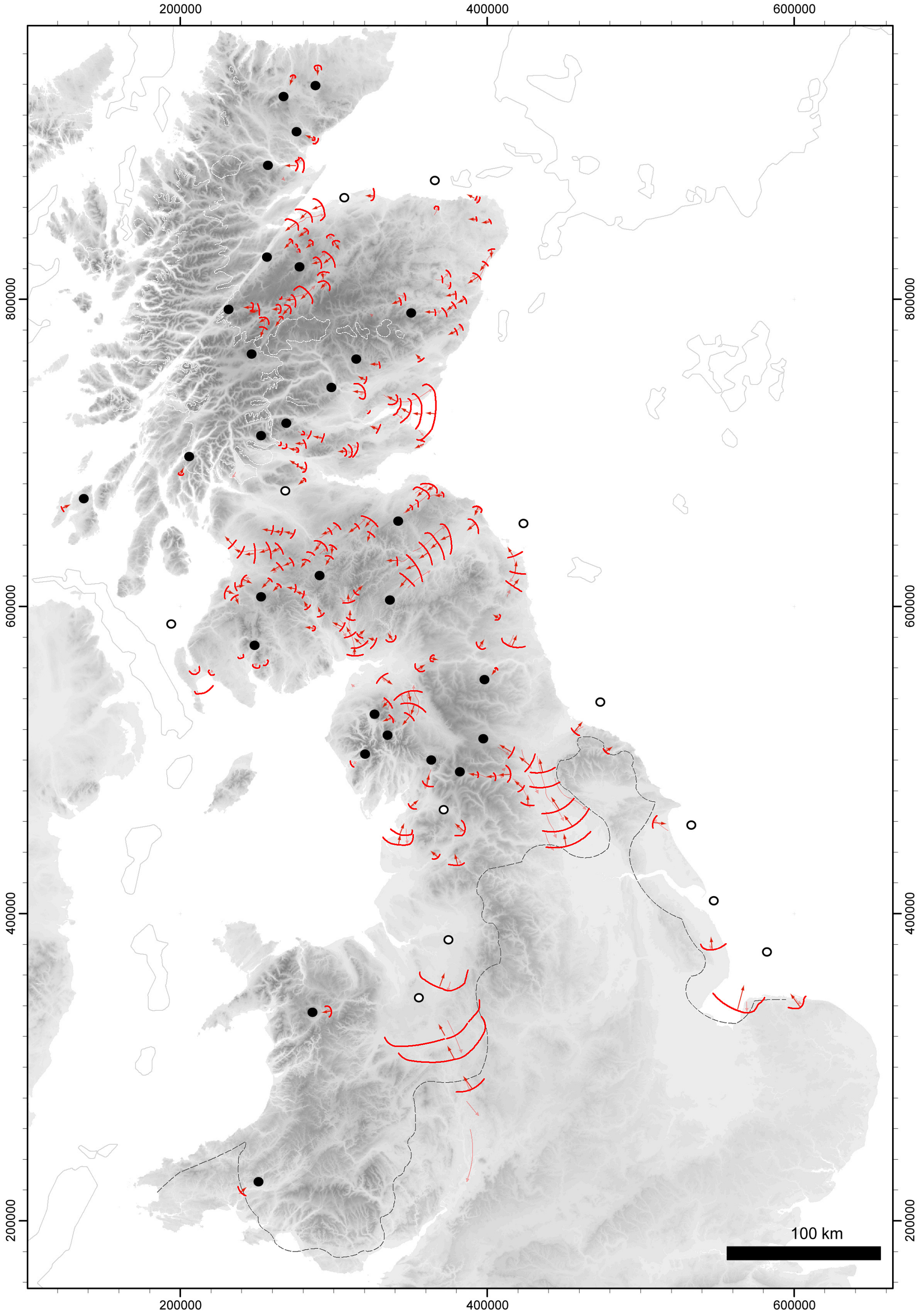


Figure 9.2 Successive retreat pattern derived from esker flowsets. Dashed white line marks limit of Loch Lomond Stadial ice sheet. Dashed grey line marks maximum southern limit of last British Ice Sheet. Red lines are margins inferred from esker flowsets. Arrows indicate direction of retreat. Esker flowsets are shown as feint arrows. Dots mark foci that the ice margin is retreating towards: solid dots mark upland locations, empty dots mark lowland locations.

Esker patterns suggest initial retreat from the maximum ice limit in the Cheshire Plain in a NNW direction. In Wales, only a few eskers were found and indicate retreat to local high ground. In NW England, eskers record S to N retreat over Lancashire and a semi-radial pattern of retreat south into the high ground of the Lake District. In the Solway Firth, ice retreated northwards into the Southern Uplands up the Nith valley. Eskers running broadly W-E along the northern flanks of the Southern Uplands and within the Tweed basin, indicate retreat from the eastern Scottish coast in a westward direction before NW retreat back towards Arran and SW retreat into the western half of the Southern Uplands. The broadly westward retreat towards the Loch Lomond limit position is documented by eskers in northern and central Scotland with the exception of the NE-SW trending eskers running along the coast in the vicinity of Aberdeen.

9.2.3 Retreat pattern from meltwater channels

In chapter 6 meltwater channels were classified into genetic categories; subglacial, submarginal, lateral and proglacial. The pattern and distribution of groups of subglacial and lateral meltwater channel networks was summarised by an arrow in the direction of flow. A flight of meltwater channels along a hill slope is taken to document the thinning and recession of cold-based ice, with each channel formed at successive margin positions (Hättestrand and Clark, 2006a).

Figure 9.3 shows the pattern of retreat derived from lateral meltwater channels. The reconstructed pattern of retreat shows that it was closely related to topography. This is, of course, partly due to the nature of the evidence, as lateral channels will only be inscribed when ice abuts against a slope. A key observation that emerges from the pattern is that the high ground in many parts of the country deglaciated before ice in the lowlands (figure 9.4), indicative of a thin ice sheet. For example, ice thinned and retreated around the Forest of Bowland in Lancashire as it retreated northwards. Lateral channels running along the Pennine escarpment in the Vale of Eden suggest that ice remained in the valley after Pennine summits had deglaciated. Likewise lateral channels on the edges of the Cumbrian Mountains suggest that Lake District peaks were ice free before the Irish Sea ice had retreated. Ice retreating up the Firth of Forth and Tweed basins split around the Lammermuir Hills. Similarly ice retreating NW into the Scottish Highlands was diverted around the Campsie Fells and Ochill Hills. In northern Scotland, ice retreated along valleys towards ice centres in the southern Grampians, and Rannoch. The pattern also indicates the significance of offshore ice. Lateral channels running broadly E-W along the Nairnshire-Buchan coast of Scotland indicate the westward retreat of a lobe of ice emanating from the Moray Firth, after inland ice from the Grampians had retreated away from the coast. Lateral channels on the southern flanks of the Pennines in Derbyshire and Lancashire record thinning of ice in the Cheshire Plain.

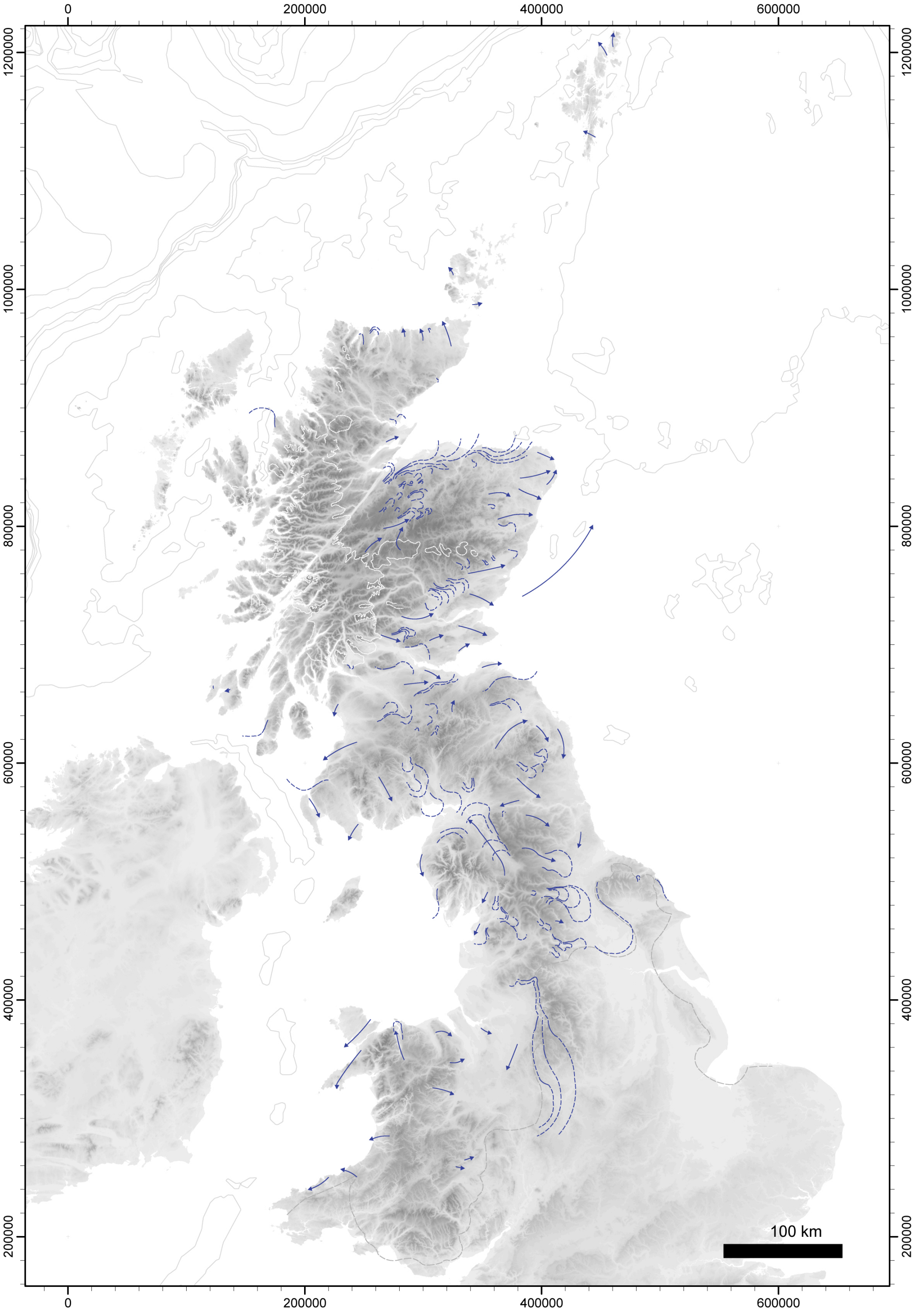


Figure 9.3 Retreat pattern from lateral meltwater channels. Dotted lines connect margins of presumed same age inferred from their relationship with topography. Dark blue arrows indicate ice flow presumed close to the margin inferred from subglacial meltwater channels.

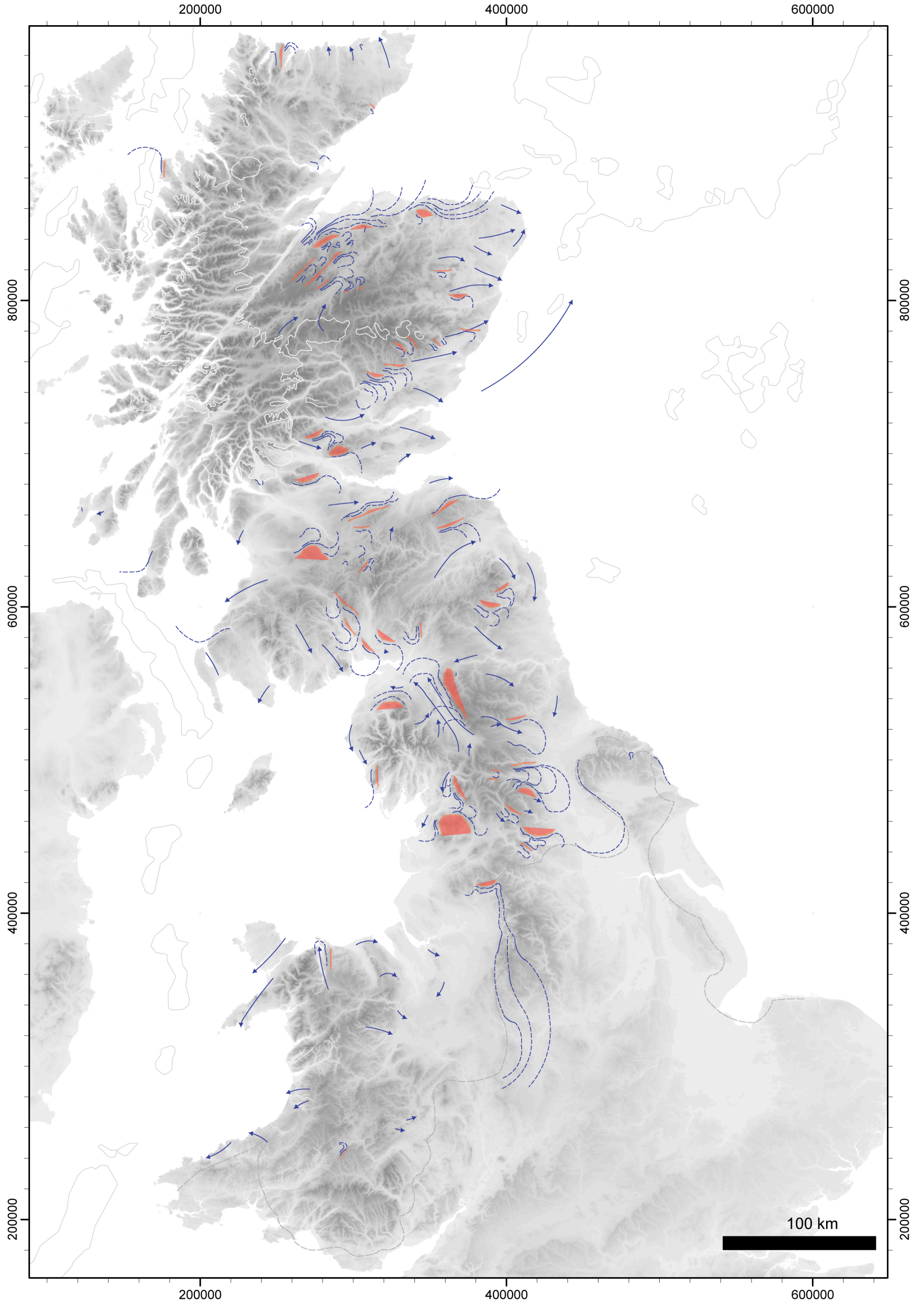


Figure 9.4 Enlargement of lateral meltwater channel retreat pattern. Retreat pattern from lateral meltwater channels in solid dark blue. Dotted lines connect margins of presumed same age inferred from topographic context. Dark blue arrows indicate presumed ice flow close to the margin inferred from subglacial meltwater channel flowsets. Red lines/patches mark locations that must have become ice free before lateral meltwater channel development. Red lines therefore delineate topographic high points that emerged as nunataks before retreat of ice from the associate lowland area.

9.2.4 Retreat pattern from ice-dammed lakes

For the Glacial Map of Britain (Clark et al., 2004), ice dam locations were inferred using the location of glaciolacustrine sediments and their relation to topography. Additional 1:50,000 scale maps of superficial sediments from British Geological Survey, in combination with topographic information were used to extend the lake dam positions of the glacial map and BRITICE database. The ice margin positions necessary to support ice dammed lakes in the areas where glaciolacustrine sediments have been described are shown in figure 9.5. It is possible that the lake sediments relate to advance of the ice sheet rather than retreat. The locations of several lakes are testament to the persistent influence of offshore ice after deglaciation of inland areas. For example, ice along the NE coast creates lakes in the Tees, Wear and Humber, ice in the Irish Sea dams lakes in the western Lake District, and lakes are impounded in Buchan in NE Scotland by ice at the northern and eastern coasts.

9.2.5 Retreat pattern from *TT retreat* flowsets

As described in chapter 6, lineation patterns that exhibit 'smudging' were classified as time-transgressive. Time-transgressive (TT) flowsets were subclassified in terms of the glaciological context under which the smudged imprint is thought to occur; rapidly changing flow patterns during marginal retreat (*TT retreat* flowsets), ice sheet thinning during deglaciation leading to increasing accordance with local bed topography (*TT thinning*), and continual bedform development during ice divide migration (*TT flow shift*). As it is assumed that *TT retreat* flowsets are a reliable indicator of the changing flow patterns experienced close to the ice margin they provide information on the position of the margin and ice divide location during retreat. A total of c.30 *TT retreat* flowsets were identified in Chapter 6. In comparison to other palaeo-ice sheets this is a relatively small proportion. From analysis of the Laurentide and Fennoscandian ice sheets (e.g. Kleman et al., 1997; Jansson et al., 2002) we would expect the majority of evidence to relate to the retreat of the ice sheet. This difference could be explained in one of two ways, little subglacial bedform generation during retreat or topographically controlled retreat precluding the retreat of the ice sheet by spatially extensive lobes.

Figure 9.6 shows the pattern of retreat inferred from *TT retreat* flowsets. In the majority of cases ice retreats back to areas of high ground, e.g. Lewis, Rannoch Plateau, Southern Uplands, Lake District, Howgill Fells, Pennines, and the Brecon Beacons. However, *TT retreat* flowsets in NE England, Cheshire Plain, Anglesey, Orkney and Shetland document retreat back the low ground of the North Sea, Irish Sea, SW Orkney and SW Shetland respectively. It is highly likely that the latter group of *TT retreat* flowsets record the initial stages of deglaciation involving retreat from offshore troughs and the first group the final stages of retreat to upland areas.

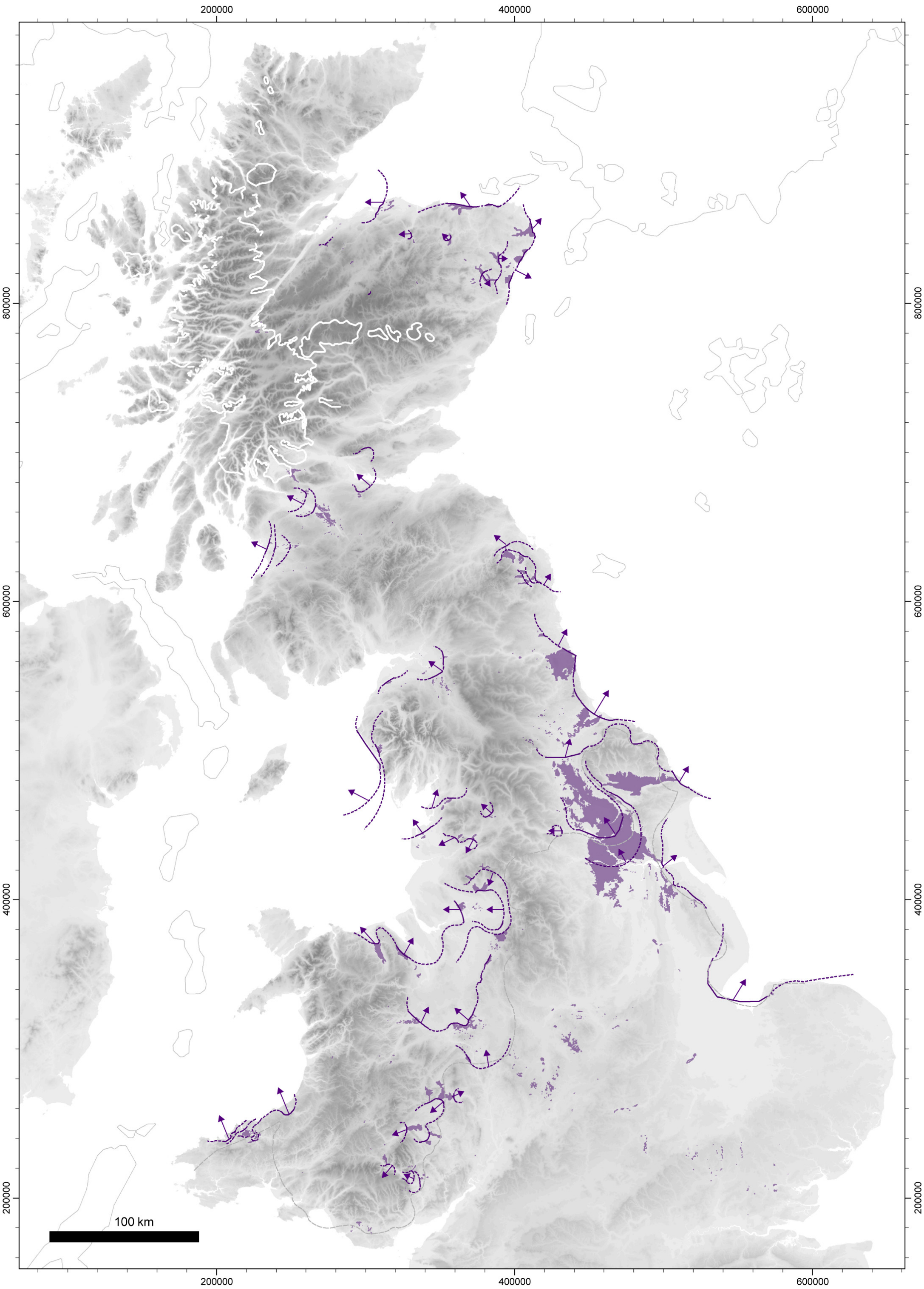


Figure 9.5 Retreat pattern from inferred ice dam positions. Location of glaciolacustrine sediments from BGS mapping in light purple. Arrows show direction of retreat

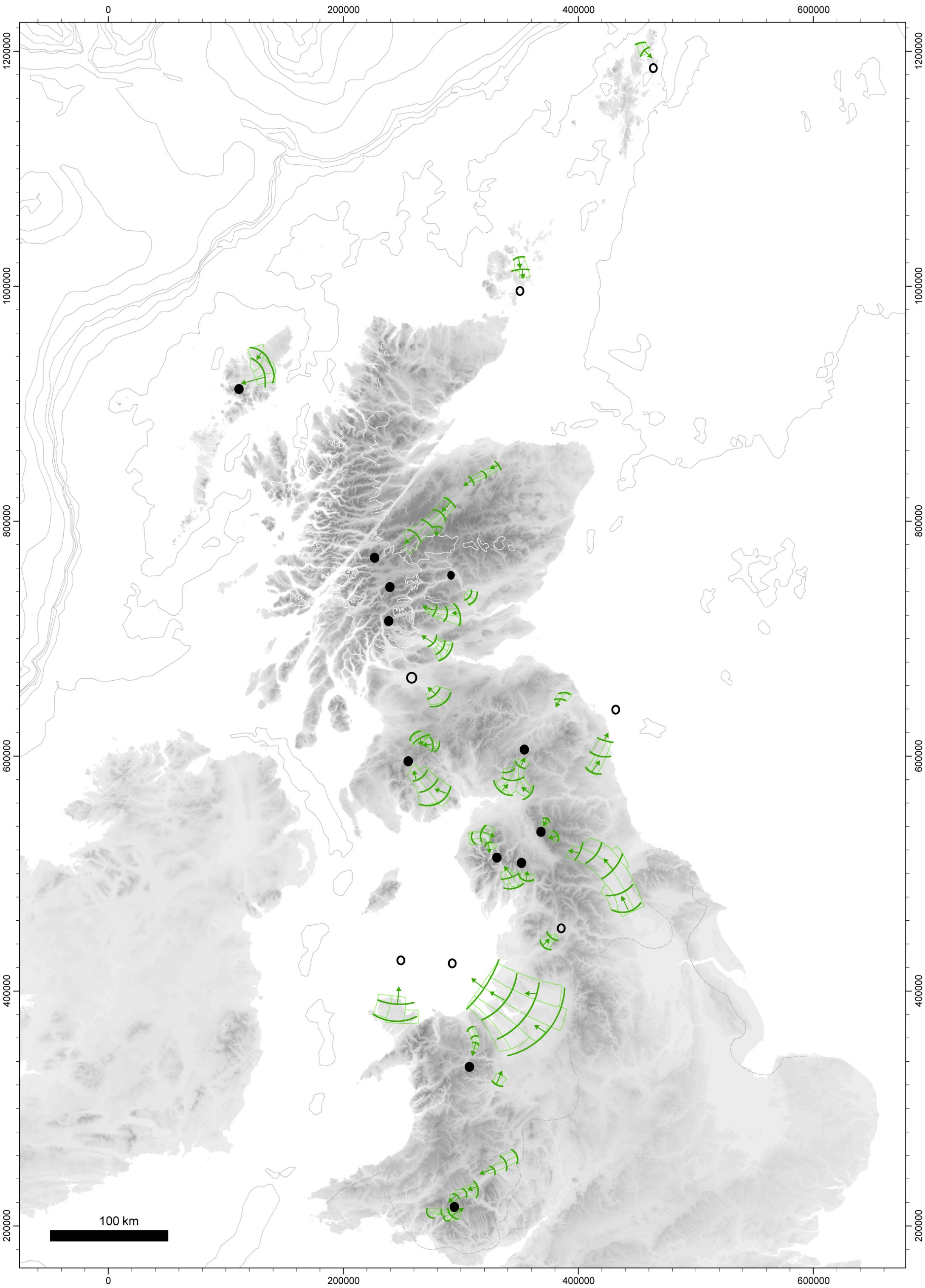


Figure 9.6 Retreat pattern inferred from time-transgressive retreat flowsets of subglacial lineations. Arrows show direction of retreat. Flowsets are shown underneath inferred margins. Dots mark point that ice margin is retreating towards: solid dots mark upland locations, empty dots mark lowland locations.

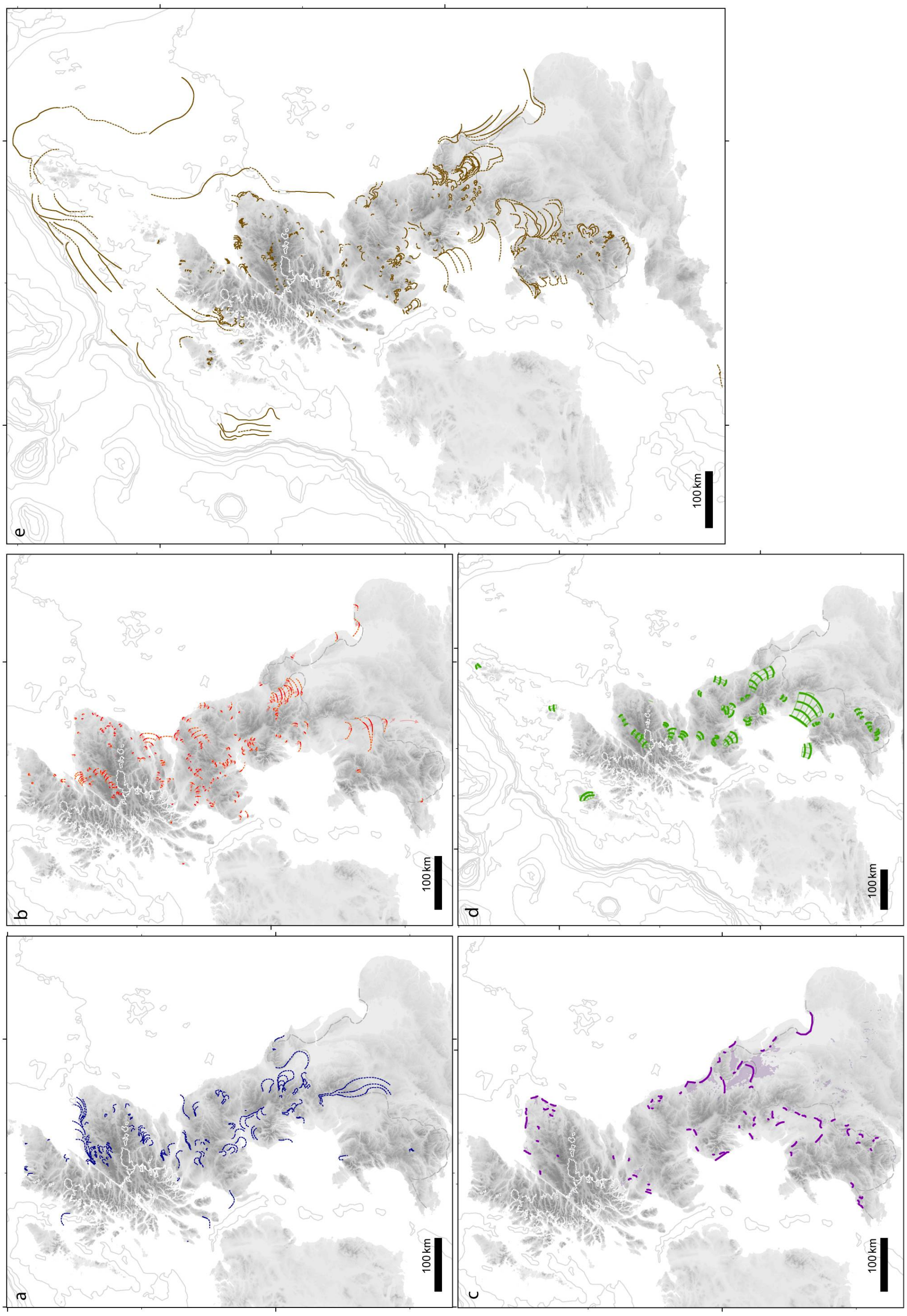


Figure 9.7 Five independent lines of evidence used to reconstruct the retreat pattern: a) meltwater channels; b) eskers; c) lake dams; d) *TT retreat* flowsets; and e) moraines. Maps are shown at scale appropriate to extent of data. It is striking and reassuring that the different lines of evidence document very similar retreat patterns.

9.3 Retreat pattern synthesis

9.3.1 Procedure for combining evidence

The five independent lines of evidence described above were combined to build a pattern of successive retreat margins. Figure 9.7 shows all the lines of evidence shown next to each other. The collective distribution covers most of the country although there is a notable absence of information from the south of the Outer and Inner Hebrides and western Scotland. This is the first time the different and independent lines of evidence have been compared and it is extremely gratifying to find that they largely describe the same pattern of retreat. This is reassuring with regard to the robustness of the retreat pattern. GIS layers of the reconstructed margins were placed together on top of a 50 m resolution DEM of Britain. A summary retreat pattern was drawn consistent with all layers (e.g. figure 9.8).

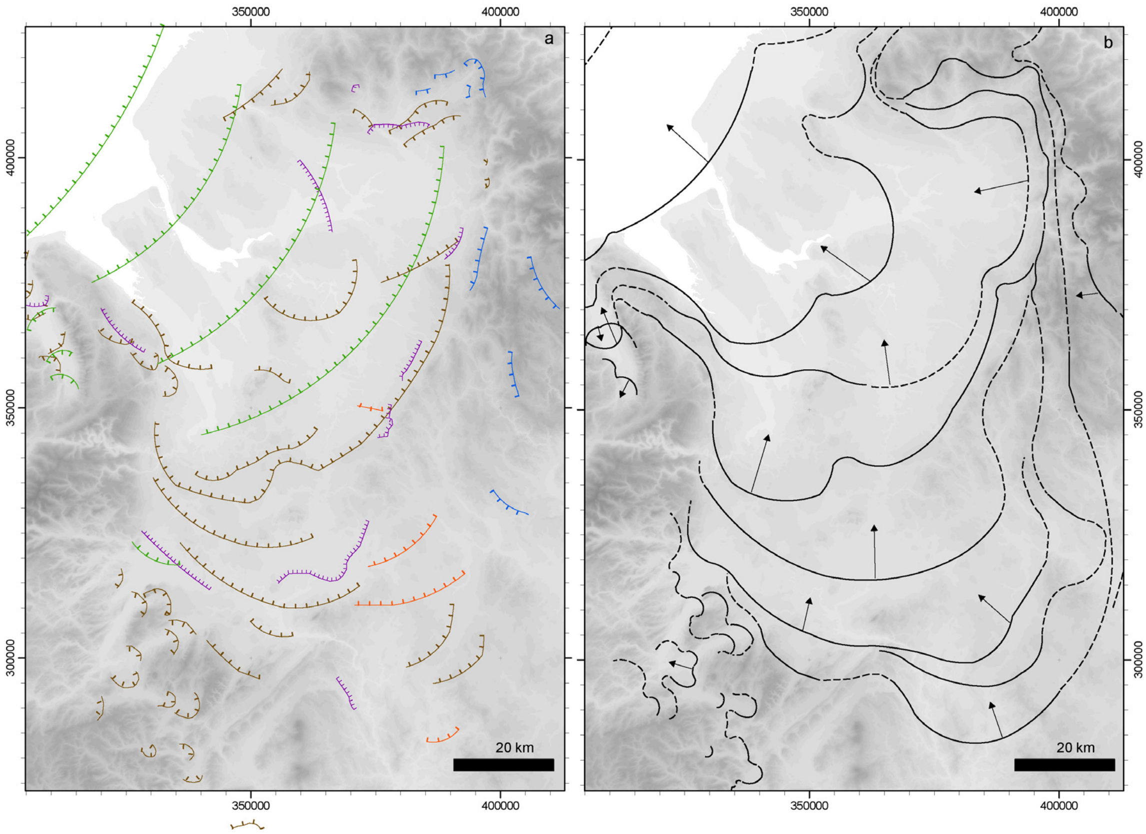


Figure 9.8 Example of synthesis of five independent lines of evidence: a) shows the margin positions from each line of evidence placed on the same map. Key: Hashes are on ice contact side of line. Bedform *TT retreat* flowsets = green, Lake dam = purple, moraines = brown, esker = orange, lateral meltwater channels = blue; b) Retreat pattern synthesis. Arrows show direction of retreat. Solid lines indicate margin positions which are constrained by geomorphological evidence. Dashed lines are estimated extension of the pattern based on topographic context. In general the evidence is mutually corroborative documenting lobate retreat out of the Cheshire Plain into the Irish Sea and retreat by smaller valley constrained lobes into Wales. In the Vale of Clwyd moraines and lake deposits indicate retreat of Irish Sea ice northward creating a small enclave. TT retreat flowset suggests final retreat up valley and overlaps with the moraine evidence suggesting a minor expansion of ice out of Wales following retreat of Irish Sea ice.

At first, margins were considered on a region by region basis then combined for the whole country. Synthesis of the retreat pattern from the different lines of evidence was an iterative process, with margins reassessed and redrawn as each region was added and different scenarios explored. Where evidence is sparse, and to connect successive margin positions, a judicious use of topography was employed to aid the reconstruction. Lines are connected on the basis of topographic setting and the principle of maintaining ice sheet symmetry (chapter 7). In areas of complex topography and across large distances lacking evidence, lines are left unconnected. In the absence of evidence to the contrary, it was assumed that the sectors of the ice sheet resting on terrain presently below sea level would retreat first and the ice mass would maintain a broadly symmetrical form during retreat. A major assumption is that the Loch Lomond Stadial Ice limits in Scotland are analogous to the final stages of the Late Devensian ice sheet. As stated in chapter 5 meltwater, esker, and moraine mapping is thought to be approximately 60% complete, and so the reconstructed retreat patterns here represent a first attempt at an ice sheet scale synthesis. Further mapping using aerial photography and fieldwork should help to fill in the gaps in the framework. Any conflicts between lines of evidence were examined on a case by case basis and the preferred scenario incorporated into the summary pattern. In general, the evidence is mutually corroborative (e.g. figure 9.8) and this is now combined to yield the final map (Map 3 enclosed with this thesis, and a smaller version shown in figure 9.9). Minor conflicts and contradictions between lines of evidence that do occur are discussed in section 9.3.3.

9.3.2 Retreat pattern synthesis result

The summary retreat pattern obtained by synthesising the five lines of evidence is presented in figure 9.9 and Map 3. It is reassuring that the independent lines of evidence reproduce broadly the same picture of retreat (figure 9.7; e.g. figure 9.8). The map shows the pattern of retreat, i.e. each line does not represent a moraine or still stand position and the linking between areas (dashed lines) is achieved by pattern filling rather than geochronology, as temporal information is yet to be included. The southern margin in the Celtic Sea is based on the limit of the Melville Till after Scourse and McCarroll (2006). The Mellville till on the Celtic Shelf is assumed to be coeval with the Late Devensian ice margin on the northern Scilly Isles extending the limit of the grounded ice margin (Scourse, 2006). There is limited evidence on the north coast of mainland Scotland, the North Channel east of the Rhins of Galloway, the southern side of the Tyne Gap, and the most northerly part if the Pennines. The pattern of retreat remains unconstrained in these areas. Figure 9.10 shows the location of areas that are discussed in more detail in the following text. Enlargements of interesting parts or where a high density of evidence enables a detailed reconstruction of the retreat pattern are also shown on Map 5.

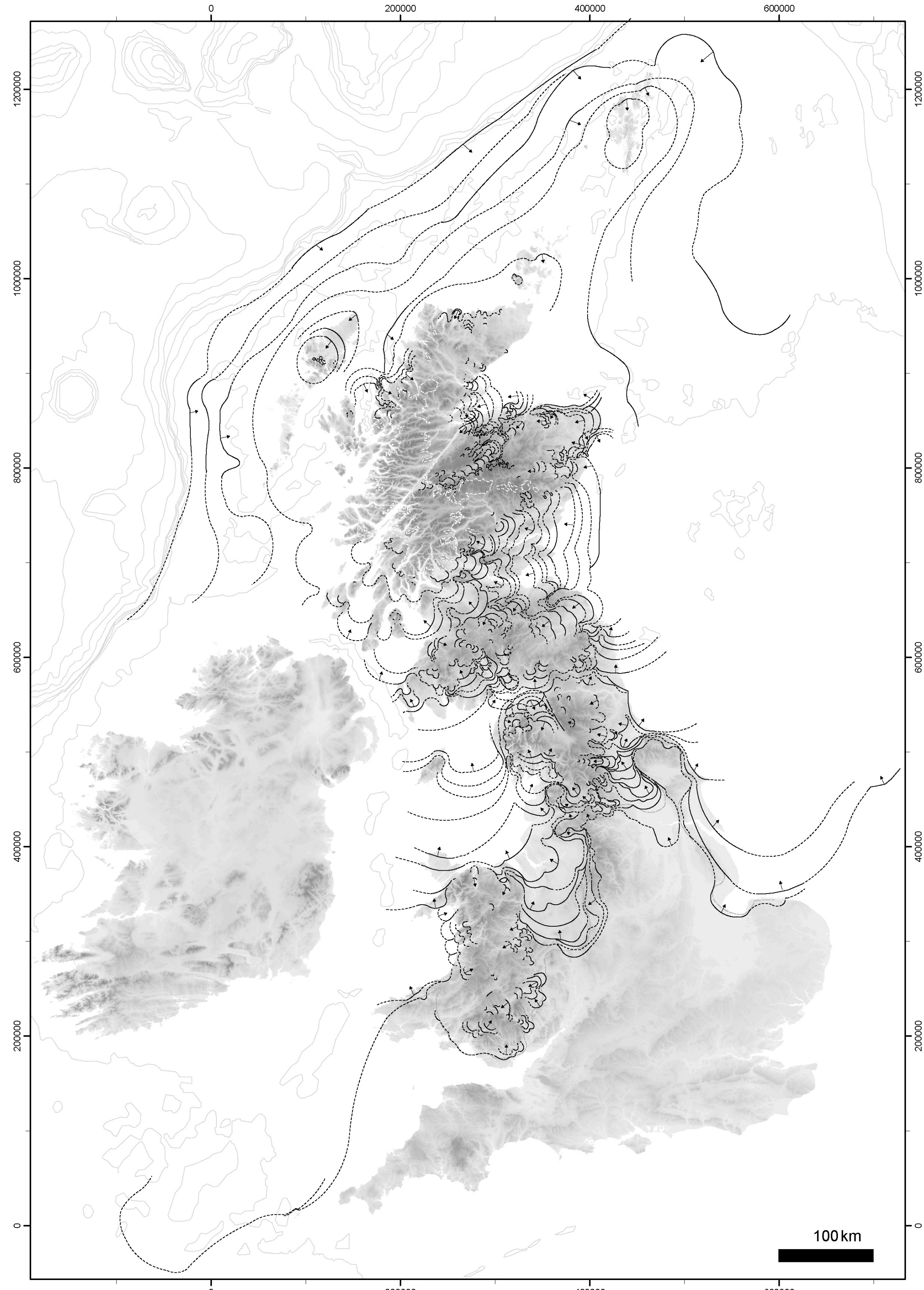


Figure 9.9 Reconstructed pattern of retreat from synthesis of five independent lines of evidence (moraines, eskers, meltwater channels, *TT retreat* flowsets, and lake dam positions. Arrows show direction of retreat and hence point towards approximate location of ice centre. Solid lines indicate margin positions which are constrained by geomorphological evidence. Dashed lines are interpolations and extrapolations based on relationship to topography. A major assumption is that ice in Scotland retreats back to approximately the Loch Lomond Stadial limit.

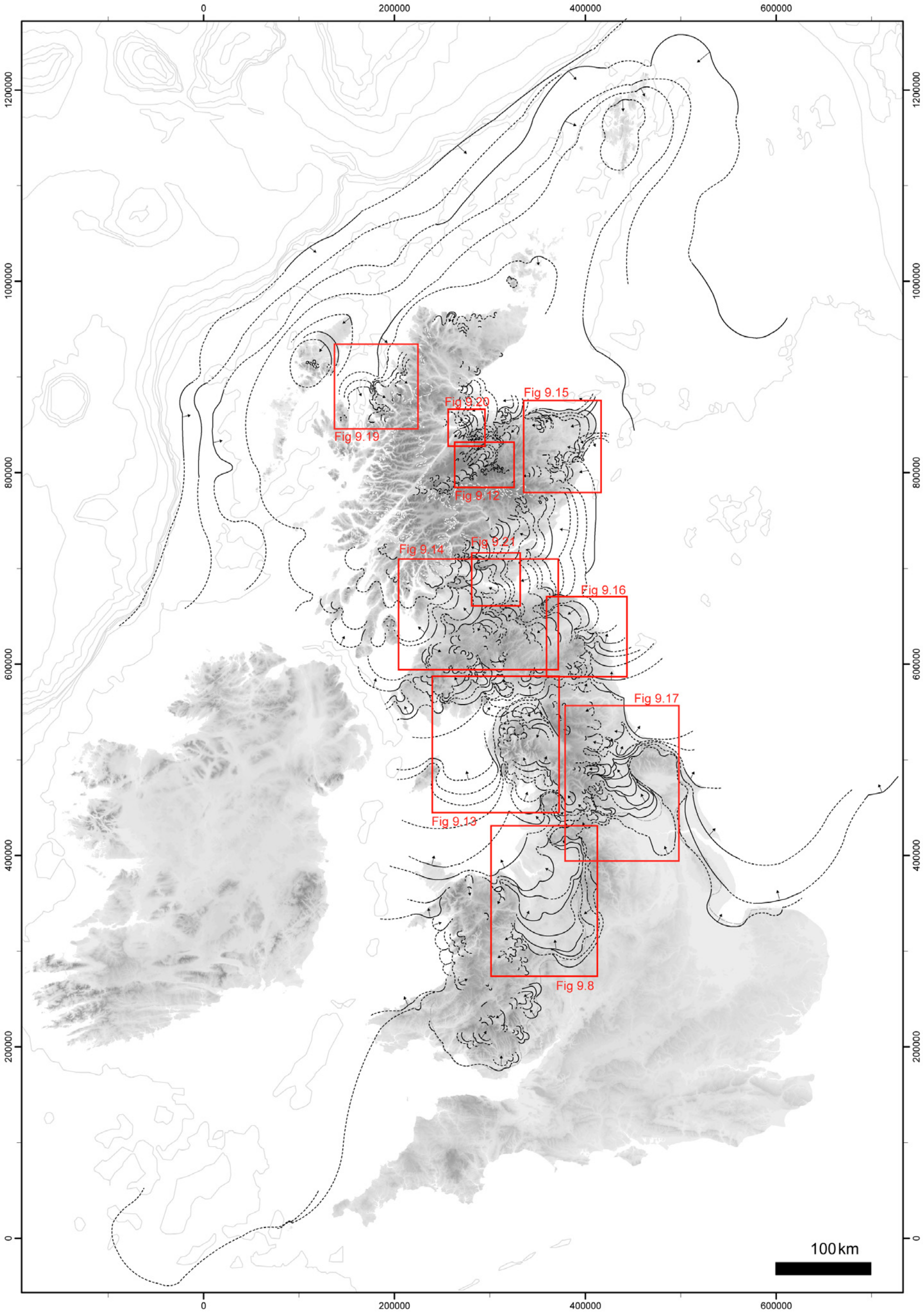


Figure 9.10 Red boxes show the locations of illustrative figures to follow.

Key observations arising from the reconstructed pattern can be summarised as follows:

- The ice sheet does not undergo a monolithic retreat but retreats to numerous independent locations, with several sites supporting local ice caps (figure 9.11). Moraines close to Stranraer indicate that the Irish Sea ice lobe retreated in a NW direction towards the north Channel suggesting that the British and Irish ice sheets maintained confluence until full deglaciation of the Irish Sea. Valley moraines document final deglaciation to the high ground on Hoy, Uist, the Trotternish of Skye, Isle of Arran, the Brecon Beacons, Yorkshire Dales, Lake District, Southern Uplands, the Cairngorms (figure 9.12), and Shetland. Final retreat is towards the western side of Britain presumably reflecting the distribution of upland areas and the general west-east precipitation gradient that exists over the British Isles. This pattern of retreat mirrors the instantaneous glacierization model of ice sheet inception as theoretically described by Ives et al. (1975) and Barry et al. (1975).

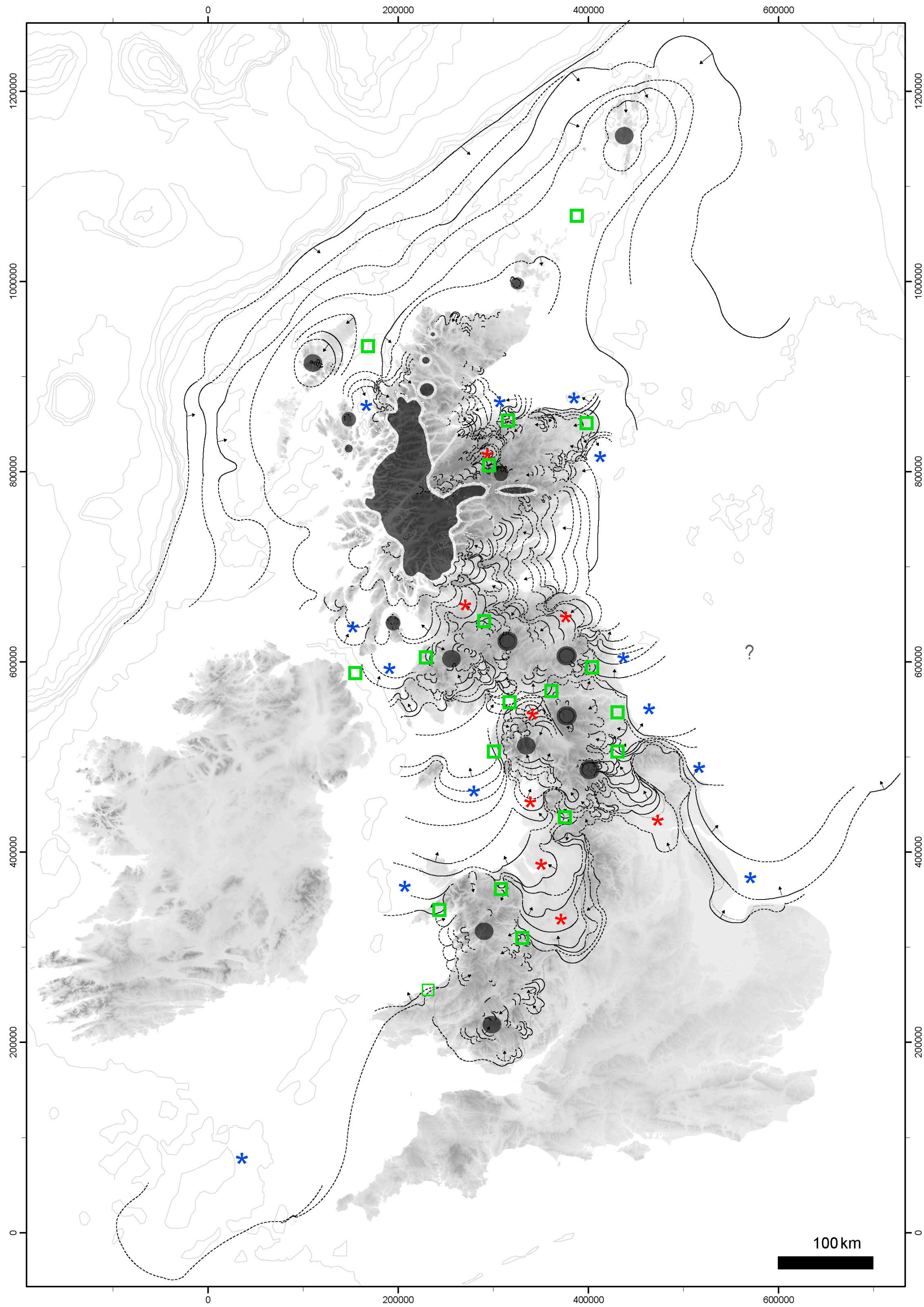


Figure 9.11 Retreat pattern presented in figure 9.8 with annotations relating to comments made in the text. Locations of final retreat are marked by a solid black circle. Delimiting the margins of these has not been attempted as they occur in areas of complex topography and modern examples are characterised by variable configurations. Solid black areas outlined with a white line mark the Loch Lomond Stadial ice cap limits in Scotland. This is assumed to be analogous to the shape of the final stages of the ice sheet in Scotland. 'Offshore' ice lobes are marked by a blue asterisk, 'onshore' by a red asterisk. Green boxes pinpoint locations of ice sheet uncoupling where the ice 'unzipped' into separate masses.

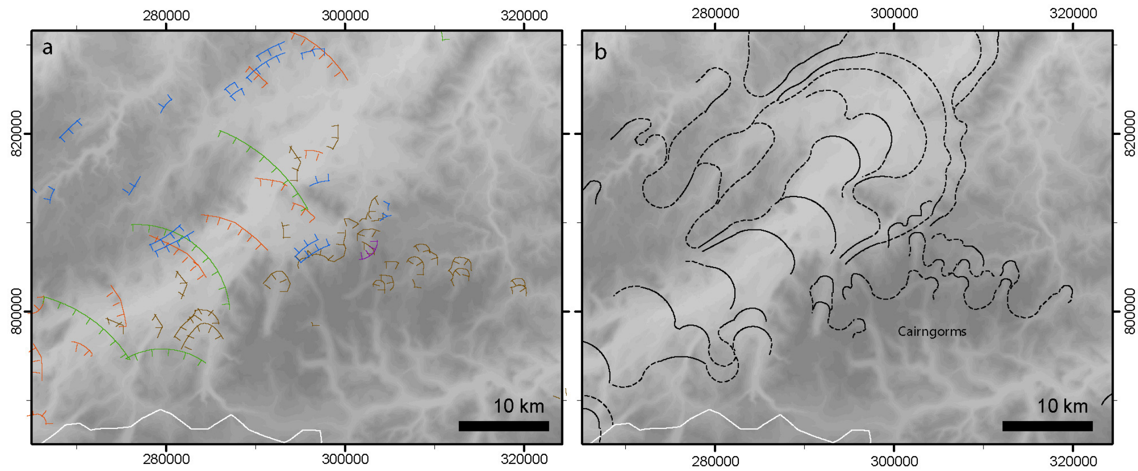


Figure 9.12 Example location where valley moraines indicate retreat to a local ice cap. Ice retreats up the Spey valley around the Cairngorms ice cap and is followed by a possible minor expansion out of the Cairngorms. Lake deposits (Golledge, 2002) indicate that glacial lakes developed between the ice lobe and ice cap during deglaciation.

- The overall pattern indicates that the ice sheet uncoupled in the Central Valley of Scotland, Solway lowlands, Irish Sea west of Lancashire, Lleyn Peninsula, Cheshire Plain, eastern England, Minch, close to Fair Isle, and in the North Channel, retreating to multiple ice domes in Wales, northern England, Southern Uplands, mainland Scotland, Outer Hebrides and Shetland (figure 9.11). In some uncoupling locations a complex record of retreat suggests competition between ice masses during or after separation. For example, the assemblage of moraines and other ice contact deposits on the Lleyn Peninsula site this as the zone of confluence and subsequent uncoupling of the Irish Sea and Welsh ice masses. It is known from sedimentological investigations that Welsh till overlies Irish Sea till on the St. Tudwals Peninsula, consistent with an advance of Welsh ice after retreat of the Irish Sea lobe (Walker and McCarroll, 2001). In the Tees-Tyne area a hummocky spread of moraine material occurs. This possibly reflects stagnation during separation of the Pennine and North Sea ice. Sites of uncoupling of the ice sheet are often characterised by conflicting retreat evidence. It is postulated that the conflicting evidence arises due to competition between ice masses and minor oscillations of the margin during retreat from these locations. It was not always possible to determine the exact location of unzipping of the ice sheet. Figures 9.13 and 9.14 show examples of uncoupling locations in the Solway lowlands and Midland Valley of Scotland.

- Ice lying beyond the present day coastline had a significant influence on the pattern of retreat. 'Offshore' lobes are indicated by the retreat pattern from the east coast of England, Moray Firth, and the Irish Sea (figure 9.11). These 'offshore' lobes even persist after thinning and retreat inland of ice from peripheral ice centres. Glaciolacustrine sediments in northeast England imply that westward retreat inland must have occurred before retreat of ice out to sea. Direction of this latter retreat is equivocal, ice abutting against the coast could have retreated either northward back up into the Tweed and Forth, or eastward to an ice centre in the southern North Sea. The stratigraphy of the north east coast has been the subject of much debate in an attempt to resolve the relative influence of inland and offshore ice and is presently unresolved (Bridgland et al., 1999). Lateral meltwater channels running parallel to the north coast in Buchan require early deglaciation inland from the coast. Such a scenario can be accommodated if ice blocking drainage at the coast was due to lobes of ice emanating from Strathmore and the Moray Firth (figure 9.15). Detailed examination of the tills of NE Scotland has enabled a regional stratigraphy of interrelationships of Moray Firth, Grampian, and Strathmore sourced ice (Merritt et al., 2000). The Grampian sourced till is overlain at the NE tip of Buchan by Moray Firth ice and on eastern coast by till sourced from Strathmore, consistent with onshore incursion of ice. Further testament to the significance of 'offshore' ice is that the largest, ice sheet scale, moraines occur beyond the present day coastline (figure 9.1).

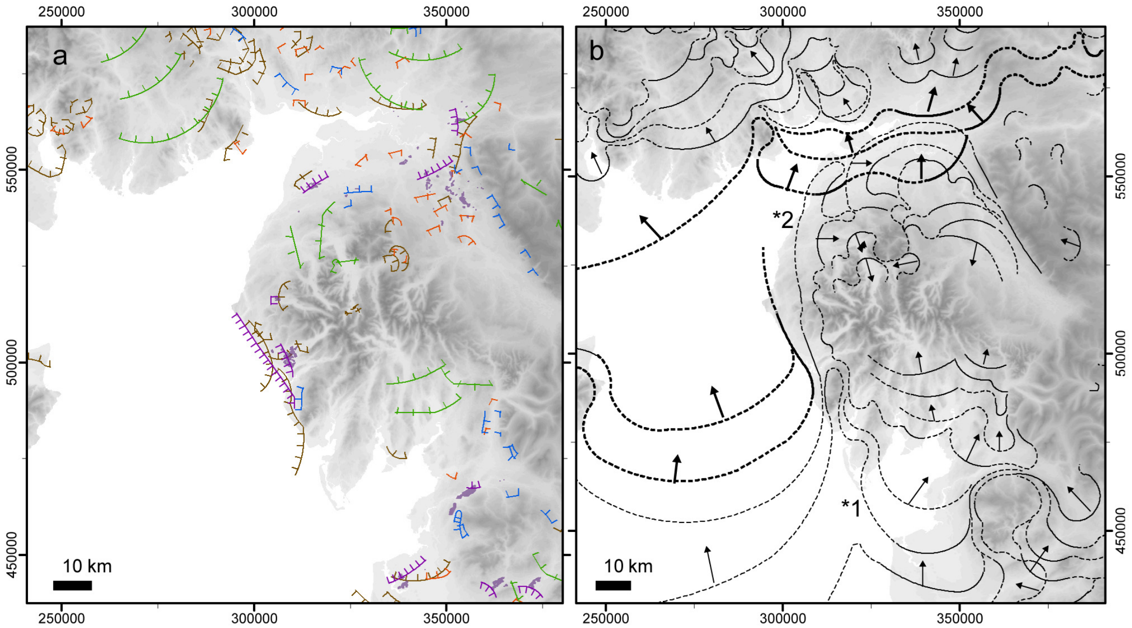


Figure 9.13 Uncoupling of ice from the Irish Sea and NW England. Lateral meltwater channels, eskers and moraines indicate retreat back into the Cumbrian Mountains accompanied by ice sheet thinning leading to the emergence of high ground. Location *1 marks the splitting of Irish Sea ice from ice emanating from the Lake District and Howgill Fells. The precise location of unzipping of the Lake District and Scottish ice is unclear. The approximate location is marked by *2. The glacial lake sediments in the Solway and Vale of Eden suggest that Scottish ice may have expanded south after Lake District ice had retreated, in order for glacial lakes to develop ice must have been blocking the drainage route into the Irish Sea at this time. This apparent conflict in evidence is interpreted as reflecting oscillations between the two ice masses during uncoupling.

- Ice persists as lowland lobes as the ice sheet thins and higher ground becomes ice free. Figure 9.10 show the locations of major ice lobes. Lateral meltwater channels document a ice thinning in central Scotland where ice is deflected around the Sidlaw and Ochill Hills and the Campsie Fells. Southwest of Edinburgh, westward retreating ice splits around the Lammermuir and Pentland Hills, creating ice lobes in the Tweed and Firth of Forth (figure 9.14). A lateral meltwater channel along the western side of Kintyre suggests lobate retreat towards the high ground of Knapdale and the Isle of Bute following the separation of the British and Irish ice masses. In Lancashire, moraines, lateral meltwater channels and glaciolacustrine deposits combine to suggest northward retreat of ice around the topographic obstacle of the Forest of Bowland (uplands). Lateral meltwater channels on Black Combe and glaciolacustrine sediments in the western Lake District suggest that the highest ground of the Lake District had emerged before deglaciation of the Irish Sea lobe (figure 9.13). In the western Lake District moraines are overlain by till with an Irish Sea provenance (Evans et al., 2005) consistent with inland ice retreat before deglaciation of the northern part of the Irish Sea. Lateral meltwater channels running along the slopes of the Pennines indicate that the Pennines were ice free while ice remained in the Vale of Eden (figure 9.13). Glacial lakes formed between the retreating lobe in the Cheshire Plain and the upland area of the Rossendale Forest to north of Manchester during retreat, an indication that ice retreated from the Rossendale area before retreating from the Cheshire Plain (figure 9.7).

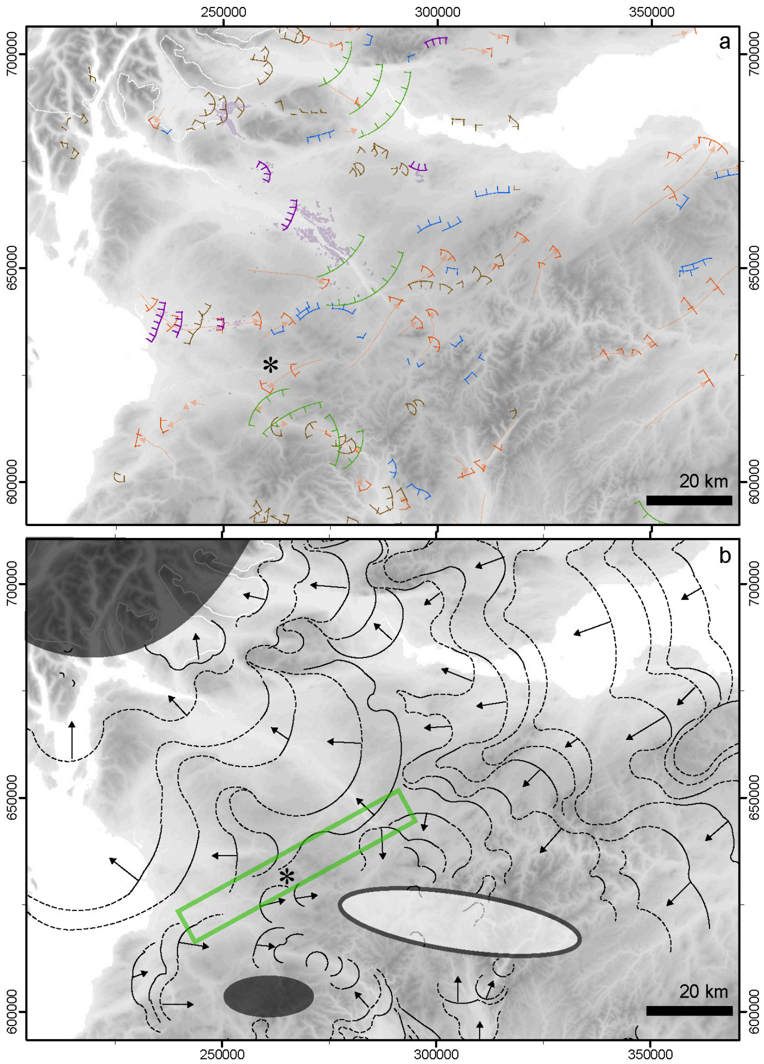


Figure 9.14 Separation of Highland and Southern Upland ice in the Midland Valley of Scotland. Lateral meltwater channels, eskers and moraines indicate initial retreat from the Firth of Forth westward. Highland and Southern Upland ice appears to have separated around the position marked by a green box. Retreat evidence back into the Southern Uplands is sparse. It is speculated that evidence has been erased by a minor expansion of the Highland ice as the ice masses uncoupled. Glaciofluvial sediments form a belt running across the Midland Valley; this possibly marks the zone of uncoupling of the ice sheet. The direction of ice flow suggested by the esker marked by an asterisk was difficult to define, presuming that the ice flow is up the valley, eastward retreat into the Southern Uplands occurs. If the esker was interpreted as representing ice flow in the opposite direction, this would suggest retreat westward probably at the same time as the retreat pattern just to the north of this location. This would imply a smaller ice mass in the Southern Uplands. Black circles mark the locations of final retreat to ice caps; hollow circles retreat to a series of valley glaciers

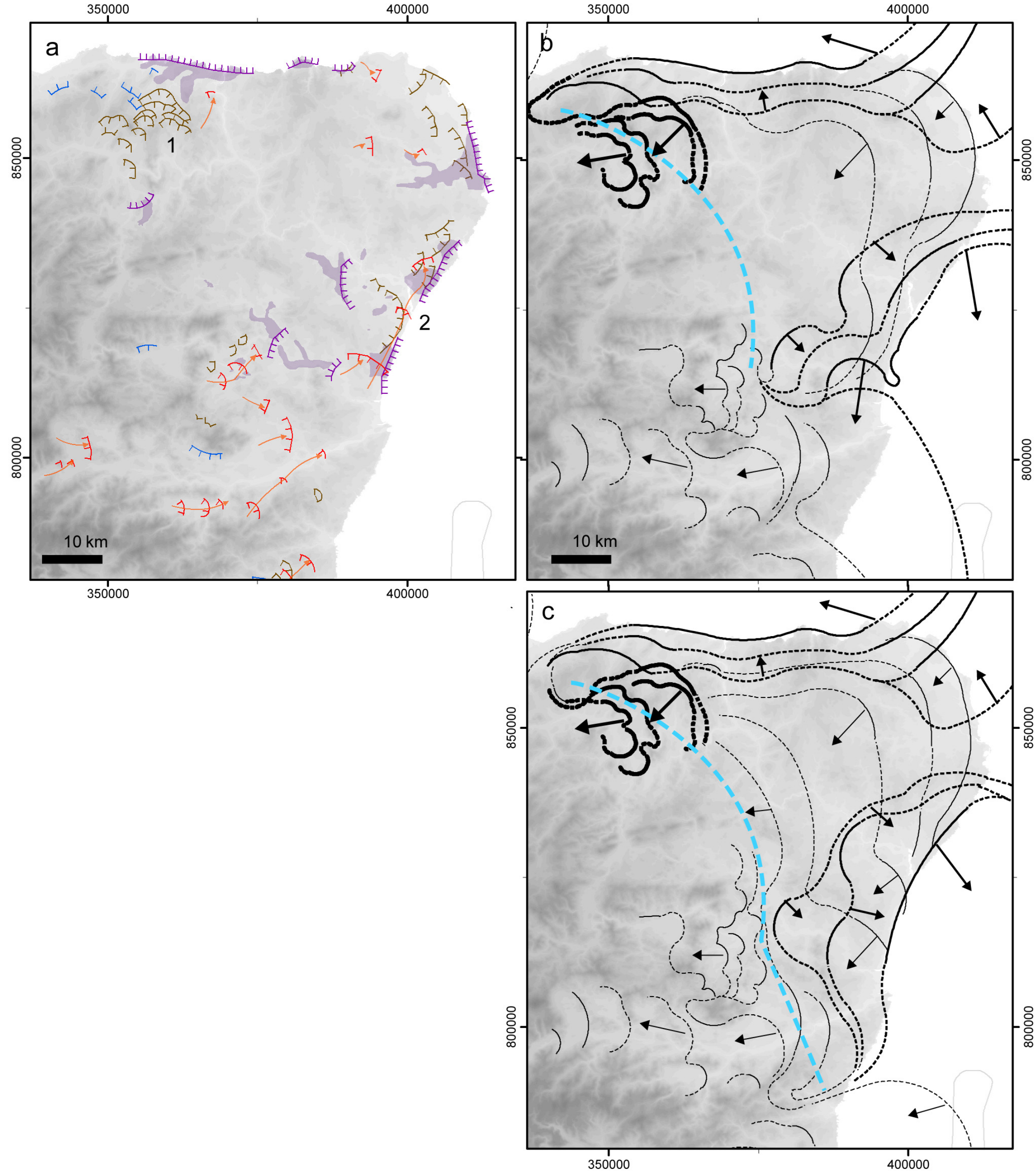


Figure 9.15 Detail of retreat pattern in Buchan, NE Scotland: a) Evidence; b) Reconstructed retreat pattern included in figure 9.8 and Map 3; and c) Alternative retreat pattern. Lines are variable thickness to indicate oscillation of the ice margin. Lateral meltwater channels and ice damned lake positions along the northern coast imply that Buchan deglaciated before offshore ice. Retreat in Buchan is to the SW, indicated by eskers and moraines. Well defined, 'fresh', moraines occur close to Aberchirder in north Buchan (marked with an asterisk). These appear to postdate the lateral meltwater channels (offshore ice), and therefore represent a minor readvance of the ice margin. These oscillations are present in both scenarios. Along the east coast, there is similar evidence for glacial lake damming by offshore ice. In addition to this there is an esker running broadly N-S along the coast. This esker is in the literature as well as new mapping and therefore is regarded as reliable. Two explanations can explain this esker and the glacial lakes: b) ice retreats from north Buchan only to the vicinity of the blue line. Offshore ice sustained by ice from Strathmore and South Buchan then flows onshore. This lobe retreats in a clockwise direction into the Dee valley forming the esker and lakes; c) Initial ice retreat from all of Buchan as far as the blue line, forming the moraines and esker. Offshore ice then flows onshore and retreats back south into Strathmore forming the glacial lakes.

- Lobes of ice are deflected around local ice caps. For example, Irish Sea ice split into a lobe retreating to the NE into Lancashire and a lobe retreating to the NW around the Lake District massif (figure 9.13). Retreat progressed in an anticlockwise direction around the eastern flanks of the Cheviots but there is little evidence for retreat towards an ice mass centred on the Cheviots (figure 9.16). This is consistent with the field observations of Mitchell (2008) who suggested that the Cheviots supported a cold based ice cap during the last glacial. Irish Sea ice is deflected by and retreats around the Welsh Ice Cap. Lobes of the Moray Firth and Strathmore are deflected around the eastern Grampians ice mass, only moving onshore after retreat of this ice (figure 9.15). Ice in the Spey valley retreats back towards central Scotland bypassing an ice mass on the Cairngorms (figure 9.12).

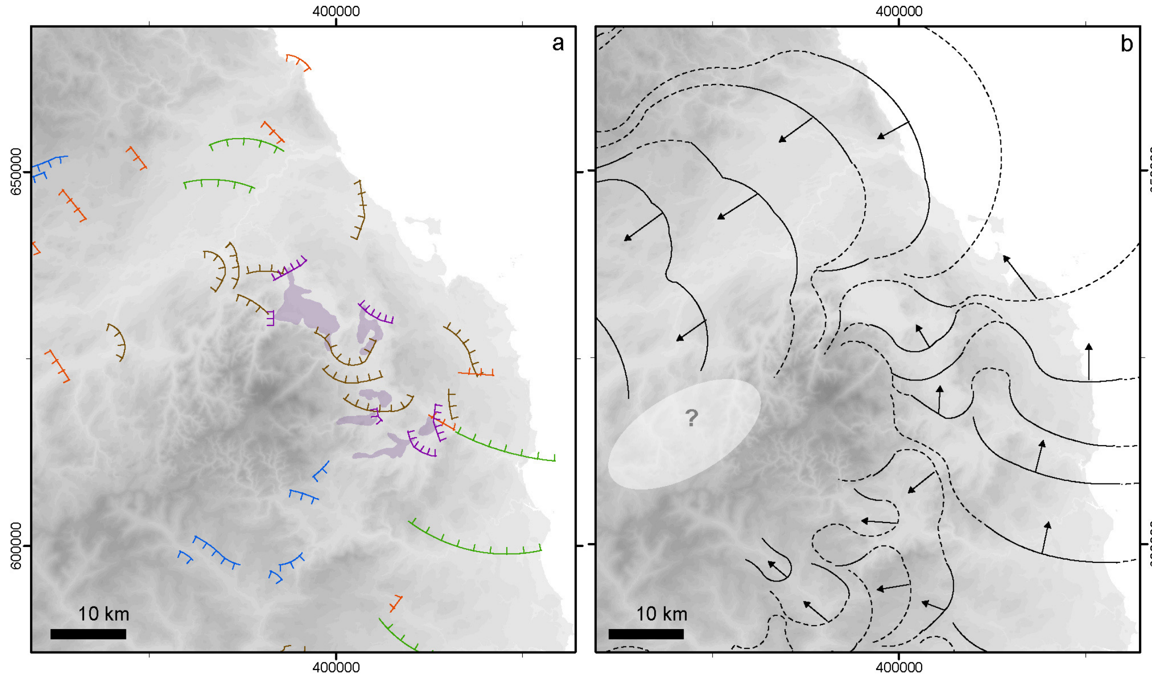


Figure 9.16 Lakes, moraines, TT retreat flowsets, and eskers combine to describe retreat of a lobe of ice anticlockwise around the Cheviot massif and westward up the Tweed valley. Retreat of ice in an anticlockwise direction around the Cheviot ice mass. To the south of the Cheviots lateral channels document ice sheet thinning and retreat into the upland region. The question mark marks an area where it is impossible to reconstruct the retreat pattern due to a lack of evidence.

- There is some evidence for minor expansion out of local ice centres following retreat of lowland lobes. For example, lateral meltwater channels and moraines in the valleys which open out into Strathmore document retreat by valley glaciers in a NW direction after retreat of the main lobe of Strathmore ice. Welsh ice expansion is suggested following retreat of the Irish Sea lobe in the Cheshire Plain as indicated by the *TT retreat* flowset in the Vale of Clwyd and moraines in eastern mid Wales (figure 9.8). In eastern mid Wales the stratigraphy is also consistent with oscillations between Welsh sourced and Irish Sea ice sourced ice (Bowen, 1999b; Evans et al., 2005). There are two scenarios for retreat of ice back into the Yorkshire Dales on the basis of the arrangement of moraines from the Vale of York (figure 9.17). Either a) retreat of ice into Wensleydale from the Vale of York in synchrony with retreat of the Vale of York ice lobe or b) once retreat of the Vale of York ice is complete, expansion of ice out of Wensleydale into the Vale of York. Deformation structures within ice contact deposits at the junction between Dales ice and the Vale of York lobe suggest that Dales ice expanded into the Vale of York prior to advance of the Vale of York lobe (Evans et al., 2005) and so the first scenario is accepted (figure 9.17, inset map on Map 3).

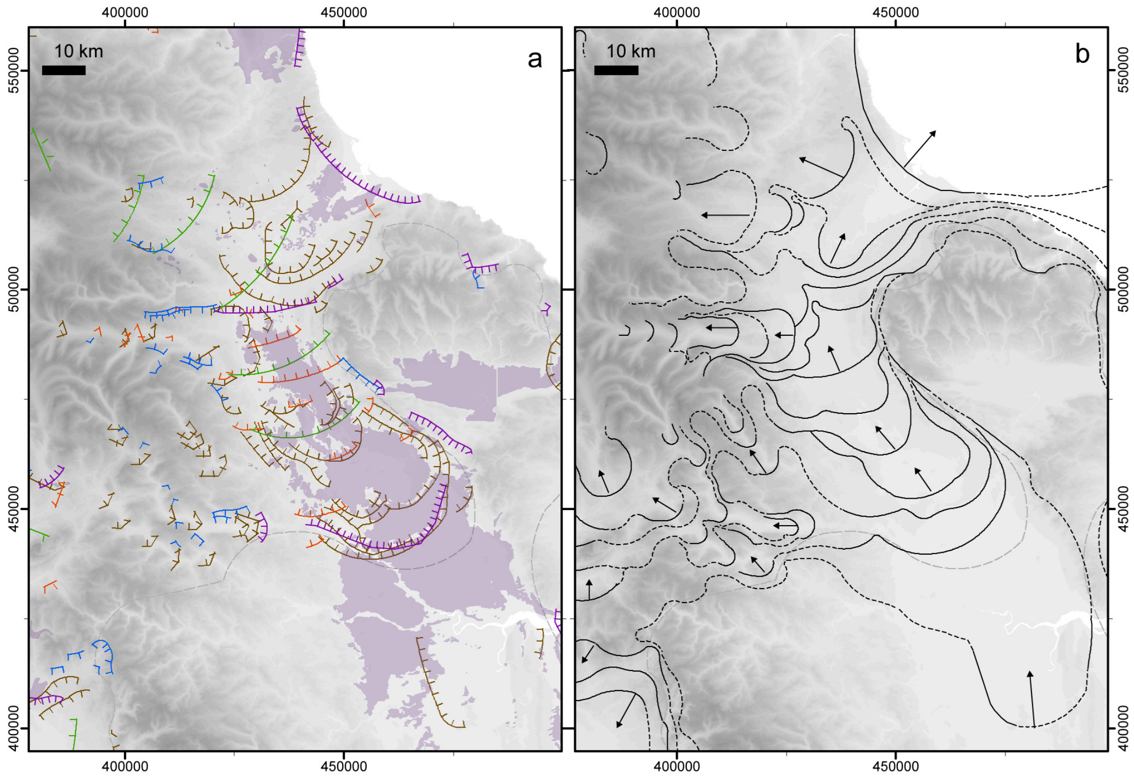


Figure 9.17 Detail of retreat up the Vale of York and into the Yorkshire Dales and southern North Sea. Ice uncouples at the head of the Vale of York and retreats by thinning into the Yorkshire Dales. North of the Tees, lowland retreat is poorly constrained.

9.3.3 Conflicts/discrepancies between lines of evidence

In some locations the lines of evidence appear to contradict each other. The preferred (simplest) solutions that can explain the conflict that have been incorporated into the overall summary (figure 9.9) are described below and sites are flagged as locations for future fieldwork.

9.3.3.1 Opposing retreat evidence – ice front oscillations

There is no overwhelming evidence for major readvances of the ice sheet on the basis of the primarily geomorphological evidence considered here. However, in some locations, overlapping evidence for retreat in opposing directions can only be accommodated if an oscillation of the ice sheet is invoked. In most cases these imply movements of the ice of the order of hundreds of metres and are therefore not taken as indicative as ice sheet scale readvances of the ice front. Figure 9.18 shows the locations of possible ice front oscillations. It is interesting that these coincide with locations of ice sheet uncoupling, e.g. Midland Valley of Scotland (figure 9.14). It is thought that these apparent conflicts arise due to the uncoupling of ice in these areas, where opposing ice margins oscillated interrupting gradual successive retreat. For example, in Buchan on the north side of the Strath Isla close to Aberchirder there are a series of thin arcuate moraine ridges (figure 9.15). These ridges are little modified and are not over printed by the lateral meltwater channels running W-E along the coast. These moraines therefore represent an expansion of inland ice following coastal deglaciation (figure 9.15). Till with a Moray Firth provenance is overlain by till with a central Grampian or Spey provenance in this area (Merritt et al., 2000) consistent with a short readvance of local ice following recession of the Moray Firth ice lobe. Interpretations made in this thesis are also consistent with the contention of Merritt et al. (1995) for an oscillation of the ice front at Ardesier.

Till stratigraphy in the Solway lowlands has been invoked to support a readvance of ice from Scotland (chapter 2). The reality of this oscillation is an ongoing debate (Huddart, 1991). Figure 9.13 shows the detail of the retreat pattern reconstruction in the Solway lowlands. North of the Lake District, lateral meltwater channels, eskers and moraines combine to document retreat southward from the Solway lowlands and up the Vale of Eden accompanied by ice thinning. In opposition to this, glaciolacustrine sediments in the Vale of Eden suggest ice blocking the Solway lowlands and retreat northwards after deglaciation of the Vale of Eden. All of this apparently contradictory evidence can be accommodated if Southern Upland sourced ice expanded south, into the recently deglaciated area (following retreat of ice southwards) thus blocking the drainage route into the Irish Sea to create a proglacial lake. Consistent with an expansion of Scottish sourced ice during deglaciation are detailed sedimentological and geomorphological observations from the Isle of Man supporting an oscillating Irish Sea ice lobe (Thomas et al., 2004) and the location and internal structure of the ice contact delta at Holme St. Cuthberts in the Solway lowlands (Livingstone, pers. comm.).

Lateral channels on the coast of Wester Ross indicate a lobe of ice retreating back between Skye and mainland Scotland after retreat of ice from the coast (figure 9.19). Well documented moraines on Wester Ross have been used to support a major still stand or minor readvance of ice during retreat (Robinson and Ballantyne, 1979). The readvance status of this suite of moraines has not yet been confirmed by stratigraphical evidence and is based on the extensive nature of the moraine across several lochs and cross-cutting striae close to the Redpoint moraine. There is no new evidence in this thesis to confirm or reject the readvance status of the moraines. The lateral channels on the coast indicating a lobe retreating between Skye and mainland Scotland forms a slightly tortuous margin with the Wester Ross moraines if sequential retreat out of the Minch is assumed. An alternative scenario would be for retreat to an undefined position on mainland Scotland within the line marked by the Wester Ross moraines, followed by an advance to the Wester Ross position. However, the evidence to support the readvance status of these moraines is far from unequivocal and in the absence of corroborating stratigraphical information, the simpler, if tortuous, retreat scenario is incorporated in the overall retreat pattern (figure 9.9; Map 3).

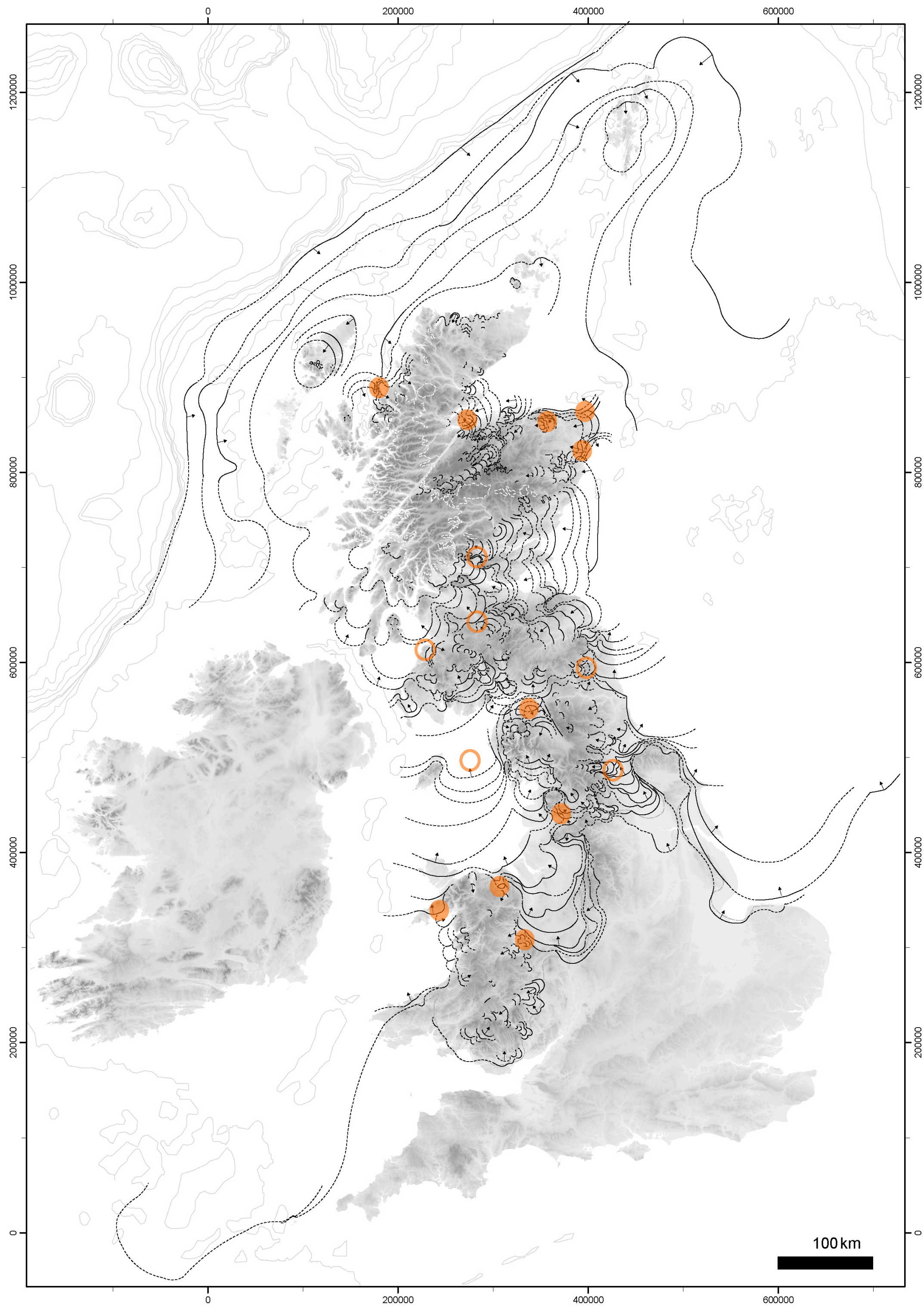


Figure 9.18 Retreat pattern presented in figure 9.8 with locations of minor oscillations of the ice margin marked by orange circles: Solway lowlands, Ayrshire and Midland Valley, Buchan, Ardesier, Wales, Vale of York and Wester Ross. It is important to note that in the absence of dated stratigraphical information all moraines are assumed to represent former still stand positions of the ice margin during retreat and not readvance positions. The majority of the suggested oscillations occur at sites of ice sheet uncoupling/unzipping. Solid circles mark locations where evidence requires oscillation. Empty circles mark position of locations of more speculative oscillations.

9.3.3.2 Coincident lateral meltwater channels and eskers

In the vast majority of case the 'rule' and assumptions (chapters 3 and 7) for interpreting landform suites appear to work in that they permit a simple deciphering of complex patterns. However, in a few areas eskers and lateral meltwater channels comprise the same pattern of retreat (figure 9.7) which contravened our 'rules' as eskers are taken as forming during retreat of warm-based ice whereas lateral meltwater channels are though to form at the margins of cold-based ice. There are several possible explanations for this:

1. The meltwater channels were inscribed during the initial stages of deglaciation when ice thinned to reveal high ground, and the margin of the ice front was some distance from the area of meltwater channel formation. As deglaciation progressed thermal conditions at the base of the ice changed so that as the ice front passed the area retreat was warm-based and eskers were formed.
2. The mapped eskers are not the depositional infill from subglacial conduits but erosional remnants of kame terraces formed at the margins of the retreating ice and subsequently modified by fluvial erosion.
3. The lateral channels were not formed during retreat but advance of the ice sheet.
4. Two discrete retreats of the ice front over the region separated by a readvance of ice in the intervening period.
5. An extreme temperature gradient existed in the glacier, whereby the ice is cold-based at the surface of the ice and warm-based close to the bed.
6. Although the channels exhibit the characteristics of lateral channels they are really subglacial in nature and therefore have been misclassified.

The strong evidence for topographic control on ice flow evident from flowset analysis (chapter 6) and the multiple examples of coincident lateral channels and eskers leads this thesis to favour the first hypothesis in the majority of cases, e.g. for the Vale of Eden and Vale of York.

Close to Inverness, in the Moray Firth, eskers and lateral meltwater channel actually overlap (figure 9.20). This implies thinning of the ice sheet followed by progression of the ice margin over an area already deglaciated. In this instance option 6 is favoured as the security of the lateral classification is only 'probable'.

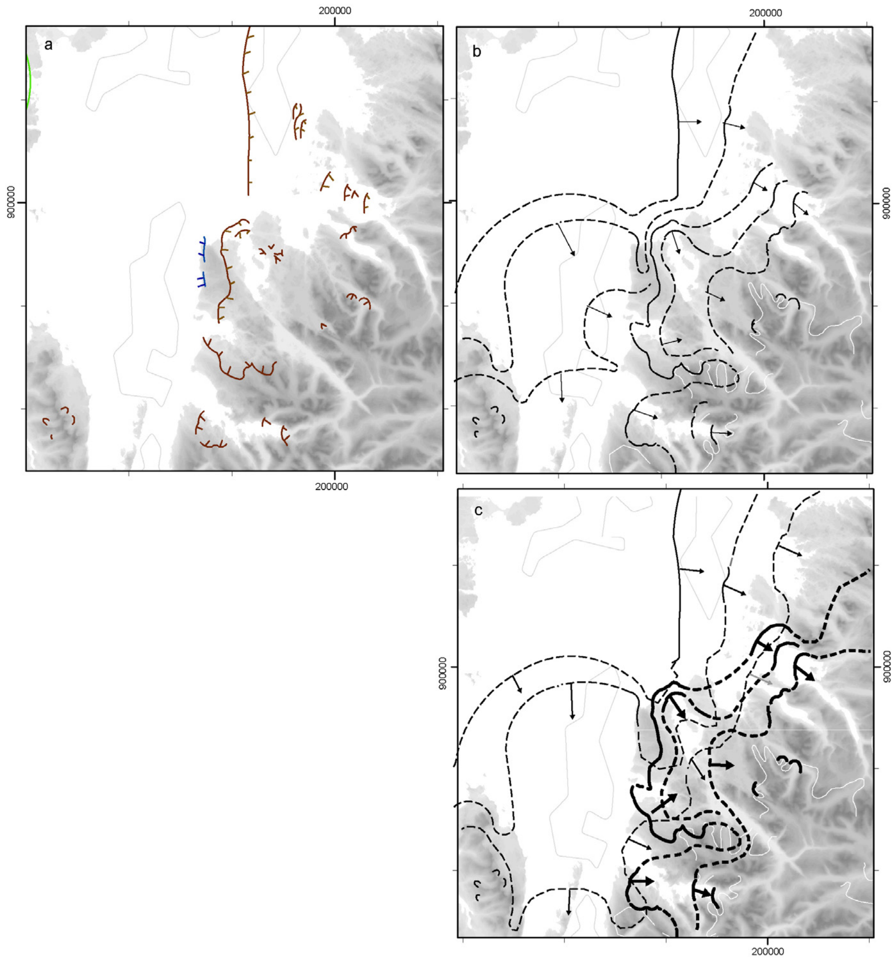


Figure 9.19 Detail of retreat in the Minch. a) Retreat evidence in Wester Ross region; b) successive retreat into Northern Scotland; and c) retreat into northern Scotland to an unknown inland position (thin lines) followed by a readvance and second stage of retreat towards the Loch Lomond Stadial limit (thick lines). Scenario b is included in the retreat pattern presented in Map 5 because it is simpler, despite the slightly tortuous margin.

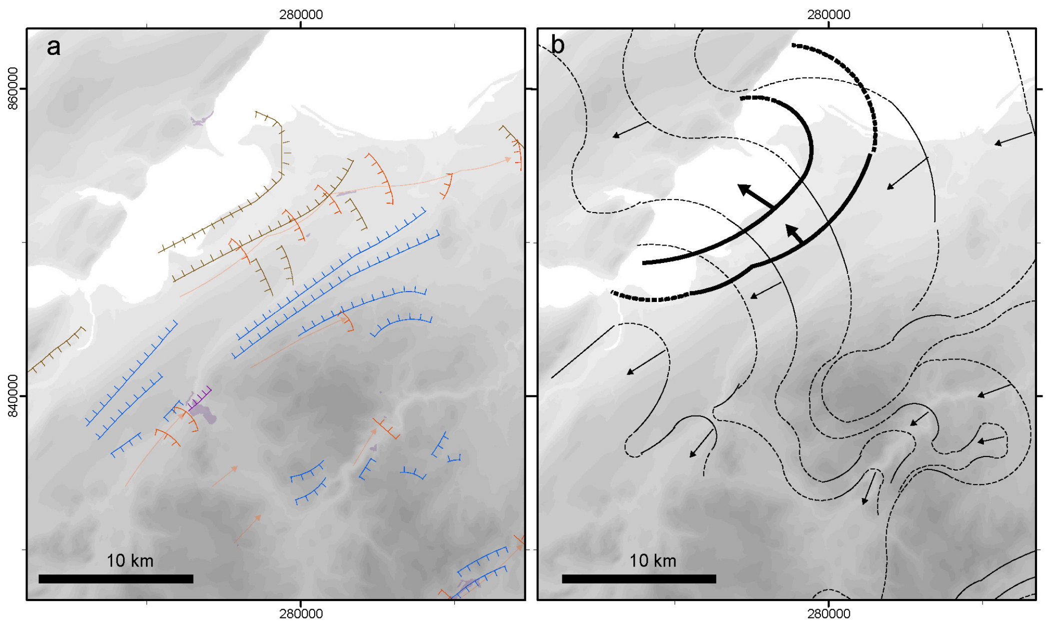


Figure 9.20 Esker and lateral meltwater conflict in the Moray Firth: a) Esker and lateral meltwater channels are superimposed on each other but describe the same direction of retreat; b) reconstructed retreat pattern in Moray Firth. The channels that were originally interpreted as lateral meltwater channels and here overlap with esker are reinterpreted as subglacial channels, thus enabling a simple and coherent reconstruction for the area. Not the minor readvance (in bold).

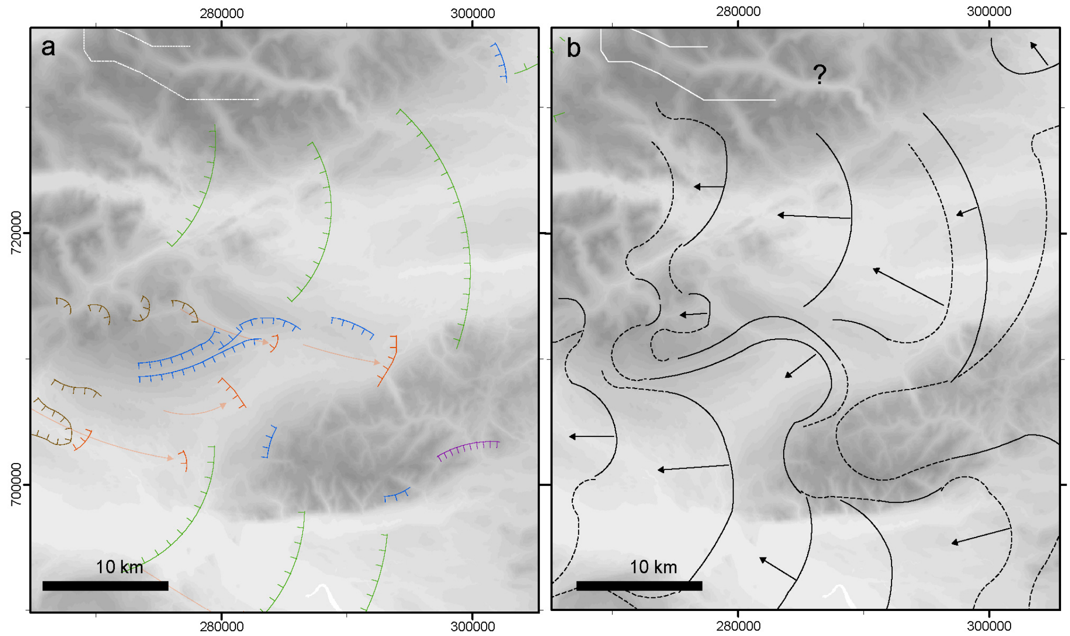


Figure 9.21 Esker and lateral meltwater conflict in central Scotland: a) eskers describe retreat to the WNW and over high topography, whereas lateral meltwater channels describe retreat by thinning and around the topographic highs; b) reconstructed retreat pattern for central Scotland. Balance of evidence suggests westward retreat and ice thinning. The awkward esker is excluded from reconstruction. Question mark where retreat is unconstrained by evidence.

In Aberdeenshire (figure 9.15) eskers, moraines and lateral meltwater channels describe thinning and westward retreat from the coast into the Grampians and Cairngorms. Glaciolacustrine sediments require ice damming supporting ice retreat eastward, i.e. in an offshore direction. As a further complication, NNE-SSW orientated eskers parallel to the coast suggest ice retreat towards the south. The evidence for opposing eastward and westward retreat can be accommodated in a scenario of initial retreat inland from the coast, followed by onshore incursion of ice to create ice damned lakes and final retreat of this lobe of ice. The NNE-SSW trending eskers are either part of the initial inland retreat or suggest that retreat of the offshore lobe retreated both eastward and southward. A further alternative is that the eskers were formed in the zone of separation of the two ice masses rather than behind a retreating ice margin. The eskers are within the BRITICE+ database as well as in the new mapping. Therefore the author is confident that they are eskers and not moraine ridges that have been misinterpreted. Alternatively, our model of esker genesis is wrong and eskers represent material deposited at junction between two separating ice masses. Arguably, this may be the more common scenario.

9.4 Summary

For the first time a systematic analysis of evidence for the whole of Britain has been conducted yielding a pattern of ice retreat. This analysis was based on 5 different lines of evidence (moraines, lateral meltwater channels, eskers, glaciolacustrine deposits, and time-transgressive retreat flowsets) and the widespread agreement between these provides a corroboratory reassurance that the final synthesis is robust. It is clear that ice retreated back to multiple regional ice centres, and final retreat was controlled by topography as the ice sheet thinned and topographic highs were exposed. This pattern of retreat is the reversal of the instantaneous glacierization model of ice sheet inception (Andrews and Barry, 1978).

Ice often retreated by lowland lobes. Lobes of ice emanating from the primary ice centres of the ice sheet were often deflected by second order regional divides or cold based ice domes. The retreat pattern presented describes retreat by several large lobes around and towards a number of regional ice centres. On the basis of the lack of warm-based retreat evidence (i.e. *TT retreat* flowsets and eskers) in Wales and the Cheviots, it is postulated that these areas supported cold based ice during retreat. In general the five lines of evidence are mutually corroborative, however some discrepancies do occur. Many of the conflicts described above occur in locations between two ice centres. These locations may document the interaction of ice flow out of the two divides and changes due to changing relative dominance of the two ice centres during the glaciation. In the case of the northern flanks of the Southern Uplands and the NE Buchan coast the esker patterns are difficult to integrate with other lines of evidence. This may suggest that the reconstruction of margins perpendicular to esker direction is incorrect. Instead eskers may occur during unzipping of ice masses. There is no new evidence for large scale readvances of the ice margin, only minor oscillations of the margin of the order of 10s km.

The retreat pattern presented in this chapter is based on newly mapped and existing geomorphological *evidence*. The summary retreat pattern is the best explanation that can accommodate what we see in the landscape. The reconstruction has been achieved at a landscape, or ice sheet scale, and is not intended to replace detailed local scale reconstructions of the retreat pattern where they have been achieved. Instead, the reconstruction should serve as a framework in which to set such studies. Locations of problematic or conflicting evidence have been flagged for further attention (section 9.3.3). There is little insight into the part of the retreat pattern that presently lies offshore. This project has focused on the terrestrial glacial evidence. Recent examinations of bathymetric data suggests that there is a wealth of information yet to be incorporated (Graham, 2007; Bradwell et al., 2008b) The reconstruction presented in Map 5 is consistent with the interpretations of Bradwell et al. (2008b). The lack of information on retreat from the offshore part of the ice sheet is problematic in the southern North Sea, North Channel and Irish Sea. In the case of the southern North Sea, one scenario is that ice retreated from the NE coast of England to the NNW towards the Tweed and Southern Scotland. Alternatively, ice retreated in a NE direction towards the Southern North Sea.

Chapter 10
Dating constraints and application to the reconstructed retreat pattern

10.1 Introduction

The previous chapter presented absolute *pattern* of retreat reconstructed from glacial landform evidence without any reference to chronology. It was noted that it was difficult to join up the pattern spatially and across blank areas. To connect the reconstructed margins and relate the retreat pattern to climate changes and the behaviour of other ice sheets during the last glacial we need to attach an absolute chronology. In order to do this it was first of all necessary to collate a database of all of the published absolute dates that relate to the last British Ice Sheet since there is no published database of chronological evidence along the lines of the BRITICE database of geomorphological evidence. This chapter details the compilation process, presents the resulting database, and describes how the dates were incorporated with the retreat pattern synthesis of chapter 9, to produce a timed framework of ice sheet deglaciation. All ages referred to in this chapter (and thesis) are calendar ages unless documented with the suffix ^{14}C yr BP.

10.2 Database of published absolute dates

It is difficult to confidently associate ice sheet events reconstructed from terrestrial geomorphology with the high resolution events recorded in marine and ice cores due to our inability to date subglacial landforms (figure 10.1b), the imprecision of dating methods, and uncertainty regarding the mechanisms controlling interactions between ice sheets and climate. Absolute deglaciation dates do however provide a means to correlate spatially distant parts of the pattern of retreat of the ice sheet and investigate the phasing of retreat in different sectors of the ice sheet. As a result of the dating methods currently available to us, the majority of absolute dates relate to ice free conditions, i.e. they are minimum dates for ice sheet retreat or maximum dates for ice sheet advance, and thus bracket the time period that the ice sheet existed in any particular area (figure 10.1a). Minimum dates for deglaciation of ice in (and maximum dates for advance of ice over) a particular area are most commonly derived from radiocarbon dating of organic sediments overlying (or underlying) till or moraines. Such dates define a relatively crude bracket for glaciation due to the lag time involved between ice melt and vegetation succession. Cosmogenic isotope exposure dating has been used to date moraine surfaces and luminescence dating has been attempted for glaciofluvial outwash sediments and loess. These dates provide a more direct means of dating the ice sheet margin but tend to have high associated errors, often of the order of 1000s of years.

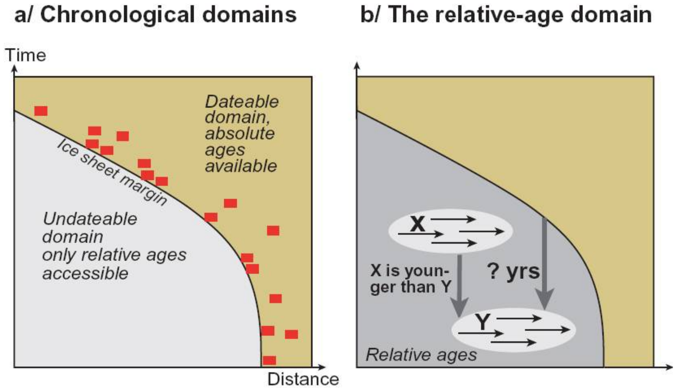


Figure 10.1 Conceptual diagrams of how we can incorporate chronological information into ice sheet reconstructions: a) absolute dates from radiocarbon, luminescence, cosmogenic surface exposure and other dating methods can only date the absence of ice, i.e. events that occur before ice sheet build up or after ice sheet retreat. We can examine the spatial pattern of dates and attempt to attach ages to the reconstructed margin positions; b) relative age information from superimposed landforms and sediment stratigraphies. Reproduced in part from Kleman et al. (2006).

10.2.1 Compilation of the database

A thorough search of the published literature and online lists for dates, relating to the advance and retreat of the last British Ice Sheet was undertaken, the results of which are presented in table A1 in the appendix. Dates were derived primarily from review papers (Sissons, 1967; Andersen, 1981; Sutherland, 1984; Sugden, 1986; Jones and Keen, 1993; Bowen, 1999a; Knight, 2001; Bowen et al., 2002; Evans et al., 2005). It is acknowledged that the search was not exhaustive and it is likely that some dates will have been missed. The search was extended beyond the Quaternary glaciological literature in order to capture a larger number of relevant dates. For example, the online date list of the Council for British Archaeology (CBA) 'Archaeological Site Index to Radiocarbon Dates for Great Britain and Ireland' was obtained in full from The Archaeology Data Service based in York (CBA, 2000 (updated 2008)). Also used was the Oxford University Radiocarbon Laboratory date list (ORAU, 2008), often to check OS grid references. A full search of this date list was not undertaken as the structure of the archive did not facilitate fast searching for multiple references. The cut off point for collection was February 2008, and so dates published after this are not included in the database. During collation of this database I have been made aware of two independent attempts to conduct a similar collection of dates from the literature (By R. Chiverell, pers. comm. and by R. Gyllencreutz, pers. comm.). Neither of these date compilations were available at the time of writing.

Where available the OS grid reference, material dated, stratigraphic position of the sample, method of dating, and pertinent comments made by the authors were recorded. Unfortunately many of the dates derived from the CBA date list contain little or no information on the stratigraphic position of the sampled material. Most of these dates are from archaeological artefacts and bone found in caves, and therefore constrain the approximate date that the cave was occupied. So, although they do not have complete stratigraphical information, where the sites lie within or close to the limit of the glaciated area, they can still provide minimum dates for when an area became deglaciated enough to allow human occupation, and maximum dates for the onset of glacial conditions that prevented settlement. Errors are presented as published, generally to one standard deviation of the mean. Where OS grid references were not given, common in review papers, reference was made back to the original source material to obtain the OS grid reference. There was some degree of variability in reporting of OS references, sometimes full 10 figure references given, but more often 6 figure references. In some cases, especially for offshore dates, Lat/Long grid references were provided. In order to turn the dates table into a GIS layer of site locations lat/long references were converted into OS grid using the online conversion sites: http://www.nearby.org.uk/conversion.cgi and http://gps.ordnancesurvey.co.uk/etrs89geo_natgrid.asp. Manual location of points was necessary for dates where no geographic location information was provided or the published reference was incorrect. In such instances published maps detailing the location of dated sites were scanned, geo-corrected and the location points digitised. This is an imprecise method as it is dependent on the scale of the map and the quality of geo-referencing information provided with it. It is estimated that the error due to misplacement of dated sites is in the order of 1 km and therefore unlikely to be problematic in consideration of reconstruction at the scale of the ice sheet. From over 50 papers and the two databases examined, 426 dates from a total of 198 locations were found and are enclosed in the database (figure 10.2 and table A1). Dates in table A1 are listed in numerical order by site number; with the exception of site 11 and sites 192-198, sites are numbered from south to north, i.e. site 1 is on the Scilly Isles and site 191 in the northern North Sea.

10.2.2 Calibration of radiocarbon dates

Dates are from a variety of dating methods, but primarily radiocarbon analysis. Of 426 dates, 323 are from radiocarbon dating (both AMS and conventional methods). All radiocarbon dates require calibration to calendar ages before they can be considered alongside absolute dates derived by other methods. It is beyond the scope of this thesis to go into the detail of radiocarbon calibration and the problems and inaccuracies of radiocarbon dating. For an examination of the issues the reader is referred to (Guilderson et al., 2005). Calibration to 12,420 years BP is regarded as being relatively secure on the basis of tree ring data (Reimer et al., 2004). Beyond this point there are a variety of calibration curves available to choose from derived from a number of different calibration datasets. In general, the intra-curve errors and inter-curve discrepancies increase towards the limit of radiocarbon dating at around 50 ka BP. Detailed discussion of the differences between the available calibration curves is documented in (van der Plicht et al., 2004).

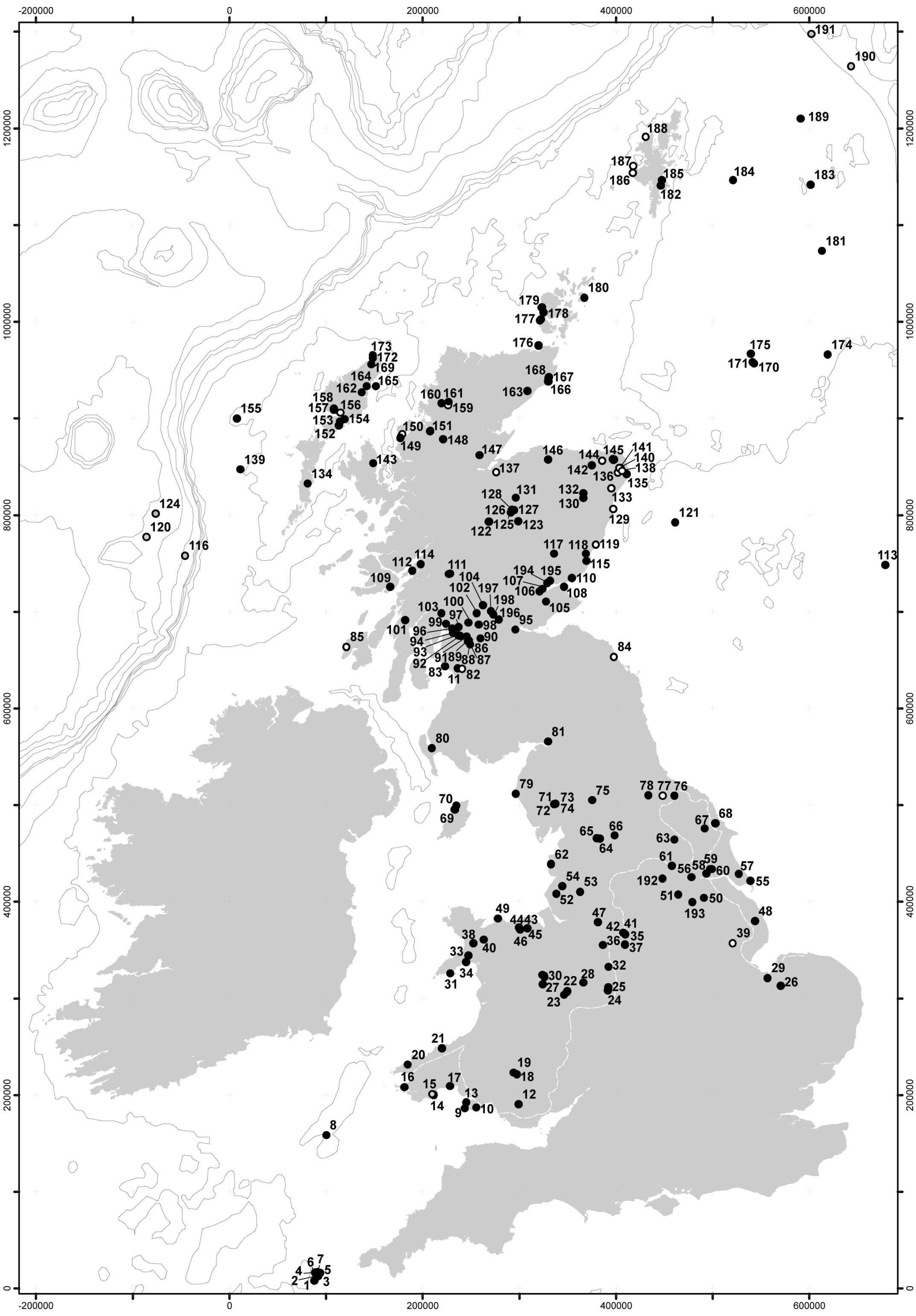


Figure 10.2 Sites contained within database of dates relating to the last British Ice Sheet compiled from published literature. Full details are given in table A1. All date locations are shown. Solid dots mark locations where dates have been used in further analysis. Dots with a white centre show locations where all dates at that site are regarded as unreliable or questionable and are therefore not used in subsequent analysis (see table A1 for details). Dots with grey centres are regarded as reliable but were not used in further statistical analysis as lie beyond the maximum limits of the British Ice Sheet, e.g. 190 and 191 relate to events associated with the Scandinavian Ice Sheet and sites 116, 124 and 120 on the Barra Fan. These dates provide useful contextual information about the ice sheet chronology.

All radiocarbon dates were calibrated using the calibration curve described in Fairbanks et al. (2005) and the associated online calibration programme at http://radiocarbon.1deo.columbia.edu/research/radiocarbon.htm. This calibration curve extends to 55 ka BP and was selected as it enabled the same calibration curve to be used for all the radiocarbon dates spanning the growth and decline of the ice sheet, approximately 32-13 cal. ka BP. A local marine reservoir correction of 347 years was applied to all marine samples. This correction value was obtained as an average for UK waters from the Marine Radiocarbon Correction Database at http://calib.qub.ac.uk/marine/ (table 10.1). This is an oversimplification as the reservoir effect is known to have varied during the deglaciation (Voelker et al., 1998).

Table 10.1 Reservoir age determinations used to find a mean average local reservoir age value to apply to marine radiocarbon samples. Determinations taken from CHRONO Marine Reservoir Database at http://calib.qub.ac.uk/marine/index.php (Reimer and Reimer, 2001).

Latitude	Longitude	Locality	Reference	Reservoir Age	Reservoir error
55.97	-3.15	Leith	Harkness 1983	396	58
54.17	-5.00	Isle of Man	Harkness 1983	346	47
54.17	-5.00	Isle of Man	Harkness 1983	397	64
55.83	-6.00	Firth of Clyde	Harkness 1983	302	46
55.83	-6.00	Firth of Clyde	Harkness 1983	293	52
57.83	-5.33	Loch Broom	Harkness 1983	372	30
57.83	-5.33	Loch Broom	Harkness 1983	456	35
59.55	-1.63	Fair Isle	Harkness 1983	402	30
59.55	-1.63	Fair Isle	Harkness 1983	449	31
55.87	-4.93	Skelmorlie Bank	Harkness 1983	214	42
55.87	-4.93	Skelmorlie Bank	Harkness 1983	200	54
55.87	-4.93	Skelmorlie Bank	Harkness 1983	297	80
55.73	-4.88	Hunterston Sands	Harkness 1983	395	38
55.73	-4.88	Hunterston Sands	Harkness 1983	409	33
55.97	-2.92	Seton Sands	Harkness 1983	376	32
55.97	-2.92	Seton Sands	Harkness 1983	283	41
53.25	-4.50	Anglesey	Harkness 1983	303	50
55.00	-5.00	Castle Rock, North Channel	Harkness 1983	347	50
			Mean	**347**	**45**

Use of the Fairbanks calibration curve is largely a pragmatic choice. The internationally agreed calibration curves INTCAL04 (Reimer et al., 2004) and MARINE04 (Hughen et al., 2004) can only calibrate to 26 cal. ka BP. An alternative would have been to calibrate using the INTCAL04 and MARINE04 curves, as appropriate for each date, to the limit of these curves at c. 26 ka BP and continued with the Fairbanks curve for the remainder, noting the offset at the point of change. However, it was decided that the advantages of such an approach were outweighed by the benefits of using the same calibration curve for all dates, thus creating an internally consistent database. A simple comparison was made to assess the implications of using the Fairbanks calibration and online calibration tool as opposed to the INTCAL04 curve and the CALIB programme. In general, the calibrated dates were within +/-300 years of each other which seems reasonable in comparison to the error margins associated with the dates. The Fairbanks calibrated dates were generally younger than the INTCAL04 dates except during the period 13-15 ^{14}C ka BP, when the largest divergence of the dates also occurred.

Seven dates were unable to be calibrated as they were either out of range of the calibration curve or no error margins were specified. The calibrated ages and original radiocarbon ages are presented in table A1 in the Appendix.

10.2.3 A note on the reliability of dates

During compilation of the database, no discrimination was made on the quality or reliability of dates. However, not all of the dates were used in further analysis. Dates were rejected where the author indicates that the age may be unreliable, or where subsequent dating at the same site has suggested to subsequent observers that a date is unreliable, and where calibration of radiocarbon dates was not possible. Rejected dates and reasons for rejection are documented in table A1. Common reasons for rejection were: contamination of radiocarbon dates, incomplete resetting of luminescence dates, signal inheritance of cosmogenic surface exposure dates, or unreasonably large error margins. Of the 427 dates, 127 are rejected and are therefore not considered in further analysis. Of the rejected dates 79 are from radiocarbon dating, 18 from luminescence dating, 4 from Uranium series dating, and 20 cosmogenic dates. For simplicity, the assumption of zero erosion was taken for cosmogenic dates when there was a choice. However, it is acknowledged that this is likely to be an unreasonable assumption in the context of a history of glacial erosion and deposition. Where there are multiple dates at a single location, it is common in cosmogenic exposure dating to take the oldest date as the most reliable (Phillips et al., 2008). However, some studies use a weighted average of the ages especially where ages occur in a cluster (Everest and Kubik, 2006). Each individual date is presented in table A1. A further 23 dates in the database were not used in analysis, as they lie beyond the limits of the glaciated area. These dates provide a useful context for glacial activity but do not constrain the ice sheet directly and are therefore excluded. These sites are 120, 124, and 116 from cores in the Barra Fan, 190 and 191 in the northern North Sea, and 14 and 15 from cave sites in South Wales (figure 10.2). Figure 10.3 shows the ages plotted against site numbers and coloured to show the method of dating. In general dates derived from luminescence and cosmogenic surface exposure dating have the largest associated error margins.

10.2.4 Classification of dates

In order to derive glaciological meaning from the database, dates were classified following the procedure of Bryson et al. (1969) into the following categories: *advance, deglacial, margin,* and *ice free*. *Advance* dates indicate that ice cover of the location occurred after this time, therefore constraining the advance of the ice sheet. Commonly these are ages derived from radiocarbon dating of organic material buried beneath, or incorporated within, glacial deposits. *Deglacial* dates indicate ice free conditions at the location beginning before this time. These are commonly ages derived from radiocarbon dating of organic material or post-glacial sediments overlying till. Where an age was derived from organics or sand sandwiched between two tills the date was classified as an *advance* date in reference to the upper till as it is the most recent, but it is noted that this date could also be a *deglacial* date for the lower till. It is also possible that such dates constrain an oscillation of the ice margin rather than the initial build up of the ice sheet.

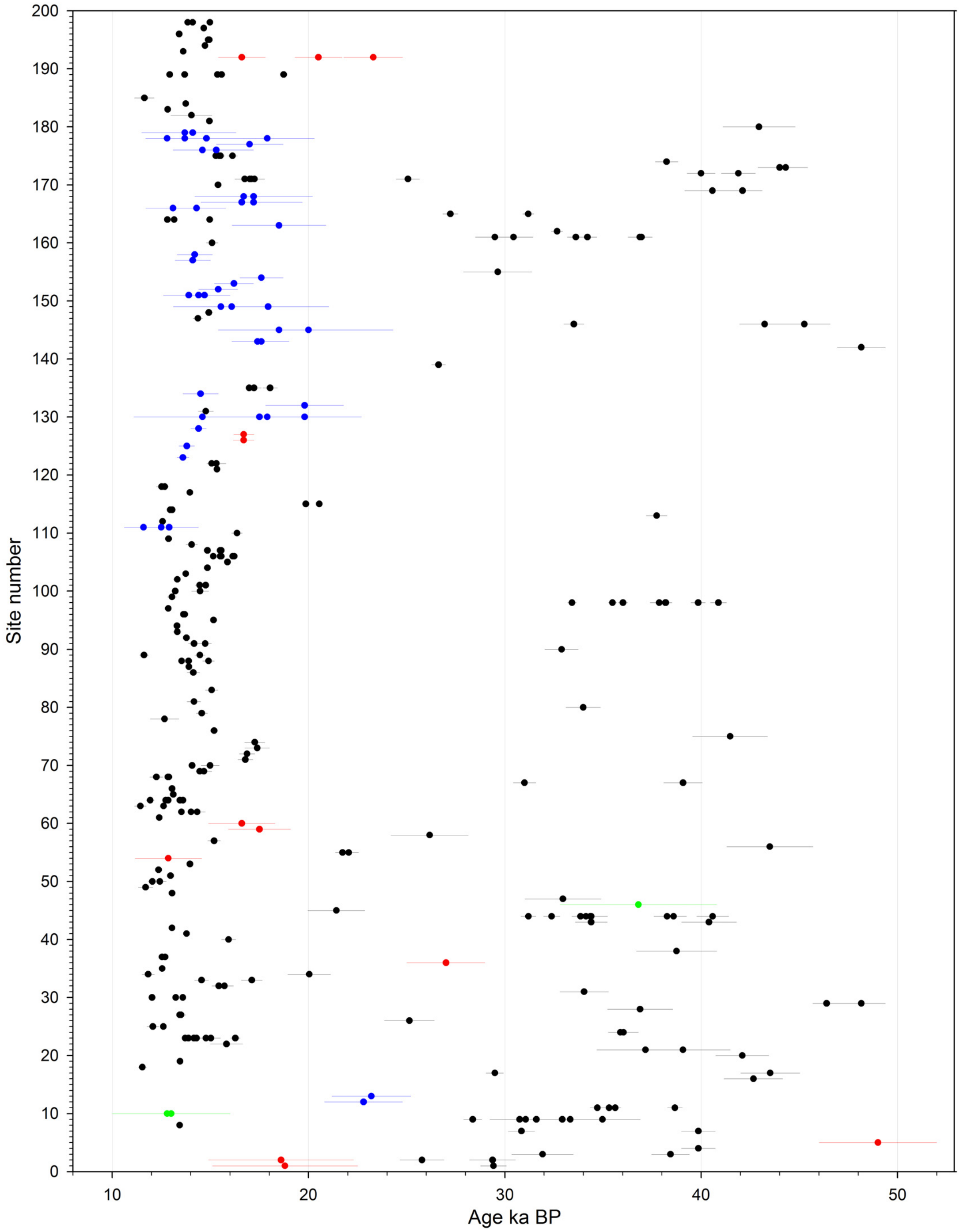


Figure 10.3 Dates plotted by site number and coloured to reflect method of dating in order to show the abundance of each dating method and differences in associated error margins. The majority of dates are from radiocarbon analysis (black). Radiocarbon dates span the full range of the time period of interest (50-10 ka BP). Cosmogenic (blue) and luminescence (red) dates have much larger error bars. Cosmogenic dates are surface exposure ages and therefore only span the last 22 ka. There are only a few dates from U series analysis (green) and these have large associated error bars.

A date from beneath the lower till would be necessary to confirm this. A *margin* date is where there is reason to consider that the ice margin is close by the site at the time. For example, a cosmogenic exposure age of the surface of a boulder on a moraine crest, or a date constraining sediment deposition assumed contemporaneous with a till deposition. *Ice free* dates are ages for ice free (or non-glacial) conditions at the site where there is no stratigraphical information for the sample. These are mainly from archaeological samples, the majority of which are from cave settings, which indicate ice free conditions by the assumption that viable human or animal occupation of a cave will only occur when the cave is some distance from the ice margin. Similarly, speleothem growth can only occur when the ground above the cave is unglaciated, so speleothem dates are also part of the ice free category. Dates from marine settings documenting glaciomarine conditions are also considered to be *ice free*. *Ice free* dates bracket the time period that a site experienced ice cover. Categories are listed for all dates regarded as reliable and useful in table A1.

Of the 306 classified dates 179 are *deglacial*, 9 are *margin*, 53 are *ice free*, and 65 are *advance*. Figure 10.4a is a histogram of the classified dates to show the distribution of ages over the time period of interest (10-50 ka BP). Figure 10.4b shows the histogram with the proportion of ages attributed to each category. Figure 10.5 shows the individual histograms and geographical distribution of each date category. The distribution of each category is discussed in the following section (10.2.5).

10.2.5 Investigating the database

Before applying the ages to the reconstructed retreat pattern, it was thought fruitful to examine if any spatial patterns could be recognised in the dates alone. *Ice free* dates neatly frame the glacial period as occurring between 26 and 18 ka BP (figures 10.4b and 10.5d). There are very few *margin* dates; one occurring before 22 ka BP and the rest occurring in a cluster between 13-18 ka BP (figures 10.4b and 10.5b). *Deglacial* dates are confined to 26-11 ka BP (figure 10.5a). Therefore sections of the ice sheet were in retreat before the global LGM (23-21 ka BP). There are significant increases in the number of *deglacial* dates at 18 ka and 15 ka BP. Figure 10.4b demonstrates that there is an overlap in time between *advance* and *deglacial* dates. Deglaciation of some parts of the ice sheet appears to have begun (figure 10.5a) while other parts of the country were yet to be glaciated. In a situation of monotonic advance/retreat of ice from a single start/end point we would expect a clear separation of *deglacial* and *advance* ages. The overlap suggests that (a) the maximum spatial extent of the ice sheet was reached at different times at different parts of the margin and/or (b) retreat was interrupted by oscillations of the ice sheet margin, i.e. some *advance* dates are really re-*advance* dates.

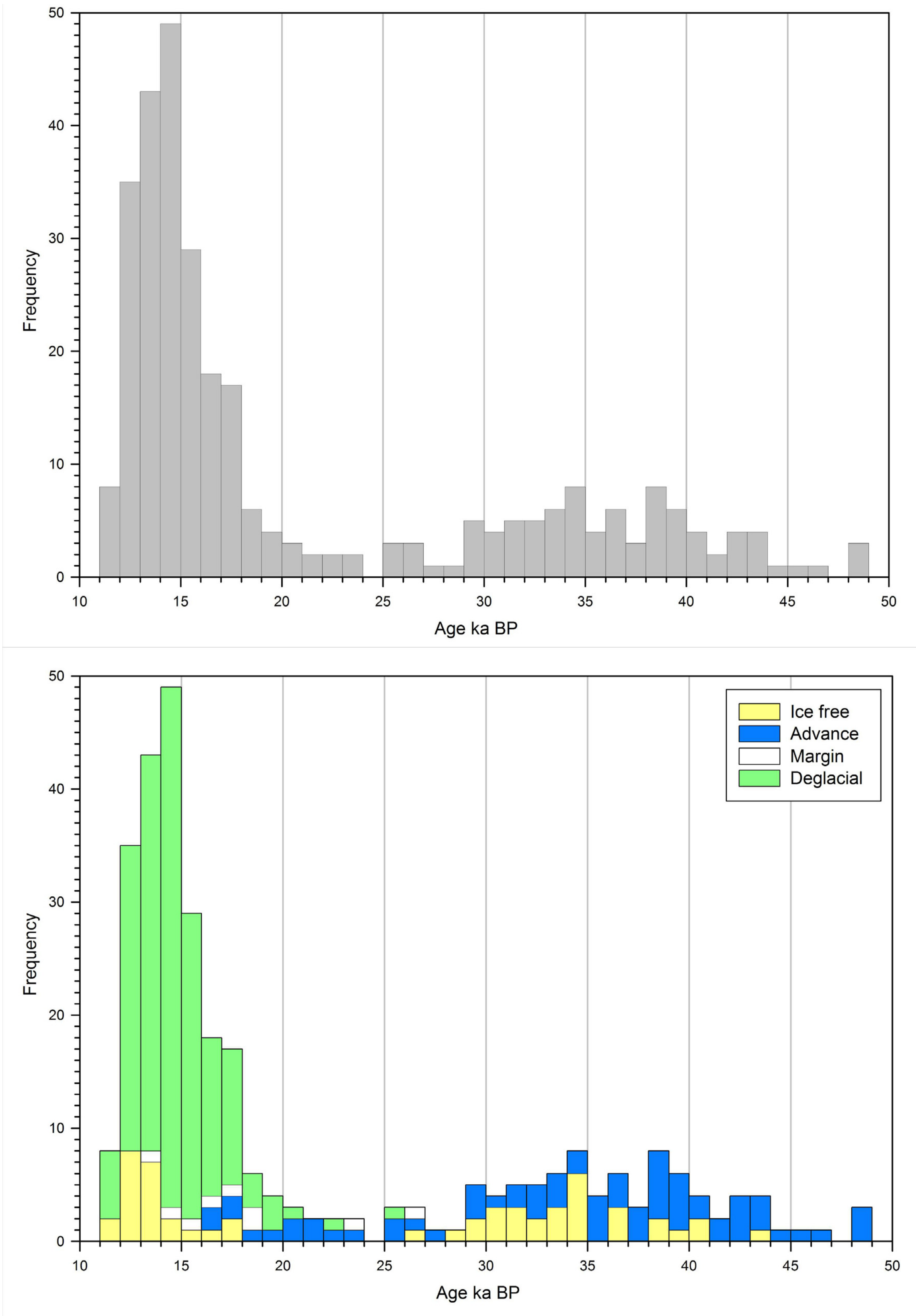


Figure 10.4 Histogram of absolute ages relating to the last British Ice Sheet to show distribution (upper figure). Unreliable and context dates excluded, see text for details (N = 306). Stacked histogram of dates to show class distributions (lower figure). Over half of the dates are classed as *deglacial* (59 %). The overlap between *advance* and *deglacial* dates (26-16 ka BP) suggests that the build up and retreat of the ice sheet was spatially variable. Either sectors of the ice sheet are in retreat while other areas were yet to be glaciated, or some of the *advance* dates are really *re-advance* dates. *Ice free* dates neatly frame the operation of the ice sheet to between 26 and 18 ka BP. It is suggested that *margin* dates older than 23 ka BP relate to maximum limits and the rest to deglacial margin positions. The stacked histogram is shown 'exploded' in figure 10.5.

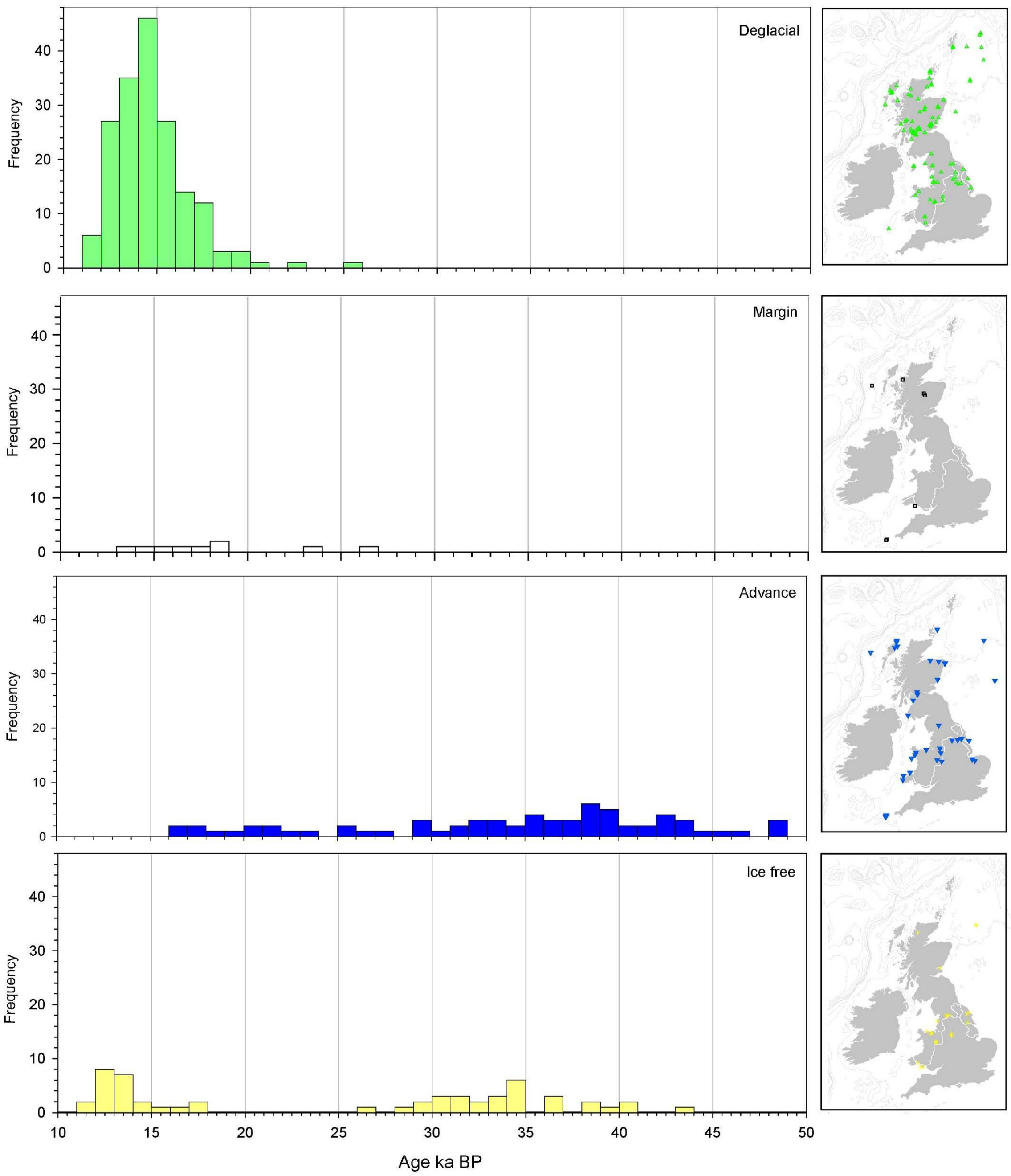


Figure 10.5 Histograms of absolute ages organised by classification and maps of distribution of dates by type: a) deglacial; b) margin; c) advance; and d) ice free

In order to examine these two possibilities we need to consider the spatial distribution of dates. For clarity, the distribution of dates is shown on two maps; figure 10.6 shows the *advance*, *margin* and 'old' (>26 ka BP) *ice free* dates and figure 10.7 shows the *deglacial, margin* and 'young' (<18 ka BP) *ice free* dates. For radiocarbon dates, only the youngest or oldest date is shown on the figures as appropriate, for example the youngest (most recent) age on figure 10.6 or the oldest date on figure 10.7. For dates derived from other methods all reliable ages are shown.

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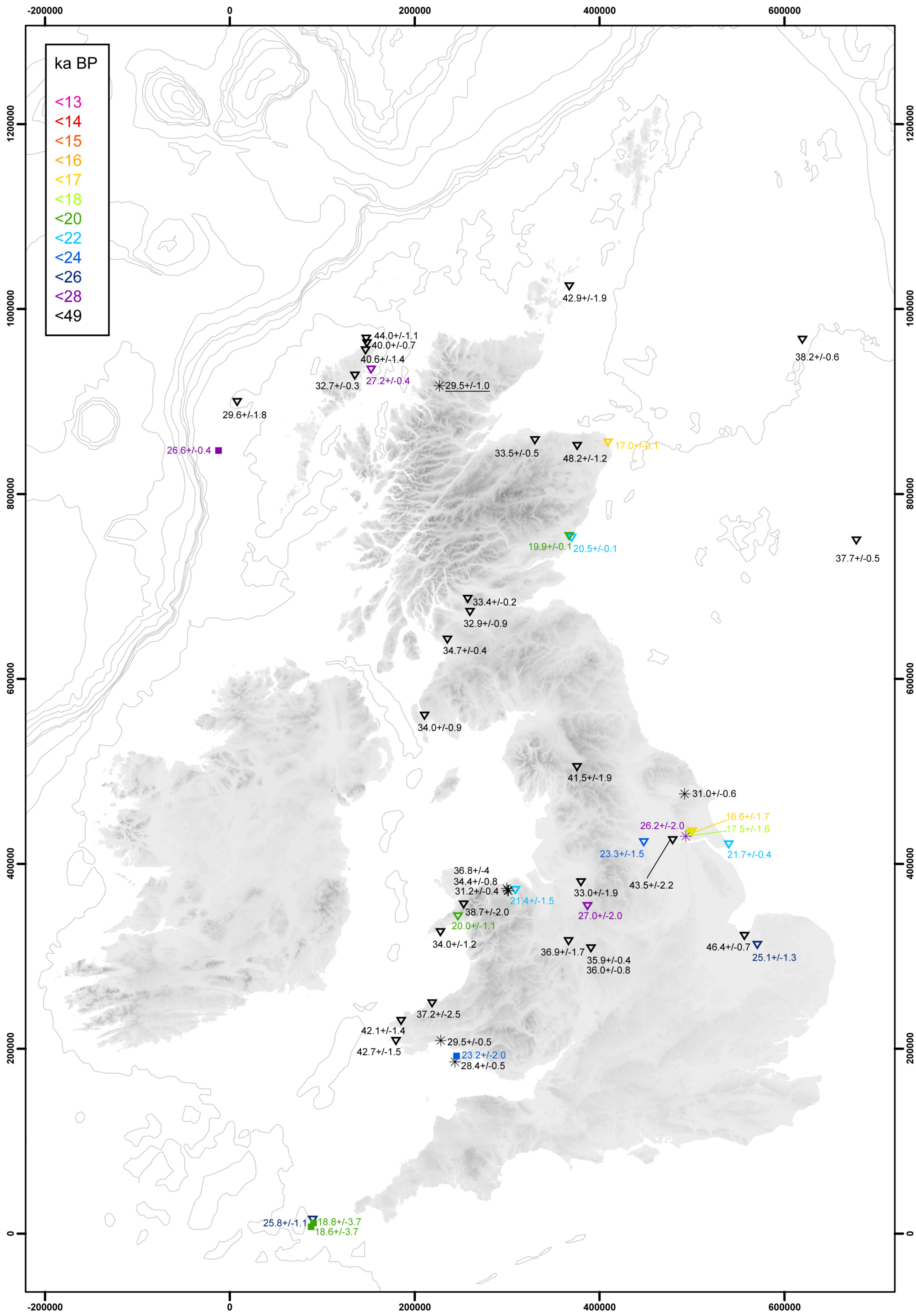

Figure 10.6 Distribution of ages relating to advance (build up) of the ice sheet. No clear pattern emerges from the dates. *Advance* (downward pointing triangle), *margin* (square) and 'old' (older than 26 ka BP) *ice free* dates (asterisk). Only the youngest dates are shown where there are multiple radiocarbon dates at a site. Dates are coloured by time bracket (see key). There are several anomalously young advance dates that stand out on the map: 20.0 ka on the Lleyn Peninsula (site 34), 21.4 ka in the Vale of Clwydd (site 45), 21.7 ka at Dimlington on the east coast (site 55), 17.5 and 16.6 ka on the Lincolnshire Wolds dip slope (sites 59 and 60), 17 ka BP at St Fergus (site 135) and 19.9 and 20.5 ka on the eastern coast of Scotland (site 115). These are anomalously young for their location and in comparison to neighbouring dates. The significance of this is discussed further in the text. The underlined date from northern Scotland is regarded as unreliable by Bradwell et al (2008b).

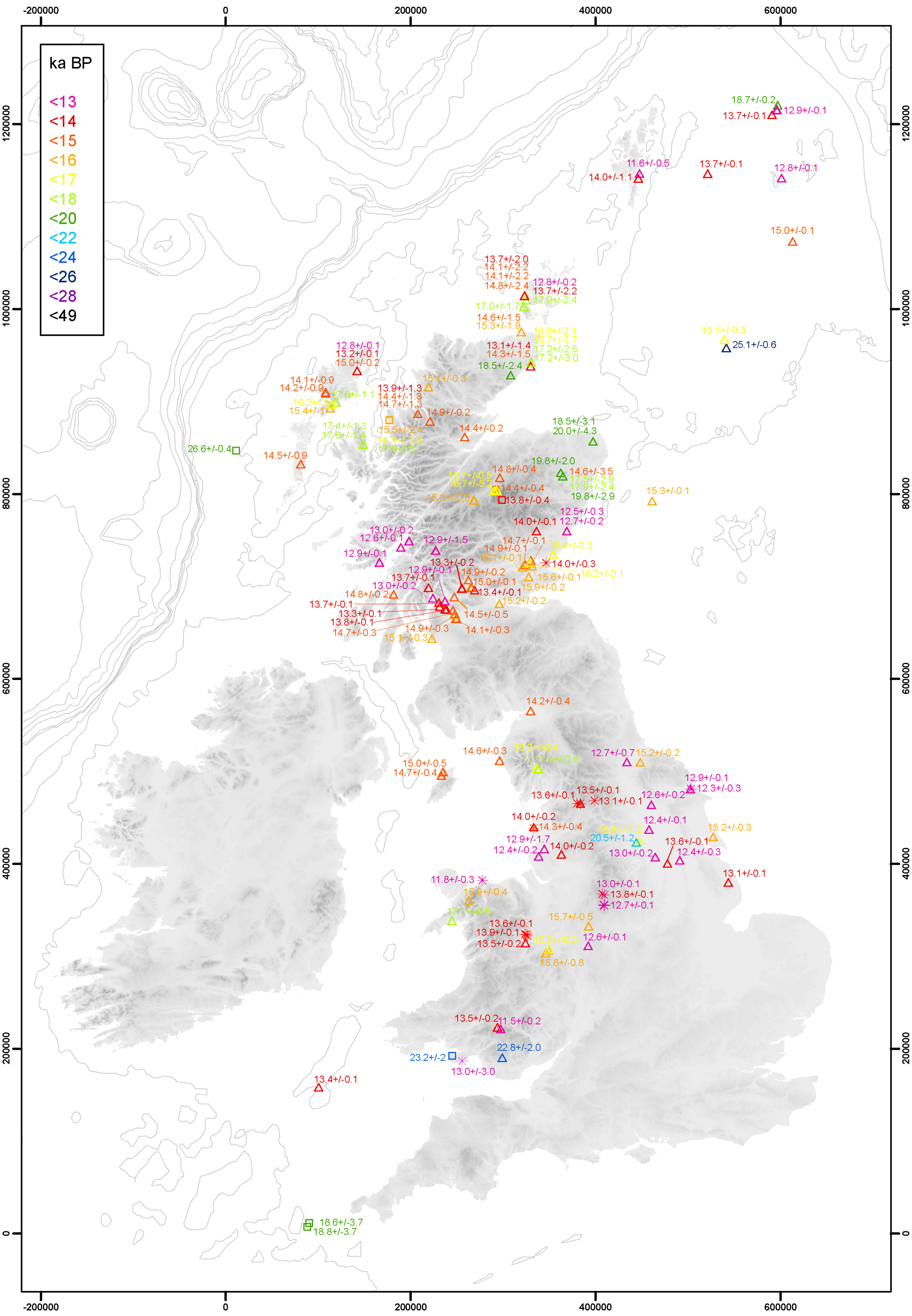

Figure 10.7 Distribution of ages relating to deglaciation of last British Ice Sheet. *Deglacial* (upward pointing triangle), *margin* (square) and ‘young’ (younger than 18 ka BP) *ice free* (asterisk) dates. Only the oldest date is shown for *deglacial* dates where there are multiple radiocarbon dates. All determinations are given where a different dating method has been used. Dates are coloured up by age bracket (see key). No clear pattern emerges from the dates. NE Scotland appears to have been deglaciated as early as 20 ka BP. The Lake District stands out as anomalous in comparison with neighbouring areas the dates suggesting ice free conditions as early as 17 ka BP. The northern North Sea was the first area to be deglaciated, with the date suggesting that coalescence of the British and Scandinavian ice sheets occurred before 25.1 ka BP. According to the dates shown in figure 10.6 this is before ice reaches the eastern English coast and the maximum limit in on the Scilly Isles.

The majority of dates relate to the absence of ice. If there were a large enough number of dates we would expect that the dates constraining ice sheet build up (*advance* and 'old', i.e. >26 ka BP *ice free* ages), bearing in mind their maximum nature, would form an envelope of time constraining the nucleation centres of the ice sheet, the oldest dates closest to the site of ice sheet build up and the youngest dates closest to the maximum limits. Likewise, if the ice sheet retreated back to a single point we would expect that sites furthest from the limit would derive the oldest and greatest number of deglaciation dates. Figure 10.8 shows a schematic graph to illustrate this concept. To investigate this, it was assumed that the Loch Lomond Stadial limit in Scotland is analogous to both the initial stages and final position of the Devensian ice sheet.

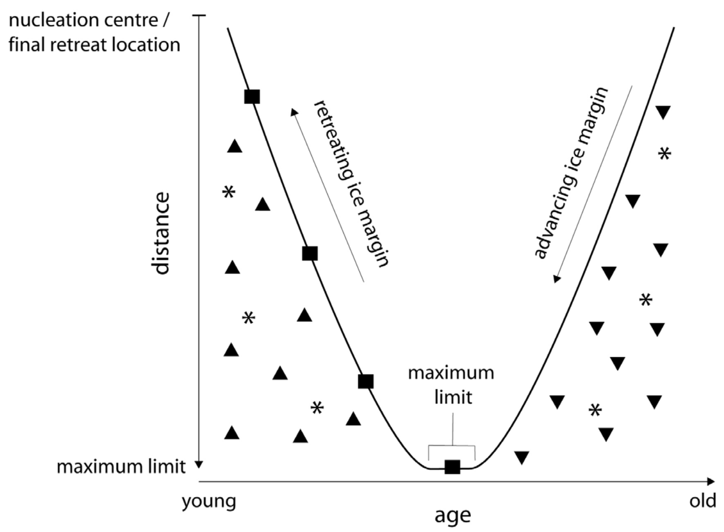

Figure 10.8 Schematic diagram to show hypothetical distribution of dates from a single nucleation point/retreat position. Maximum/minimum dates form a cloud of points that frames the build up/retreat of the ice mass. *Margin* dates (square) plot on the line. *Ice free* dates (asterisk), *advance* (downward pointing triangle) and *deglacial* (upward pointing triangle) plot below the line.

The *advance*, *margin,* and 'old' (>26 ka BP) *ice free* dates were plotted against distance from the Loch Lomond Stadial Limit in Scotland (figure 10.9). Figure 10.9 does not appear to show a clear relationship between distance from the Loch Lomond limit and age. Therefore advancement of the ice margin does not occur progressively from Highland Scotland. This likely supports the concept of multiple ice nucleation centres for the last British Ice Sheet. Alternatively, there are too few dates for a pattern to emerge. The *advance* dates from two sites (115 and 135), circled by a dotted line in figure 10.9a stand out from the rest of the data points as anomalously young (20.5, 19.9 and 17.0 ka BP). It is suggested that these dates are *re*-advance dates and reflect an oscillation of the ice margin during deglaciation, not the initial incursion of ice. The location of these dates within the maximum limits of the last ice sheet close to the eastern Scottish coast (figure 10.7c) supports this interpretation. Dates from site 115 have been used by McCabe et al. (2007) to propose a re-advance of the last British Ice sheet into the Tay estuary after 20 ka BP. The margin dates from sites 149, 125 and 128 (marked with a circle on figure 10.9a) also appear anomalously young. The location of these ages supports the interpretation of these dates as positions during retreat of the ice sheet (figure 10.7c).

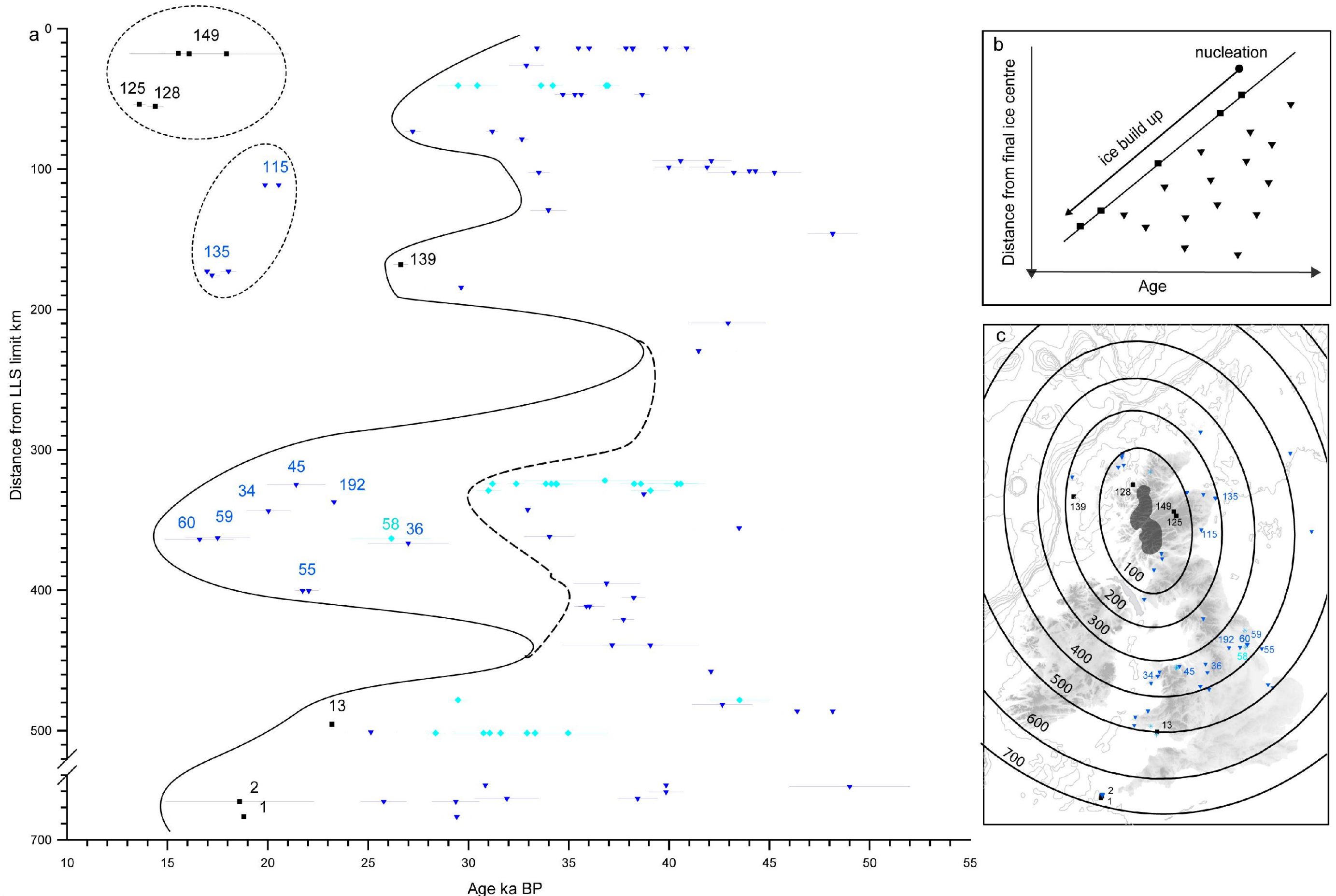

Figure 10.9 Plot of *advance* (dark blue), *ice free* (light blue), and *margin* (black) ages against distance from Loch Lomond Stadial (LLS) ice cap extent (a). If we assume that the LLS limit is equivalent to the initial stages of the last BIS we would expect the ages to form an envelope with the youngest ages furthest from the limit. Margin dates (square) should sit on the line (b). Location of dates and concentric distances from LLS limit edge (c). The plotted dates (a) do not resemble the hypothetical graph shown in (b). One explanation of this is that there are insufficient data points. Another is that some of the dates are not related to the initial build up of ice but to a re-advance or oscillation of the margin during retreat. Two sites (circled and labelled with the site number) clearly stand out from the rest of the data cloud. Their position suggests that they are re-advance dates and represent an oscillation of the ice margin. The dashed line is an alternative position for the build up of the ice sheet where the sites to the left of the line are regarded as re-advance dates. The re-advance status of these dates is more equivocal. The five margin dates also circled are likely retreat margin positions rather than maximum limits so should be ignored in the graph. Their location is marked on (c). A third explanation for the dissimilarity of plot (a) to figure (b) is that the nucleation point for the last BIS was not analogous to the LLS limit, and/or the ice sheet developed from a number of spatially separate locations.

The other margin dates (sites 1, 2, 13 and 139) are located close to the maximum limits. A third group of dates also stands out on the graph as anomalously young (< 25 ka BP) in comparison to other dates a similar distance from the Loch Lomond limit (bounded by the solid and dashed lines; figure 10.9a). These dates are located in North Wales (sites 45 and 34; 21.4 and 20.0 ka BP respectively) and eastern England (sites 59, 60, 55 and 192; 17.5, 16.6, 21.7 and 22.0, and 23.3 ka BP respectively) (figure 10.9c). If these dates are not taken as re-advance ages they imply that the southern limits of the last British Ice Sheet were reached after the maximum limits in the north.

Deglacial, margin and 'young' (<18 ka BP) *ice free* dates were also plotted against distance from the Loch Lomond Stadial limit (figure 10.10). The dates do not form a cloud of points with the oldest dates furthest away. This suggests that the ice sheet did not retreat to a single point analogous to the Loch Lomond Stadial limit. On the basis of the time-distance retreat patterns in figure 10.8a it is suggested that ice retreated to three locations at a distance of 430, 250 and 0 m away from the Loch Lomond limit. This suggests final deglaciation centres in the vicinity of central Wales, the Lake District-northern Pennines in addition to the Loch Lomond limit (figure 10.10c). Deglaciation is completed in all of these areas by c.14 ka BP.

Despite the number of dates and the reasonable distribution of dates across the country it is still difficult to draw lines connecting isochrones of ice sheet build up or retreat using figures 10.6 and 10.7. There are hints from the crude analysis above and the distribution of dates shown in figures 10.6 that the build up of the ice sheet was spatially variable and that there were oscillations of the ice margin during retreat. The ice sheet appears to have been at its maximum limits at different times in different locations. To understand the timing of retreat it is therefore necessary to consider the dates in conjunction with the pattern of retreat presented in chapter 9.

10.2.6 Context dates

Further constraint on the chronology of build up and retreat of the ice sheet is provided by dates that lie beyond the ice sheet margin. Figure 10.11 shows additional dates and chronological information that provide a context for ice sheet development. A number of marine cores from around the western continental margin constrain the timing of ice rafted debris flux from the British Ice Sheet. Ice rafted debris is a crude proxy for fluctuations in the ice sheet and the proximity of the ice margin. Collectively the ice rafted debris record of these cores frame the activity of the last British Ice Sheet to between 30-16 ka BP. Evidence from cores on the Barra Fan document peaks in ice rafted debris at 24 and 16.5 ka BP (Wilson et al., 2002). These dates from the western continental margin place major deglaciation commencing c. 17 ka BP and restriction of the ice sheet to non-marine margins by 16 ka BP.

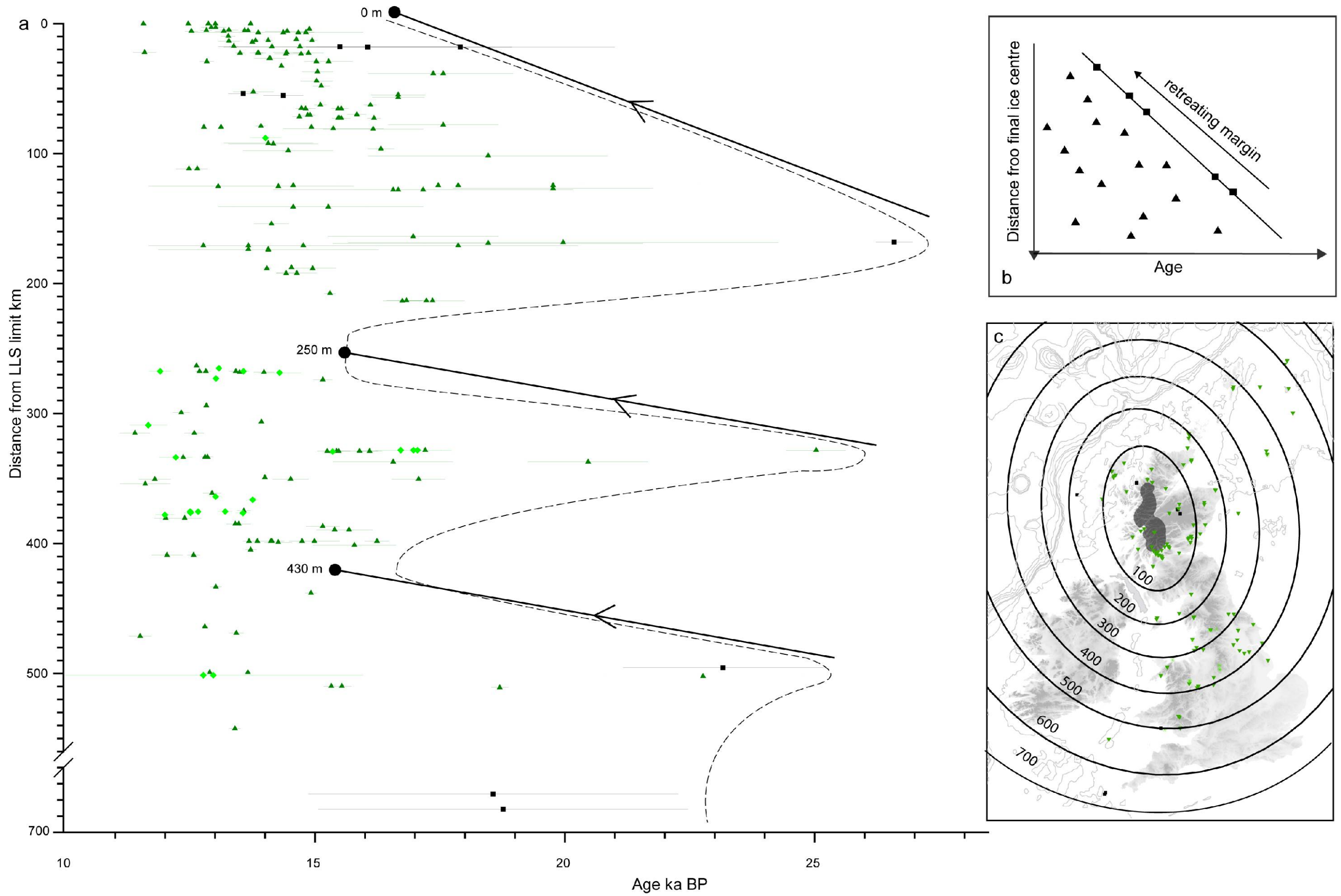

Figure 10.10 Plot of *deglacial* (dark green), *ice free* (light green), and *margin* (black) ages against distance from Loch Lomond Stadial (LLS) ice cap extent (a). If we assume that the LLS limit is equivalent to the extent of the last BIS at the end of the glacial period we would expect that the generally minimum dates for deglaciation would form a data cloud below a line with younger ages increasing in number as distance from the final ice centre decreases (b). Map showing location of dates and concentric distances from LLS limit edge (c). The plot (a) does not form a single data cloud that conforms to the hypothetical plot (b) but can be resolved into three 'mini' lines that do exhibit younger ages with decreasing distance. These are marked on the graph as arrows and suggest that the ice sheet retreats to three locations at distances of 0, 250 and 430m from the LLS limit. Areas at these distances from the LLS limit may represent final centres of the ice sheet are the Lake District and Pennines, and Wales (c).

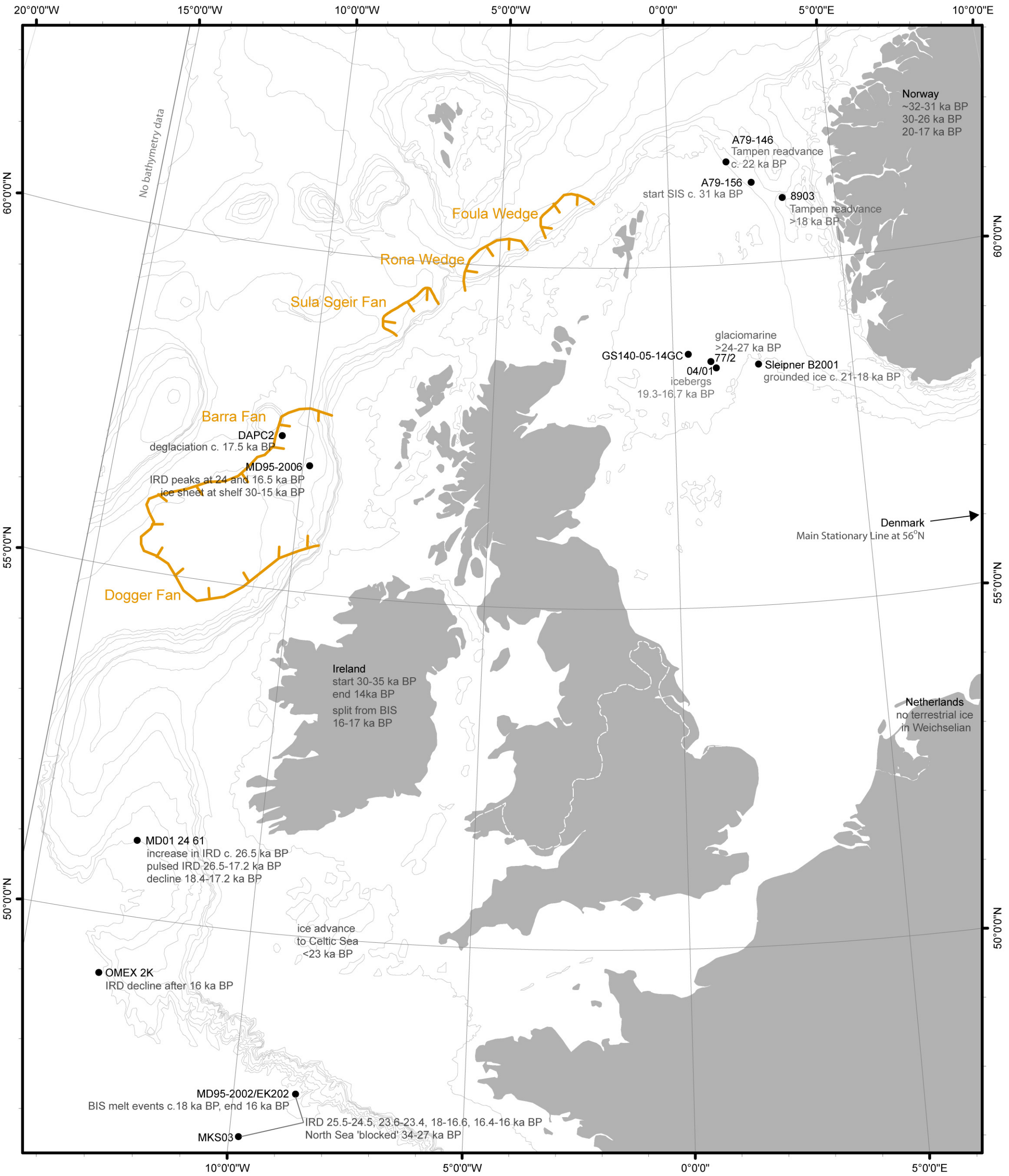

Figure 10.11 Dates that provide contextual information for the last British Ice Sheet. Information derived from a number of sources (Kroon et al., 2000; Auffret et al., 2002; Wilson et al., 2002; Carr, 2004; Houmark-Nielsen, 2004; Laban and van der Meer, 2004; Mangerud, 2004; Graham, 2007; O Cofaigh and Evans, 2007; Greenwood, 2008). The white line marks the accepted southern limit of ice in England and Wales.

The dated stratigraphy in Norway suggests a two phase glacial history with a re-advance of the Scandinavian Ice Sheet c. 21 ka BP (the Tampen readvance). A similar collation of ages for Ireland suggests that the Irish Ice Sheet built up around 35 ka BP and decoupled from the British Ice Sheet between 17 and 16 ka BP (Greenwood, 2008).

10.3 Dating the maximum limits

The maximum limits of the ice sheet appear to have been reached at different times in different locations. Although we are primarily concerned with timing the retreat of ice, before we attempt to attach ages to the reconstructed retreat pattern it is necessary to define the starting points for retreat by dating the maximum limits. The youngest 'build up' date (figure 10.9) in mainland Scotland is 29.5 ka BP (at site 161, Reindeer Cave near Inchnadamph, Assynt). Ice inundated the Minch after 27.2 ka BP (site 165, Garrabost, Lewis) presumably converging from the Outer Hebrides and Scotland, and was at the western continental margin by at least 26.6 ka BP (site 139; shelf west of St Kilda). In contrast to these dates, evidence from the Barra Fan (core MD95-2006) implies ice at the continental shelf from 30 ka BP (figure 10.11). The reliability of the reindeer bone dates from Inchnadamph have been questioned on the basis of contamination from the local carbonate geology and revised dates that have been derived from other UK faunal remains using new techniques (Bradwell et al., 2008b). Even if these dates and the date from Garrabost are rejected, a collection of dates support widespread ice free conditions in Scotland until c. 32 ka BP (figure 10.8; sites 11, 98, and 146) (Whittington and Hall, 2002). That confluence of Scandinavian and British Ice Sheets in the northern North Sea occurred before 25 ka BP is based on the *deglacial* date from site 171 suggesting commencement of glaciomarine conditions at 25.1 ka BP (figure 10.10). This is supported by evidence for fluvial input to the ocean from a site off the Celtic continental margin suggesting that the North Sea was 'blocked' between 34-27 ka BP (Auffret et al., 2002) (figure 10.11). It is assumed that confluence of ice in the North Sea was concurrent with shelf edge glaciation and therefore the North Sea date provides a minimum age for ice advance to the north-western margin. The starting point for deglaciation in the north (the continental shelf edge) is taken as 27-25 ka BP, although ice may have reached the continental shelf before this time. If this date is taken as the local maximum extent and the dates from central Scotland are accepted, the last British Ice Sheet was confluent in the North Sea for a relatively short period of time.

Ice was at the southern Welsh limit at 23 ka BP (site 13; range 25.2-21.2 ka) but may have reached the limit in Wales as early as 29.5 ka BP (site 17; range 29.0-29.9 ka) (figure 10.9). *Advance* dates from the Isles of Scilly suggest that the islands were reached after c. 25 ka BP (range 26.9-24.6 ka) (figure 10.9). This is consistent with dates from the Celtic Sea placing ice advance after 23 ka BP (figure 10.11) (O Cofaigh and Evans, 2007). Loess deposition in the south of the islands is dated to 18.6 and 18.8 ka BP (sites 1 and 2) (figure 10.9). The stratigraphy of the loess mirrors that of till in the north of the island group, supporting the deposition of the till to MIS 2 (Scourse, 2006). The loess dates are classified as *margin* dates but the actual position of the margin could be at any point north of the islands during loess deposition. An *advance* date from the Lleyn Peninsula suggests that Welsh sourced ice advanced west after 20 ka BP (site 34). This implies that the Irish Sea glacier had retreated north of the Peninsula before this time (figure 10.9). For the rest of the southern margin the picture is more complex. The youngest date for advance into the Cheshire Plain suggests that ice advanced inland here after 27 ka BP (site 36; range 29-25 ka) (figure 10.9). However, a woolly mammoth bone dated to between 20.0-22.9 ka BP (site 45) lying below Irish Sea till could be used to suggest that Irish Sea ice did not advance up the Vale of Clywdd, and potentially the Cheshire Plain, until after 21 ka BP (figure 10.9). Although this date is significantly younger than the rest of the *advance* dates in the Cheshire Plain, as maximum ages such a situation is not inconsistent with them. Alternatively, initial incursion of ice into the Vale of Clywdd was initially prevented by the presence of Welsh sourced ice, the location existed as an ice free enclave until 21 ka BP, the bone date is unreliable, or the date reflects an oscillation of the ice margin in this region around 21 ka BP. Ice advanced down the Vale of York after 23.3 ka BP (site 192; range 24.8-21.8 ka) but had retreated to north of site 192 by 20.5 ka BP (range 21.7-19.3) (figures 10.6 and 10.7). Dates from Dimlington on Holderness suggest ice did not reach the eastern English coastline until after 22 ka BP (site 55; range 22.5-21.3 ka) and dates from inland Lincolnshire suggest ice did not progress inland until after c. 17 ka BP (sites 59 and 60; range 19.1-14.9 ka). Ice at this position at this time is consistent with a recently published age for a beach deposit (16.6 ka BP, site 192; range 17.8-15.4) related to Glacial Lake Humber, the existence of which requires ice damming the Humber Gap (figure 10.9). The new date is significantly younger than the previously quoted maximum age for Lake Humber of 26.2 ka BP (site 58; range 28.1-24.2 ka). It was suggested earlier that the dates at these sites could reflect oscillations of the ice margin (figure 10.7). In the absence of *deglacial* dates preceding the 'young' *advance* dates it not possible to confirm or disprove this. If all of the above dates are accepted there are two possible interpretations:

1. Ice did not reach eastern England or the Cheshire Plain until after 17 and 21 ka BP respectively.
2. The dates reflect oscillations of the ice margin within the last glaciation. This implies advance into the Cheshire Plain after 27 ka BP. Followed by retreat to an unknown position north of Wales before 21 ka BP and a subsequent readvance south after 21 ka BP. This could reflect oscillations of the Irish Sea glacier during uncoupling with Welsh ice. In eastern England, the dates could be interpreted as advance after 25 ka BP (site 26) followed by retreat to an unknown offshore position, followed by a readvance at least as far as Dimlington after 22 ka BP, with ice reaching the Lincolnshire Wolds after 17 ka BP. The Dimlington date has been invoked to support a contemporaneous readvance of the British Ice Sheet with the Tampen readvance of the Scandinavian Ice Sheet (Carr, 2004).

The starting points for retreat from the southern limit are taken as 23-20 ka BP in the Scilly Isles, 25-21 ka BP in South Wales and the Cheshire Plain, 23-21 ka BP in the Vale of York and 19-15 ka BP in along the eastern English coastline. Figure 10.12 shows the reconstructed retreat pattern with the maximum limits, or the starting points for retreat, marked with a date or range of dates suggested by the build up chronology described above. The northern margin thus appears to have been in retreat before advancement of ice to the Scilly Isles and eastern English coastline. The deglaciation of the northern North Sea before 25 ka BP is difficult to resolve with the advancement of ice to the eastern English coast after 22 ka BP (figures 10.9 and 10.10). Two potential explanations for this are examined in figure 10.13.

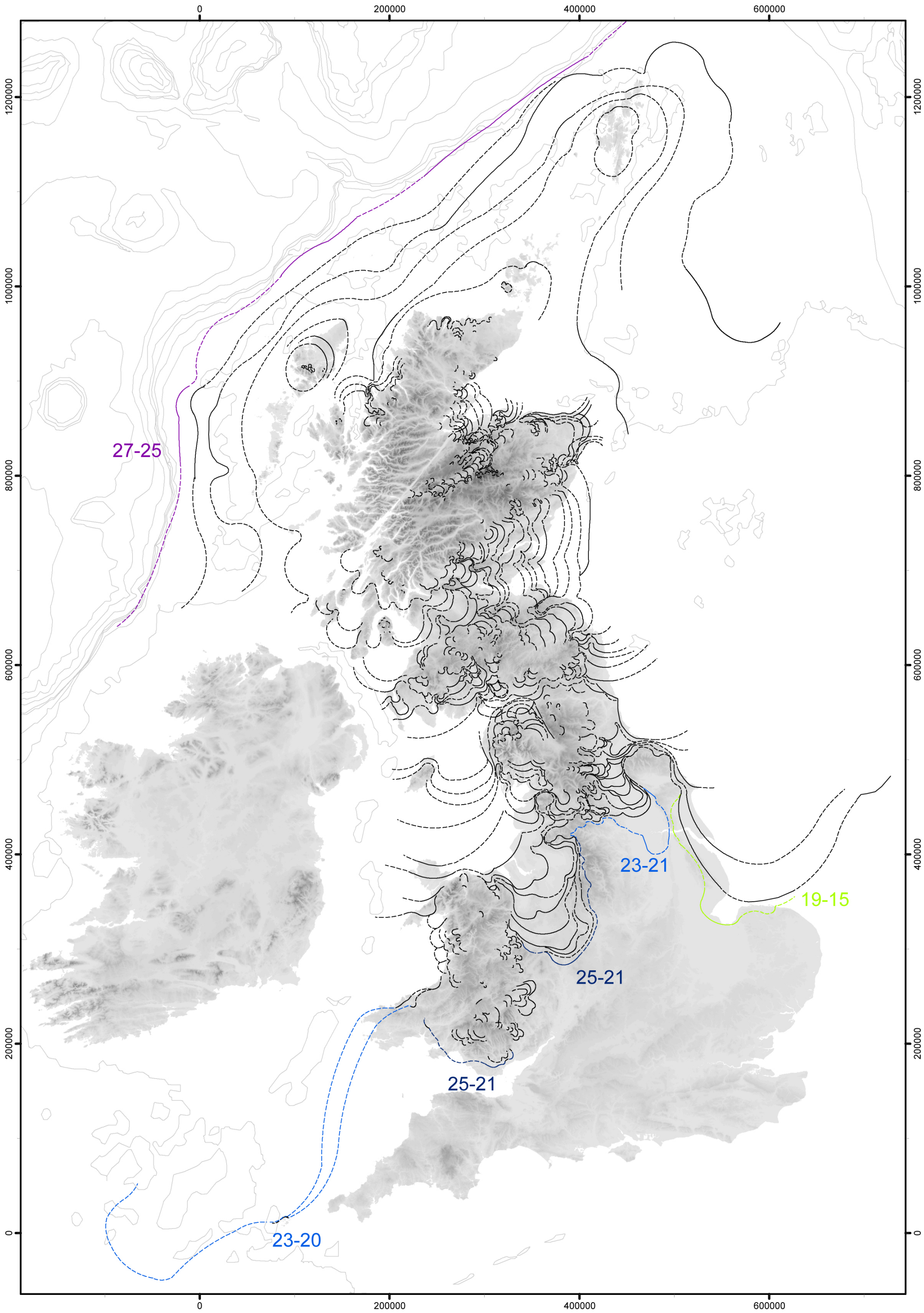

Figure 10.12 Retreat pattern with maximum limits marked with approximate ages and coloured up to correlate similar ages. It appears from the currently available chronology that the maximum limits of the last British Ice Sheet were reached at different times. The youngest date for *advance* date and the oldest date for retreat are used, where available, to attach a range of ages to the margin. The southern margin is reached after the northern margin at the continental shelf edge.

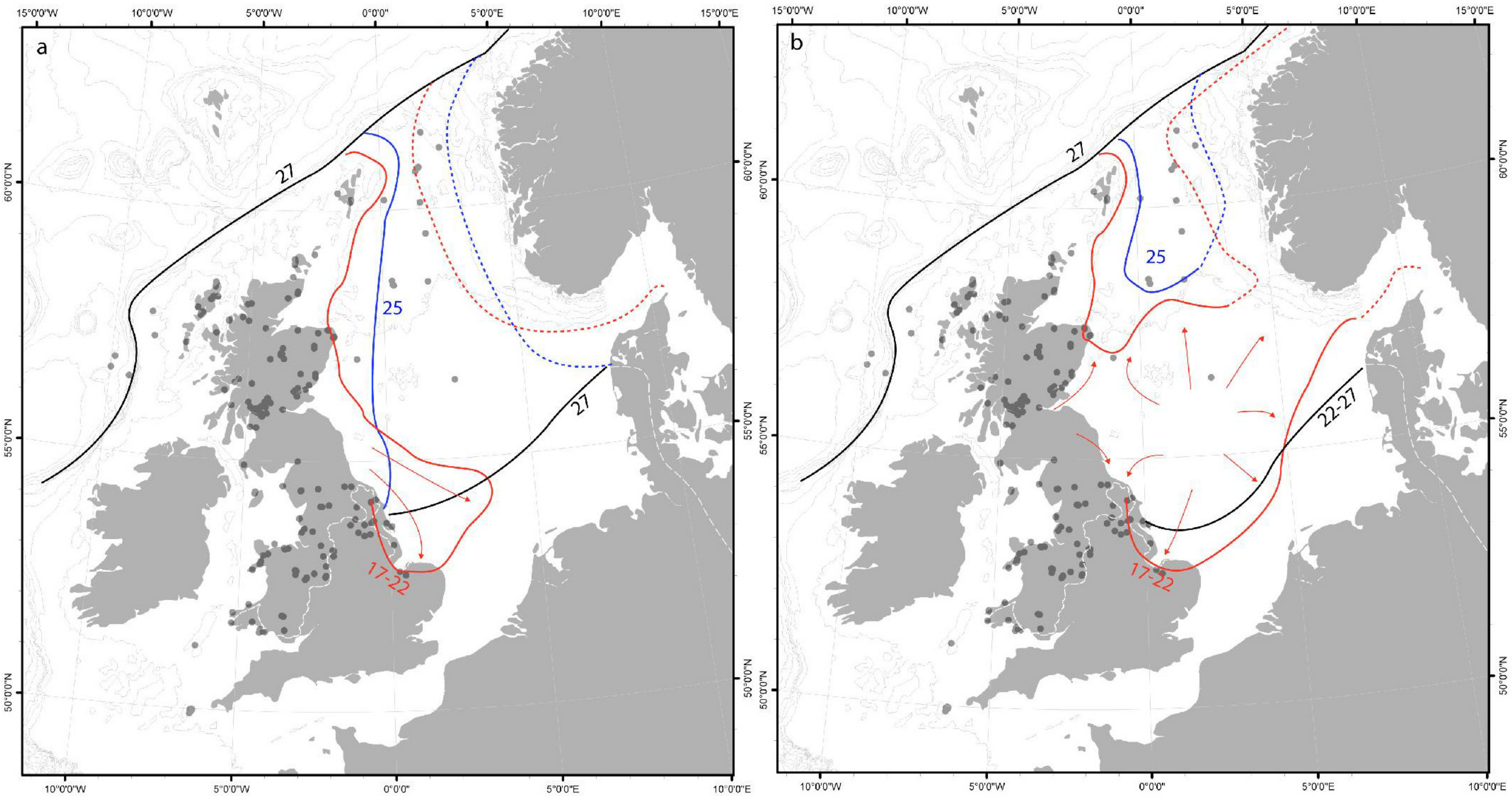

Figure 10.13 There is a lack of chronological constraints for the southern North Sea. This, coupled with the apparent inconsistency of ice advancing down the east coast after deglaciation of the northern North Sea, is problematic in attempting to resolve the terrestrial chronology. Dates from core 77/2, Fladen Ground in the northern North Sea suggest that the British and Scandinavian Ice Sheets were separate in this location after c. 25.1 ka BP (Sejrup et al. 1994). We would expect that coalescence of the ice masses would occur at the same time as maximum glaciation. However, dates from the Holderness coast suggest that ice did not advance inland at this location until after c. 22 ka BP at Dimlington and after 16.6 ka BP on the Lincolnshire dip slope. We can envisage two scenarios to account for this apparent discrepancy. a) Ice breaks up over the whole of the North Sea at 26 ka BP, and a lobe of ice advances southward down the English coastline after 22 ka BP in a correlative advance from the British Ice Sheet with the Tampen readvance of the Scandinavian Ice Sheet (Sejrup et al. 1994). This is the essence of the 2 stage glaciation model presented by Sejrup et al (1994) and the Cape Shore and Bolders Bank stages of Carr et al. (2008). The emerging consensus view of the North Sea is that of a two stage model: coalescent ice sheets 30-26 ka BP followed by an advance out of both ice sheets c. 21 ka BP (Carr, 2004). An alternative model is shown in b) an embayment opens up in the northern North Sea, but the higher ground of the southern North Sea remains glaciated. This scenario requires a persistent ice dome in the southern North Sea to account for the ice advance on to the eastern English coastline. It would be fruitful to obtain more deglacial dates from the whole of the North Sea to investigate this problem.

A version of the 'two stage' model is presented in figure 10.13a. This was initially proposed by Sejrup et al. (1994) and was refined and supported by the micromorphological work of Carr et al. (2006). This model suggests collapse of ice in the North Sea and full separation of the Scandinavian and British Ice Sheets after 26 ka BP, followed by a readvance of a lobe of ice down the NE English coast after 21 ka BP to correlate with the Tampen readvance of the Scandinavian ice sheet (Sejrup et al., 1994). The concept of a lobe of ice down the eastern coast has been postulated for some time and persists in the literature in the absence of an alternative explanation for the glacial evidence of this coastline (Eyles et al., 1994). In figure 10.12b an alternative model is presented. Here only the northern North Sea is deglaciated at 26 ka BP, with an ice mass persisting on the higher ground of the southern North Sea. Ice remains close to the English coast, and advances a short distance at c.17-22 ka BP to satisfy the dates from Dimlington and Lincolnshire. This model has the advantage of not requiring the advance of a lobe of ice down the NE English coast. The deflection of this lobe is difficult to explain in the absence of an obstacle in the North Sea. The bathymetry of the North Sea does not suggest this as a probable course for ice flow, and we regard it as glaciologically implausible.

10.4 Application of dates to reconstructed retreat pattern

The low density of dates means that understanding the timing of deglaciation requires appeal to the reconstructed pattern of retreat to connect disparate parts of the ice sheet and understand the operation of multiple ice centres. The retreat pattern and dates are examined on a region by region basis and margins set into a timeframe of operation that is consistent with the local dates constraining build up and deglaciation. The 'dated' margins are then considered collectively at the countrywide, or ice sheet scale, to link spatially separate parts of the retreat pattern and examine discrepancies.

10.4.1 Regional assessments of retreat chronology

Figure 10.14 shows the boundaries for the regional assessments. It is important to note that there are considerable parts of the country that are virtually devoid of ages, exacerbating attempts to interpret the temporal evolution of these parts of the retreat pattern; for example, the Southern Uplands, and a broad stretch from Edinburgh to the Tyne. In the following enlarged figures of sections of the retreat pattern (figures 10.13 a-n), the reconstructed margins have been assigned an age value where possible. If the age is followed by a plus sign (+) the margin is at least that age and could be older, a negative sign (-) following the age indicates that the margin is no older than that age, and probably younger. A range is given when the margin is known to fall between two dates.

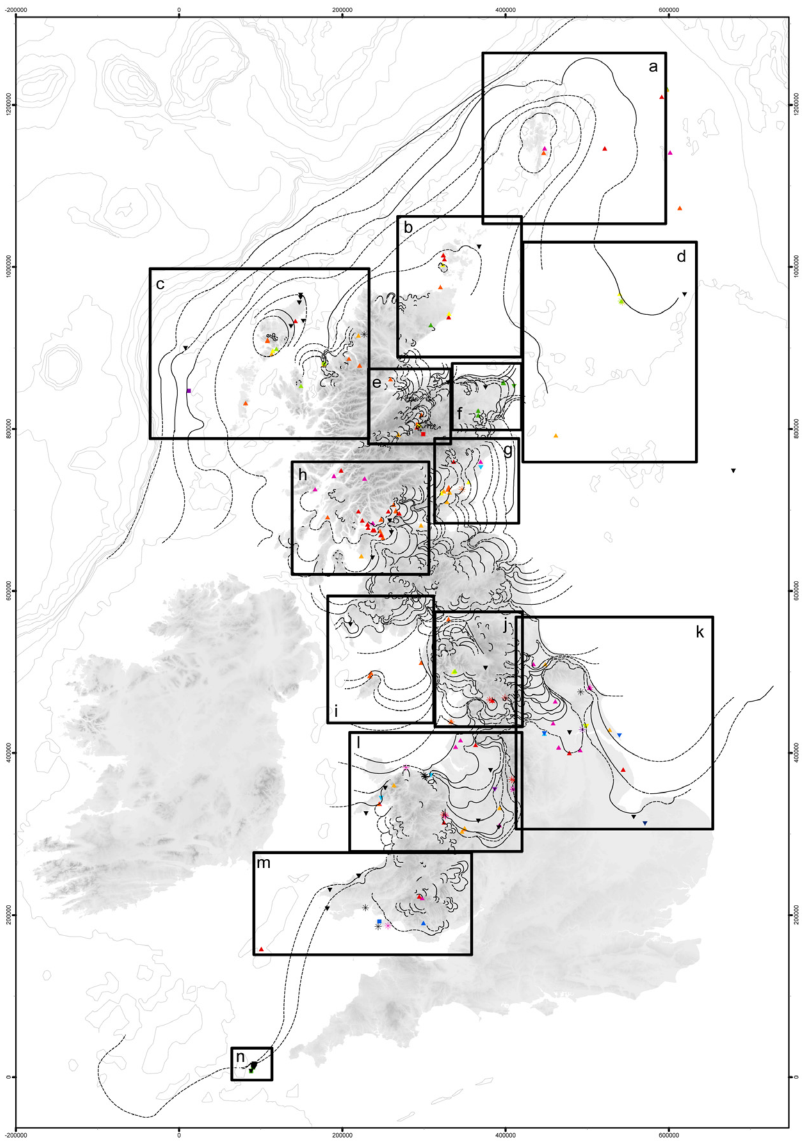

Figure 10.14 The reconstructed retreat pattern is many times more detailed than the density of the chronological constraints. Note that there is a lack of dates constraining the retreat pattern in NE England and southern Scotland. Retreat pattern, date locations and boundaries of enlargements shown in detail in figures 10.14a-n are shown. Dates coloured up by time bracket. Symbol delimits classification of date. *Advance* = down triangle, *deglacial* = up triangle, *margin* = square, *ice free* = asterisk. Notation and colour scheme for dates is the same as in figures 10.6 and 10.7.

10.4.1.1 Shetland Islands

Deglaciation of Shetland is constrained by dates from two terrestrial locations and several offshore locations east of the islands (figure 10.14a). The terrestrial ages indicate that the coast of Shetland was deglaciated before 14.0 ka BP (site 182; range 15.0-13.0). It is postulated that the reconstructed margin of an ice cap around Shetland occurs c. 15 ka BP. This is consistent with offshore dates east of the islands indicating ice free conditions for this part of the North Sea commencing c.18.7 ka BP (site 189). The earlier retreat margin positions are therefore suggested to be between 18.7 and 15 ka BP and the outermost margin at the continental shelf must be older than 18.7 ka BP. This is consistent with figure 10.12 which sets this margin as 27-26 ka BP.

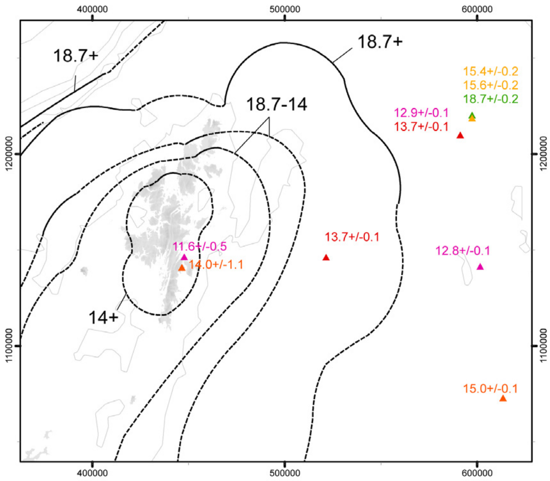

Figure 10.14a Retreat pattern and dates on Shetland and adjacent seas. It is postulated that Shetland was ice free before 14 ka BP. An age or age range has been attached to ice margin positions where possible (black). A positive sign following the value denotes a minimum age (the margin is at least this old); a negative sign a maximum age (the margin is younger than this).

10.4.1.2 *Orkney and Caithness*

Several cosmogenic surface exposure dates from Orkney (figure 10.14b) collectively suggest that the islands of Orkney were ice free by at least 14.8 ka BP (sites 179 and178). These dates have large associated error bars (up to +/- 2400) but collectively support commencement of ice free conditions c. 14-15 ka BP. Two dates on Orkney are older than this (17.0 and 17.9 ka BP; sites 177 and 178) suggesting ice free conditions from c.18 ka BP. Phillips et al. (2008) suggested, on the basis that the older dates are from higher elevations, that the difference in ages indicates that deglaciation progressed by ice sheet thinning. Dates from Caithness show a similar affinity to elevation, with initial thinning of the ice sheet to expose higher ground at c. 18 ka BP and ice retreating inland after 16 ka BP (sites 166-168 and 176) (Phillips et al. 2008). On figure 10.13b a range is given to the retreat margin positions between the two groups of ages. Ice is at the north coastline of Caithness by 15.3 ka BP (site 176).

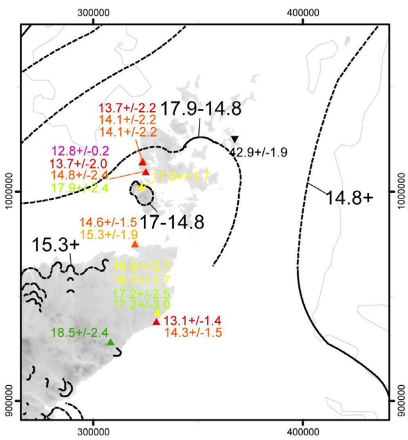

Figure 10.14b Retreat pattern and dates from Caithness and Orkney. Cosmogenic surface exposure ages demonstrate a range of derived ages at each site. It is suggested, on the basis of site elevations, that the older dates 18-17 ka BP reflect initial deglaciation of high ground by ice sheet thinning with lowlands deglaciated around 15-16 ka BP (Phillips et al, 2008). An age or age range has been attached to ice margin positions where possible (black). A positive sign following the value denotes a minimum age (the margin is at least this old); a negative sign a maximum age (the margin is younger than this).

10.4.1.3 *Northwest Scotland and the Outer Hebrides*

An age of 26.6 ka BP for the moraine banks west of Uist (figure 10.14c) is consistent with placing the start of deglaciation from the continental margin at 27 ka BP (figure 10.12). In Northwest Scotland and the Outer Hebrides the majority of dates are from cosmogenic isotope exposure dating, with many dates initially obtained for the purpose of investigating the existence of nunataks during the last glacial (Ballantyne, 1998, 1999). The dates are therefore mainly from high elevations. Collectively dates on Uist and Lewis indicate that the island summits were ice free by 14 ka BP, with deglaciation commencing c. 17 ka BP (sites 164, 158-156, 152-154). Dates on Skye indicate this island's summits were also ice free around 17 ka BP (site 143). On mainland Scotland, the weighted mean of the three cosmogenic dates from the Gairloch moraine date the limit on Wester Ross to 16.5 ka BP, (Everest and Kubik, 2006); although the dates range from 17.9-15.5 ka BP (site 149). These dates are consistent with separation of mainland Scottish from Outer Hebrides ice at around 17 ka BP coincident with thinning of the ice sheet. Dates from Cam Loch and Loch Droma place the start of the late glacial sedimentation in the area at 15 ka BP (sites 148 and 160). In the absence of unequivocal evidence for a readvance in this area this thesis assumes regular retreat from the coast (see chapter 9) with the area becoming ice free by 15 ka BP. In conflict with this interpretation, a series of recently published cosmogenic dates imply an ice mass in the Wester Ross region throughout the late glacial (Bradwell et al., 2008a). These new dates are in conflict with the loch dates and Bradwell et al. (2008a) question the reliability of the Loch Droma date (14.9 ka BP) in particular. These dates were published after the cut off point for collation of the database.

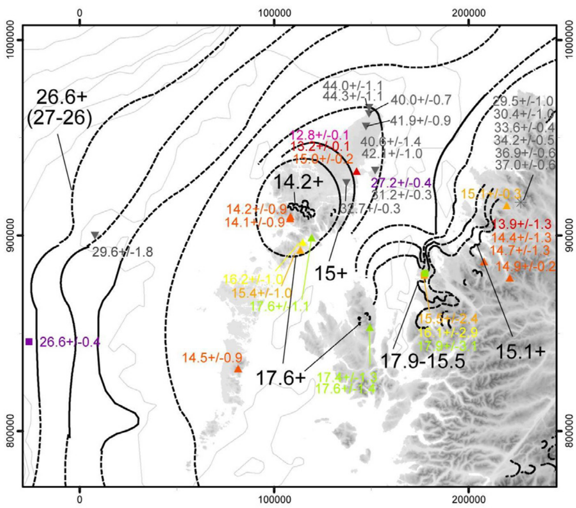

Figure 10.14c Retreat pattern and dates for Outer Hebrides and Northwest Scotland. An age or age range has been attached to ice margin positions where possible (black). A positive sign following the value denotes a minimum age (the margin is at least this old); a negative sign a maximum age (the margin is younger than this). It is suggested that the Outer Hebrides ice cap split from the mainland ice sheet around 17 ka BP. Although, like in Orkney and Caithness, the dates on Skye and Lewis suggesting this are surface exposure ages from high elevations and may therefore record the thinning of the ice sheet rather than full deglaciation of these areas. The Minch may therefore have been deglaciated slightly earlier, possibly around 16 ka BP.

10.4.1.4 Northern North Sea

Dates derived from glaciomarine sediments in the Witch Ground area of the North Sea suggest ice free conditions commencing at this location before 25.1 ka BP (figure 10.14d). Extension of the inner retreat position to the south enables us to attach a minimum date of 15.3 ka BP to this position. It is noted that new seismic and core evidence, including radiocarbon dates, have been used to suggest that ice advanced over this part of the North Sea (core GS140-14GC; figure 10.11) from the NW on two separate occasions close to 17 and c.16 ka BP (Sejrup, H. P and Nygard, A., pers comm.). This has interesting implications in respect of the national synthesis to follow (section 10.4.2).

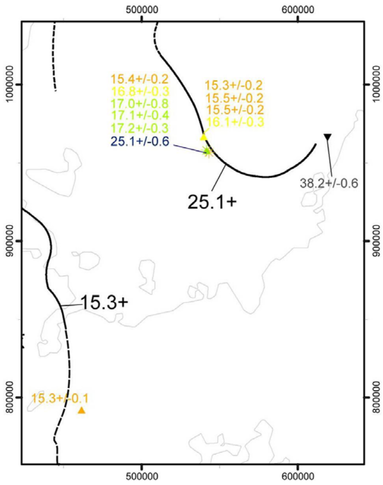

Figure 10.14d Retreat pattern and dates for the northern North Sea. An age or age range has been attached to ice margin positions where possible (black). A positive sign following the value denotes a minimum age (the margin is at least this old); a negative sign a maximum age (the margin is younger than this). Ice must have retreated as far west as the inner margin position before 15.3 ka BP.

10.4.1.5 Moray Firth and Cairngorms

Deglaciation of the Moray Firth is constrained by a single date (figure 10.14e) to before 14.4 ka BP (site 147). Consistent with this, dates from Loch Etteridge further south suggest that the Spey valley was ice free by 15 ka BP (site 122). Deltaic sediments presumed to indicate the development of glacial lakes between ice in the Spey valley and the Cairngorms suggest decoupling of ice at 16.7 ka BP (sites 126 and 127; range 17.2-16.1 ka) (Everest and Kubik, 2006). Moraines close to these lake sediments have been dated to 14.4 ka BP and 13.8 ka BP (sites 125 and 128) (Everest and Golledge, 2004). This, in addition to a *deglacial* date of 13.8 ka BP and a *margin* date of 13.6 ka BP in the north and south Cairngorms respectively, indicate that ice persisted in this upland region for approximately 1000 years after retreat of Spey ice. Recently published cosmogenic exposure dates on rock glaciers, not included in the database, suggest that the Cairngorms were ice free before 15 ka BP (Phillips et al., 2008) contradicting the moraine dates but consistent with the retreat of ice from the Spey. The readvance of ice postulated at Ardesier (chapter 9), on the basis of the time bracket attached to the reconstructed retreat margins, occurred close to 15 ka BP consistent with the interpretation of Merritt et al. (1995).

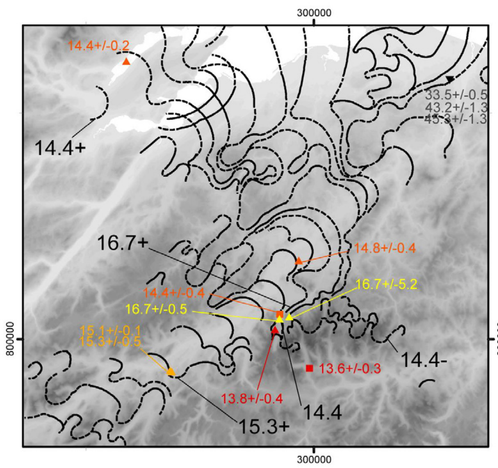

Figure 10.14e Retreat pattern and dates for Moray Firth and Cairngorms. An age or age range has been attached to ice margin positions where possible (black). A positive sign following the value denotes a minimum age (the margin is at least this old); a negative sign a maximum age (the margin is younger than this). The ice sheet was thin and Spey ice separated from Cairngorms ice around 17 ka BP. The Spey valley was ice free by 15 ka BP.

10.4.1.6 Buchan

Three radiocarbon determinations date marine silts sandwiched between tills at St Fergus to 17.0-18.0 ka BP (site 135) (figure 10.14f). These dates support deglaciation inland from the coast at or before 18 ka BP, followed by incursion of ice after c.17 ka BP. This is consistent with the geomorphological reconstruction of the incursion of lobes of ice inland after initial recession of ice required to support ice dammed lakes during recession of ice in this area (chapter 9). Support for early inland retreat of ice towards the Grampian Highlands is also supported by *deglacial* dates of 18.5 and 20.0 ka BP c.20 km inland (sites 145, 130 and 132). These dates are considered to represent ice sheet thinning commencing c. 20 ka BP by Phillips et al. (2008) rather than full deglaciation. It is significant to note that the dates have high associated error margins (up to +/-2,900 years). It is assumed that the reconstructed lobes of ice from the W and SW into the Buchan coastal lowlands are contemporaneous, although the southern lobe could have occurred any time after 20 ka BP, if the dates are accepted. Only the lobe emanating from the Moray Firth is constrained by the St. Fergus dates. The advance of the ice margin close to Aberchirder must have occurred after recession of the Moray Firth lobe, therefore after 17 ka BP.

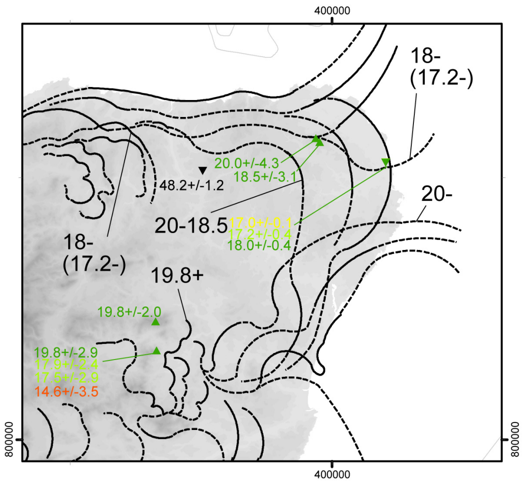

Figure 10.14f Retreat pattern and dates for Buchan. Dates support reconstruction of initial inland retreat followed by advance of two lobes from the north and south on to the deglaciated lowland area. An age or age range has been attached to ice margin positions where possible (black). A positive sign following the value denotes a minimum age (the margin is at least this old); a negative sign a maximum age (the margin is younger than this).

A series of optically stimulated luminescence dates from NE Buchan do not fit with this scenario (sites 133, 136, 129, 138, 140, 141 and 144). These dates are included in table A1 for reference but were rejected as unreliable and are therefore not shown on figure 10.14f. The stratigraphic position of the dates above till, and not overlain by till, imply that the area was not glaciated during the Devensian (Gemmell et al., 2008). An ice free enclave in this area is a persistent concept in the literature (Chapter 2). However, the balance of evidence suggests that the area was glaciated. A possible explanation for the apparent lack of sediment relating to the last glacial phase and the old ages is that the area was under predominantly cold based conditions with minimal erosion. It is significant in this respect that the luminescence dates are all from glaciofluvial sediments, and therefore incomplete bleaching could explain the apparently old ages (Gemmell et al., 2008).

10.4.1.7 East-central Scotland

Dates in east central Scotland, suggest that ice had retreated from the coast before 16.4 ka BP and the margin was west of Ochill Hills before 16.1 ka BP (figure 10.14g). Retreat of valley glaciers into the eastern Grampians before 14 ka BP is consistent with this. Dates are mainly derived from marine shells contained within glaciomarine sediments known collectively as the 'Errol beds' (Peacock, 1999). Recently published radiocarbon dates from Lunan Bay in the north of the region adds further complexity to the pattern (McCabe et al., 2007). These dates are derived from marine sediments underlying what are described as ice contact deposits. This stratigraphy implies that ice had retreated to an unknown western position by approximately 20.5 ka BP before re-advancing over the location. This oscillation of the ice margin can be incorporated with the rest of the dates in this region but suggests relatively early deglaciation of this part of Scotland and by association the central sector of the North Sea. It is not clear how far the ice re-advanced following initial retreat. The reliability of the dates as well as the stratigraphic interpretation is questioned by Peacock et al. (2007).

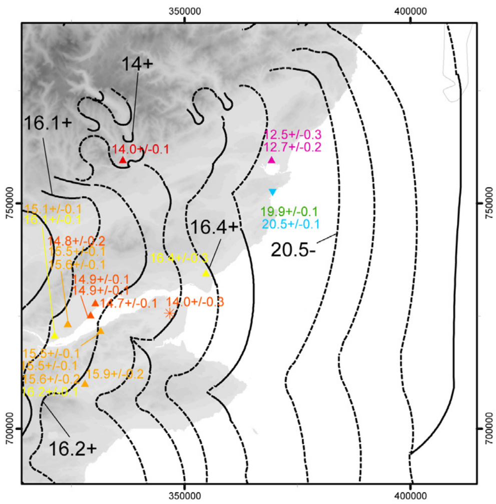

Figure 10.14g Retreat pattern and dates for south-central Scotland. An age or age range has been attached to ice margin positions where possible (black). A positive sign following the value denotes a minimum age (the margin is at least this old); a negative sign a maximum age (the margin is younger than this). Two dates from glaciomarine sediments below ice contact deposits suggest that the coast was ice free after c. 20 ka BP. This appears anomalous with the rest of the dates for glaciomarine sediments in the region (16-13 ka BP).

10.4.1.8 Central Scotland

To the west, a dense network of dates around the margins of the Loch Lomond Stadial ice cap constrain the start of late glacial sedimentation and hence deglaciation of the Devensian ice sheet (figure 10.14h). The pattern of dates reflects retreat back to the vicinity of the Loch Lomond Stadial position by 14.5 ka BP. On the basis of the dates and the reconstructed pattern of retreat, Highland ice had separated from Southern Upland ice by 15.1 ka BP (site 83).

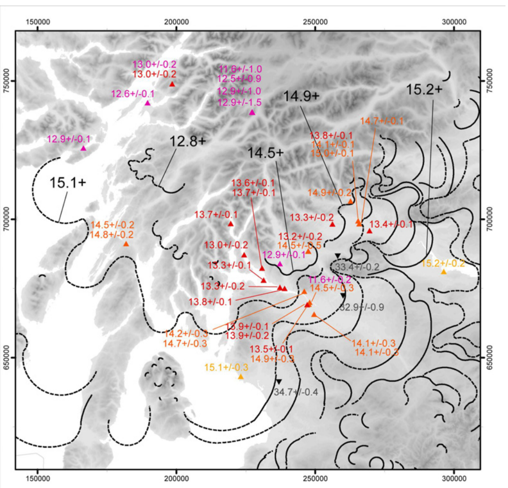

Figure 10.14h Retreat pattern and dates for central Scotland. An age or age range has been attached to ice margin positions where possible (black). A positive sign following the value denotes a minimum age (the margin is at least this old); a negative sign a maximum age (the margin is younger than this). The dates are compatible and suggest that the ice sheet was in the vicinity of the Loch Lomond Stadial position by 14 ka BP.

10.4.1.9 Northeast Irish Sea Basin and Isle of Man

Organic material on the surface of the St. Bees moraine on the Cumbrian coast constrains the deposition to before 14.5 ka BP (figure 10.14i; sites 70 and 69). The St Bees moraine is often correlated with the Bride moraine on the northern tip of the Isle of Man. Organics from kettle holes on the northwest coast of the Isle of Man dated to 14.5-15 ka BP support this (site 79). Older dates from the kettle holes suggesting deglaciation on the Isle of Man around 22-18 ka BP have been rejected as too old due to contamination (see table A1). The dates suggest that the ice margin was north of the Irish Sea by 15 ka BP.

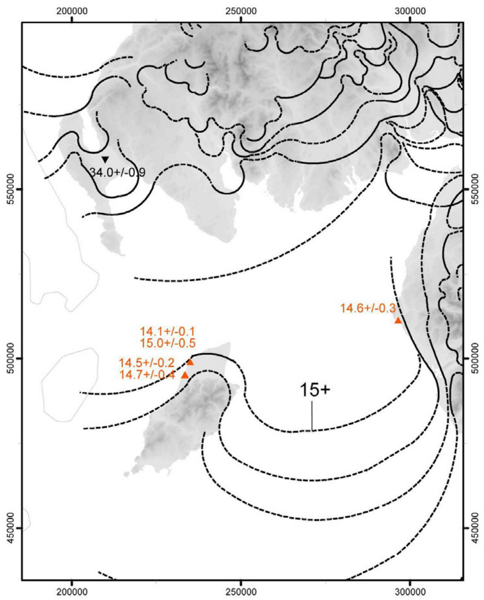

Figure 10.14i Retreat pattern and dates for Irish Sea and Isle of Man. An age or age range has been attached to ice margin positions where possible (black). A positive sign following the value denotes a minimum age (the margin is at least this old); a negative sign a maximum age (the margin is younger than this). The Irish Sea is deglaciated before 15 ka BP.

10.4.1.10 Northwest England

A group of dates for the start of organic sedimentation from four sites close to Lake Windermere suggest that the southern Lake District was ice free before 17 ka BP (figure 10.14j; sites 71-74). By extension, on the basis of the reconstructed pattern of retreat towards the Cumbrian Mountains, the Howgill Fells and Lancashire lowlands were also deglaciated before 17 ka BP. Organics from lake mud and an elk bone at Poulton-on-the-Flyde dated to c.14 ka BP are consistent with this. It is also likely that the Yorkshire Dales were ice free by this time although the presence of small valley glaciers cannot be rejected. The lateral channels running down the western slopes of the Pennine escarpment support initial deglaciation by ice sheet thinning. Radiocarbon dates of bones indicate that human occupation of caves in the Pennines was established by 13 ka BP (sites 64-66). Basal peat at Redkirk Point indicates that the northern Solway lowlands were deglaciated before 14 ka BP (site 81). These dates indicate that the suggested minor re-advance (chapter 9) of ice from the north into the deglaciated Solway lowlands occurred between 17-14.2 ka BP.

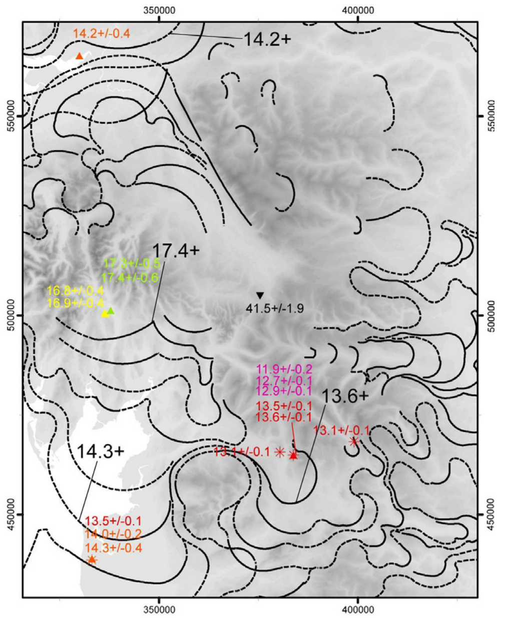

Figure 10.14j Retreat pattern and dates for northwest England. An age or age range has been attached to ice margin positions where possible (black). A positive sign following the value denotes a minimum age (the margin is at least this old); a negative sign a maximum age (the margin is younger than this). Four dates from close to Lake Windermere indicate that the lake and by extension the Cumbrian Mountains were ice free by 17 ka BP.

10.4.1.11 *Northeast England*

Deglaciation of northeast England (figure 10.14k) is indicated by *deglacial* dates north of the Cleveland Hills of 15.2 ka BP (site 76) and 12.7 ka BP (site 78). The Tees estuary was therefore ice free before 15.2 ka BP. *Deglacial* dates clustering around 13 ka BP in the Vale of York are consistent with this. Recently published dates from the southwest of the Vale of York constrain advance of ice to the maximum limit occurring after c. 23 ka BP, and deglaciation from this point commencing at c. 20.5 ka BP (site 192). A further date from the same site constrains the existence of Glacial Lake Humber to approximately 16.6 ka BP. For this lake to exist drainage must have been prevented by ice blocking the Humber Gap and the ice margin in the Vale of York must have been somewhere between the Tees and site 192. Along the east coast of Lincolnshire, the advance of ice on land is dated to after 22 and 17 ka BP at Dimlington and on the Wolds dip slope respectively (sites 55, 59 and 60). These dates are consistent with the new luminescence date for the age of Glacial Lake Humber. Ice had retreated from the east coast by 15.2 ka BP consistent with the dates in the Tees estuary.

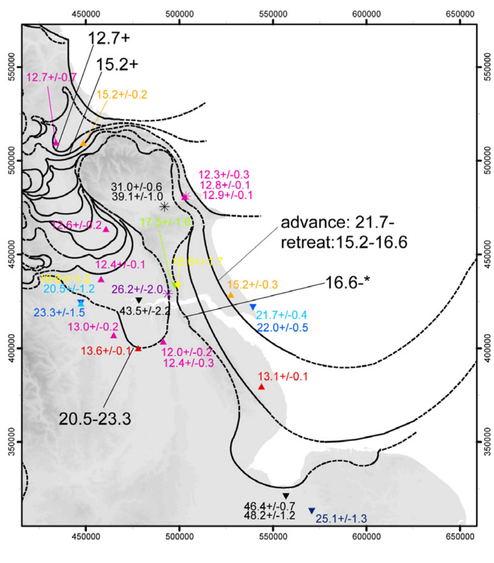

Figure 10.14k Retreat pattern and dates for NE England. An age or age range has been attached to ice margin positions where possible (black). A positive sign following the value denotes a minimum age (the margin is at least this old); a negative sign a maximum age (the margin is younger than this). The dates are consistent with older deglacial dates further south in the Vale of York. Advance dates on the east coast constrain the build up of ice to after 21.7 ka BP, and advancement to the Lincolnshire Wolds after 16.6 ka BP. This is consistent with the date for the existence of glacial Lake Humber at 16.7 ka BP (Bateman et al. 2008).

10.4.1.12 *North Wales*

Figure 10.14l shows the chronological evidence and retreat pattern in North Wales and the Welsh-English borders. Discussion of the anomalously young date in the Vale of Clywdd was made in section 10.3; retreat from the maximum limit is taken as occurring before 21 ka BP. Caves in the Southern Pennines were occupied around 13 ka BP suggesting retreat before this time. Basal organic deposits overlying glaciofluvial gravels and within kettle holes at Condover (site 23), Church Street (site 22), and Stafford (site 32) indicate that the Cheshire Plain lobe retreated from the Welsh borders before 16 ka BP. Welsh ice did not retreat from the border until c.14 ka BP (site 27). In the west, an infilled kettle hole at Glanllynnau indicates that Welsh and Irish Sea ice uncoupled and the Irish Sea lobe retreated from the Lleyn Peninsula before 17 ka BP. Dates framing the formation of the Bryncir moraine in this area between 20 and 12 ka BP (site 34) suggest that Irish Sea ice had retreated north before 20 ka BP and Welsh ice expanded westward after removal of the buttressing effect of Irish Sea ice (Foster, 1968). In this context, the interpretation of the Vale of Clywdd date as due to an oscillation of the Irish Sea ice lobe during decoupling from the Welsh ice sheet seems reasonable. An infilled lake basin in Snowdonia suggests that ice had retreated from upland NW Wales before 16 ka BP.

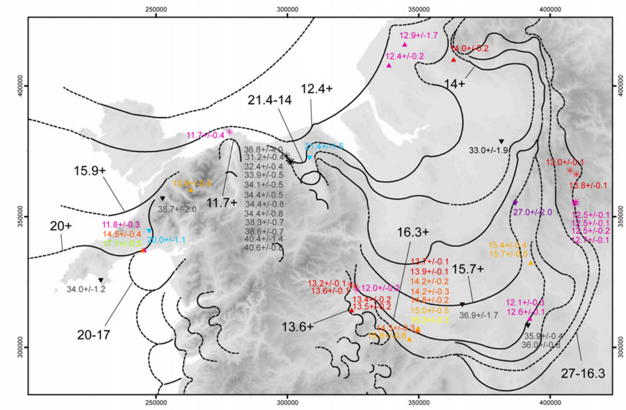

Figure 10.14l Retreat pattern and dates for North Wales. An age or age range has been attached to ice margin positions where possible (black). A positive sign following the value denotes a minimum age (the margin is at least this old); a negative sign a maximum age (the margin is younger than this). An advance date from the Lleyn Peninsula suggests that Welsh ice advanced into Cardigan Bay after 20 ka BP. This suggests that Irish Sea ice had retreated north before 20 ka BP.

10.4.1.13 *South Wales*

In South Wales, late glacial sediments in the Brecon Beacons indicate that the ice cap here melted before 13.5 ka BP (figure 10.14m). Cosmogenic exposure dates indicate that retreat from the maximum limit in South Wales commenced around 22.8 ka BP (site 12; range 24.8-20.8 ka). There are no dates constraining retreat of ice from the northern Pembrokeshire coast. The Southern Irish Sea was ice free before 14 ka BP.

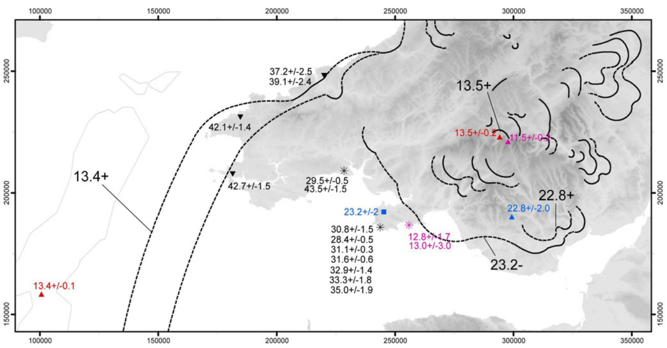

Figure 10.14m Retreat pattern and dates for South Wales. An age or age range has been attached to ice margin positions where possible (black). A positive sign following the value denotes a minimum age (the margin is at least this old); a negative sign a maximum age (the margin is younger than this). The ages are sparse but consistent.

10.4.1.14 *Scilly Isles*

There are no *deglacial* dates from the Scilly Isles (figure 10.14n). Ages for deposition of the Old Man sandloess in the southern islands range between 15.9 and 22.5 ka BP. If this event is taken as contemporaneous with the deposition of till in the north, the maximum limit in the Irish Sea must have occurred within this time frame. Loess deposition could have occurred when the margin was north of the islands. It is suggested that the Irish Sea lobe reaching the islands was a short-lived event with the recently deglaciated bed of the Irish Sea providing the material for loess deposition. A minimum age for ice advance to the Scilly Isles of 19.8 ka BP has been derived from cosmogenic dating of the Shipman Head Boulder Moraine on Bryher (McCarroll et al. 2006). This date was described as preliminary and so not included in the database (table A1) but is consistent with the ages derived from the Old Man Sandloess.

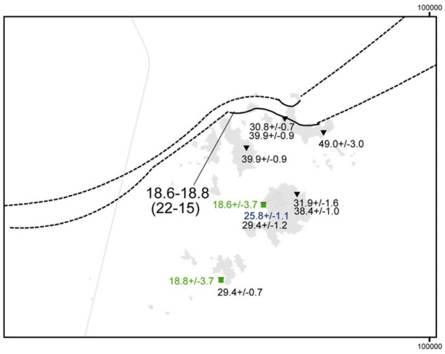

Figure 10.14n Retreat pattern and dates for Scilly Isles. An age range has been attached to ice margin positions where possible (black). A positive sign following the value denotes a minimum age (the margin is at least this old); a negative sign a maximum age (the margin is younger than this).

10.4.2 Synthesis of dated margins

Figure 10.15 shows the pattern of retreat with the ages from the above regional assessments attached. In general the ages are consistent across regions. For example, the deglaciation of the Lake District before 17.4 ka BP is consistent with the dates for retreat from the Cheshire Plain before 15.7 and 14 ka BP. However, the map also highlights discrepancies between some dates. For example, dates for the decoupling of ice in the Spey valley with ice in the Cairngorms at c. 16.7 ka BP (Everest and Golledge, 2004) appears inconsistent with an ice margin position across the Humber Gap necessary to dam glacial Lake Humber recently dated to 16.6 ka BP (Bateman et al. 2008).

Two syntheses that attempt to accommodate all of the dates discussed above are presented in figures 10.16 and 10.17. The difference between the two is the choice of scenario for the North Sea; lobate readvance down the east coast or a southern North Sea ice mass (as hypothesised in figure 10.12). Otherwise the scenarios are the same. In the absence of detailed information for Ireland, ice is presumed to retreat back monotonically to the centre of the island from a maximum at 27 ka BP separating from the British Ice Sheet between 17-16 ka BP (figure 10.11).

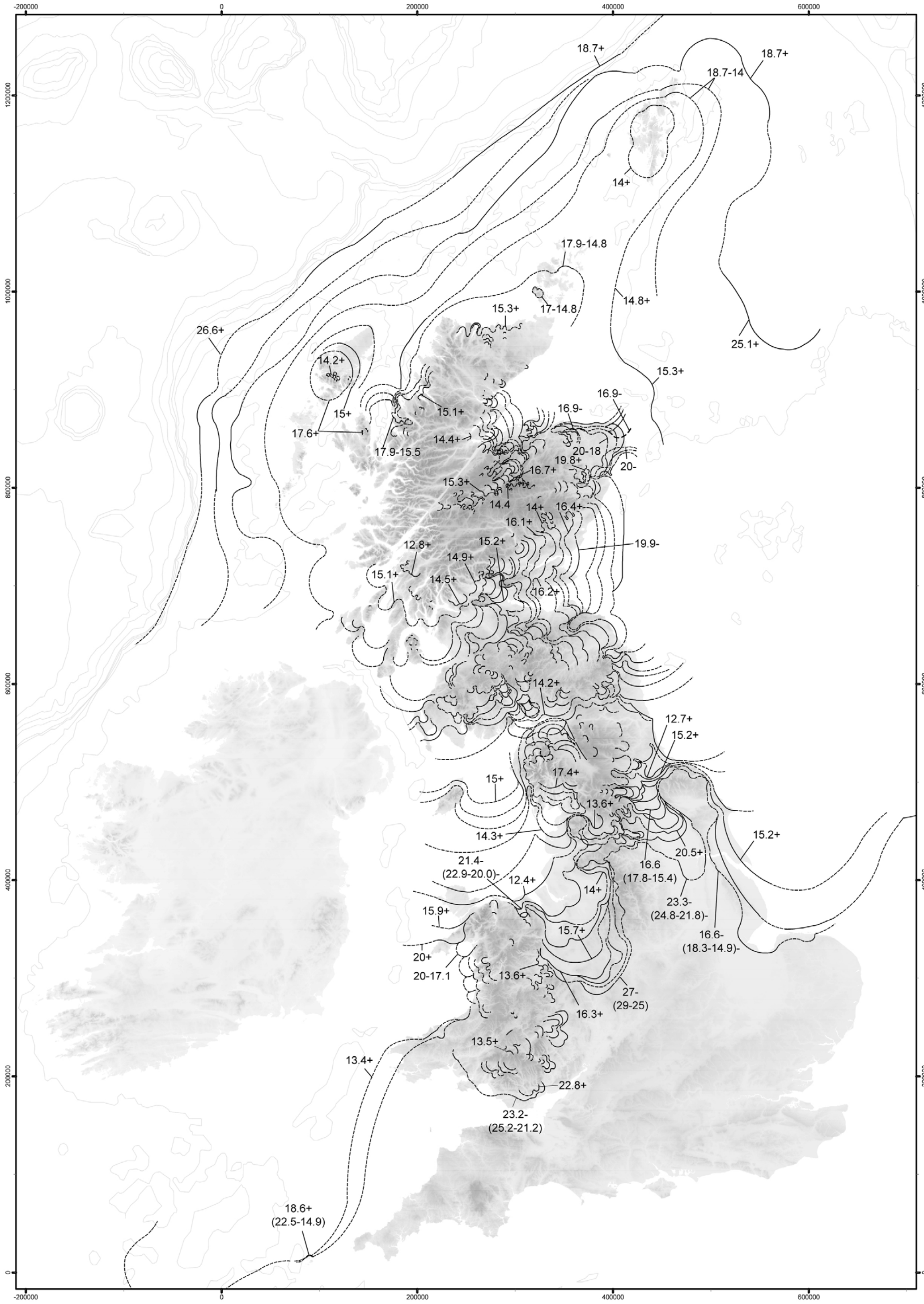

Figure 10.15 The reconstructed pattern of retreat with ages and/or age ranges attached to each margin where possible. Positive signs following ages indicate that the age is a minimum one for the margin. Negative signs indicate that the age is a maximum one. Following this, the majority of discrepancies between regions can be accommodated.

- Scenario 1: lobate readvance following break up of ice in the North Sea

At 27 ka BP ice is at the western continental shelf edge. The position in the south is undefined. A judicious consideration of the likely positions places the 27 ka BP margin across the whole of Ireland, pinned between southeast Ireland and Pembrokeshire in the Irish Sea, at the Welsh maximum limit, half-way down the Cheshire Plain and across the northern part of the Vale of York, connecting across the southern North Sea with the Main Stationary Line in Denmark at approximately 56ºN (figure 10.16). In this synthesis ice collapses over the whole of the North Sea around 26 ka BP, and thus the 25 ka isochron runs north-south from east of Shetland to the Tees estuary. At 25 ka BP ice is at the maximum limit in the Cheshire Plain, South Wales, and is still pinned across the Irish Sea. At 23 ka BP ice advances down the Vale of York and to the Scilly Isles and remains at the Welsh limit. The 23 ka BP position is placed half way up the Cheshire Plain in sympathy with the drawdown of ice to the limit in the Scillys. The 21 ka BP margin is placed along the Holderness coast but this margin could remain close to the 23 ka BP position. The figure shows the most extreme version of events that the dates can support. Ice retreats from the Scilly Isles and the Cheshire Plain and Welsh ice starts to decouple at 21 ka BP. By 20 ka BP ice has retreated to the Lleyn Peninsula and Welsh ice expands slightly as the buttressing effect of the Irish Sea ice lobe is removed. For symmetry the ice limit at 20 ka BP is placed at the Cheshire coast. Ice retreats a short distance up the Vale of York. In order to accommodate the re-advance date in eastern Scotland (site 115) the 20 ka BP margin is placed close to the Scottish coast. The early deglaciation of this area is consistent with the oldest dates derived from cosmogenic surface exposure dating in Caithness (Phillips et al. 2008). These dates were interpreted by Phillips et al (2008) as due to ice sheet thinning but in conjunction with the dates from Lunan Bay support 'early' deglaciation of this part of eastern Scotland. The 18 ka BP limit is largely speculative and placed close to the 20 ka BP position except in the Irish Sea. To satisfy the Lincolnshire dates, a major ice advance down the east coast at c.17 ka BP is invoked. The glaciological plausibility of a lobe in the southern North Sea emanating from the British Ice Sheet as late as 17 ka BP is further questioned considering deglaciation of most of northern England before this time, as indicated by the *deglacial* dates close to Lake Windermere and the pattern of retreat to this point (figure 10.16). The eastern English lobe is correlated with advances out of the Moray Firth and Strathmore into the Buchan lowlands. By 16 ka BP the mainland ice sheet had decoupled from the Irish Ice Sheet, and ice caps on Shetland and the Outer Hebrides. Highland ice separated from Southern Upland ice before 15 ka BP.

- Scenario 2: a southern North Sea ice mass

Figure 10.17 shows the alternative North Sea scenario. The positions of the isochrones are the same as in figure 10.16 on the western side of the country. In this scenario, an embayment opens up in the northern North Sea after 26 ka BP and ice persists as an ice dome in the southern North Sea. The early deglaciation of northeast Scotland is still accommodated by unzipping of the British Ice Sheet from the North Sea dome along the Aberdeenshire coastline. All of the activity along the eastern English coast is a function of changes in the southern margins of the North Sea ice dome. Although controversial, this scenario has the advantage that the relatively small 17 ka BP British Ice Sheet does not need to contribute to a large ice lobe down the east coast. In this respect the Lake District dates are easier to reconcile with the existence of Lake Humber as late as 16.6 ka BP.

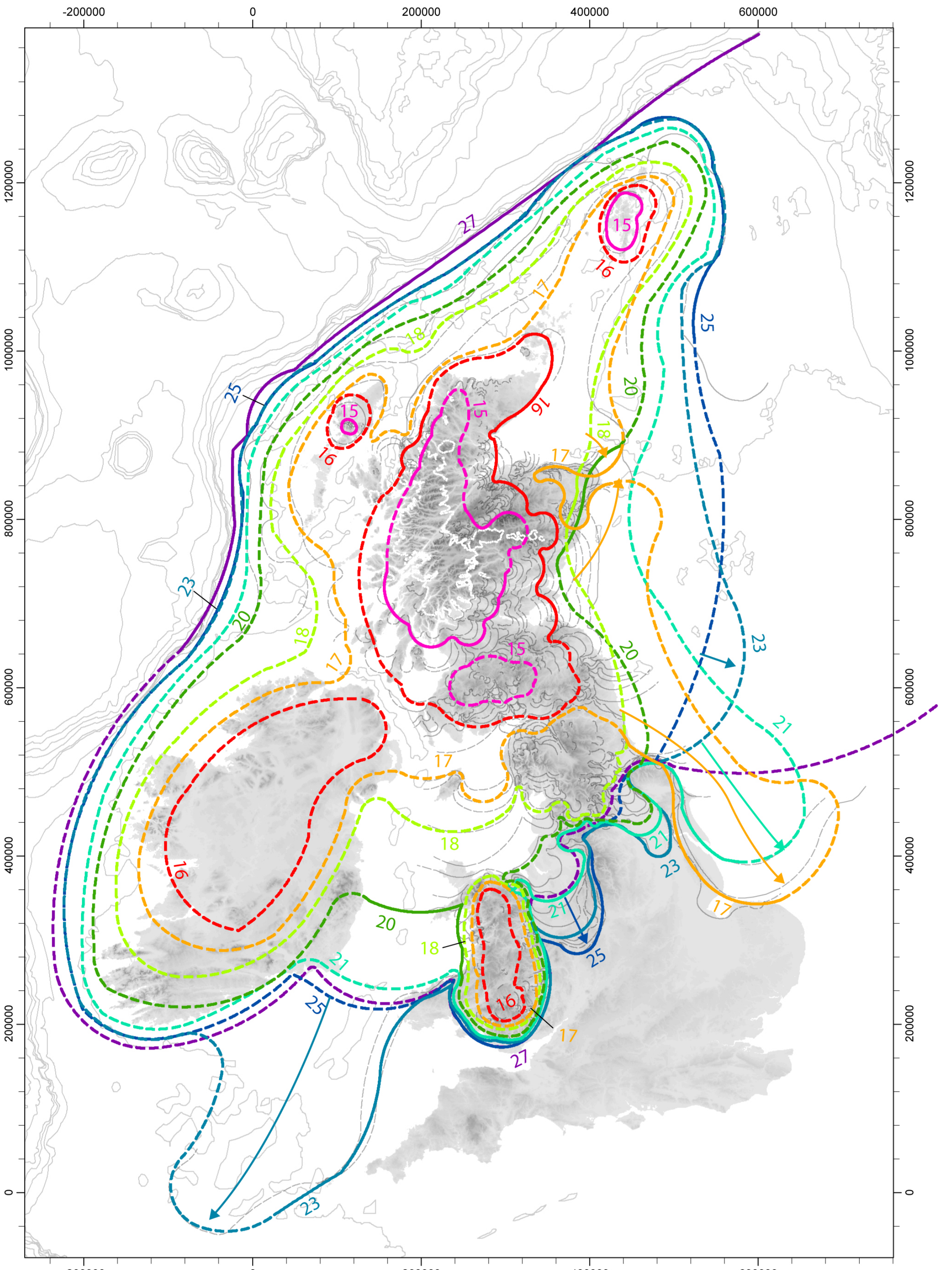

Figure 10.16 Dated retreat pattern option 1 (all dates accommodated): ‘Two stage’ model of North Sea glaciation (collapse followed by advance of lobe(s) down the east coast). Simplified isochrones are shown overlain on top of reconstructed pattern of retreat. The isochrones frame the time period in which the underlying retreat margin positions existed. The isochrones are necessarily coarser than the retreat pattern due to the lower density of dates compared to geomorphological evidence. In this scenario, ice collapses in the southern North Sea at the same time as ice collapse in the northern North Sea (c. 26 ka BP) and the ‘late’ advance onto the eastern English coast is explained solely by expansion out of the British Ice Sheet. In the scenario above two separate phases of ice advance down the east coast at 21 and 17 ka BP are hypothesised to explain the Dimlington dates and damming of Lake Humber at c.17 ka BP. These dates could be accommodated by a single advance at c. 17 ka BP. In which case, the position of the 21 ka BP isochron in the North Sea would be between the 23 and 20 isochrones. Full details are given in the text. The 20 ka BP isochron is placed along the east coast to accommodate the date from Lunan Bay. The lobe down the east coast at 17 ka BP is difficult to accept in terms of glaciological plausibility as northern England is fully deglaciated by this time and the lobe does not appear to follow the bathymetry of the southern North Sea. Solid lines where dates constrain the ice margin, dashed lines are estimated position of margins connecting these points. Lines are colour-coded by age to aid differentiation of readvance positions.

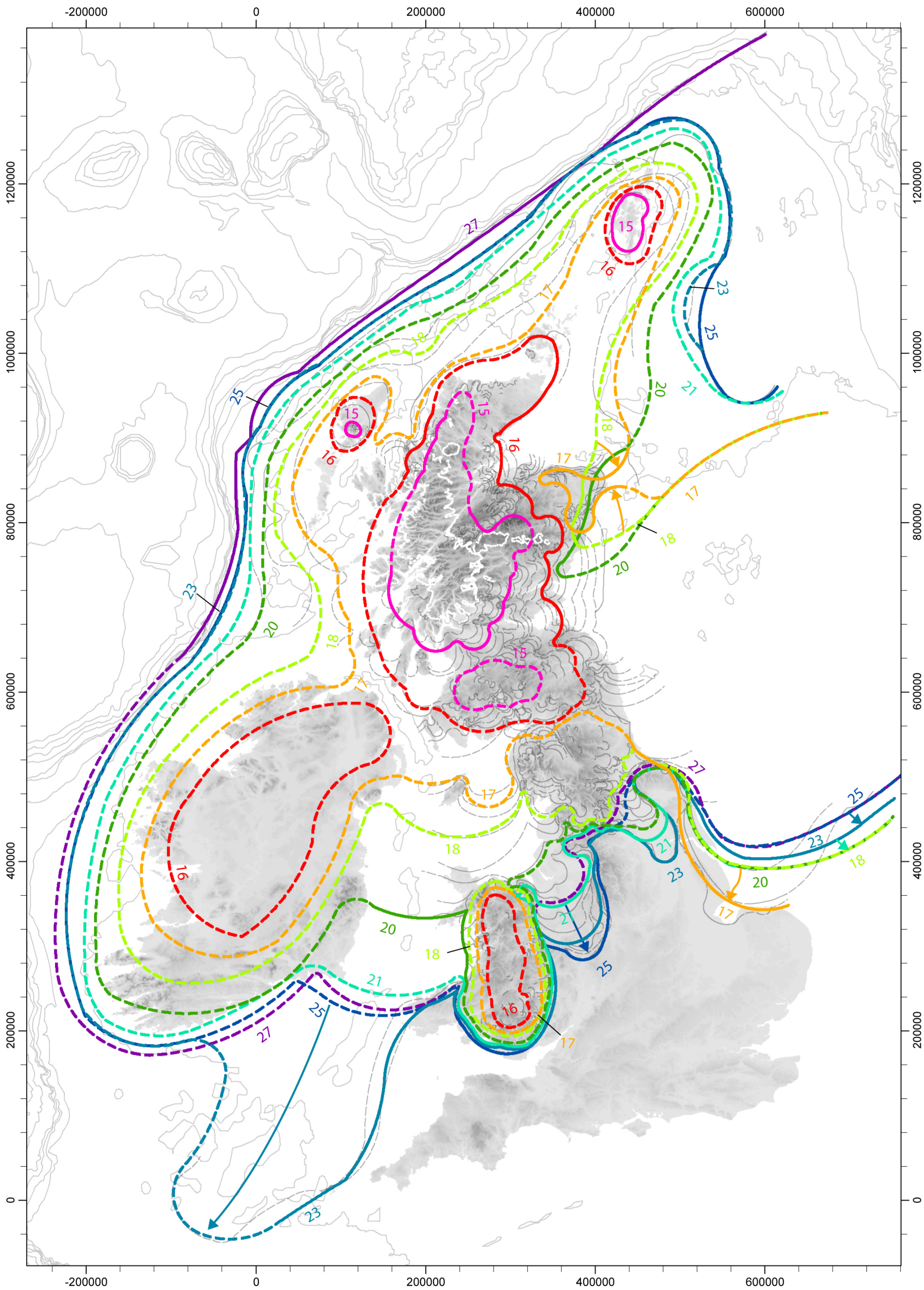

Figure 10.17 Dated retreat pattern option 2 (all dates accommodated): Ice mass in the southern North Sea until 17 ka BP. Simplified isochrones are shown overlain on top of reconstructed pattern of retreat. The isochrones frame the time period in which the retreat margin positions existed. The isochrones are necessarily coarser than the retreat pattern due to the lower density of dates compared to geomorphological evidence. In this scenario, an ice mass is present in the southern North Sea after break up of ice in the northern North Sea at 26 ka BP to explain the 'late' advancement of ice along the eastern English coast and the existence of glacial lake Humber at c. 17 ka BP when northern England was ice free. Ice hovers just off the coast of England until 20 ka BP. Ice collapses rapidly in the southern North Sea after 17 ka BP.

In both of the scenarios that accommodate all of the dates, the ice sheet experiences rapid retreat between 17-16 ka BP. There is some evidence to suggest peaks in the contribution of ice rafted debris to the Barra Fan and Celtic shelf at this time, which would be consistent with, but does not necessarily provide conclusive support for, a major ice sheet destabilisation at this time. Neither of the timed retreat patterns that accommodate all of the dates produces what we consider to be plausible ice sheet configurations. Although apparently consistent with the break up of ice in the North Sea at 26 ka BP, the 'early' deglaciation of the eastern coast of Scotland at c.20 ka BP is difficult to resolve with dates from NE England which suggests that ice did not advance onto the Holderness coast until after 21 and/or as late as 17 ka BP. In the first scenario, if all these dates are accepted, to maintain the principle of ice sheet symmetry, ice advanced onto the Holderness coast at 21 ka BP, followed by retreat to an unknown position, and a second advance of ice down the eastern coast at around 17 ka BP (figure 10.16). These are dramatic changes in the ice sheet margin.

The lobe at 17 ka BP must have been very short lived as it is difficult to reconcile a large ice lobe emanating from Scotland (if the dates from Lake Windermere are accepted northern England is ice free by this time) with the inland margin positions suggested for the Grampians and Midland Valley at 16 ka BP. In the alternative scenario, the deglaciation of northern England, is easier to reconcile with the existence of an ice mass along the eastern English coast as the hypothesised southern North Sea ice mass can solely contribute to this ice position. However, the presence of an ice mass in the southern North Sea is controversial and goes against the emerging consensus view of exposed land in the Southern North Sea after 26 ka BP based on the dates from mollusc and forams from deposits interpreted as glaciomarine by Sejrup et al. (1994) (site 171).

An alternative to the above two scenarios (which accommodate all dates but, perhaps, with some glaciological contrivance) is to selectively ignore one or more problematic dates and build a more plausible ice sheet. A southern North Sea ice mass with a broadly radial flow pattern geometry, as envisaged in figure 10.13b, is in opposition to micromorphological observations of sediments from the southern North Sea, close to the Dogger Bank (54-55ºN and 2-4ºE), are interpreted to indicate grounded ice but with a flow direction from the NW and not the NE-E (Carr, 1999). It seems arbitrary however, to reject one or more dates to resolve these apparent inconsistencies. In the absence of additional information to support or refute specific dates we take a conservative position and attempt to include all of the dates and flag those that are difficult to resolve:

1. Site 115 at Lunan Bay. Glaciomarine sediments underlying till dated to approximately 20 ka BP. The date has been questioned as being too old by Peacock et al. (2007). If these dates were rejected the 20 ka BP isochron would not have to be placed inland of the coast in the

Tay. The cosmogenic dates from Buchan, Caithness and Orkney can be taken as representative of ice sheet thinning commencing at 18-19 ka BP. The NE coast of Buchan must have been deglaciated before 17 ka BP however, in order to account for the damming of proglacial lakes by a lobe of ice from the Moray Firth and the dates from glaciomarine silts at St. Fergus.

2. Dates along the eastern English coast (sites 59, 60 and 55). The date at site 55 has long been used as the type site for the stratigraphic demarcation of the Dimlington Stadial in Britain, although its reliability has been questioned by Hall et al. (2003). The consistency between the loess dates and the new dates for glacial Lake Humber provides mutual support for the reliability of these dates so they are difficult to ignore.
3. If the date from the northern North Sea is false, coalescence between the British and Scandinavian ice sheets may have persisted until 17-22 ka BP. This is not consistent with the Scandinavian chronology which supports the two stage model of glaciation of the North Sea. Furthermore, open water conditions are implied by the presence of iceberg scour marks in the Witch Ground region of the North Sea identified in seismic imagery and dated to 16.2 to 14 ^{14}C ka BP (approximately 18-16 cal ka BP) (Graham, 2007). It would be advantageous to derive additional dates from the North Sea. As yet unpublished dates from the Fladen Ground support an ice margin positions in this part of the North Sea as late as 17.5 and 16.5 (Sejrup/Nygard, pers. comm.). These margins in the North Sea appear more consistent with the 17 ka BP ice margin along the eastern English coast but are still difficult to resolve with dates suggesting proglacial lake development in the Cairngorms at 16.7 ka BP.
4. The dates from close to Lake Windermere in the Lake District may be erroneous. These dates appear inconsistent if the dates for glacial Lake Humber are believed.

At present the dates reveal a complex picture. It is possible that the ice sheet experienced dramatic changes in the position of the ice margin around 17 ka BP but more dates are necessary to reveal this. The hope is that more dates will lead to a clearer picture, although thus far additional dates has led to more confusion as the complexity of the pattern has increased. All of the dates mentioned in the discussion above would benefit from repeat measurements. Focus should be on improving the chronology of the east coast of Britain, southern and northern North Sea, and filling in the gap in dates in the Southern Uplands. The analysis of dates in this chapter is dependent on the stratigraphical and sedimentological interpretations of the papers in which the dates were published.

10.5 Summary

A thorough search of the Quaternary and archaeological literature was undertaken to amass a database of dates relating to the build up and retreat of the last British Ice Sheet. This database is presented in table A1 and figure 10.2. Over 400 dates were collated and 306 regarded as reliable. Dates were classified on the basis of stratigraphic setting in order to simplify interpretations and derive glaciological meaning from the dates. There did not appear to be a spatial pattern in the dates when examined without reference to topography or knowledge about the ice sheet geometry. Dates were applied to the reconstructed retreat pattern of chapter 9.

If the ice simply retreated back to Rannoch Moor, then the dates would show this. The fact that they do not suggests that the ice sheet retreated to multiple points and did not experience monotonic retreat. Minor oscillations also occurred during retreat. The most dramatic changes in size of the ice sheet appear to have occurred between 17-16 ka BP. The dates suggest that the maximum limits of the ice sheet were reached at different times and that the North Sea ice had collapsed prior to advancement to the southern margins. This creates problems for resolving the dates into a sensible ice sheet configuration that does not require long distance movement of the ice margin with a diminished source area. For the first time the pattern of glaciation has been brought together with a presumed near complete database of dates to yield the pattern and timing of retreat of the ice sheet. It is obvious that the chronology of the last British Ice Sheet requires further attention. More dates are necessary to constrain the timing of the retreat pattern and assess support for long distance movement of the ice margins during deglaciation. It would be beneficial to conduct repeat dating in areas that have been flagged as problematic and also to expand chronological constraint into the areas where little information is available.

The retreat pattern is yet to be integrated with the flow evolution information to build snapshots of ice sheet geometry. Incorporation of this information and the relative chronological information held therein may serve to solve some of the issues raised in this attempt to attach absolute dates to the retreat pattern and vice versa. This may also enable us to more confidently ascertain which dates are truly problematic and should be rejected or revisited.

Chapter 11
Discussion and conclusion

11.1 Introduction

For the first time a holistic approach has been applied to the analysis of the glacial landform record of Britain in order to develop our understanding of the last British Ice Sheet (BIS). This required systematic mapping of glacial geomorphology to produce the first fully comprehensive and consistent glacial maps. The landform data were interpreted using a set of clearly stated assumptions to tease out individual ice flow events, ice stream locations and margin positions. These building blocks were used to reconstruct glimpses of regional flow configuration evolution and the pattern of retreat. Published absolute dates relating to the growth and decline of the last BIS were compiled and used to fix the pattern of retreat in time. This concluding chapter is in four parts: a discussion of the implications of the main results and interpretations for knowledge of the last British Ice Sheet, an assessment of the limitations of the research, suggested directions for future work, followed by a summary of achievements and the thesis conclusions.

11.2 Discussion

11.2.1 Ice sheet extent

As discussed in chapter two, debates about the spatial extent of ice in Scotland have fluctuated between two extreme positions. Part of the argument for a restricted spatial extent rests on the existence of ice free enclaves (e.g. 'moraineless' Buchan) throughout the last glaciation. The new mapping which includes drumlins, moraines, eskers and meltwater channels across Buchan (chapter 5; Maps 3 and 4) directly negates the existence of an ice free enclave in this area and confirms and replicates the conclusions of Clapperton and Sugden (1977) and Merritt et al. (2003) who also reject an ice free enclave in Buchan. The existence of any ice free enclaves is regarded as highly improbable in the context of the growing evidence for shelf edge glaciation. The second dimension to the debate on spatial extent is the question of British and Scandinavian ice sheet confluence in the North Sea. Two coherent, but spatially separate, flowsets are identified in northern Scotland, Orkney and Shetland (fs1 and fs59; chapter 6). These are grouped into a single phase of ice sheet geometry (chapter 8). This regionally widespread (c. 55,000 km^2) and topographically unconstrained ice flow pattern records a major ice flow event. The orientation of ice flow is best explained by the convergence of British and Scandinavian ice in the North Sea resulting in the deflection of British ice towards the northwest (chapter 8). The flow geometry is consistent with the orientation of mega-scale lineations (MSGL) identified in the Fladen Ground of the North Sea, the existence of which supports the presence of grounded ice east of the Moray Firth and Orkney at this time (Graham et al., 2007). The MSGL have been attributed to an ice stream emanating from the Scandinavian Ice Sheet (the Witch Ground Ice Stream). I speculate that the ice stream developed at the zone of convergence of the two ice sheets. Taken together with recently published evidence for an extensive suite of moraines on the continental shelf surrounding Scotland it is highly probable that the ice sheet reached the continental shelf during this stage (Bradwell et al., 2008b).

11.2.2 Flow patterns

Whilst on a superficial level the interpreted flow patterns (Map 4) bear some resemblance to the generalised patterns known since Geikie (1894), the key distinction is that we now recognise the subglacial bedform record as a palimpsest of several flow configurations and not a snapshot. The process of systematic mapping, followed by careful analysis of the pattern and distribution of landforms has untangled the cumulative record of flow events. Cross-cutting flowsets indicate changes in the flow geometry of the ice sheet over time and made possible the sorting of flowsets into a relative age stack. Overall, the flow patterns are indicative of a multi-dome ice sheet. The complexity of the flowsets in the central sector of the ice sheet (chapter 8) reflects the changing relative dominance and interaction of different ice domes. For example cross-cutting flowsets in east-central Scotland document variations in the relative vigour of Highland and Southern Upland ice centres (chapter 8). Grouping of flowsets into glaciologically plausible snapshots of flow configuration (chapter 8) revealed that some ice divides are persistent features recurring in successive flow geometries whilst others are more transient. For example, the Welsh ice divide appears to have been a relatively stable feature with only minor changes in position. Whereas in northern England predominantly east-west ice flow patterns initially record ice flow breaching the Pennine escarpment from an ice divide centred on, or west of, the Cumbrian Mountains. This configuration is followed by the development of an ice divide running from the Cumbrian Mountains to the Howgill Fells and orientated WSW to ESE which conflicts with the view of a permanent ice dome centred on the Lake District. The latter ice configuration is consistent with the observations based on field mapping of drumlins in east Cumbria (Letzer, 1978). In western Scotland an ice centre over Galloway, suggested by erratic evidence, only existed during the later stages of the ice sheet configuration. This finding that the western Southern Uplands did not support an ice divide throughout the glacial, in contrast to the traditional view (figure 2.10), is consistent with the conclusions of Salt and Evans (2005) who conducted subglacial lineation mapping over just Carrick and Galloway.

11.2.3 Ice streams

With the exception of 'Strathmore 1' (fs51) (which has only tentative ice stream status), all of the palaeo-ice stream tracks are topographically constrained or aligned with offshore troughs. It is notable that the ice streams identified for the last British Ice Sheet are an order of magnitude smaller that those of the Laurentide and Fennoscandian ice sheets, but are comparable in size to the Siple Coast ice streams of the Antarctic Ice Sheet (figure 11.1). This reflects the smaller size of the BIS, and the fact that this thesis has only been concerned with the terrestrial record. If we assume ice streams are most likely to operate during maximum ice sheet conditions or just after, when the ice reached the shelf edge, then the majority of evidence will be offshore. Mapping of the Norwegian continental shelf has identified numerous palaeo ice stream tracks that commence immediately offshore of the present day coastline (Ottesen, 2006; Ottesen et al., 2008). It is proposed that fs8 represents the vestigial terrestrial imprint of an ice stream in the North Channel draining out towards the Barra Fan. It is somewhat disappointing that more evidence relating to an ice stream in this location has not been found. Both the size of the Barra Fan and the prominence of the bathymetric trough in the North Channel lead us to suspect that this was an important ice flow path for the last BIS.

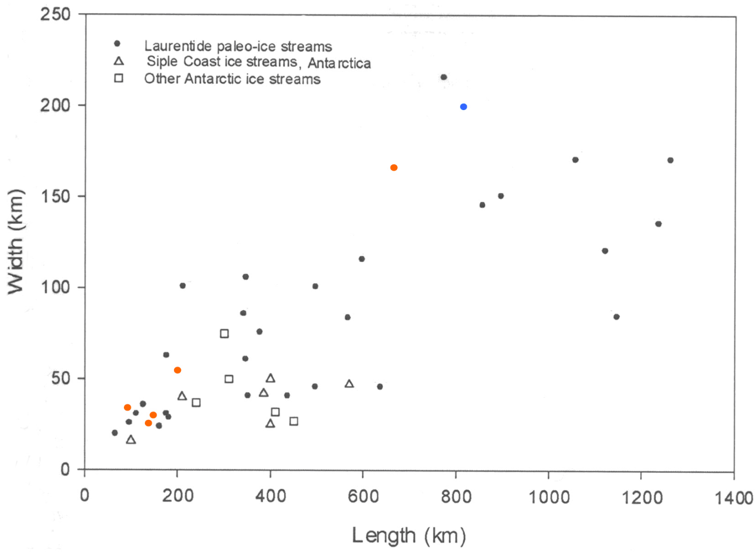

Figure 11.1 British Ice Sheet ice stream imprints (red) are generally at the lower end of the dimension spectrum of ice stream imprints of the Laurentide Ice Sheet. The only ice stream with comparable dimensions is the Irish Sea Ice Stream (c. 650 x 160 m). This may, in part, be due to the fact that we are only capturing part of the ice stream signatures and therefore not recording the true lengths. The widths are similar to those of the Siple Coast ice streams in Antarctica however. The Norwegian Channel Ice Stream (blue) is closer to the larger end of the spectrum. Modified from Winsborrow (2007).

11.2.4 Retreat pattern

Deglaciation clearly progresses by ice surface lowering and retreat to multiple western and northern ice centres (figure 11.2). This confirms that the ice sheet comprised multiple ice divides, at least during the deglaciation. There has been much debate in the literature over possible readvances of the ice margin during deglaciation (see chapter 2). The reconstructed retreat pattern does not support nor require large scale readvances of the ice margin. However, minor oscillations of the margin do occur at sites of uncoupling where ice retreats in opposite directions towards different ice centres. Bringing together the reconstructed pattern of retreat with the dating database was something of a challenge. The synthesis, if slavishly followed (i.e. all dates are correct), leads to the proposal of a late-surviving ice dome over the southern North Sea (chapter 10; figure 10.17). This is a radical reconstruction; especially as I provide no new evidence for it, other than it is the most plausible scenario to satisfy all the dates. It is regarded as more plausible than the alternative – a lobe of ice advancing down the east coast from an ice sheet of restricted size (figure 10.16). A less radical reconstruction, that does not require either of the suggested scenarios, could be produced if some or all of the awkward dates (advance of ice at Lunan Bay (site 115) after 20 ka BP, 'young' advance dates from the Eastern English coast (sites 59, 60 and 55), deglaciation of the North Sea before 25 ka BP (site 171), and 'old' deglacial dates from the central Lake District (sites 71-7)) are ignored. The pattern of retreat presented in chapter 9 is considered robust because of the consistency between the five independent lines of evidence. Therefore, I consider that at least some of the flagged dates are unreliable.

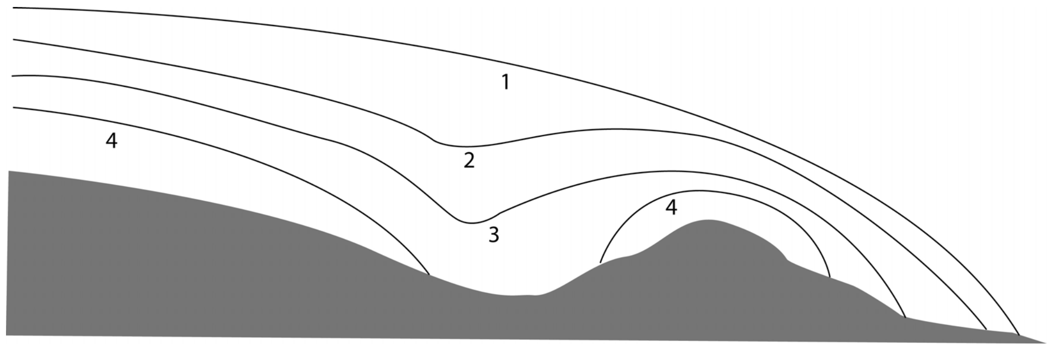

Figure 11.2 Schematic cross section through an ice sheet to show deglaciation by thinning and retreat to multiple points. The ice sheet surface lowers from position 1 to 4 as deglaciation progresses. Lowland lobes of ice retreat fastest leaving behind independent ice caps. This is essentially the reverse of the instantaneous glacierization model for ice sheet build up.

A crude estimate of the speed of ice sheet retreat can be obtained from the less disputed parts of the dated retreat pattern (figure 11.3). The maximum speed of retreat is achieved in the Irish Sea: 87 ma^{-1}. For the rest of transects, the speed of retreat ranges from 10 ma^{-1} (North Sea to Shetland, following separation of the British and Scandinavian Ice Sheets) to 4 ma^{-1} (southernmost Welsh margin to the Black Mountains). Thus, different sectors of the ice sheet retreated at different rates, with lowland lobes exhibiting the fastest rates of retreat. These retreat rates are at the lower end of the ranges calculated for other palaeo-ice sheets, e.g. 260-10 ma^{-1} for the Laurentide Ice Sheet (Andrews, 1973). The grounding line position of the West Antarctic Ice Sheet in the Ross Sea retreated at a rate of c. 120 ma^{-1} during the Holocene (Conway et al., 1999).

11.2.5 Ice sheet evolution

A major revelation from the flowset map (Map 4) is the close relationship of ice flow patterns with topography. Whilst earlier in the analysis I classified flowsets in terms of their generation time (i.e. isochronous vs. time-transgressive) (chapter 6), I now subdivide the flowsets on the basis of correspondence to topography (figure 11.4). For other palaeo-ice sheet reconstructions it has been relatively straightforward to distinguish the deglacial *(TT retreat)* flow patterns from the non deglacial *(isochronous)* and correspondence to topography has rarely been examined. However, relatively few *TT retreat* flowsets were observed in Britain. For the small BIS resting on a bed with large variations in relief over short distances it is a useful division. The logic is that those flowsets that ignore topographic variations are produced when the ice is thick and ice flow directions are primarily controlled by the ice surface slope. Flowsets that are constrained by topography are generated when the ice is thin and variations in the subglacial relief have an increased influence over flow patterns. The majority of flowsets exhibit at least some accord with topographic variations (figure 11.4b). On the basis of the relative age information these are also the youngest flowsets. There is however a modest number of topographically unconstrained flowsets (figure 11.4a).

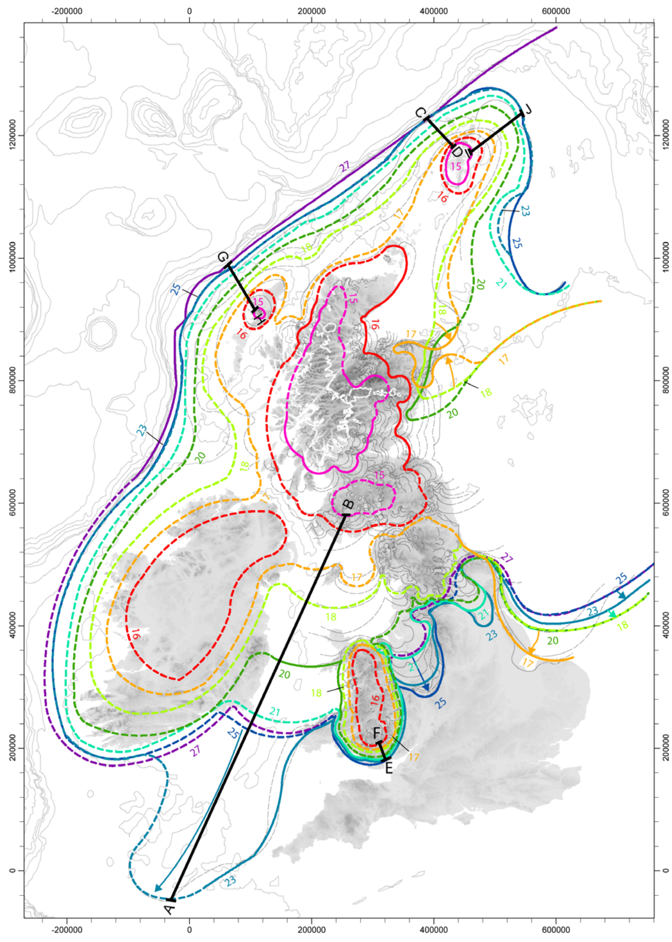

Figure 11.3 Transects used to calculate average speeds of retreat. AB (Irish Sea) 87 ma^{-1}, CD (Western Shetland) 8 ma^{-1}, EF (South Wales) 4 ma^{-1}, GH (Western Outer Hebrides) 8 ma^{-1}, IJ), IJ (Eastern Shetland) 10 ma^{-1}. Estimates assume steady retreat from the age of the maximum margin.

The topographically unconstrained flowsets are interpreted as a record of the *pre-deglacial* ice sheet configurations. As such they provide a glimpse of the ice sheet geometry during build up and maximum extent. Using this interpretation, it is possible to sketch out the form of the ice sheet at its maximum using some the flowsets in figure 11.4a (figure 11.5). Not all, as the relative chronology indicates that they cannot all be contemporary. The principle ice divide runs from the Scottish Highlands to the Lake District, with a secondary divide forking out over the Grampians. Wales and the Outer Hebrides support peripheral autonomous ice domes. The ice sheet is confluent with the Scandinavian and the Irish Ice sheets. Saddles are formed over the North Channel and North Sea.

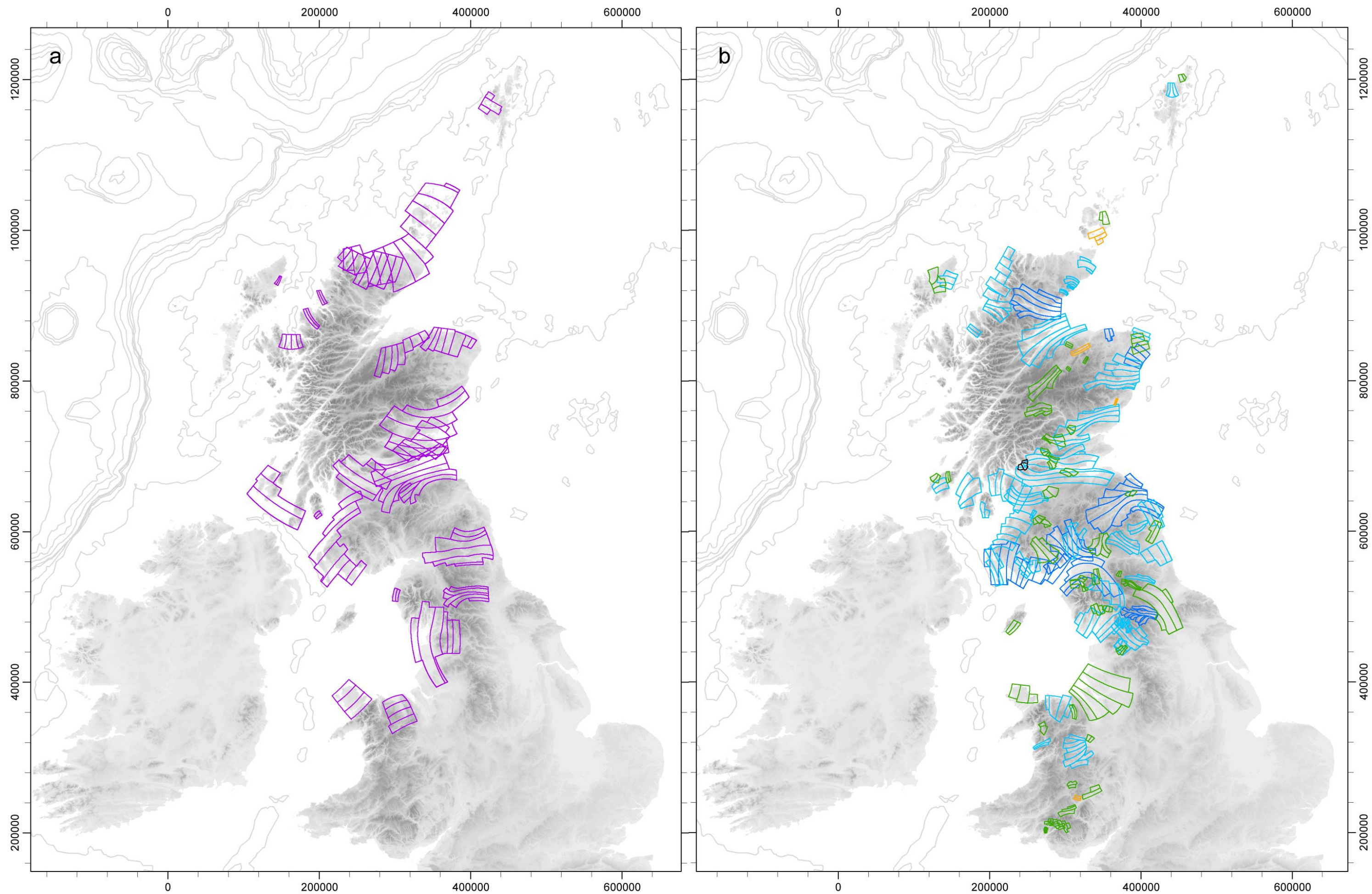

Figure 11.4 Flowsets separated into two groups on the basis of relationship to topography: a) These flowsets are independent of topography and are thus related to the LGM or earlier ice sheet configurationsThese are also the stratigraphically oldest flowsets. Fs19, 11, and 15 which are classified as TT thinning because on the basis of this classification would have been independent of topography at some instant although this did not continue; b) These flowsets have a strong relationship to topography. The majority also 'fit' within the reconstructed retreat pattern. Differences in colour relate to approximate stage of the retreat configuration. Dark blue flowsets have a slight relationship with topography and are likely part of the configuration immediately subsequent to the start of deglaciation. Light blue flowsets are strongly confined by topography and operated when the ice sheet was thin. Green flowsets are TT retreat flowsets and therefore record retreat of the ice.

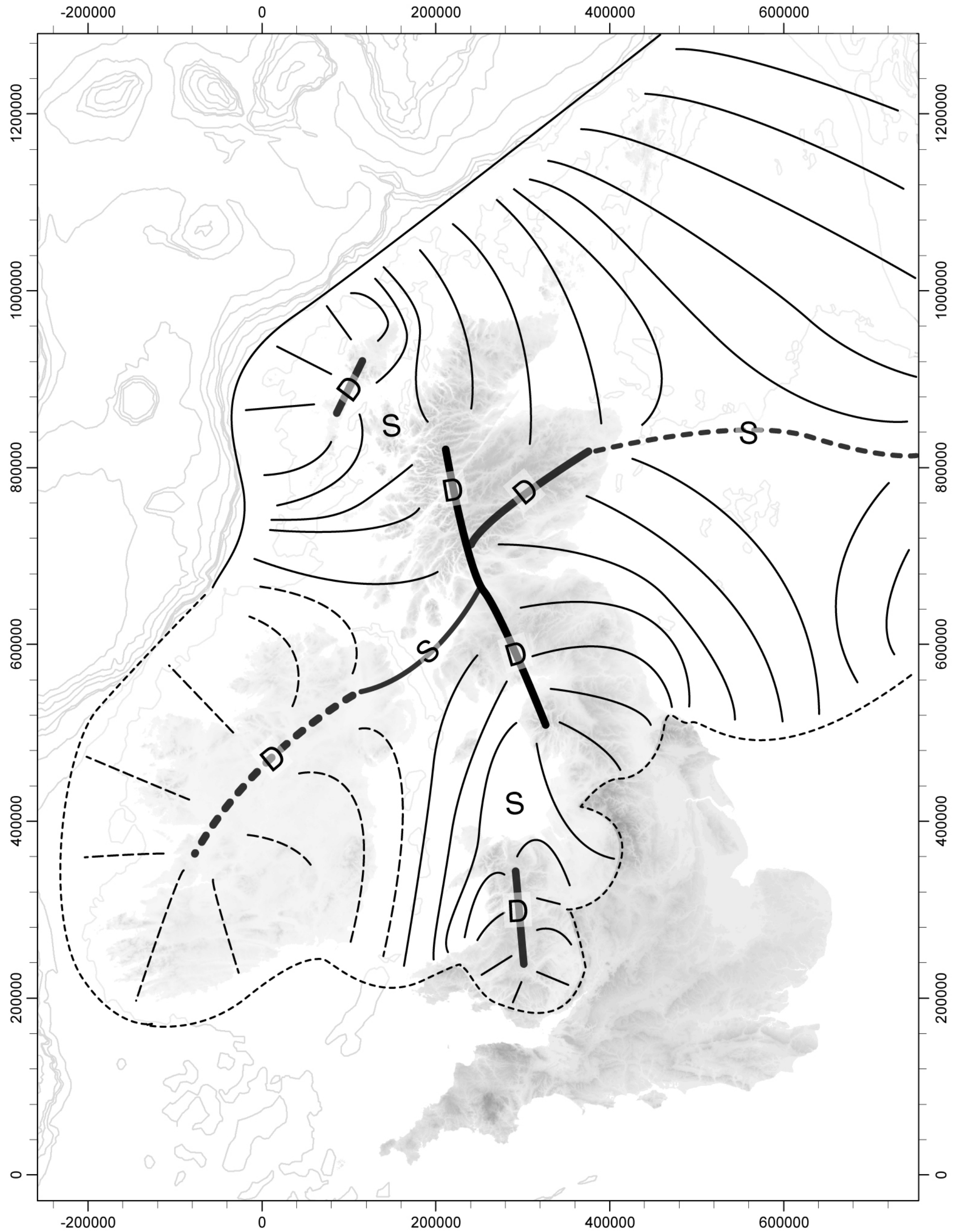

Figure 11.5 Hypothesised ice sheet form during confluence of ice in the North Sea (on the basis of currently available dates c.27-25 ka BP). Ice reaches the continental shelf edge. Ice divides are simple with a saddle forming over the North Channel. Flow patterns in Ireland are speculative and are therefore shown by dashed lines. From the dating database (chapter 10) the precise position of the southern limit is uncertain so is also shown by dashed lines. On the basis of the currently available dates for the deglaciation of the northern North Sea, ice does not reach the maximum southern limit in the Celtic Sea until after break up of ice in the North Sea (c.23 ka BP). Saddles are marked with an 'S' and divides are marked with a 'D'

The flow pattern configuration during this stage of confluence of British and Scandinavian ice is remarkably similar to that produced by Geikie in 1894. There are also glimpses of build up of ice. Southwest ice flow from the Southern Uplands (fs9) documents expansion of ice from Scotland into Ireland uninhibited by Irish ice, suggesting that the Irish Ice Sheet was not substantial enough at this stage to deflect Scottish ice. In contrast, the deflection of ice around

Wales (fs17) implies that this ice cap existed prior to advance of Scottish ice down the Irish Sea. The latter finding is in agreement with the conclusion of Jansson and Glasser (2008) but the evidence contrasts with the results of the numerical modelling of Boulton and Hagdorn (2006) that shows ice expansion from a single Scottish ice mass invading both Ireland and Wales.

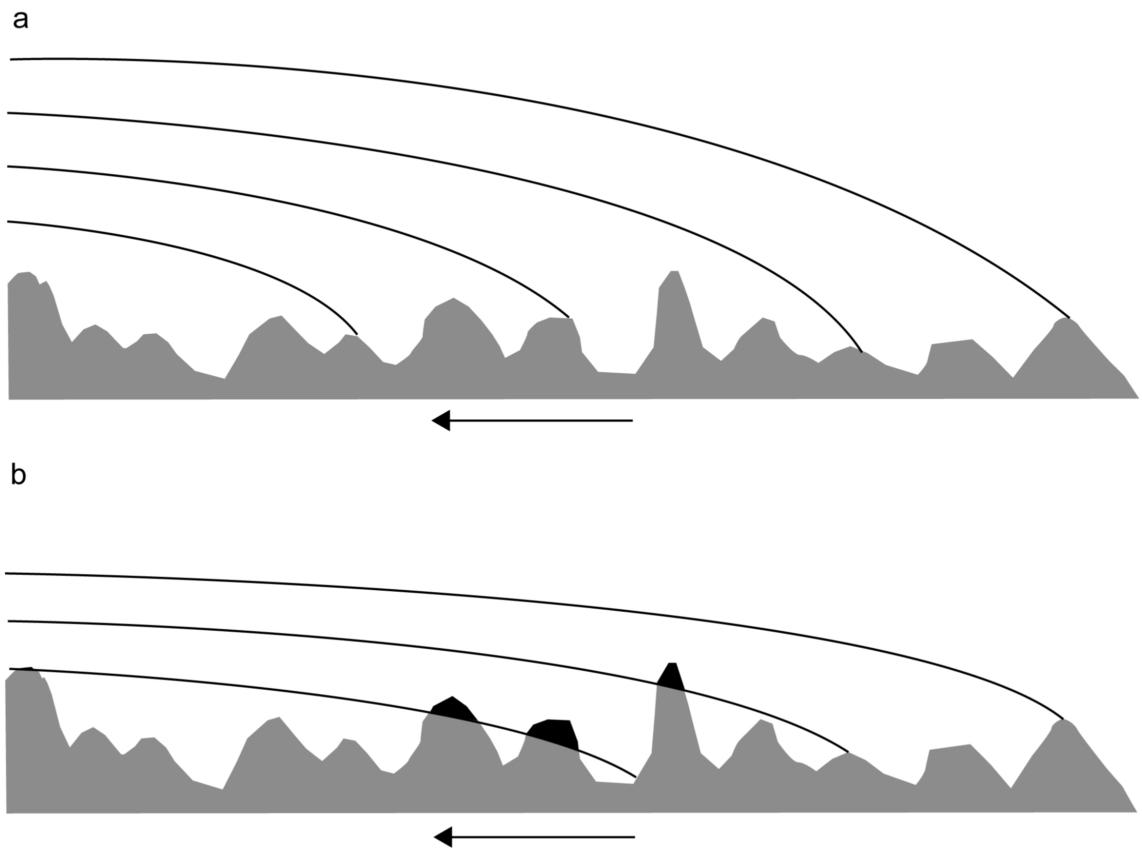

Figure 11.6 Retreat of an ice sheet that maintains its thickness during deglaciation (a) and retreat of an ice sheet that thins as it retreats (b). The last British Ice Sheet retreated following ice sheet thinning so that the variability in relief was close to the thickness of the ice at the periphery. Nunataks were revealed prior to retreat of the ice margin position and flow patterns were controlled by subglacial relief variations rather than ice surface slope.

The remaining flowsets are regarded as documenting the changing geometry of the ice sheet during deglaciation (figure 11.6). This interpretation is supported by their sympathy with the reconstructed pattern of retreat. The retreat pattern and flow patterns record a signature of ice sheet thinning. For example, lateral meltwater channels document lobes of ice retreating around the topographic obstacle of the Forest of Bowland towards the Howgill Fells (figure 9.3). This is consistent with the flow pattern information which records a change from ice flow overriding the topographic bump (fs31) to being deflected around it (fs69, fs70 and fs73) (figure 8.18). This pattern of deflection followed by retreat *around* topographic obstacles is repeated around the country at various scales. For example, ice is deflected by and retreats around the Cheviots; the Moray Firth and Strathmore ice lobes retreat around the Eastern Grampians. The Irish Sea lobe is deflected by and retreats around the Welsh Ice Cap and Scottish Ice is deflected by and retreats around the Outer Hebrides Ice Cap. The picture that emerges is of a dominant ice mass from western Scotland that encompasses (by lateral flow around, rather than overriding) satellite English and Welsh ice caps and peripheral ice caps in eastern Scotland. This conception of the ice sheet form explains the limited extension of erratics out of the Lake District and Cheviots and the lack of foreign geologies within these regions. Similar ice sheet configurations incorporating 'multiple domes and lobes' have been proposed for the Innuitian Ice Sheet (England et al., 2006) and the deglacial stages of the Scandinavian ice sheet on Denmark (Kjaer et al., 2003). The dominance of the western side of the ice sheet is also reflected in the combined observation from the retreat pattern, flow patterns and dates that the confluence of British and Irish ice in the North Channel persisted until after deglaciation of the Irish Sea. Based on the currently available dates separation of the two ice masses occurred between 17 and 16 ka BP; this follows retreat of ice from northern England and the NE corner of Buchan. During the later stages of deglaciation, the ice sheet thus resembled an elongated ellipse straddling the western upland areas of the British Isles from Shetland across Orkney and the NW Highlands to Northern Ireland. Such an orientation reflects the dominant west-east precipitation gradient over the British Isles (Chandler and Gregory, 1976).

It is tentatively proposed that break up of ice in the North Sea resulted in a reorganisation of the ice sheet; from a relatively thick ice sheet reaching the shelf edge with a central ice divide running broadly north to south (figure 11.5) to a thin ice sheet comprising multiple ice centres. We saw in chapter 8, how ice streams can be divided into a minimum of two phases of ice sheet configuration (figure 8.21). It is proposed that the initiation of ice streams along the east coast initiated lowering of the ice sheet surface and the development of a multi-domed ice sheet. The ice sheet then retreated from this position.

A question that arises from of the discovery of an ice sheet comprising local domes encompassed by far-travelled lobes, is whether some of the peripheral ice domes were cold-based. This could explain their limited expansion and the deflection of ice flow around them. Jansson and Glasser (2004; 2008) suggest that the Welsh ice cap was cold-based for much of the last glaciation particularly when coupled to the Irish Sea ice lobe, Mitchell (2008; 2007) describes evidence for cold-based ice on the Cheviots and the northern Pennines, and the landscape of the Cairngorms has for a long time been ascribed to the distribution of cold-based ice at the bed of the ice sheet (Sugden, 1968; Hall and Glasser, 2003). The presence of cold-based ice close to the periphery of the ice sheet has implications for the position of the southernmost limit in England. For example, cold-based ice could explain the apparent absence of glacial deposits and landforms on the Cleveland Hills and Peak District and therefore support a more southerly ice limit incorporating these areas. Approximately 40% of the mapped area contains landform patterns. There are surprisingly few gaps and those that do exist generally coincide with upland locations. The largest absences of information are in Wales and within the Loch Lomond Stadial ice cap limits in Scotland. Reasons for the latter gap are discussed in chapter 5 – the favoured explanation being that the hummocky moraine characteristic deposited by the Loch Lomond Ice Cap masks any pre-existing evidence. It is difficult to make firm conclusions from the absence of information in Wales; the paucity of landforms could reflect the lack of drift or represent regions of cold-based ice. There is a growing literature on the landscape characteristics that typify cold-based zones (Kleman and Stroeven, 1997; Hättestrand and Stroeven, 2002; Stroeven et al., 2006; Kleman and Glasser, 2007; Goodfellow et al., 2008). I did not attempt to map these areas and so it is not possible to make firm conclusions about the thermal regime of the last British Ice Sheet. This could be a fruitful avenue for further research.

11.3 Limitations

The research presented in this thesis is restricted to the terrestrial part of the ice sheet bed, i.e. that which currently lies above sea level. Furthermore, mapping was limited to England, Scotland and Wales, thus excluding Ireland. This thesis therefore only considers approximately one third of the former bed of the ice sheet (figure 11.7). However, this is still a major piece of the jigsaw and this thesis represents a major step forward in the collation of evidence of the last British Ice Sheet. Extrapolation and interpolation, and the scraps of offshore evidence contained within the BRITICE database are used to make statements beyond the British coastline. A geomorphological reconstruction of the Irish sector of the last British-Irish Ice Sheet was undertaken by a separate, but contemporary, PhD thesis (Greenwood, 2008). Our respective results are yet to be combined.

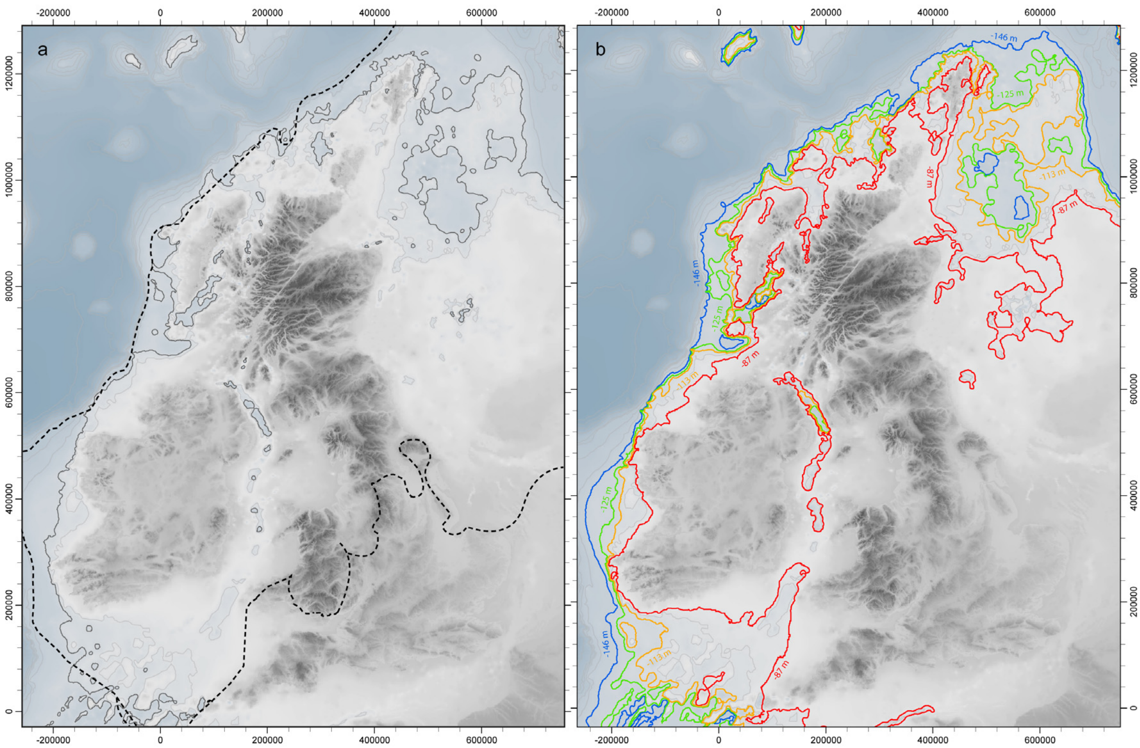

Figure 11.7 Map of the British Isles coloured up to demonstrate the land area available for the last British Ice Sheet: a) the grey line marks the -120 m contour, the dashed line the maximum limit of the ice sheet. Approximately 57% of the former ice sheet bed presently lies offshore; b) Shorelines as reconstructed from calculated eustatic fall in sea level by Lambeck et al. (2002). No account is taken of isostatic adjustments and so this gives only an approximate picture. Shoreline position at 22 ^{14}C ka BP (c. 25 ka BP) (blue), 18 ka ^{14}C ka BP (c. 22 ka BP) (green), 16 ^{14}C ka BP (c. 18 ka BP) (orange) and 14 ^{14}C ka BP (c. 16 ka BP) (red)

The reconstructed retreat pattern and regional flow configurations (chapters 8 and 9) are based on newly mapped and existing *geomorphological* evidence. They are the most parsimonious explanations that can accommodate what we see in the landscape. Deliberately, and to keep interpretations as objective as possible, no systematic attempt was made to incorporate interpretations from the literature, although in the case of a few equivocal scenarios, reference was made to corroborating sources. The mapping on which all interpretations are based was conducted remotely from DEM and satellite imagery and was not accompanied by a systematic field campaign to 'ground truth' observations. The lack of 'ground truthing' is not regarded as a significant weakness. The resolution of the principal data source (the NEXTMap DEM) is very high relative to the size of the majority of target landforms which therefore have a clear expression in the data. The rigorous quality control checks (detailed in chapter 4) and favourable comparison to detailed field observations, where available, substantiate the reliability of the final maps. Furthermore, the use of earth observation data is the only way to conduct rapid consistent mapping of the whole of the glaciated area. This approach to data collection was chosen specifically to resolve the restrictions of previous field based research. Now we have a synoptic view we can add detail from local scale field investigations. For this purpose, locations of problematic or conflicting evidence have been flagged for further attention.

The reconstructions of ice sheet flow geometry and retreat pattern are dependent on the accurate abstraction of the geomorphological evidence (e.g. flowsets and margin positions). The process of abstraction (flowset-ology) cannot be entirely objective. Attempts have been made to automate the identification of flowsets to reduce subjectivity although at present no method is an adequate substitute for the human eye (Smith, 2003). It is therefore possible that others may reconstruct different flowsets from the maps. For this reason there has been a deliberate and clear separation of data (mapping results) from interpretations (flowsets, summaries and then reconstructions) in this thesis. The mapping will be published and available for future workers who may interpret the maps in new and different ways based on our evolving knowledge of ice sheet glaciology.

The strong association of flowsets and topography presented challenges to the flowset approach. It was necessary to introduce an additional conceptual model for interpreting smudged imprints to accurately capture the landform record (*TT thinning*). Unlike the Laurentide and Scandinavian ice sheets, where the flowset approach was developed, the bed of the former British Ice Sheet has a high variability of relief over short distances. The flowsets produced for the BIS are numerous and complex (compare 100 flowsets in Britain to 10 for the Labrador sector of the Laurentide Ice Sheet, which is four times the size of Britain (Clark et al. 2000)). In Britain flowsets are also spatially fragmented, increasing the number of possible permutations of flow configurations that satisfy the relative chronology. The concept of networks of ice flow around cold based patches may be a useful concept for flowset identification in the British context (Kleman and Glasser, 2007). It would be interesting to see if these principles would lead to a different reconstruction of the ice sheet geometry.

11.4 Directions for future research

An obvious next step is to combine the retreat pattern (chapter 9) with the flow pattern geometries (chapter 10) to reconstruct the time-slice evolution of the ice sheet. Combining the observations from this thesis with the results of a parallel investigation into the Irish landform record (Greenwood, 2008) is also a priority.

It is expected that the mapping contained within this thesis will serve as a framework for sedimentological and stratigraphical information as well as a starting point for field based geomorphological mapping efforts. In particular, the moraine mapping would benefit from field investigations to determine the type of moraines. In addition, it is hoped that there will be a drive to obtain high resolution and three-dimensional seismic data from the offshore portion of the ice sheet in the near future. Recently published work has demonstrated the wealth of information that may exist (Bradwell et al., 2008b; Graham et al., 2007). Obtaining bathymetric data is expensive; it is expected that the new mapping in this thesis will serve to identify locations for targeted investigations. The mouths of ice stream imprints, the Irish Sea basin, the North Channel, and the southern North Sea, (in particular along the eastern English coast) should be a priority.

The work in chapter 10 to attach a chronology to the retreat pattern highlighted inconsistencies within the presently available dates for the last British Ice Sheet. There is also an absence of information for large areas, e.g. the Southern Uplands. It is necessary for dating experts to re-examine the presently available dates to reject those that may be erroneous as well as conduct additional dating.

Numerical modelling is also the only way we can investigate the reasons for the dynamic behaviour of the ice sheet (Boulton et al., 2001). Numerical modelling can use the results of this research in two ways:

1. The new mapping and identified flowsets and margin positions can be used to validate model outputs. The flowset map (Map 4) should be invaluable to numerical modellers as it assimilates the subglacial lineation evidence into flow pattern units that are of a comparable size to the resolution of most models (e.g. Napieralski et al., 2006; Li et al., 2007; Napieralski et al., 2007).
2. Models can be employed to test the glaciological plausibility of the regional scenarios of flow pattern evolution (e.g. Naslund et al., 2003).

It would be interesting to compare the reconstructed retreat pattern with the sea level positions of the last glacial (figure 11.7). This would serve to identify the sites of calving margins. This information can be used to model the trajectories of icebergs to examine the possible effect of ablation from the BIS on the ocean circulation of the North Atlantic (e.g. Death et al., 2006).

11.5 Conclusion

11.5.1 Summary of achievements

This thesis makes several contributions to both knowledge of the glacial landform record of Britain and our understanding of the last British Ice Sheet. The results are summarised in order of significance.

- *The first map of subglacial bedforms for England, Scotland and Wales (Map2).* The map is thought to be near complete and a reliable representation of the true population and distribution of British drumlins, mega-scale glacial lineations, crag and tails, and ribbed moraine. The map considerably extends and adds detail to the previously known distribution and pattern of subglacial bedforms.
- *The first countrywide map of moraines, eskers and meltwater channels (Map 3).* This map summarises reconnaissance level mapping of these landforms and is likely to be improved by future fieldwork and reference to aerial photographs. In addition to the paper maps, both maps (Maps 2 and 3) exist digitally as GIS vector layers. This enables rapid comparison with digital versions of topographic and geological maps.
- *The first attempt at a fully comprehensive geomorphological inversion model of the last British Ice Sheet.* The spatial distribution of landforms has been investigated and the essential patterns summarised into flowsets and margin positions. Instances of cross-cutting were used to organise the flowsets into a relative age stack in order to examine flow pattern evolution. These summaries will be invaluable in validating numerical models of the ice sheet (e.g. Napieralski et al., 2006; Li et al., 2007; Napieralski et al., 2007).
- *Identification and confirmation of the locations of ice streams of the last British Ice Sheet.* The criteria of Stokes and Clark (1999) were used to identify those flowsets delineating ice stream imprints. The new mapping does not support all of the proposed palaeo-ice streams in the literature but does confirm that ice streams operated in the Minch, Moray Firth, Strathmore, Tweed, and Irish Sea. There is additional evidence for an ice stream in the Firth of Forth as hypothesised by Golledge and Stoker (2006) and suggested by numerical modelling (Boulton and Hagdorn, 2006). Future models of the ice sheet need to be able to simulate ice streams in these locations.
- *Synthesis of deglacial evidence to reconstruct the pattern of retreat of the last British Ice Sheet.* Five independent lines of evidence were used to build a picture of the pattern of retreat of the last British Ice Sheet. In general, the evidence is corroborative. The ice sheet retreated to multiple centres, and not necessarily the nearest high ground. Deglaciation by

thinning of lobes of ice to expose peripheral high ground before final retreat of the ice front is a common feature across the country. Initial retreat was generally towards the west and the North Channel indicating that connection with the Irish Ice Sheet was maintained during deglaciation of the Irish Sea. Following separation from the Irish ice mass ice retreated towards the Scottish Highlands.

- *Regional flow pattern evolution.* Flowsets have been organised into regional level reconstructions of flow pattern evolution. The Welsh Ice Sheet appears to have been a relatively stable feature throughout the glaciation. Other ice divides are more transient. Complex flowsets in inter-divide areas suggest competition between ice centres during retreat. There is evidence for confluence of British ice and Scandinavian ice in the North Sea, followed reorganisation of the ice sheet after break up of the North Sea ice. The majority of flowsets relate to the deglacial stages and indicate a multi-domed ice sheet.
- *A large consistent dataset of drumlin dimensions.* Research into the formation mechanism behind drumlins is ongoing and high resolution maps of drumlin shape are essential for hypothesis testing. Robust statistical analysis of drumlin morphometry requires large sample sizes such as provided by the new mapping presented in this thesis. Lengths, widths, and elongation ratios of the database of 36,222 drumlins, has been analysed and published elsewhere (Clark et al., in press).
- *A database and map of dates relating to the last British Ice Sheet.* A thorough search of the Quaternary and archaeological literature was conducted in order to compile a list of dates relating to the last glaciation of Britain. Date locations were digitised and the dates now exist as a GIS vector layer (n = 426) and accompanying table.
- *A method for comprehensive mapping of formerly glaciated areas using digital data sources.* A method for systematic mapping of subglacial bedforms from digital elevation data (Clark and Meehan, 2001) was applied to the NEXTMap Britain (5 m horizontal resolution) digital elevation model. This facilitated precise mapping of landform shape and avoided the problems of azimuth bias that can reduce the reliability of mapping from satellite imagery which is illuminated from a single solar position. The method was extended to map moraines, eskers and meltwater channels. Other digital datasets (e.g. geological maps) were used to check interpretations.
- *Revision of the protocol for flowset classification to reflect the peculiarities of the British landscape.* An additional conceptual model for lineation cross cutting was used to capture the observed 'smudging' of lineation patterns around topographic obstacles.
- *An up to date (to December 2007) version of the BRITICE GIS database.* The BRITICE project and glacial map did a great service to the palaeo-glaciological community in Britain by summarising the 170 years of published maps of British glacial landforms in one place (Clark et al 2004; Evans et al 2005). The census date of the compilation was 2002. Throughout the life-time of this PhD research, following publication of the map in 2004,

there has been an upsurge in published maps of glacial landforms. Much of the new mapping has been digitised and added to a working copy of the BRITICE dataset. This will facilitate publication of BRITICE version 2 in the near future. Once published, Maps 2 and 3 can also be entered into the updated BRITICE.

11.5.2 Palaeoglaciology of the last British Ice Sheet

The central aim of this thesis has been to reconstruct the ice sheet scale characteristics of the last British Ice Sheet based on existing and newly acquired geomorphological evidence. In an ideal reconstruction, glimpses of flow pattern evolution would extend over the whole of the former ice sheet bed and be integrated with the reconstructed retreat pattern to produce a time-slice stack of snapshots of ice sheet configuration, with stratigraphic evidence and absolute chronological information used to frame the operation of the ice sheet. Given the quantity of information this involves (including dates and already published literature), it is a large task. Within this thesis I have focused on producing high quality mapping for the whole of the accessible area of the former bed (i.e. land presently above sea level) and constraining the pattern of retreat. This thesis represents a major step forward in bringing together the necessary geomorphological (mapping and flowsets) and chronological (database of dates) evidence towards the goal of a full ice sheet scale reconstruction.

From the preceding discussion (section 11.4) we can make several conclusions about the form and dynamics of the last British Ice Sheet. It is evident that the British glacial landform record is a palimpsest. In light of this it is inaccurate to reduce drumlin patterns, in particular, into generalised ice flow patterns. It is essential that any future research also examines the detailed distribution and pattern of drumlins to tease out flow pattern information. A total of 100 flowsets were identified by careful examination of the lineation mapping. The fact that many of these cross cut each other is testament to changing configuration of the last BIS during the glacial cycle. Grouping of flowsets into plausible ice sheet geometries suggests that some ice divides were persistent features (e.g. Wales and NW Highlands) whereas others were more transitory (e.g. the ice dome over the western Southern Uplands). Unlike other ice sheets, the majority of flowsets exhibit a close relationship to subglacial relief. During deglaciation, the ice sheet was thin relative to variations of the bed and comprised a dominant Scottish centred ice mass, lobes of which radiated out to encompass peripheral ice masses in England and Wales. The ice retreated to multiple sites coincident with the westernmost upland regions. It is proposed that the majority of geomorphological evidence relates to the deglacial stages of the ice sheet. However, there is some vestigial evidence for an earlier ice flow configuration during confluence of British and Scandinavian ice and shelf edge glaciation.

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Appendix

Table A1: List of absolute dates related to the last British Ice Sheet collated from published literature and online date lists. Most of the more recently derived dates are taken from the original publications, older published dates from review articles. This is indicated in the 'cited from' column, where 1 = Jones and Keen (1993); 2 = Evans et al. (2005); 3 = Centre for British Archaeology (CBA) datelist; 4 = Knight (2001); 5 = Sutherland (1984); 6 = Bowen (2005); 7 = Bowen et al. (1999); 8 = Andersen et al. (1981); 9 = Sutherland (1986); 10 = Scourse (2006); 11 = Thomas et al. (2004); 12 = Gray and Lowe (1977); 13 = Sissons (1967); 14 = Everest and Kubik (2006); 15 = Birnie et al. (1993); 16 = Sejrup et al. (1994); and 17 = Lukas et al (2004). Stratigraphic position of sample is listed when provided by the source reference. Comment column includes pertinent observations from source reference. This column also includes reason for date being excluded from analysis where appropriate. For example, if the original paper regarded the sample as contaminated then the date was not used. Dates used in analysis are marked in bold. Some dates derived from the CBA date list have limited source information and/or a lack of information on stratigraphy. Type column describes the nature of date in terms of the chronology of ice sheet; advance = sample below till, deglacial = date above till or in lateglacial sediments, margin = date close to margin of ice, e.g. date of moraine, ice free = ice free conditions but unspecified stratigraphy e.g. a date for human/animal occupation of a cave suggests that cave location was ice free at this time, IRD = dated unit recording ice rafted debris input to ocean. Site number is same as on map of date locations, figure 10.2. *Published ^{14}C ages calibrated using Fairbanks0107 calibration curve Fairbanks et al. (2005), see chapter 10 for details. #Average marine reservoir correction for UK of 347 years used where appropriate for marine samples. This value was calculated as mean average for UK seawaters from the Marine Radiocarbon Online database.

Site	Location: Name	OS Grid ref. Northing	OS Grid ref. Easting	Dated Material	Dating Method	^{14}C age / yr BP	Calibrated age* / yr BP	Age / yr BP	Stratigraphic position	Comment	Date type	Source Reference	c.f.
1	Little Porth Askin	88200	7400	Sand	TL	-	-	**18800 +/-3700**	Old Man sandloess; breccia overlain by loess in south and till in north	-	Margin	Wintle (1981); Scourse (1990)	10;2
				Organics	RC	25920 +/-325	31144 +/-379	-			-		
				Humic	RC	20960 +/-180	25067 +/-267	-			-		
				Humic	RC	22960 + 625/ -580	27559 +/-725	-	Overlain by Old Man Sandloess	Possible contamination discarded from analysis as unreliable; humin and humic dates from reassessment of site	-		
				Humin	RC	23980 + 1400/- 1200	28764 +/-1682	-			-	-	10
				Humin	RC	24550 + 500/ – 400	**29417 +/-658**	-		Regarded as most reliable	Advance		
2	Carn Morval	90600	11700	Sand	OSL	-	-	20000+/-7000	Old Man sandloess	Large errors	-	Smith et al. (1990)	10
				Sand	OSL	-	-	26000+10000-9000			-		
				Humin	RC	21500 + 890 – 800	**25778 +/1137**	-		Regarded as most reliable	Advance		
				Humic	RC	19300 +/-120	22936 +/-194	-	Organic silt overlain by solifluction breccia	Regarded as unreliable	-		
				Humic	RC	19860 + 220/ – 210	23724 +/-277	-			-	-	10
				Humin	RC	24490 + 960/ – 860	**29370 +/-1181**	-		Regarded as most reliable	Advance		
				Sand	TL	-	-	**18600+/-3700**	Well sorted sandy silt, loess, overlies breccia	Old Man Sandloess	Margin	Wintle (1981)	
				Organics	RC	20630 + 480/ – 450	24638 +/-622	-	Organic beds overlain by solifluction breccia and well sorted silt (loess)	High risk of contamination at this site discarded from analysis as unreliable	-		10
				Organics	RC	26550 + 700/ – 650	31818 +/-775	-			-		
3	Watermill Cove	92500	12300	Humin	RC	26680 + 1410/ – 1200	**31916 +/-1573**	-		Most reliable of series of dates taken on basis of radiocarbon content	Advance	-	
				Humin	RC	33050 + 960/ – 860	**38434 +/-966**	-	Overlain by solifluction breccia		Advance		10
				Organics	RC	21200+900/ -600	25395 +/-1159	-		Regarded as least reliable of series	-	Page (1972)	
				Organics	RC	22200+/-400	26690 +/-484	-			-		
4	Scilly Isles	89634	14932	Organics	RC	34500 + 880/ – 885	**39853 +/-862**	-	Located below glacigenic and periglacial sediments	approx location	Advance	-	1;10
5	Bread & Cheese Cove,	94000	15800	Sand lens	OSL	-	-	**49000 +/-3000**	Depth 3 m, glaciotectonised Silly till	Max age for glaciotectonic event;	Advance	-	10
6	Battery	88700	16500	Sand	OSL	-	-	22700 +/-900	Ice marginal sandy gravel overlain by breccia, overlies 'Scilly till'	Caution as lots of feldspar problems discarded from analysis as unreliable	-	-	10
				Sand	OSL	-	-	25100 +/-2200			-		

Site	Location: Name	OS Grid ref.: Northing	OS Grid ref.: Easting	Dated Material	Dating Method	^{14}C age / yr BP	Calibrated age* / yr BP	Age / yr BP	Stratigraphic position	Comment	Date type	Source Reference	c.f.
				Humic	RC	11220 + 1550/– 1300	13005 +/- 1910	-			-		
				Humin	RC	15450 +/-120	18675 +/- 119	-		Discarded from analysis as unreliable	-		
7	Porth Seal	91800	16600	Humin	RC	18780 +260/ – 250	22374 +/- 271	-	Organic silt overlying beach and underlain by breccia		-	Scourse (1991)	10
				Humic	RC	25670 + 560/ – 530	**30842 +/- 674**	-		Considered most reliable by Scourse (1991)	Advance		
				Humin	RC	34500 + 885/ – 800	**39853 +/- 866**	-			Advance		
8	Celtic Sea	100628	158438	Mollusc valves	AMS	11570 +/-100	**13433 +/- 112**		Late glacial sediments – shallow water infer low sea level	Core 51/07/199	Deglacial	Scourse and Austin (1994)	4
				Bone	RC	25650 +/-1300	**30752 +/- 1526**	-	Human occupation	Bos bone	Ice free	Molleson and Burleigh, (1978)	1
				Humic	RC	28000 +/-1700	**33324 +/- 1803**	-		Charred bone	Ice free	Gowlett et al. (1986)	3
				Bone	RC	18460 +/-340	22006 +/- 431	-		Young date in comparison to others, and earliest determination – excluded as unreliable	-	Barker et al. (1969)	3
9	Paviland Cave	243700	185900	Bone	RC	25840 +/-280	**31058 +/- 332**	-	Human burial	-	Ice free	Aldhouse-Green (2000)	6
				Bone	AMS	26350 +/-550	**31606 +/- 615**	-		-	Ice free		6
				Bone	RC	23670 +/-400	**28363 +/- 472**	-		-	Ice free	Hedges et al. (1994)	3
				Bone	RC	29600 +/-1900	**34970 +/- 1940**	-		-	Ice free	Gowlett et al. (1986)	3
				Bone	RC	27600 +/-1300	**32922 +/- 1394**	-	Human occupation	Bos bone	Ice free	Burleigh et al. (1982)	3
				Bone	RC	38000 +/-8000	42984 +/- 1767	-		Very large error, excluded from analysis	-	Gowlett et al. (1986)	3
				Bone	RC	38800 +/-8000	43516 +/- 2742	-			-	Gowlett et al. (1986)	3
				Tooth	RC	31500 +/-1200	36884 +/- 1207	-	Ages conflict with rest of faunal assemblage	Younger than expected, possible reworking, discarded from analysis as unreliable	-	Hedges et al. (1996)	3
				Tooth	RC	33200 +/-950	38583 +/- 954	-			-		3
10	Bacon Hole Cave	255900	186800	stalagmite	U	-	-	12000 +/-10000		Very large error so excluded	-	Currant et al (1984)	6
				stalagmite	U	-	-	**12800 +/-1700**	-	-	Ice free		6
				Stalagmite	U	-	-	**13000 +/-3000**			Ice free		6
		633800	241390	Antler	RC	29900 +430/ -410	**35306 +/-435**	-			Advance		
11	Sourlie	633650	241470	Plant	RC	29290 +/350	**34706 +/-383**	-	Overlain by till and underlain by till		Advance	Jardine et al (1988)	
				Organic silt	RC	30230 +/-280	**35621 +/-294**	-			Advance		
		633650	241743	Organic silt	RC	33270 +/-370	**38662 +/-392**	-			Advance		
12	Arthur's Stone, Cefn Bryn	299300	190300	Cairn	CO	-	-	**22800 +/-2000**	-	Constraint on max extent of ice responsible for deposition of Langland member	Deglacial	Bowen (1994); Phillips et al (1994)	7
13	Gower Peninsula	245289	192192	Boulder	CO	-	-	**23200 +/-2000**	Sample from erratic on top of late Devensian end moraine	Quartzite approx location	Margin	Phillips et al (1994)	4
				Tooth	RC	23340 +/-350	27991 +/- 419	-			-		3
				Bone	RC	23550 +/-290	28228 +/- 354	-	Predates human occupation		-	Hedges et al. (1993)	3
				Tooth	RC	28930 +/-800	34325 +/- 830	-			-		3
				Tooth	RC	34590 +/-1500	39916 +/- 1435	-			-		3
				Bone	RC	17600 +/-200	20827 +/- 265	-			-		3
14	Little Hoyle	211180	199970	Bone	RC	22800 +/-300	27380 +/- 366	-	-	Approximately 37 km from maximum drift limit – therefore not used to constrain the glaciation. Human occupation here throughout the glacial? Supports ice free conditions throughout the glacial in Pembrokeshire.	-	Hedges et al (1987)	3
				Bone	RC	29200 +/-700	34603 +/- 720	-			-		3
				Bone	RC	17050 +/-1000	20285 +/- 1145	-			-		3
				Bone	RC	18200 +/-1300	21661 +/- 1574	-	Human occupation		-	Green et al. (1984)	3
				Bone	RC	20100 +/-1100	24001 +/- 1384	-			-		3
				Bone	RC	20800 +/-900	24882 +/- 1156	-			-		3
15	Hoyles Mouth	209992	200768	Bone	RC	27900 +/-600	33257 +/- 650	-	-	As above	-	Hedges et al (1987)	3
16	Mullock Bridge	181405	207739	Shell	RC	37960 +1700/ – 1400	**42656 +/- 1502#**	-	Outwash gravel beneath till	-	Advance		8

Site	Location			Dated Material	Dating Method	^{14}C age / yr BP	Calibrated age* / yr BP	Age / yr BP	Stratigraphic position	Comment	Date type	Source Reference	c.f.
	Name	OS Grid ref. Northing	OS Grid ref. Easting										
17	Coygan Cave	228400	209100	Bone	RC	24620 +/-320	**29484 +/- 448**	-	Min date for end of human occupation; human occupation before	Woolly rhino	Ice free	Hedges et al. (1994)	3
				Bone	RC	38684 + 2713/ – 2024	**43512 +/- 1507**	-	Same level as hand axes, date for human occupation of site	Reindeer	Ice free	Stuart, (1982)	1
18	Craig-y-Fro, Brecon Beacon	297648	221177	Organics	RC	10030 +/-100	**11537 +/- 220**	-	Basal organic material	Features produced during the Loch Lomond Stadial, outer moraines	Deglacial	Walker, (1980, 1982)	1
19	Traeth Mawr, Mynydd Illtyd	294131	223060	Organics	RC	11600 +/-140	**13460 +/- 147**	-	Dead ice hollow with complete late glacial vegetation sequence	Start of Loch Lomond Stadial dated	Deglacial	Walker, (1982)	1
20	Tre-llys	184654	231126	Shell	RC	37310 + 1515/ – 1275	**42089 +/- 1350#**	-	Within ice contact deposits	Bulk sample	Advance	-	8
21	Banc y Warren	219965	248172	Wood	RC	33750 + 2500/ - 1900	**39068 +/- 2407**	-	Organic lenses with glaciofluvial outwash	-	Advance	John, (1967)	8; 1
				Wood	RC	31800 + 2500/ - 1900	**37163 +/- 2485**	-	From sands and gravels	Bowen (1984 demonstrated that sequence Late Devensian and earlier RC dates due to reworking	Advance	-	2
22	Church Street, Shropshire	346415	303236	Peat	RC	13555 +/-620	**15825 +/- 829**	-	Rests on Irish Sea till	-	Deglacial	-	8
23	Condover	349500	306500	Tooth	RC	12400 +/-160	**14299 +/- 274**	-	Late glacial sediments within kettle hole within limit of late Devensian ice	Mammoth	Deglacial	Coope and Lister, (1987)	3
				Bone	RC	12700 +/-160	**14776 +/- 237**	-			Deglacial		1
				Bone	RC	12920 +/-390	**15022 +/- 505**	-			Deglacial		1
				Coleoptra	RC	11880 +/-130	**13715 +/- 115**	-		-	Deglacial	Hedges et al. (1989)	3
				Coleoptra	RC	12080 +/-130	**13882 +/- 128**	-			Deglacial		3
				Tooth	RC	12300 +/-180	**14152 +/- 268**	-		Mammoth	Deglacial		3
				Tooth	RC	12330 +/-120	**14173 +/- 199**	-		Mammoth	Deglacial		3
				Coleoptra	RC	13950 +/-160	**16275 +/- 248**	-		-	Deglacial		3
24	Four Ashes	391600	308200	Organics	RC	30500 +/-400	**35878 +/- 405**	-	Organic lenses within sands and gravels underlies red till with Irish Sea erratics	Youngest date obtained	Advance	Morgan, (1973)	1
				Organics	RC	30655 + 765/ – 700	**36037 +/- 765**	-		-	Advance		8
25	Rodbaston	392290	311140	Peat	RC	10300 +/-170	**12074 +/- 312**	-	-	-	Deglacial	Morgan, (1973); Shotton and Strachan (1959)	1
				Peat	RC	10670 +/-130	**12606 +/- 126**	-			Deglacial	Morgan, (1973)	1
26	Pentney	570700	313100	Moss	RC	21000 +/-1000	**25138 +/- 1279**	-	Within sands and gravels		Advance	Ventris (1985)	7
27	Pillaton Hall Penkridge	324460	314354	Peat	RC	11660 +/-250	**13508 +/- 244**	-	Above sand	Assume same location as Penkridge date	Deglacial	Morgan, (1973)	1
				Organics	RC	11580 +/-140	**13440 +/- 149**	-	Within gravels	-	Deglacial		
28	Buildwas, Shropshire	366553	316229	Shell	RC	31840 + 1660/ – 1360	**36883 +/- 1662#**	-	Within kame complex	Ice extended at least as far as Wolverhampton moraine	Advance		8
29	Tattershall	557000	321000	Organics	RC	42100 + 1400/ – 1100	**46387 +/- 722**	-	Within sands and gravel	-	Advance	Girling, (1974)	1
				Organics	RC	44200 + 1600/ – 1300	**48151 +/- 1232**				Advance		1
30	Porth-y-Waen	326500	322000	Peat	RC	10270 +/-100	**12031 +/- 187**	-	-	-	Ice free		3
				Bone/Antler	RC	11740 +/-150	**13593 +/- 143**	-		Barbed points	Ice free		3
				Bone/Antler	RC	11390 +/-120	**13238 +/- 137**	-			Ice free	Hedges et al. (1990)	3
31	Porth Neigwl	229000	325500	Shells	RC	29000 +/-1200	**34035 +/- 1244#**	-	Shells within Irish Sea Till	-	Advance		2
32	Stafford	392600	332400	Organics	RC	13490 +/-375	**15716 +/- 469**	-	Basal organic deposits in a depression in fluvioglacial gravel	-	Deglacial	Morgan, (1973)	1
				Organics	RC	13250 +/-300	**15429 +/- 365**	-			Deglacial	Bartley and Morgan, (1990)	1
33	Glanllynnau, Lleyn Peninsula	244900	337300	Peat	RC	14468 +/-300	**17110 +/- 534**	-	Sample from base of kettle hole over a complex till sequence	Date for melting ice on Lleyn Peninsula	Deglacial	Coope and Brophy, (1972)	2; 4
				Organics	RC	12556 +/-230	**14548 +/- 358**	-	Sample from within basal clays, kettle hole within outwash in filled from sediments	Date from organics prior to Lateglacial sequence	Deglacial		4

Site	Location: Name	OS Grid ref.: Northing	OS Grid ref.: Easting	Dated Material	Dating Method	^{14}C age / yr BP	Calibrated age* / yr BP	Age / yr BP	Stratigraphic position	Comment	Date type	Source Reference	c.f.
34	Bryncir Moraine	245500	337300	Organics	RC	10170 +/-160	**11830 +/- 318**	-	Kettle hole peat overlying moraine	Readvance of moraine before this time	Deglacial	Foster, (1968)	2
				Organics	RC	16830 + 970/ – 860	**20034 +/- 1094**	-	Within the Bryncir Moraine	possibility for readvance of Welsh ice into Irish sea after this time	Advance	Foster, (1968, 1970)	2
35	Elderbush Cave	409700	354800	-	RC	10600 +/-110	**12543 +/- 122**	-	-	-	Ice free	Gowlett et al (1986)	3
36	Chelford	386729	354948	Sand	OSL	-	-	**27000 +/-2000**	Below Stockport formation	-	Advance	Bateman, pers. Com	
37	Ossom's Cave	409600	355700	Bone	RC	10590 +/-70	**12545 +/- 76**	-	Human occupation	-	Ice free	Taylor (1980)	3
				Antler	RC	10600 +/-140	**12533 +/- 163**	-			Ice free		3
				Bone	RC	10780 +/-160	**12697 +/- 141**	-			Ice free		3
38	Moel Tryafaen	252518	356754	Shells	RC	33740 + 2100/ – 1800	**38747 +/- 2045#**	-	On summit	-	Advance	Foster (1968)	
39	Tattershall Castle	521100	357100	Sand	TL	-	-	21000 +/-8500	Sand and gravel with silts within channel infill	Very large error so almost meaningless	-	Perkins and Rhodes (1994)	7
40	Cwm Cywion	263200	360400	Mud	RC	13670 +/-280	**15927 +/- 364**	-	In filled lake basin	-	Deglacial	Ince, (1981)	2
41	Fox Hole	409970	366180	Antler	RC	11970 +/-120	**13788 +/- 106**	-	Human occupation	Artefact	Ice free	Hedges et al (1989)	3
42	Dowel Cave	407600	367600	Antler	RC	11200 +/-120	**13046 +/- 115**	-	Human occupation	Artefact	Ice free	Hedges et al (1989)	3
43	Cae Gronw Cave	301500	371000	Bone	RC	29000 +/-800	**34397 +/- 827**	-	Above unit containing human evidence	Bear, min date for end human occupation	Ice free	Hedges et al (1997)	3
				Bone	RC	20200 +/-460	24105 +/- 561	-	-	Reindeer, disturbed unit - unreliable	-		3
				Bone	RC	35100 +/-1500	**40396 +/- 1412**	-		Bear	Ice free		3
44	Pontnewydd Ice free	300900	371200	Bone	RC	25970 +/-330	**31198 +/- 383**	-	Within debris flow breccia, predates human occupation	Bear	Ice free	Hedges et al (1996)	3
				Bone	RC	27070 +/-360	**32380 +/- 414**	-		-	Ice free		3
				Bone	RC	28470 +/-410	**33857 +/- 452**	-			Ice free		3
				Bone	RC	28730 +/-420	**34128 +/- 461**	-		Wolf	Ice free		3
				Bone	RC	28950 +/-450	**34355 +/- 488**	-			Ice free		3
				Bone	RC	32870 +/-660	**38261 +/- 675**	-		-	Ice free		3
				Bone	RC	33200 +/-650	**38589 +/- 660**	-			Ice free		3
				Bone	RC	35270 +/-860	**40582 +/- 817**	-		Horse	Ice free		3
				Bone	RC	29000 +/-800	**34397 +/- 827**	-	No information; presume as rest of site	-	Ice free	Hedges et al (1987)	3
45	Tremeirchion Caves	308500	372400	Bone	RC	18000 +/-1200	**21415 +/- 1447**	-	Woolly mammoth bone within cold climate assemblage beneath Irish Sea Till	Max age for glaciation OR a max age of a readvance to Bodfari-Trefant moraine	Advance	Rowlands, (1971) Bowen, (1974)	1; 2
46	Goats Hole Cave	299722	373321	Stalagmite	U	-	-	**36800 +/-4000**	-	Stalagmite formation; large error	Ice free	Aldhouse-Green (2000)	6
47	Stockport	381495	378595	Shell	RC	28000 +/-1800	**32956 +/- 1936#**	-	Marine fauna within Stockport formation	-	Advance		8
48	Aby Grange	543900	379800	Peat	RC	11205 +/-120	**13051 +/- 116**	-	Basal peat in a kettle hole	Min age for Hogsthorpe moraine	Deglacial	Suggate and West (1959)	2
49	Kendrick's Cave	278000	382400	Bone	RC	10100 +/-200	**11699 +/- 372**	-	Human occupation	-	Ice free	Gillespie et al (1985)	3
50	Messingham	491300	403800	Organics	RC	10550 +/-250	**12427 +/- 335**	-	Organic material 2m higher in the sequence	-	Deglacial	Buckland, (1982)	1
				Peat	RC	10280 +/-120	**12047 +/- 226**	-	Peat below cover sands		Deglacial	Buckland, (1976)	1
51	West Moor	464840	407180	Soil	RC	11110 +/-200	**12974 +/- 181**	-	Buried soil (palaeosol) on laminated clay interpreted as lacustrine sediment	Min age for disappearance/emptying of lake Humber	Deglacial	Gaunt et al (1971)	1; 2
52	Clieves Hills	338600	408000	Pollen	RC	10455 +/-100	**12358 +/- 169**	-	Grasses, sedges and dwarf shrubs flora within peat below sand	Date for deposition of Shirdley Hill Sand	Deglacial	Tooley and Kear, (1977)	1
53	Red Moss	363200	410200	Organics	RC	12160 +/-140	**13963 +/- 159**	-	Lake deposits containing coleoptera assemblages	-	Deglacial	Ashworth, (1972) Coope, (1977)	1
54	Mere Sands Wood	344667	415986	Sand	TL	-	-	**12860 +/-1690**	Shirdley Hill Sand , post dates glacial deposits	-	Deglacial	Bateman (1995)	11
55	Dimlington, Holderness	539300	421700	Organics	RC	18240 +/-250	**21734 +/- 372**	-	Between basement and skipsea tills	Glacier overrode area after this time; max age for onset of Dimlington stadial	Advance	Penny et al (1969), Catt, (1987)	1; 2
				Organics	RC	18500 +/-400	**22043 +/- 497**	-			Advance		1; 2
56	River Aire	478356	425258	Bone	RC	38600 +1720/ -1420	**43492 +/-2199**	-	Remains from silt above sands and gravel	Approximate location, mammoth	Advance	Gaunt et al. (1970)	1

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57	Roos	527400	428800	Peat	RC	13045 +/-270	**15190 +/- 335**	-	Organics from kettle hole	-	Deglacial	Beckett (1981)	2
58	Brantingham	493850	429180	Bone	RC	21835 +/-1600	**26165 +/- 1973**	-	In or at the base of lacustrine sediments	Max age for Lake Humber 1	Advance	Gaunt (1974, 1976)	2
59	Eppleworth	497644	433295	Loess	TL	-	-	**17500 +/-1600**	Solifluction deposit below Drab till incorporates loess	Reassessment of originally derived age below	Advance	Wintle and Catt, (1985)	1
60	Wolds dip slope	499251	433295	Sand	TL	-	-	**16600 +/-1700**	Beneath Skipsea till	-	Advance	Wintle and Catt, (1985)	2
61	Selby	458130	437020	Peat	RC	10469 +/-60	**12398 +/- 109**	-	Peat above levee sand	-	Deglacial	Jones and Gaunt, (1976)	1
62	Poulton-le-Flyde	333091	438646	Bone	RC	12400 +/-300	**14325 +/- 425**	-	-	Elk	Ice free	Jacobi et al. (1986)	1
				Bone	RC	21250 +/-250	25822 +/- 360	-		Elk, anomalously old, discarded from analysis as unreliable	-	Gillespie et al (1985)	3
				Lake mud	RC	11665 +/-140	**13524 +/- 141**	-		-	Deglacial	Hallam et al. (1973)	1
				Lake mud	RC	12200 +/-160	**14014 +/- 202**	-			Deglacial		1
63	York	460675	463835	Organics	RC	9950 +/-180	**11433 +/- 300**	-	Above blown sand	-	Deglacial	Matthews, (1970)	1
				Peat	RC	10700 +/-190	**12619 +/- 193**	-	Peat from lower part of blown sand	-	Deglacial		1
64	Victoria Cave	383800	465000	Antler	RC	10810 +/-100	**12724 +/- 85**	-	Rests directly on glacial deposits	-	Deglacial	Hedges et al (1992)	3
				Bone	RC	10970 +/-120	**12851 +/- 103**	-		Reindeer	Deglacial		3
				Bone	RC	11590 +/-130	**13451 +/- 139**	-			Deglacial		3
				Antler	RC	10220 +/-110	**11936 +/- 217**	-	-	-	Ice free		3
				Antler	RC	11750 +/-120	**13604 +/- 115**	-			Ice free		3
65	Kinsey Cave	380400	465690	Antler	RC	11270 +/-110	**13112 +/- 116**	-	-	Reindeer	Ice free	Hedges et al (1992)	3
66	Coniston Dib Cave	399100	468400	Bone	RC	11210 +/-90	**13052 +/- 89**	-	Human occupation	-	Ice free	Hedges et al (1992)	3
67	West Heslerton	492050	475650	Organics	RC	25800 +/-500	**31000 +/- 586**	-	-	-	Ice free	Hedges et al (1994)	3
				Charcoal	RC	33700 +/-1000	**39074 +/- 992**	-			Ice free		3
68	Seamer Carr	502800	480900	Peat	RC	10950 +/-90	**12834 +/- 79**	-	Post dates shoreline of glacial lake	-	Deglacial		3
				Peat	RC	11010 +/-120	**12884 +/- 103**	-			Deglacial		3
				Organics	RC	10413 +/-210	**12250 +/- 337**	-	Human occupation	-	Ice free	Godwin and Willis (1959)	3
69	Glen Ballliera, Isle of Man	233331	495277	Organics / Peat	RC	15150 +/-350	18254 +/- 522	-	Overlying Jurby Formation, from base of kettle hole	Possible contamination.	-	Thomas et al. (2004), Tooley (1977)	-
				Moss	RC	18550 +/-185	22154 +/- 213	-	Overlying Orrisdale Formation	Possible hard water error as for sample below?	-	Thomas et al. (2004)	
				Moss	RC	18700 +/-500	22272 +/- 609	-			-		
				Plant macro	AMS	12492 +/-95	**14459 +/- 199**	-	Within kettle hole	Most recent date regarded as reliable	Deglacial	Roberts et al (2006)	
				Moss	RC	18900 +/-330	22502 +/- 371	-	Sample from base of kettle hole located above calcareous till	Possible hard water contamination; discarded from analysis as unreliable	-	Shotton and Williams, (1971, 1973)	1; 2
				Plant fragments	RC	12645 +/-280	**14672 +/- 406**	-	Sample from within detrital mud 30-35cm above moss sample	-	Deglacial	Shotton and Williams (1971)	4
70	Jurby, Isle of Man	234987	499174	Organics	RC	12890 +/-360	**14988 +/- 471**	-	Overlying Jurby Formation	-	Deglacial	Thomas et al. (2004)	-
				Moss	RC	18400 +/-500	21905 +/- 638	-	Overlying Orrisdale Formation	Kettle hole: possible hard water error?	-		
				Plant macro	AMS	12276 +/-45	**14071 +/- 78**	-	Within kettle hole	-	Deglacial	Roberts et al (2006)	-
71	Blelham Tarn	336666	500527	Organics	RC	14280 +/-230	**16783 +/-388**	-	Below YD sediments, on top of clay	-	Deglacial	-	8
72	Blelham Bog	336319	500686	Organics	RC	14330 +/-230	**16865 +/- 396**	-	Kettle hole	-	Deglacial	Pennington, (1977)	4
73	Low Wray Bay, Lake Windermere	337852	501327	Organics	RC	14623 +/-360	**17386 +/- 641**	-	Organics within silt above laminated clay	-	Deglacial	Coope and Pennington (1977)	2
74	Lake Windermere	337861	501333	Organics	RC	14557 +/-280	**17263 +/- 515**	-	-	-	Deglacial	Pennington, (1977)	4
75	Scandal Beck	375400	504861	Organics	RC	36300 + 2100/ – 1700	**41469 +/- 1910**	-	Underlying boulder clay	-	Advance	Shotton et al, (1970)	-
76	Seamer Carrs	448600	509700	Pollen	RC	13042 +/-140	**15191 +/- 187**	-	Birch pollen peak above glacial and gravel	-	Deglacial	Jones, (1976)	1

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77	Kildale Hall	460900	509700	Organics	RC	16713 +/-340	19859 +/- 369	-	Kettle hole in outwash on basal organic material	Min age for deglaciation on northern slopes of Cleveland Hills. Possibly contaminated.	-	Jones, (1977)	1
78	Neasham	434000	510000	Bone	RC	10851 +/-630	**12664 +/- 741**	-	Skeleton of alces alces (elk) from Zone II muds	-	Deglacial	Blackburn, (1952)	1
79	St Bees	296500	511500	Wood	RC	12560 +/-170	**14564 +/- 285**	-	On St Bees Moraine	Considered reliable	Deglacial	Coope and Joachim (1980)	4
				Organics	RC	13290 +/-310	15070 +/- 398	-	-	Likely hard water effect discarded from analysis as unreliable	-		
80	Stranraer	209928	558669	Shell	RC	28940 + 850/ – 770	**33985 +/- 890**	-	Overridden by ice	-	Advance	Sutherland (1986)	-
81	Redkirk Point	330000	565300	Peat	RC	12290 +/-250	**14163 +/- 347**	-	Basal peat	-	Deglacial	Bishop and Coope, (1977)	4
82	Kilmaurs	241000	641000	Tusk/Antler	RC	13700 +/-1300	16096 +/- 1732	-	Bed of clay underlying a till and an arctic shell bed	Elephant/reindeer used to support Perth readvance, regarded as unreliable as second date from deposits gave a date of >40,000 (Sissons 1981)	-	Gregory and Currie (1928)	13
83	Roberthill	223176	643249	Wood	RC	12940 +/-250	**15066 +/- 319**	-	Sample within basal peat overlying gravel	-	Deglacial	Bishop and Coope, (1977)	4
84	Berwick	398200	653200	Shells	RC	41100	No error so not calibrated	-	Gravel layer underlying till	Maximum RC date so excluded from analysis	-	Sissons (1967)	
85	Kilcohman, Islay	121500	663500	Sand	TL	-	-	41400 +4500 - 4300	Clay sediments +70m OD Glaciomarine sediments with no evidence of overriding	Support MIS 4 Ice margin on Islay possibility of ice free enclave in Late Devensian	-	Dawson et al (1997)	
				Sand	TL	-	-	51400 +5700 - 5500			-		
				Sand	TL	-	-	53900 +6300 - 5900			-		
86	Gallowhill, Paisley	249618	665737	Shell	RC	12610 +/-210	**14122 +/- 294#**	-	Marine clay	-	Deglacial		8
				Shell	RC	12615 +/-230	**14136 +/- 319#**	-			Deglacial		8
				Shell	RC	15625 +/-240	18480 +/- 310#	-		Contamination by old carbon cannot be ruled out	-	Peacock (1971)	8
87	Turnyland Farm	247080	669220	Shell	RC	12458 +/-80	**13909 +/- 87#**	-	Clyde beds	-	Deglacial	Browne et al (1983)	
88	Garnieland Farm	247680	669400	Shell	RC	12011 +/-80	**13534 +/- 88#**	-	Clyde beds	-	Deglacial	Browne et al (1983)	
				Shell	RC	12424 +/-157	**13891 +/- 159#**	-			Deglacial		
				Shell	RC	13147 +/-221	**14904 +/- 300#**	-			Deglacial		
89	Inchinnan	247956	670108	Shell	RC	12840 +/-150	**14467 +/- 268#**	-	Marine bed	-	Deglacial	Hedges et al (1989)	3
				Shell	RC	10410 +/-100	**11624 +/- 228#**	-			Deglacial		3
90	Bishopbriggs	260060	672297	Bone	RC	27550 +/-790	**32886 +/- 851#**	-	Remains within sands below till	Woolly rhinoceros	Advance	Rolfe (1966), Sissons (1967b)	1
91	Wester FulWood	246056	674053	Shell	RC	12650 +/-200	**14174 +/- 296#**	-	Clay below terrace gravel	Late glacial sea in Clyde	Deglacial	Bishop and Dickson (1970)	8
				Shell	RC	13020 +/-220	**14733 +/- 325#**	-			Deglacial		8
92	Inverleven	238968	675066	Shell	RC	12300 +/-120	**13780 +/- 106#**	-	Top of glaciomarine bed	-	Deglacial	Hedges et al (1989)	3
93	Dumbarton	237275	675481	Shell	RC	11805 +/-205	**13318 +/- 213#**	-	Marine horizon above boulder clay	-	Deglacial	-	8
94	Cardross	231428	678080	Shell	RC	11787 +/-122	**13300 +/- 139#**	-	Laminated marine sediments	-	Deglacial	-	8
95	Kinneil Kerse	296300	681200		RC	13360 +/-120	**15160 +/- 167**	-	Marine unit	-	Deglacial	Hedges et al (1988b)	3
96	Townhead	230823	682435	Shell	RC	12110 +/-70	**13626 +/- 74#**	-	-	-	Deglacial	Browne et al (1983)	9
				Shell	RC	12190 +/-70	**13694 +/- 70#**	-			Deglacial		9
97	Balloch	237253	684042	Shell	RC	11320 +/-130	**12860 +/- 110#**	-	-	-	Deglacial	Browne and Graham (1981)	9
98	Balglass Burn	258110	686630	Coleoptra	AMS	30080 +/-200	**35481 +/- 230**	-	Organic sample from unit above diamicton and below sand and diamicton attributed to LGM and drumlins in area	-	Advance	Brown et al. (2007)	-
				Coleoptra	AMS	30650 +/-220	**36017 +/- 246**	-			Advance		
				Pollen	AMS	32770 +/-290	**38168 +/- 328**	-			Advance		
				Pollen	AMS	32800 +/-280	**38198 +/- 318**	-			Advance		
				Pollen	AMS	34480 +/-340	**39844 +/- 376**	-			Advance		
				Pollen	AMS	32768 +/-151	**33418 +/- 227**	-			Advance		
				Humic	RC	35575 +425/ - 405	**40877 +/- 424**	-			Advance		
				Humin	AMS	32460 +435/ - 410	**37854 +/- 466**	-			Advance		

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99	Rhu	224394	687257	Shell	RC	11520 +/-250	**13042 +/- 235#**	-	-	-	Deglacial	Rose (1980); Otlet and Walker (1979)	9
100	Drymen	247436	688514	clay-gyttja	RC	12510 +/-310	**14479 +/- 445#**	-	Oldest limnic terrestrial sediments	-	Deglacial	Vasari (1977)	12
				Shells	RC	11700 +/-170	**13209 +/- 179#**	-	Gravel band in a sand pit		Deglacial	Simpson (1933)	13
101	Lochgilphead	181900	691300	Shell	RC	12830 +/-120	**14452 +/- 232#**	-	Marine bed deposited during Windermere IS	-	Deglacial	Hedges et al (1989)	3
				Shell	RC	13020 +/-130	**14757 +/- 198#**	-			Deglacial		3
102	Menteith	256182	698355	Shell	RC	11800 +/-170	**13313 +/- 183#**	-	Glacially transported marine clay interbedded with fluvioglacial sediment	-	Deglacial	Sissons (1967b)	8
103	Loch Goil	219572	698508	Shell	RC	12260 +/-150	**13748 +/- 132#**	-	-	-	Deglacial	Sutherland (1981)	9
104	Doune Lodge, Callander	262700	706700	Peat/gyttja	RC	12750 +/-120	**14851 +/- 170**	-	Basal peat of kettle hole in glaciofluvial deposits	-	Deglacial	Lowe, (1978)	2
105	Easter Kilwiss, Cupar	327950	710180	Plant material	RC	13636 +/-130	**15873 +/- 187**	-	Late glacial marine sediments	Errol beds	Deglacial	Peacock and Browne (1998)	
106	Gallowflat	321200	720900	Shell	AMS	13340 +/-60	**15143 +/- 118#**	-			Deglacial	Peacock and Browne (1998)	
				Shell	RC	14205 +/- 50	**16143 +/-126#**	-	Marine unit	Errol beds	Deglacial		
				Shell	RC	14260 +/- 60	**16216+/- 136#**	-			Deglacial	Peacock (2002)	
				Shell	RC	13710 +/- 130	**15561 +/-183#**	-			Deglacial		
				Foram	AMS	13675 +/-40	**15521 +/- 116#**	-	Marine mud above till	-	Deglacial	McCabe et al (2007)	
				Foram	AMS	13655 +/-45	**15498 +/- 118#**	-		Suggest date for Perth readvance	Deglacial		
107	Inchcoonans Claypit	324100	723400	Bivalve	RC	13090 +/-140	**14847 +/- 197#**	-		Min age; age lower than expected	Deglacial	Hedges et al (1989)	3
				Seaweed	RC	13650 +/-70	**15498 +/- 133#**	-	Type site for Errol beds,	Errol beds No. 3 borehole	Deglacial	Peacock and Browne (1998)	
				Shell	RC	13710 +/-80	**15561 +/- 140#**	-			Deglacial		
108	Morton	346700	725700	Charcoal	RC	12200 +/-240	**14044 +/- 305**	-	Human occupation	-	Ice free	Switsur and West (1972)	3
109	Kinlochspelve	166529	725833	Shell	RC	11330 +/-170	**12869 +/- 144#**	-	-	-	Deglacial	Gray and Brooks (1972)	9
110	Barry claypit	354700	734700	Shell	RC	14350 +/-170	**16354 +/- 267#**	-	Errol beds, before Windermere interstadial	-	Deglacial	Peacock and Browne (1998); Hedges et al (1989)	3
111	Beinn Inverveigh	227797	738840	Boulder	CO	-	**-**	**12900 +/-1500**	From highest point of boulders on the summit ridge of Beinn Inverveigh	Oldest date	Deglacial	Golledge et al. (2007)	-
				Boulder	CO	-	-	**11600 +/-1000**		-	Deglacial		
				Boulder	CO	-	-	**12500 +/-900**			Deglacial		
				Boulder	CO	-	-	**12900 +/-1000**		Oldest date	Deglacial		
112	Balure of Shian	189620	742160	Bivalve	RC	10960 +/-120	**12561 +/- 129#**	-	Portlandia arctica from shelly lenticule at base of cliff in marine silts overlain by beach gravels	Samples from glaciomarine silts immediately within limit of former Creran glacier	Deglacial	Hedges et al (1988a)	
113	Aberdeen Ground Beds	679031	748241	Wood	RC	32682 +530/ - 500	**37728 +/-531#**	-	Within cold shallow marine sediments	-	Advance		8
				Wood	RC	47750 + 1940/ - 1560	Beyond calibration curve	-			-		
114	South Shian, Arglishire	198466	748983	Shell	RC	11430 +/-220	**12958 +/- 198#**	-	Glacially disturbed marine clay below LLR till	-	Deglacial		8
				Shell	RC	11530 +/-210	**13047 +/- 199#**	-			Deglacial		
115	Lunan Bay	369512	752363	Foram	AMS	17065 +/-40	**19860 +/-76#**	-	Marine mud below ice contact gravel	Propose readvance of the last British Ice Sheet c. 18 ka BP termed the 'Lunan Bay' readvance. Reliability questioned by Peacock et al (2007).	Advance	McCabe et al (2007)	
				Foram	AMS	17720 +/-50	**20545 +/-83#**	-			Advance		
116	Barra Fan	-45641	757980	Shell	AMS	13075 +/-120	**15229 +/- 169#**	-	Borehole 56/-10/36 depth 431.5cm	-	-	Kroon et al (2000)	
117	Springfield Claypit	336300	759800	Shell	RC	12510 +/-80	**13954 +/-95#**	-	Errol beds	-	Deglacial	Peacock and Browne (1998)	

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118	Montrose	369200	759800	Shell	RC	11110 +/-210	**12680 +/- 200#**	-	Errol beds	-	Deglacial	Peacock and Browne (1998)	
				Shell	RC	10610 +/-220	**12513 +/- 267#**	-			Deglacial		
119	Benholm Burn	379500	769200	Pollen	RC	42000	No error so not calibrated	-	Peats interbedded with till	-	-	Donner (1979)	5
120	Barra Fan	-85824	777269	Shell	AMS	12995 +/-90	**15138 +/- 140#**	-	Borehole 57/-11/59 depth 281-283cm	-	-	Kroon et al (2000)	
121	Marr Bank Beds	461416	792238	Wood	RC	17734 +/-480	21041 +/- 623	-	-	Borehole 74/7, inverted sequence of dates, regarded as unreliable by Sejrup et al (1994), take 15.3 ka as minimum date for deglaciation	-	Sutherland (1984)	8
				Wood	RC	21707 +/-680	26056 +/- 874	-			-		8
				Wood	RC	13171 +/-40	**15335 +/-112**	-			Deglacial	Sejrup et al. (1994)	
122	Loch Etteridge	268800	792900	Clay-gyttja	RC	13151 +/-390	**15308 +/- 484**	-	Oldest limnic terrestrial sediments infilling kettle hole	Possible contamination by mineral carbon	Deglacial	Sissons and Walker (1974)	12
				Clay-gyttia	AMS	12930 +/-40	**15063 +/- 102**	-	Lowest organic horizon	-	Deglacial	Everest and Golledge, (2004)	14
123	Glen Geusachan	299006	793545	Boulders	CO	-	-	**13600 +/-300**	6 samples, 3 from crest of outermost lateral moraine, 2 from crest if innermost lateral moraine	Erratic ^{10}Be mean no erosion	Margin	Everest and Kubik, (2006)	
				Boulders	CO	-	-	14600 +/-600		Erratic ^{10}Be mean, erosion of 5mm/kyr	-		
				Boulders	CO	-	-	15700 +/-700		Erratic ^{10}Be mean. Erosion 10mm/kyr	-		
124	Barra Fan	-76180	801379	Shell	AMS	18115 +/-130	**21543 +/- 224#**	**-**	Silty contourite sedimentation, rare dropstones	Core MD95-2006 depth 1320cm	-	Kroon et al (2000)	
				Shell	AMS	24765+/-280	**29679 +/- 421#**	**-**	Glaciomarine sedimentation with dropstones	Depth 1990cm	-		
				Shell	AMS	26265 +/-270	**31518 +/- 325#**	**-**	Silty contourite sedimentation, rare dropstones	Depth 2140cm	-		
				Shell	AMS	29455 +/-370	**34872 +/- 393#**	**-**		Depth 2260cm	-		
				Shell	AMS	15315 +/-140	**18548 +/- 160#**	**-**	Glaciomarine sedimentation with dropstones	Depth 760cm	-		
				Shell	AMS	29795 +/-470	**35193 +/- 476#**	**-**	Silty contourite sedimentation, rare dropstones	Depth2390cm	-		
125	Glen Einich Moraine	291466	802216	Boulders	CO	-	**-**	**13800 +/-400**	4 samples, 2 from crest of outermost lateral moraine beneath Coire Cregach, 2 from crest of recessional lateral moraine	Erratic ^{10}Be mean no erosion	Margin	Everest and Kubik, (2006)	
				Boulders	CO	-	-	14600 +/-700		Erratic ^{10}Be mean, erosion of 5mm/kyr	-		
				Boulders	CO	-		15800 +/-800		Erratic ^{10}Be mean. Erosion 10mm/kyr	-		
126	Glen Einich	292411	804588	Sand	OSL	-	-	**16700 +/-540**	Within former lake basins	-	Deglacial	Everest and Golledge, (2004)	17
127	Lairig Ghru	294584	805058	Sand	OSL	-	-	**16700 +/-520**	Within former lake basins	-	Deglacial	Everest and Golledge, (2004)	17
128	Glen More Moraine	292519	805479	Boulders	CO	-	-	**14400 +/-400**	4 samples, 2 from proximal slope on fluvioglacial ridge, 2 from crest	Erratic ^{10}Be mean no erosion	Margin	Everest and Kubik, (2006)	
				Boulders	CO	-	-	15400 +/-800		Erratic ^{10}Be mean, erosion of 5mm/kyr	-		
				Boulders	CO	-	-	16600 +/-900		Erratic ^{10}Be mean. Erosion 10mm/kyr	-		
129	Nigg Bay	397528	806191	Sand	OSL	-	-	63000 +/-7000	Glaciofluvial outwash	Max age for deposition of overlying tills	-	Gemmell et al (2008)	
130	Pitfichie	366503	817097	Bedrock	CO	-	-	**17900 +/-2400**	Surface if exposed bedrock/boulder	Granite	Deglacial	Phillips et al. (2008)	
				Bedrock	CO	-	-	**19800 +/-2900**		Granite oldest date	Deglacial		
				Boulder	CO	-	-	**14600 +/-3500**		Granite	Deglacial		
				Boulder	CO	-	-	**17500 +/-2600**		Granite	Deglacial		
131	Abernethy Forest	296700	817500	Sandy-gyttja	RC	12710 + 270/ - 270	**14764 +/- 384**	-	Oldest limnic terrestrial sediments	-	Deglacial	Vasari (1977)	12
132	Bennachie	366309	822618	Bedrock	CO	-	-	29400 +/-2900	-	Granite outlier discarded from analysis as unreliable	-	Phillips et al. (2008)	
				Bedrock	CO	-	-	**19800 +/-2000**		Granite oldest date	Deglacial		
133	Cross Stones	395445	827540	Sand	OSL	-	-	111000 +/-9000	Glaciofluvial outwash overlying till and overlain by till	Questionable date discarded from analysis as unreliable	-	Gemmell et al (2008)	
134	Beinn Mhor col, S. Uist	81400	832200	Boulder	CO	-	-	**14500 +/-900**	Below mapped tramline	Assuming no prior erosion and no erosion during ^{10}Be accumulation	Deglacial	Stone and Ballantyne (2005)	

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135	St Fergus	408899	840655	Shell	RC	14750 + 60/ - 60	**16974 +/- 145**[#]	-	Moranic topography overlies glaciomarine silt	-	Advance	Peacock (1999)	
				Shell	RC	15320 +200/ - 200	**18043 +/- 381**[#]	-			Advance		
				Shell	RC	14880 +200/ - 200	**17221 +/- 382**[#]	-			Advance	Hall and Jarvis, (1989)	16
136	Oldmill	402088	843757	Sand	OSL	-	-	74000 +/-6000	Glaciodeltaic toesets overlain by till including rafts of sediment from Moray Firth	-	-	Gemmell et al (2008)	
137	Clava	276570	844100	Shell	RC	43800 +/-3300	Beyond range of calibration curve	-	-	-	-	Hedges et al (1993)	3
138	Toddlehills	406585	845601	Sand	OSL	-	-	31000 +/-2000	Glaciofluvial outwash overlying till	Min age for underlying till and glaciolacustrine sediments NO overlying till therefore no MIS 2 glaciation?	-	Gemmell et al (2008)	
139	Shelf South of St Kilda	11681	846993	Shells	RC	22480 +/-300	**26625 +/- 367**[#]	-	Unit covering outer shelf/ west of morainal banks on the shelf	Approximate location; contemporaneous with morainal banks	Margin	Peacock et al (1992); Hedges et al (1988)	2
140	Wester Rora	405162	848529	Sand	OSL	-	-	76000 +/-5000	Glaciolacustrine under glaciodeltaic sand	Possible incomplete zeroing	-	Gemmell et al (2008)	
				Sand	OSL	-	-	101000 +/-13000	Glaciofluvial outwash	Questionable date	-	Gemmell et al (2008)	
141	Woodside of Auchlee			Sand	OSL	-	-	108000 +/-8000	Glaciofluvial outwash	Questionable date	-	Gemmell et al (2008)	
142	Crossbrae Farm	375300	851200	Peat	RC	22380 +/-250	26902 +/- 309	-	Underlain by probable early Devensian till and overlain by solifluction breccia	Discarded from analysis as unreliable	-	Hall, (1984)	1
				Peat	RC	26400 +/-170	31664 +/- 234	-			-		
				Humic carbon	RC	44030 + 910/ - 820	**48151 +/- 1232**	-	-	Min ages for Crossbrae peat bed earlier ages are unreliable	Advance	Whittington et al (1998)	
				Humic carbon	RC	47180 + 1390/ - 1190	Beyond calibration curve	-			-		
143	Trotternish, Isle of Skye	149100	853200	Outcrop	CO	-	-	**17400 +/-1300**	Below weathering limit	36Cl date of basalt outcrop	Deglacial	Ballantyne et al (1998a)	
				Outcrop	CO	-	-	**17600 +/-1400**		Basalt oldest date	Deglacial		
144	Howe of Blyth	385708	856127	Sand	OSL	-	-	61000 +/-4000	Glaciofluvial outwash in upper gravels	No overlying till – implies ice free during Devensian?	-	Gemmell et al (2008)	
145	Momond Hill	397609	856853	Granite	CO	-	-	**18500 +/-3100**	-	Boulder	Deglacial	Phillips et al. (2008)	
		398506	857224	Boulder	CO	-	-	45600 +/-6200		Granite outlier discarded from analysis as unreliable	-		
		396903	857595	Boulder	CO	-	-	**20000 +/-4300**		Granite oldest date	Deglacial		
146	Teindland, Morayshire	329805	857217	Palaeosol	RC	28140 + 480/ - 456	**33511 +/- 527**	-	Beneath glacial sediments	-	Advance	Fitzpatrick, (1965)	1
				Organics	RC	38400 +1000/ - 1000	**43226 +/- 1289**	-	Soliflucted organic palaeosol horizon below glacial sediments		Advance	Caseldine and Edwards, (1982)	1
				Organics	RC	40710 +2000/ - 2000	**45251 +/- 1325**	-			Advance		1
147	Cromarty	258790	861540	Shell	AMS	12780 +130/ - 130	**14362 +/- 244**[#]	-	Depth 63.17 m to 63.46 m	-	Deglacial	Hedges et al (1988b)	3
148	Loch Droma	221179	878532	Silt	RC	12810 +155/ - 155	**14920 +/- 209**	-	Oldest limnic terrestrial sediments	Min age for Wester Ross Readvance	Deglacial	Kirk and Godwin, (1963)	12
149	Gairloch Moraine	177206	879563	Boulder	CO	-	-	**15532 +/- 2429**	On surface of moraine close to or at moraine crest	-	Margin	Everest et al. (2006)	
		177651	880643	Boulder	CO	-	-	**16087 +/-2885**			Margin		
		177717	880694	Boulder	CO	-	-	**17943 +/-3087**			Margin		
		177768	880782	Boulder	CO	-	-	12526 +/-1817		Regarded as unreliable	-		
150	Cnoc Breac Moraine	179388	883345	Boulder	CO	-	-	11900 +/-3000	On surface of moraine close to or at moraine crest	Approx location, dismissed as outliers	-	Everest et al. (2006)	
		179388	883345	Boulder	CO	-	-	23100 +/-4000			-		
151	An Teallach	207900	886700	-	CO	-	-	**13900 +/-1300**	Below 'trimline'	-	Deglacial	Ballantyne et al (1998c)	
		208000	886800	-	CO	-	-	**14700 +/-1300**		Oldest date	Deglacial		
		208100	886900	-	CO	-	-	**14400 +/-1300**		-	Deglacial		
152	Leac a'Li, South Harris	113400	892600	Boulder	CO	-	-	**15400 +/-1000**	Ice moulded whalebacks below mapped trimline	Age assuming no prior erosion and no erosion during 10 Be accumulation	Deglacial	Stone and Ballantyne (2005)	
				Boulder	CO	-	-	22600 +/-1400		Considered erroneous due to inheritance	-		
153	Meavag, South Harris	114700	896700	Boulder	CO	-	-	**16200 +/-1000**	Ice moulded whalebacks below mapped trimline	Age assuming no prior erosion and no erosion during 10 Be accumulation	Deglacial	Stone and Ballantyne (2005)	

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154	Carragreich, Harris	119200	899100	Boulder	CO	-	-	**17600 +/-1100**	Ice moulded whalebacks below mapped trimline	Age assuming no prior erosion and no erosion during 10 Be accumulation	Deglacial	Stone and Ballantyne (2005)	
				Boulder	CO	-	-	20900 +/-1300		Considered erroneous due to inheritance	-		
155	Hirta, St Kilda	7772	899841	Organic sand	RC	24710 + 1470/ - 1240	**29635 +/- 1755**	-	Below head	Limiting age of interstadial conditions separating local valley glaciations	Advance	Sutherland et al. (1984)	1
156	Tarsaval summit, Harris	115000	905600	Boulder	CO	-	-	19300 +/-1500	Below mapped trimline	Age assuming no prior erosion and no erosion during ^{10}Be accumulation. Considered erroneous due to inheritance	-	Stone and Ballantyne (2005)	
						-	-	19300 +/-1200			-		
157	Oreval col, North Harris	108200	908800	Boulder	CO	-	-	**14100 +/-900**	Below mapped trimline	Age assuming no prior erosion and no erosion during ^{10}Be accumulation	Deglacial	Stone and Ballantyne (2005)	
158	Oreval summit, Harris	108300	910000	Boulder	CO	-	-	**14200 +/-900**	Above mapped trimline	Age assuming no prior erosion and no erosion during ^{10}Be accumulation	Deglacial	Stone and Ballantyne (2005)	
159	Assynt	226493	913833	Speleothems	U	-	-	26000 +/-3000	-	Large errors	-	Atkinson et al (1986)	1
				Speleothems	U	-	-	30000 +/-4000			-		1
				Speleothems	U	-	-	38000 +/-6000			-		1
160	Cam Loch	219572	915501	Organic silt	RC	12956 +/-240	**15086 +/- 304**	-	Oldest limnic terrestrial sediments	Basal late glacial date	Deglacial	Pennington, (1975)b	12
161	Reindeer Cave, Assynt	226800	917000	Antler	RC	24590 + 790/ - 720	**29487 +/- 993**	-	-	Min age for ice free conditions around cave	Ice free	Lawson, (1984)	5
				Antler	RC	25360 + 810/ - 740	**30442 +/- 997**	-			Ice free		1
				Antler	RC	22300 +/-240	26811 +/- 300	-		Possible outlier?	-		3
				Antler	RC	28240 +/-390	**33616 +/- 438**	-		-	Ice free	Hedges et al (1994);	3
				Antler	RC	28800 +/-450	**34200 +/- 487**	-			Ice free		3
				Antler	RC	31490 +/-570	**36866 +/- 597**	-		Min age for ice free conditions around cave	Ice free		3
				Antler	RC	31580 +/-520	**36957 +/- 548**	-			Ice free		3
162	Tolsta Head, Isle of Lewis	137111	926815	Organics	RC	27333 +/-240	**32661 +/- 300**	-	Lake detritus underlying late Devensian till	-	Advance	von Weymarn and Edwards, (1973)	1; 2
163	Scaraben	308321	928429	Boulder	CO	-	-	**18500 +/-2400**	Boulder oldest date	Quartzite	Deglacial	Phillips et al. (2008)	
164	Stornoway	142419	933182	Shell	RC	11260 +/-120	**12811 +/- 101**$^{\#}$	-	Base of LLS sequence	Approximate location	Deglacial	Hedges et al (1989)	3
				Shell	RC	13185 +/-140	**14963 +/- 187**$^{\#}$	-	Overlies equivalent of errol beds		Deglacial		3
				Shell	RC	11650 +/-130	**13155 +/- 139**$^{\#}$	-	-	Approximate location; short lived warm episode	Deglacial		3
165	Garrabost, Lewis	152063	933182	Shell	RC	23000 +/-320	**27221 +/- 387**$^{\#}$	-	Middle/base of glacial deposits	-	Advance	Sutherland and Walker (1984)	9
				Shell	RC	26300 +/-230	**31188 +/- 283**$^{\#}$	-			Advance		9
166	Clyth	330112	938171	Boulder	CO	-	-	11200 +/-1300	-	Sandstone outlier discarded from analysis as unreliable	-	Phillips et al. (2008)	
				Bedrock	CO	-	-	10400 +/-1300	Striated		-		
				Boulder	CO	-	-	**14300 +/-1500**	-	Sandstone, oldest date	Deglacial		
				Bedrock	CO	-	-	**13100 +/-1400**	Striated	Sandstone	Deglacial		
167	Morven	330205	941301	Bedrock	CO	-	-	**16600 +/-2100**	-	Quartzite	Deglacial	Phillips et al. (2008)	
		330600	942397	Bedrock	CO	-	-	**17200 +/-2500**		Quartzite oldest date	Deglacial		
168	Hill of Yarrows	330205	941301	Boulder	CO	-	-	**16700 +/-1700**	-	Sandstone	Deglacial	Phillips et al. (2008)	
				Bedrock	CO	-	-	**17200 +/-3000**		Sandstone oldest date	Deglacial		
169	Peicir, Lewis	147241	955685	Shell	RC	35630 + 1520/ - 1270	**40571 +/- 1421**$^{\#}$	-	Middle/base of glacial deposits	-	Advance	Sutherland and Walker (1984)	9
				Shell	RC	37320 + 1130/ - 990	**42107 +/- 1006**$^{\#}$	-			Advance		
170	North Sea core 91-7	543138	956591	Mollusc	AMS	13215 +/-110	**15389 +/- 163**$^{\#}$	-	In situ mollusc 1.88m	Glaciomarine unit no drop stones	Ice free	Sejrup et al (1994)	

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171	North Sea Fladen Ground core 77/2	541640	957939	Foram mixed	AMS	14390 +/-460	**17004 +/- 758[#]**	-	Fine grained glaciomarine unit, no drop stones overlain by coarser unit	In situ 2.5m	Ice free	Sejrup et al (1994)	
				Foram mixed	AMS	14265 +/-165	**16751 +/- 284[#]**	-		In situ 2.8m	Ice free		
				Foram mixed	AMS	17395 +/-270	20593 +/- 314[#]	-		In situ 2.99m rejected as anomalously high	-		
				Mollusc	AMS	14465 +/-200	**17089 +/- 369[#]**	-	Coarse grained diamicton, glaciomarine with dripstones, fines upwards. Dates are mixed and reversed, regard mollusc dates as most reliable	In situ 8.89m mollusc dates regarded as reliable	Ice free		
				Foram mixed	AMS	19190 +/-225	22814 +/- 298[#]	-		In situ 9.0m rejected as anomalously high	-		
				Foram mixed	AMS	14825 +/-115	17753 +/- 270[#]	-		In situ 12.7m	-		
				Foram mixed	AMS	17670 +/-165	20913 +/- 232[#]	-		In situ 16.4m rejected as anomalously high	-		
				Mollusc	AMS	14555 +/-155	**17242 +/- 311[#]**	-		In situ 17.55m mollusc dates regarded as reliable	Deglacial		
				Foram mixed	AMS	16195 +/-185	19322 +/- 187[#]	-	Fine grained partly laminated unit (glaciomarine) above till, in situ mollusc and rich in forams	In situ 18m	-		
				Mollusc	AMS	20955 +/-430	**25063 +/- 591[#]**	-		In situ 18.48m mollusc dates regarded as reliable	Deglacial		
				Foram mixed	AMS	22775 +/-335	27352 +/- 402[#]	-		In situ 18.52m	-		
				Foram mixed	AMS	19835 +/-330	23676 +/- 417[#]	-		In situ 19.22m	-		
172	West Dell, Lewis	148848	962114	Shell	RC	34470 + 720/ - 660	**39499 +/- 719[#]**	-	Middle/base of glacial deposits	-	Advance	Sutherland and Walker (1984)	9
				Shell	RC	37070 + 970/ - 860	**41892 +/- 870[#]**	-			Advance		
173	Traigh Chumil, Lewis	148848	965329	Shell	RC	39500 + 1270/ - 1100	**43998 +/- 1116[#]**	-	Middle/base of glacial deposits	-	Advance	Sutherland and Walker (1984)	9
				Shell	RC	39850 + 1270/ - 1100	**44302 +/- 1119[#]**	-			Advance		
174	North Sea core Sleipner	619204	965894	Shell fragment	AMS	32845 + 550/ - 559	**38238 +/- 569[#]**	-	Within till unit	Glaciation covering this core after this time	Advance	Sejrup et al (1994)	
175	Witch Ground Basin	539699	966786	Shells	RC	13660 +/-180	**15510 +/- 231[#]**	-	2.4-2.6 m depth	Dates suggest 13.5 ^{14}C ka BP for influx of temperate North Atlantic water to central North Sea	Deglacial	Hedges et al (1988b)	3
				Shells	RC	21320 +/-280	25090 +/- 402[#]	-	2.8-3 m depth	Possible reworking discarded from analysis as unreliable	-		
				Shells	RC	14180 +/-170	**16128 +/- 247[#]**	-	4-4.2 m depth	Dates suggest 13.5 ^{14}C ka BP for influx of temperate North Atlantic water to central North Sea	Deglacial		
				Shells	RC	13460 +/-150	**15281 +/- 199[#]**	-	5.2-5.4 m depth		Deglacial		
				Shells	RC	13620 +/-150	**15464 +/- 201[#]**	-	5.2-5.4 m depth		Deglacial		
176	Dunnett Head	319913	975221	Bedrock	CO	-	-	**15300 +/-1900**	Striated	Sandstone oldest date	Deglacial	Phillips et al. (2008)	
		319998	975548	Boulder	CO	-	-	**14600 +/-1500**	-	Sandstone	Deglacial		
		320052	975617	Boulder	CO	-	-	53300 +/-5400	-	Sandstone outlier discarded from analysis as unreliable	-		
177	Ward Hill	321625	1001280	Bedrock	CO	-	-	29300 +/-2900	-	Sandstone outlier discarded from analysis as unreliable	-	Phillips et al. (2008)	
		322899	1002553	Boulder	CO	-	-	**17000 +/-1700**		Sandstone oldest date	Deglacial		
178	Stromness	325054	1009677	Quartz vein	CO	-	-	**12800 +/-2000**	-	-	Deglacial	Phillips et al. (2008)	
				Bedrock	CO	-	-	**14800 +/-2400**	-	Gneiss	Deglacial		
				Boulder	CO	-	-	**17900 +/-2400**	Oldest date	Gneiss	Deglacial		
				Boulder	CO	-	-	**13700 +/-2000**	-	Gneiss	Deglacial		
179	Yesnaby	323326	1014251	Boulder	CO	-	-	**13700 +/-2200**	-	Gneiss	Deglacial	Phillips et al. (2008)	
				Boulder	CO	-	-	**14100 +/-2200**	Oldest date	Gneiss	Deglacial		
				Boulder	CO	-	-	11800 +/-1800	-	Sandstone outlier	-		
				Boulder	CO	-	-	**14100 +/-2200**	Oldest date	Sandstone	Deglacial		
180	Mill Bay	367448	1024801	Shell	RC	38300 + 2100/ - 1800	**42947 +/- 1859[#]**	-	-	-	Advance	Rae (1976)	9
181	Witch Ground	613373	1073022	Shell	RC	13175 +/- 70	**14954 +/- 117[#]**	-	4.8-4.9m depth in core BGS vibrocore 59/+01/156	-	Deglacial	Peacock (1995)	

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182	Loch of Clickhimin	446500	1141000	Organics	RC	12090 +/-900	**14033 +/- 1049**	-	Base of 150 cm core	Min date for deglaciation	Deglacial	Hoppe (1974)	8
183	Bergen Bank	601491	1141572	Shell	AMS	11290 +/-55	**12830 +/-56**	-	Vibrocore 60/00/98 1.7 m	-	Deglacial	Peacock (1995)	
184	Pobie Bank	521471	1146330	Shell	AMS	12670 +/-130	**13748 +/- 114[#]**	-	Vibrocore 60/00/49; late glacial shell bed above diamicton, 0.8 m	-	Deglacial	Peacock (1995)	
185	Sandwater	447759	1146472	Organics	RC	10055 +/-300	**11637 +/- 502**	-	From base of organic section	Min for deglaciation	Deglacial		8
186	Sel Ayre	417600	1154000	Humic	RC	22450 +/-80	26983 +/- 156	-	Organic band with sand and gravel overlies breccia and till units	Possible contamination discarded from analysis as unreliable	-	Mykura and Phemister, (1976)	15
187	Loch Brouster	418086	1160975	Organics	RC	15080 +/-850	17999 +/- 1162	-	Non glacial deposit	Possibly contaminated with old carbon	-		8
188	Fugla Ness	431200	1191300	Peat	RC	34000 +900/ -800	39369 +/- 890	-	Peat overlies till, and overlain by breccia and another till	Too young based on pollen spectra in peat discarded from analysis as unreliable	-	Page (1972)	15
				Peat	RC	37000 + 1200/-1100	42123 +/- 1066	-			-	Birnie et al. (1993)	
				Wood	RC	38980 + 950/-850	43839 +/- 845	-			-	Harkness (1981)	15
				Peat	RC	40000 + 2000/-1600	44381 +/- 1317	-			-	Mykura and Phemister, (1976)	15
				Wood	RC	43970 + 1270/-1020	48151 +/- 1232	-			-		
				Wood	RC	44970 + 1450/-1230	Beyond calibration curve	-			-	Birnie et al. (1993)	
				Wood	RC	47500 + 2900/-2100	Beyond calibration curve	-			-		
189	Viking Bank	591088	1209994	Shell	AMS	11405 +/-75	**12928 +/- 69[#]**	-	Vibrocore 60/+/-01/44	Shallow sea 15.5-13.5 14C ka BP	Deglacial	Peacock (1995)	
				Shell	RC	12185 +/-55	**13691 +/- 59[#]**	-			Deglacial		
				Shell	AMS	14050 +/140	**15572 +/-191[#]**	-			Deglacial		
				Shell	AMS	13940 +/-90	**15361 +/- 145[#]**	-	Vibrocore 60/+01/46		Deglacial		3
				Shell	AMS	15860 +/-180	**18733 +/- 171[#]**	-			Deglacial		3
190	Northern North Sea	643453	1264040	Organics	RC	30190 +/-360	35255 +/- 371[#]	-	Within possible littoral or fluvioglacial sediments	Approximate location	-	Rise and Rokoengen (1984)	1
				Shells	RC	31150 +/-1200	36196 +/- 1203[#]	-		Late Weichselian offshore moraine west of Norwegian Trench related to Scandinavian IS	-	Milling (1975)	1
191	Statfjord Field	602187	1297286	Shells	RC	18860 +/-260	22099 +/- 315[#]	-	In till near Statfjord Field	Tampen readvance of Scandinavian Ice Sheet	-	Roekoengen et al (1982)	5
192	Ferrybridge	447441	424178	Sand	OSL	-	-	**16600 +/-1200**	Lake beach sediment overlies till	Date for high stand phase of Lake Humber	Deglacial	Bateman et al. (2007)	
				Sand	OSL	-	-	**20500 +/-1200**	Above till and beneath lake beach	Max age for high stand Lake Humber	Deglacial		
				Sand	OSL	-	-	**23300 +/-1500**	Beneath diamict interpreted as till	Advance down Vale of York	Advance		
193	Cove Farm	448009	400128	Sand	OSL	-	-	14200 +/- 2800	Sand below clay	Overestimates due to incomplete resetting	-	Bateman et al (2001)	
				Sand	OSL	-	-	14100 +/- 2100	Basal sand		-		
				Wood	RC	11760 +/-150	**13611 +/-141**	-	Organic unit	Drainage event of Lake Humber	Deglacial		
194	Burnside	332590	728610	Shell	RC	12990 +/-85	**14721 +/-141[#]**	-	Marine sediments	-	Deglacial	Peacock (2002)	
195	Powgavie	329120	725320	Shell	RC	13124 +/-90	**14889 +/- 134[#]**	-	Marine sediments	-	Deglacial	Peacock (2002)	
				Shell	RC	13165 +/-80	**14937 +/-101[#]**	-	Marine sediments		Deglacial		
196	Stirling	269500	696140	Shell	RC	11890 +/-60	**13409 +/-85[#]**	-	Marine sediments	-	Deglacial	Peacock (2002)	
197	IMAU	265580	699610	Shell	RC	12945 +/-65	**14662 +/-124[#]**	-	Marine sediments	-	Deglacial	Peacock (2002)	
198	Moss-side of Boquhapple	265880	698480	Shell	RC	12390 +/-60	**13845 +/-65[#]**	-	Marine sediments	-	Deglacial	Holloway et al (2002)	
				Shell	RC	12640 +/-50	**14096 +/-86[#]**	-	Marine sediments		Deglacial		
				Shell	RC	13200 +/-50	**14977 +/-104**	-	Marine sediments		Deglacial		